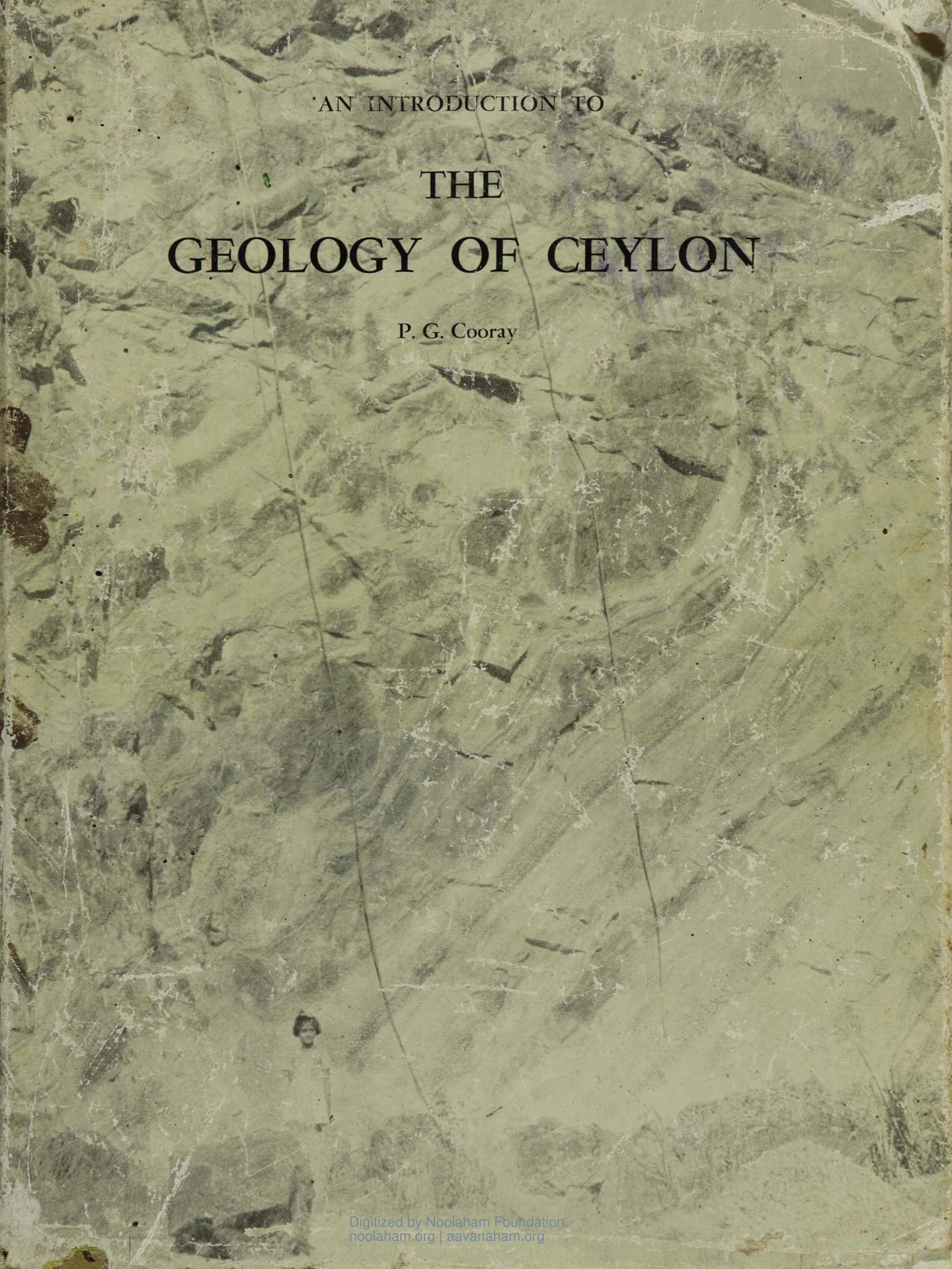
AN INTRODUCTION TO

THE
GEOLOGY OF CEYLON

P. G. Cooray



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GEOLOGY OF CEYLON

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Frontispiece

Flat-lying Miocene limestone of the Jaffna Peninsula as seen in the Kankesanthurai Quarry—(*Joe Perera*)

AN INTRODUCTION TO

THE GEOLOGY OF CEYLON

BY

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TO THE MEMORY OF MY FATHER

for his gift

AND FOR MY DAUGHTER

as a gift

FOREWORD

THERE are few subjects which are more likely to arouse a general interest in science than the study of the geology in the countryside around one's home. The science of geology grew up, in the first instance, in Western Europe, and it was there, in the latter part of the 18th century and in the early part of the 19th century, that the principles of geology were first set out. Naturally enough, most attention was paid to the rocks and geological phenomena which could best be studied in Western Europe. But as the science developed, it became clear that in many respects that small part of the earth's surface was by no means typical of our earth as a whole. It is, therefore, a pleasure to find that Dr. Cooray has written a book which provides at the same time an account of the geology of Ceylon, expressed in simple terms, and an introduction to the wider subject of earth science.

Those who are fortunate enough to read this book will find that they are led, step by step, through a remarkable range of geological phenomena, which can be observed on the Island of Ceylon, and are thus brought to an understanding of geological processes. The method that Dr. Cooray has employed, the study of the surrounding rocks and landscape, is precisely the same as was developed by the founders of the science of geology. But whereas they, and so many of the writers of geological textbooks who have followed them, drew many examples from lands where the landscape was fashioned by temperate climates, and where the rocks had accumulated comparatively recently in geological history, Dr. Cooray takes advantage of the rather different and equally remarkable series of geological events which have fashioned Ceylon.

Here, naturally enough, we find the effects of tropical climate, but we also, as the author so clearly shows, have the advantage of studying very old rocks, and of investigating large areas which were never obscured by the younger layers of sediment which are so widespread in some other parts of the world. This situation presents Dr. Cooray with an opportunity to introduce geology in a way which is both logical and novel. He shows us how many of the basic principles of geology can be understood through a study of the ancient rocks of Ceylon, of the younger deposits which have formed around the mass of very old rocks which make up most of the island, and of the landscape as it exists at the present day. With this book, anyone with an interest in the subject can easily teach himself or herself something about the country which will certainly be of interest and may well be of practical profit in addition. The visitor to Ceylon can quickly learn the essentials of the geology of the island, and students of geology, living in other parts of the world where ancient rocks are equally abundant, may well find that this text provides an introduction to the subject which could usefully supplement texts which draw heavily for examples on Europe and North America.

John Sutton.

PREFACE

GEOLOGY being the science of the earth, a knowledge of it is useful to those who live on the earth and by it. The aim of this book is, therefore, to introduce such people to the earth in general, and in particular to that small portion of the earth's crust called Ceylon. This is done by showing the reader how the rocks that build the island's mountains and plains also affect the islander's water supply, agriculture, building, and his aesthetic delight in the beautiful scenery of the land he lives in.

The book is not addressed primarily to the professional geologist, though even he may find something useful within its pages as it incorporates much of the information gained within the last twelve years by the systematic geological mapping carried out by the Geological Survey of Ceylon. It is, on the other hand, quite definitely a book for all those who concern themselves with irrigation, soils, agriculture, industry, engineering, and building, to whom an elementary knowledge of the geology of their own country is essential. It is also intended for the large numbers of teachers and students of geography and the sciences both in the Senior Schools and in the Universities to whom geology has hitherto been a closed subject but whose appetite for some geological knowledge has been whetted. It will certainly be useful to those who will read geology for a University degree in Ceylon. Finally, it is written for the layman who does not fall into any of these categories, yet takes enough interest in his environment to want to know something about the rocks and minerals in his own country and the manner in which they affect his life.

The book is in three parts. Part One, GEOLOGICAL PRINCIPLES AND PROCESSES, explains, very briefly, the fundamental principles, necessary for a proper understanding of the rest of the book, and presumes that the reader has little or no previous knowledge of geology ; it may conveniently be omitted by those who possess such knowledge. This part deals mainly with the origin and structure of the earth, with what rocks are and how they are formed, and with the evolution of life upon the earth during its long history. Part Two, THE GEOLOGY OF CEYLON, describes the major physical features of the island, discusses the nature, origin, and distribution of the main types of rocks and economic minerals found within it, and attempts to tell the story, in broad outline, of the geological evolution of Ceylon. Part Three, GEOLOGY

AND THE COMMUNITY, deals with the ways in which geology influences our own lives in such important spheres as water supply, engineering construction, and agriculture. The Appendix contains matters of academic interest that would probably not interest the general reader; a Glossary, a Geographical Index, and a General Index are provided at the end of the book.

Every account of the geology of a region must inevitably be built on what has been known before, and the present one is no exception. It is therefore a pleasure for me to record here my indebtedness to the many whose writings have influenced my own thinking and on which I have freely drawn. Of these I would like especially to mention A. K. Coomaraswamy (*various*), E. J. Wayland (*various*), F. D. Adams (*The geology of Ceylon*, 1929), J. S. Coates (*The geology of Ceylon*, 1935), D. N. Wadia (*various*), and L. J. D. Fernando (*various*). Although the source of information for every single fact is not recorded in the text, I have indicated the most important, particularly for the benefit of those who wish to read further on specific topics.

The idea of a book on the geology of Ceylon was suggested to me by Professor John Sutton early in 1961, and I began collecting material for it as soon as I returned from London in March that year. Early in 1962, however, it became apparent to me that what was needed first was not a professional and highly academic account but an introductory book on the geology of the island. I found then—and still do—that increasing numbers of people were wanting to know something about the island's geology and mineral resources but did not know from where to get such information. Where the information was available, it was to be found in various professional journals, much of it too technical for the non-geologist to follow. Moreover, many of these publications had been published outside Ceylon and some of the most important of them have long been out of print. It was clear, therefore, that an up-to-date book, written as far as possible in non-technical terms, yet incorporating our present knowledge of the geology of Ceylon, was badly needed. In spite of its obvious shortcomings, it is my hope that such a need will be adequately met by this book. I hope, too, that those who read it will not hesitate to let me know of any errors or omissions, or make suggestions for its improvement.

Many friends have, in various ways, helped in the preparation of the book, and to them I am greatly indebted. Mr. Narayana Money and Mr. Stephen Kumarapeli read the early draft and made several detailed suggestions for its improvement; the former was also largely responsible for compiling the glossary. The Head of the Palaeontological Division of the Geological Survey of India, Dr. Derek Ager, Prof. B. A. Abeywickrema, and Mr. P. Kirthisinghe very kindly checked the lists of fossils found in Appendix III. Mr. Leslie de Silva helped in the drawing up of the table of Gemstones ; and Mr. C. H. L. Sirimanne, Mr. J. W. Herath, and Dr. C. R. Panabokke gave freely of their specialized knowledge of water supply, clays, and soils respectively. Several colleagues in the Geological Survey were instrumental in preparing the Geographical Index. Mr. A. D. N. Fernando helped in selecting suitable aerial photographs for publication, and Mr. E. Weerasinghe gave me invaluable assistance in preparing the figures and the Geological Map for publication. To all of them I would like to offer my grateful thanks.

My thanks are also due to Mr. L. J. D. Fernando, Director of the Geological Survey Department, for access to unpublished data in the records of the Department ; to the Permanent Secretary of the Ministry of Industry and Fisheries for permission to publish the book ; and to Mr. M. J. Perera, Permanent Secretary to the Ministry of Education and Cultural Affairs, and Dr. P. H. D. H. de Silva, Director of National Museums, for making possible its publication in Spolia Zeylanica.

I would like to record my sincere thanks to Professor John Sutton for his original suggestion, his constant encouragement, and for his very kind Foreword.

And last, but certainly not least, I am grateful to my wife for her patience and understanding through the many long evenings during which this book was written.

P. G. C.

Colombo, 31st July, 1966.

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MINERAL MAP OF CEYLON .. *In pocket (inside back cover)*

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AN INTRODUCTION TO

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PART ONE

GEOLOGICAL PROCESSES AND PRINCIPLES

CHAPTER I

ORIGIN AND STRUCTURE OF THE EARTH

Geology is the music of the earth

Hans Cloos, 1954.

The Earth is like a vast orchestra continually playing Enigma Variations on, not one, but a whole series of original themes.

Arthur Holmes, 1965.

What Geology is about

We live today in the Space Age, and we should feel privileged that we do so. It is an age when man's knowledge about the infinite space outside his own planet is increasing by leaps and bounds and when the first steps have already been taken for man to explore that unknown region himself. But knowledge about the other planets in the solar system could not have been acquired until man had first learned a good deal about the planet on which he himself lives—the Earth. It is this science of the earth or *earth science* that is called geology.

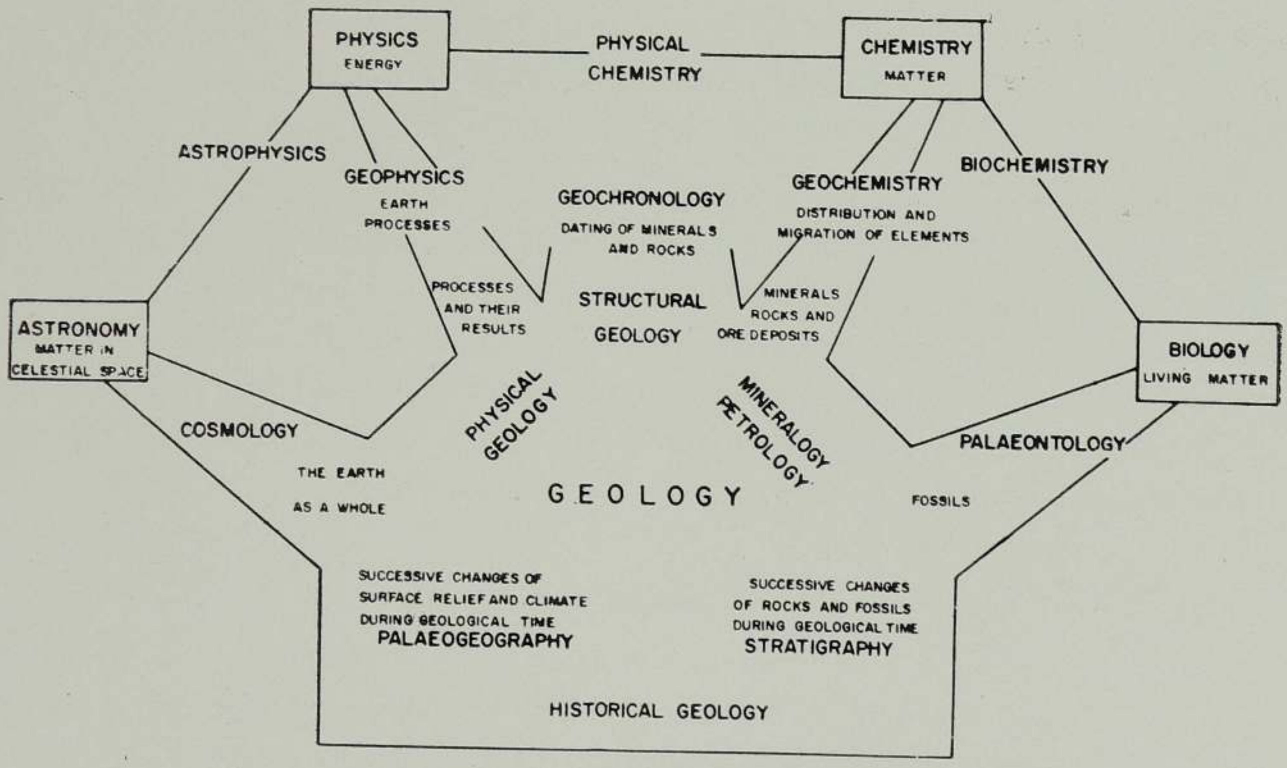

Fig. 1. Subdivisions of the science of geology and their relations to other sciences. (*A. Holmes, 1965*)

GEOLOGICAL PROCESSES AND PRINCIPLES

The story of how the earth was formed, how the rocks we see around us came to occupy their present positions, or how old the mountains are is, we shall find, as fascinating as the wonders of space travel, taking us back thousands of millions of years in time and several miles below the earth's surface. This story, which in fact is what geology is about, is made more exciting by the fact that though now ' dead ', the rocks and mountains were once ' alive ' at the time when they were being formed.

The story has therefore, like some detective stories, to be based largely on circumstantial evidence and on deductive reasoning. But although geology is broadly concerned with the earth as a whole, it is more particularly concerned with the outer, comparatively thin, layer known as the *crust*.

There are many branches of geology, as there are in all other sciences, and each is a specialized subject in its own right (Fig. 1). For example, *geomorphology* deals with the evolution of the surface features of the earth, *petrology* is the study of the rocks of the crust, *mineralogy* is to do with the minerals which are the bricks out of which rocks are made, *palaeontology* is the study of the fossils preserved in the rocks, and *stratigraphy* is the study of the succession of rock strata and the evolutionary history of the crust. Within recent years, two new sciences known as *geophysics* and *geochemistry* have developed ; these deal with the physical and chemical properties of the earth respectively.

We will be concerned in this book with that small portion of the earth's crust which is Ceylon, and especially with the nature, origin, evolution, and distribution, both in time and space, of the rocks in this small area ; such a study is known as *regional geology*. Consequently, we shall have to draw on many of the special aspects of earth science, and some appreciation of general principles and processes is therefore necessary before we can understand fully the geology of our own little island.

The Origin of the Earth

From the beginning of recorded human history we find that man has speculated upon the origin of the earth. The earliest concepts, being either poetic or religious in their approach, were fanciful and picturesque in the extreme, owing to the very limited knowledge man had of himself or of his planet. It was not until the end of the 18th century that what could

ORIGIN AND STRUCTURE OF THE EARTH

be described as the first scientific theory of the earth's origin was put forward. This was the *nebular hypothesis* proposed by the philosopher Emmanuel Kant and elaborated by the Marquis de Laplace in 1796. According to Laplace, the earth was formed by the gradual cooling and contraction of an intensely hot, gaseous mass (or nebula) which was produced by an internal explosion in the sun.

Other theories which followed were based essentially on the idea of the break-up of the sun by the impact or near approach of another star. The best known of this group of theories is the *planetismal hypothesis* of the American geologist, T. C. Chamberlian, at the beginning of the 20th century. According to him, the earth began as a small nucleus of solid meteoric matter and grew by the continued accretion of cold solid particles (or planetismals), all of which originated as matter thrown off by the sun in explosions during the passage of a star near by. The most recent of this group of theories was the one propounded in the 1920's by Sir James Jeans and Sir Harold Jeffreys. It stated that the planets were originally gaseous matter drawn off from the sun merely by the gravitational pull of a passing star, without the aid of explosions in the sun.

Within recent years, however, entirely new and revolutionary views of the Earth's origin have been produced, some of which suggest that the planets were not formed from ' sun matter ' at all. Perhaps the best known of these views is the theory put forward by two Cambridge scientists, R.A. Lyttleton and Fred Hoyle. According to them the sun may once have formed part of a double star or ' binary system ', such systems being very common in the sky even today. The companion of the sun in such a binary system was a *supernova,* a type of star which tends to break up violently owing to atomic explosions within it. When this happened, a huge cloud of brightly incandescent gas was released which was captured gravitationally by the sun to form a gaseous ring. The planets condensed out of such a ring of gas.

We are still, therefore, much in the realm of speculation concerning the origin of the earth and there is as yet no generally accepted theory of how it all began. For example, the earth may once have been in either a hot gaseous state or in a cold solid state, and it may or may not have contracted during its history. What seems to be fairly certain, however, is that the earth and the other planets originated at the same time, and that, so far as we can tell, it is the only planet in the solar system that can support life as we know it.

The Earth's Interior

The earth can most easily be described as a nearly spherical mass of solid and viscous (non-crystalline) material, with a volume of about 260 million cubic miles, a diameter of nearly 8,000 miles (13,000 kms. approximately), and an average density of 5.5*. The outer skin of this mass is known as the *crust,* but our direct knowledge of even this comparatively thin layer of the earth is restricted to the top 25,000 feet or so, the depth to which the deepest oil well (in Texas) has been drilled. The deepest mines in the world are those in the Kolar gold fields of Mysore and the Witwatersrand gold district of South Africa, and these go down only about 10,000 feet. Even the Mohole Project, now going on off the Hawaiian islands in the Pacific, will attempt to penetrate the crust to a surface known as the *Mohorovičić Discontinuity* (see Figs. 2 and 3) at a depth of 31,000 feet, and we can see that this is still only 0.00125 of the radius of the earth!

Some things we do know, such as the fact that the further we descend into the earth the higher the temperature becomes, the increase being of the order of 16°F (9°C) per 1,000 feet. It follows that only a few thousand feet below the surface the temperature must reach the boiling point of water, namely, 212°F (100°C), a fact demonstrated by the frequent presence at the surface of the earth of hot springs and geysers (as in Yellowstone National Park, U.S.A.). If this temperature gradient continues to great depths, the temperature at 30 miles (50km.) below the surface should be 3300°F (1833°C), and at this depth no known rock can remain in a solid state but must be molten. That this is not so we know from the fact that

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* Some dimensions of the earth are :

	Feet	*Metres*
Highest point (Mt. Everest)	29,028	8,848
Greatest depth (Marianas Trench)	36,204	11,035

	Miles	*Km.*
Equatorial radius	3,963	6,378
Equatorial circumference	29,902	40,077

	Millions of	
	Sq. Miles	*Sq. Km.*
Land area (29.2 per cent.)	57.5	149
Oceans and seas (70.8 per cent.)	139.4	361
Total area of earth	196.9	510

Volume	1.08 × 10^{21} cubic metres
Mass	5.98 × 10^{27} grammes
Mean density	5.515 grammes per cubic centimetre

Conversion factors

1 foot	= 0.3048 metre	1 metre	= 3.281 ft.
1 mile	= 1.609 km.	1 km.	= 0.621 mile
1 sq. mile	= 2.59 km.^{2}	1 km.^{2}	= 0.386 sq. mile
1 cubic mile	= 4.17 km.^{3}	1 km.^{3}	= 0.24 cubic mile

even at depths of about 700 km. the rocks are subject to deep-seated earthquakes and behave as if in a solid state. We can therefore assume that high temperatures are confined mainly to the crust of the earth and that both the crust and the portion below it known as the mantle are made up of solid rocks.

At the same time, the periodical extrusion of vast amounts of molten lava through volcanoes and fissures shows that molten rock material does exist within the earth's crust. We must assume therefore that such molten rock material exists in local centres where certain conditions have raised the temperature so much as to melt the earth material present. Some of the heat in the crust is probably due to radioactivity present in the rocks, but this would not be sufficient for the fusion of rocks to make lavas. Here again we are uncertain of the true causes of rock melting at depth, and the most promising of the theories put forward is that heat is brought up by convection currents under the crust or that the fused rocks may be dragged down to great depth by the same currents and melted.

Another thing we do know about the earth's interior is that pressure also increases with depth and that, at the centre of the earth, it is of the order of 20,000 tons per square inch. As a result of such fantastically large pressures the earth materials found in the deeper parts of the earth are condensed into smaller and denser shapes.

Most of our knowledge of the earth's interior, however, comes to us in the form of indirect evidence from several sources. One such source is the study of *meteorites*, those 'stones from the sky' that have fallen at various times in its history on several spots of the earth's surface. Meteorites are masses of solid matter of varying sizes from outer space which reach the surface of the earth with great impact, sometimes great enough to form enormous holes or 'meteoric craters' on the surface. Meteor Crater in Arizona, for example, is 4,250 feet wide and 570 feet deep, and a meteorite fall in Siberia on February 12, 1947, produced a cluster of over 100 craters, some being 90 feet wide and 40 feet deep. Meteorites are of two types, namely, stony meteorites (composed mainly of silicates) and iron meteorites (of iron and nickel). The nickle-iron meteorites have the same density as the interior of the earth, and measurements of the radioactivity of meteorites and of rocks from the earth show that they are roughly of the same age. From this and other evidence it is now clear that meteorites belong to the solar system, of which the earth is a part, and that they may represent the interior of a planet, formed at the same time and in the same way as the earth, which must have broken up in a gigantic collision or explosion.

Another and more important source of information about the earth's interior comes from *earthquake waves.* When an earthquake takes place, three types of vibration or ' waves ' are generated and radiate in all directions from the centre or focus of the disturbance. The passage of such waves through any point at the earth's surface can be recorded on a seismograph.

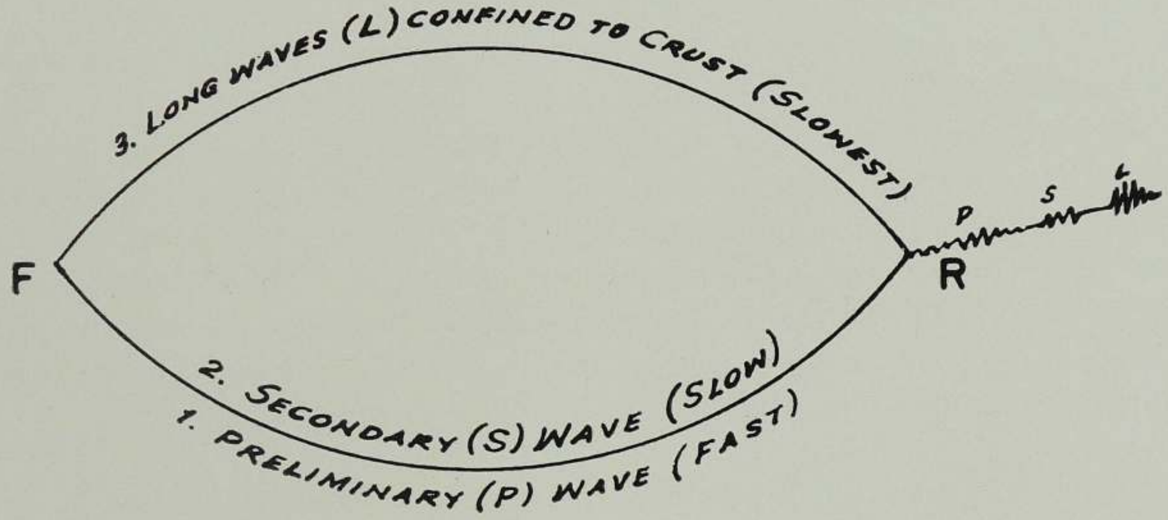

Fig. 2. Section through segment of the earth to show the paths followed by earthquake waves originating at focus F and recorded at station R. (*A. Holmes, 1965*)

The earliest waves to arrive at the recording station are P waves, these being followed by S waves, and finally by the L waves, which are the main vibrations (Fig. 2). The velocities of the P and S waves depend on the physical properties of the material they pass through within the earth, the L waves being confined to an upper layer of the earth. It has been found that a succession of P and S waves arrives at different times at the same station, showing that they have travelled at varying velocities through different portions of the earth's interior. The latter must therefore be made up of material that is not uniform. Further, because only the P waves pass through the centre or core of the earth and are slowed down in their passage through it, this core must be of liquid material. From such evidence it has been deduced that the earth is composed of three main concentric *shells—crust, mantle* and *core*—which differ from each other considerably in their physical properties (Fig. 3).

The outermost shell, known as the crust, is made up of two layers. The upper, lighter layer is dominantly granitic in composition, and is commonly known as the *sial* (being composed mainly of *silica* and *alumina*). It is a discontinuous layer, being present in the continents but absent or very thin in the ocean basins (Fig. 4). In the continental portions of the crust, the sial is about 25 miles (50 km.) thick and the continents themselves being lighter, are thought of as floating on the denser layer underneath. It is the sialic portion of the crust that is made up of rocks as we know them—igneous, sedimentary and metamorphic.

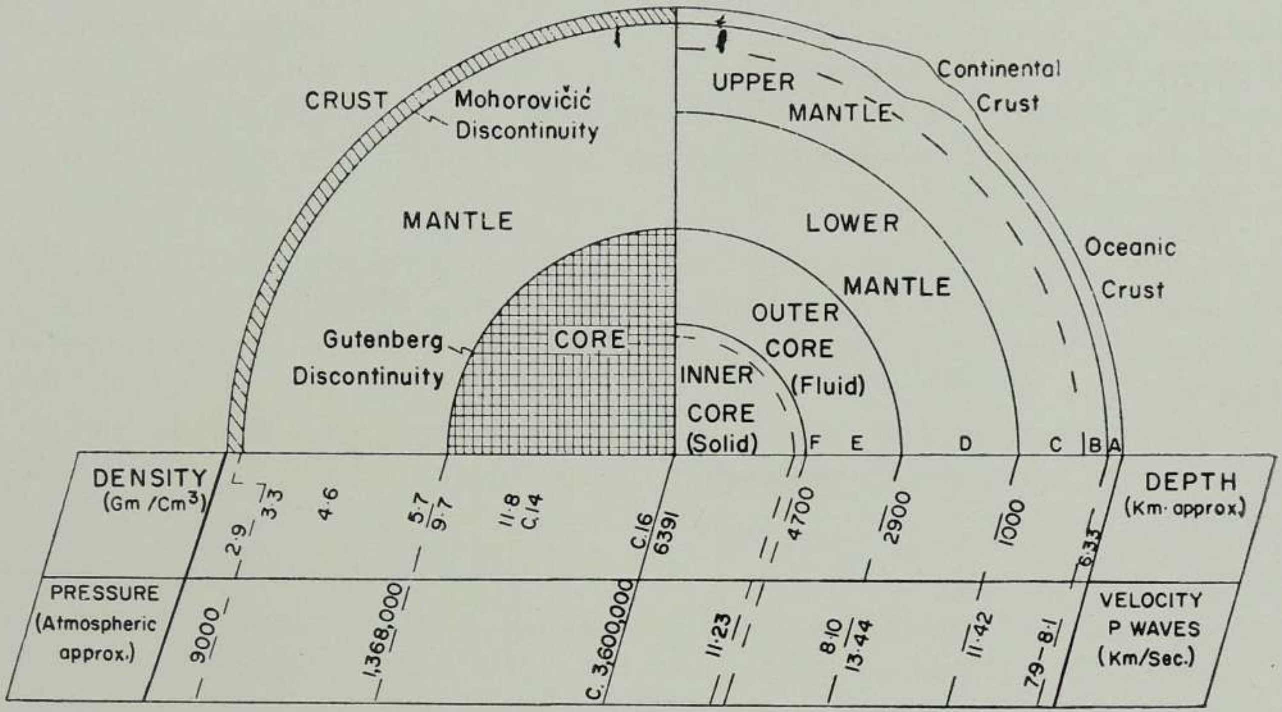

Fig. 3. Diagrammatic section showing the layered structure of the earth. Thickness of the crust (35 km. in continental areas, 6 km. in oceanic areas) is greatly exaggerated in diagram. (*Based on data computed by H. Jeffreys, K. E. Bullen, E. C. Bullard and B. A. Bolt, and modified from A. Holmes, 1965*)

Under the sial is the *sima*, (composed mainly of *silica* and *magnesium*). It is a denser layer, being made up dominantly of a rock known as basalt, and under the oceans it is almost 6 miles thick (10 km.). The maximum thickness of the crust is therefore about 31 miles (60 km.) though its average thickness is about 35 km., and its average density is 2.7.

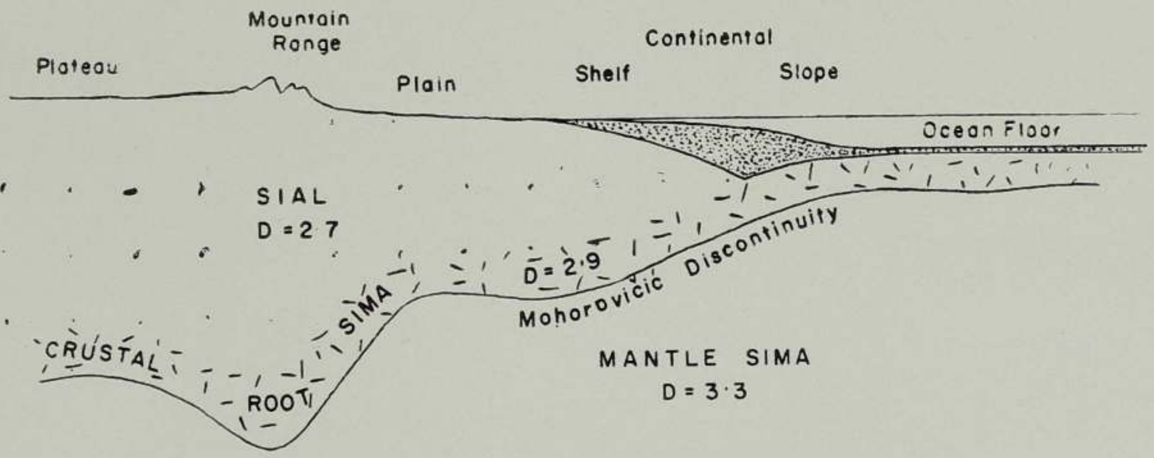

Fig. 4. Section showing relationship between surface features and crustal structure and the nature of the sial and sima. (*A. Holmes, 1965*)

Below the crust is the mantle, and separating the two is the ‘ surface ’ known as the *Mohorovičić Discontinuity* which is named after its discoverer (Fig. 3); the physical properties of the rocks on either side of this discontinuity (often known as the *Moho*) are recognizably different. The mantle is also made up of two layers, namely, an outer layer which is about 700 miles (430 km.) thick and is composed of the mineral olivine in a highly plastic state ; and an inner layer, about 1,360 miles (800 km.) thick, the composition of which is not really known. The average density of the mantle is 3.5.

At the centre of the earth, and separated from the mantle by the *Weichert-Gutenberg Discontinuity* is the *core,* 4,000 miles (7,000 km.) across, with an average density of 10.7 but reaching 17.2 at the very centre (see Fig. 3). The density of the core being roughly the same as the metallic meteorites, the core is thought to be composed of fluid nickel-iron, though some recent research suggests that it may be of highly compressed hydrogen.

This concentric or layered structure of the earth probably resulted from the separation of material according to density while the hot, homogeneous molten earth material cooled to form the earth. In the process, the heavier elements like nickel and iron were concentrated in the centre whereas the lighter, more easily oxidised ones like magnesium, aluminium, silica, potassium and sodium were concentrated in the outer layers.

CHAPTER 2

THE MATERIALS OF THE EARTH'S CRUST

> *Go, my sons, buy stout shoes, climb the mountains, search the valleys, the deserts, the sea shores, and the deep recesses of the earth. Mark well the various kinds of minerals, note their properties and their mode of origin.*
>
> Petrus Severinus (1571)

Rock-forming Minerals

The thin, outer layer of the earth known as the crust is, as we have seen, made up of what are known as rocks but rocks themselves are made up of *minerals,* so we must first say a little about minerals before we can talk about rocks.

A mineral is defined as a naturally occurring substance with a definite chemical composition and a fixed atomic structure, both of which determine its properties. Most minerals are compounds of two or more elements, but of the ninety elements that occur in minerals, eight of them are so abundant that they make up nearly 99 per cent. by weight of the many thousands of rocks that have been chemically analysed. In order of abundance, they are *oxygen, silicon, aluminium, iron, calcium, sodium, potassium* and *magnesium* as shown below in Table 1. The elements that follow occur in amounts of less than one per cent. and are *titanium,* Ti, 0.44 ; *hydrogen,* H, 0.14 ; *phosphorous,* P, 0.12 ; *manganese,* Mn, 0.10 ; *fluorine,* F, 0.08 ; *sulphur,* S, 0.05 ; *chlorine,* Cl, 0.04 ; and *carbon,* C, 0.03.

TABLE 1—Average Composition of Crustal Rocks

(after V. M. Goldschmidt and Bryan Mason)

IN TERMS OF ELEMENTS

Name	*Symbol and Valency*	*Per cent.*
Oxygen	O^{2-}	46·60
Silicon	Si^{4+}	27·72
Aluminium	Al^{3+}	8·13
Iron	Fe^{2+} Fe^{3+}	5·00
Calcium	Ca^{2+}	3·63
Sodium	Na^{+}	2·83
Potassium	K^{+}	2·59
Magnesium	Mg^{2+}	2·09
Titanium	Ti^{4+}	0·44
Hydrogen	H^{+}	0·14
Phosphorus	P^{5+}	0·12
		99·29

IN TERMS OF OXIDES

Name		*Formula*	*Per cent*
Silica		SiO_2	59·26
Alumina		Al_2O_3	15·35
Iron Oxides	Ferric	Fe_2O_3	3·14
	Ferrous	FeO	3·74
Lime		CaO	5·08
Soda		Na_2O	3·81
Potash		K_2O	3·12
Magnesia		MgO	3·46
Titania		TiO_2	0·73
Water		H_2O	1·26
Phosphorus pentoxide		P_2O_5	0·28
			99·23

GEOLOGICAL PROCESSES AND PRINCIPLES

TABLE 2—Major Rock-forming Minerals

Mineral Group Chief Varieties	Chemical Composition	Occurrence
Quartz		
Quartz	Silica	All types of rocks
Feldspars	Aluminium silicates with potassium, sodium, calcium :	
Orthoclase	K, Na	All types of rocks
Microcline	K, Na	
Plagioclase	Na, Ca	
Micas	Aluminium silicates with potassium, sodium, iron, magnesium :	
Biotite	K, Mg, Fe	All types of rocks
Muscovite	K, Al	
Phlogopite	K, Mg, Al	
Pyroxenes	Silicates of iron, calcium, magnesium :	
Augite	Ca, Mg, Fe, Al	Igneous rocks
Hypersthene	Mg, Fe	Igneous & metamorphic rocks
Diopside	Ca, Mg, Fe	
Amphiboles	Hydrated silicates of iron, calcium, magnesium :	
Hornblende	Ca, Mg, Fe, Al	Igneous & metamorphic rocks
Tremolite	Ca, Mg, Fe	
Olivines	Silicates of iron and magnesium :	
Olivine	Mg, Fe	Igneous rocks
Forsterite	Mg	Metamorphic rocks
Garnets	Complex silicates of iron, calcium, magnesium, aluminium :	
Almandine	Fe, Al	Sedimentary and metamorphic rocks
Pyrope	Mg, Al	
Grossularite	Ca, Al	
Carbonates		
Calcite	Ca	Sedimentary and metamorphic rocks
Dolomite	Ca, Mg	
Aluminium Silicates		
Sillimanite		Metamorphic rocks
Kyanite		
Andalusite		
Cordierite	With Mg, Fe	
Accessory minerals		
Magnetite	Fe oxide	All types of rocks
Ilmenite	Fe, Ti oxide	
Rutile	Ti oxide	
Zircon	Zr oxide	
Pyrite	Fe sulphides	
Pyrrhotite		
Apatite	Ca phosphate with F, Cl.	
Sphene	Ca, Ti silicate	
Graphite	Carbon	Metamorphic rocks

Al = aluminium, Ca = calcium, Cl = chlorine, F = fluorine, Fe = iron, K = potassium, Mg = magnesium, Na = sodium, Ti = titanium, Zr = Zirconium

MATERIALS OF THE EARTH'S CRUST

Oxygen and silicon are the most abundant elements, and in combination (as *silica*) form the commonest mineral of all, namely quartz, SiO_2. Most of the rock-forming minerals are, however, silicates, the fundamental unit of the atomic structure of silicates being a tetrahedron of four ions of oxygen with an ion of silicon in the middle. The silicate minerals are classified according to the internal arrangement of these SiO_4 tetrahedra—whether singly, in pairs, in sheets, in chains, or in rings. The details of this classification are beyond the scope of this book, but we need to know that the chief rock-forming silicate minerals are *olivine, pyroxenes, amphiboles, micas, feldspars* and *quartz* (see Table 2) ; accessory minerals like *garnet, zircon, tourmaline,* etc. are also silicates. Other rock-forming minerals are mostly oxides (*magnetite, ilmenite, corundum*), carbonates (*calcite, dolomite*), phosphates (*apatite*), sulphides (*pyrite, pyrrhotite*) and sulphates (*anhydrite, gypsum*)*.

The minerals mentioned above make up three main classes of rocks, namely, *igneous, sedimentary,* and *metamorphic* rocks. We shall, in the rest of this chapter, examine briefly what constitutes these rocks, how they were formed, and how they came to occupy their present positions.

Igneous rocks

The word igneous, from the Latin *ignis* meaning fire, suggests that they are fire-made rocks, but in fact they are the products of the cooling and crystallisation of hot, molten material known as *magma* in which very high temperatures rather than actual fire is involved. The magma, which probably occurs in scattered pockets within the sima, generally comes up through volcanic vents, fissures, and other passages in the overlying rocks. When magma reaches the surface and solidifies the rocks so formed are said to be *extrusive*, and when magma solidifies below the surface the rocks are said to be *intrusive*.

Extrusive rocks, because they reach the surface, cool very rapidly and are therefore fine-grained or glassy rocks, of which *rhyolite, basalt,* and *obsidian* are good examples. They generally take the form of volcanoes or lava flows which spread out for great distances and are either gently sloping or flat in attitude (Fig. 5 and Pl. 1A). The Deccan Plateau, for

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* The reader is advised to refer frequently to Table 2 during the rest of this chapter. If any further information on minerals is desired a text-book on mineralogy should be consulted and actual specimens of minerals looked at and handled, if possible.

A. Columnar basalt with hexagonal joints, Giants's Causeway, N. Ireland. Columns about one foot across.

(*H. M. Geological Survey* (*London*) *Photographs*)

B. Pegmatite dykes cutting across veined gneisses, Galgamuwa.

example, is made up largely of black basalt which came up to the surface in several large fissures, spread out over an area of about 500,000 miles, and was as much as 10,000 feet thick. Many modern volcanoes like Mt. Etna in Italy and the Hawaiian Islands also consist largely of basalt.

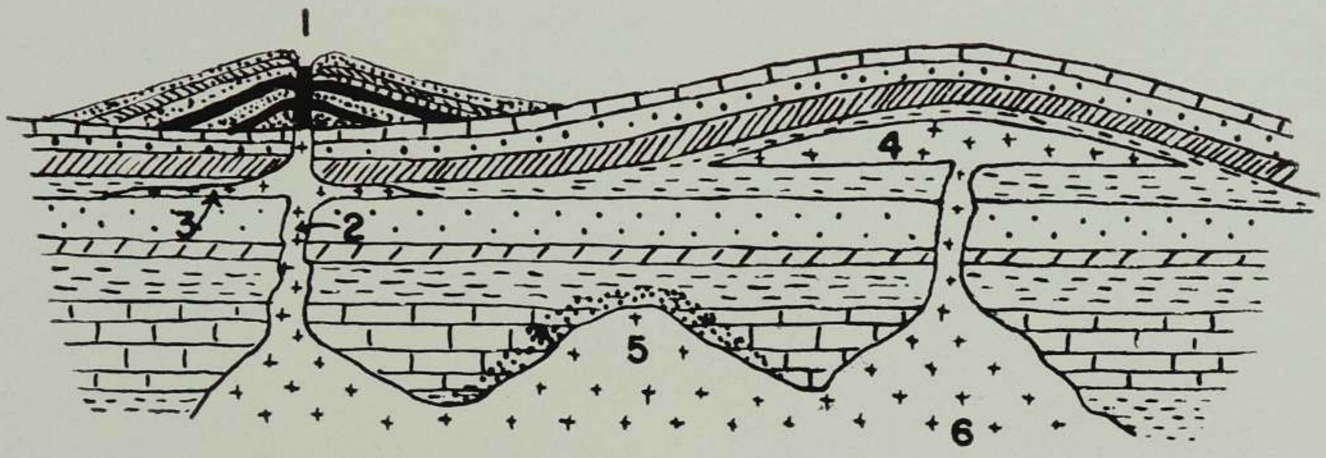
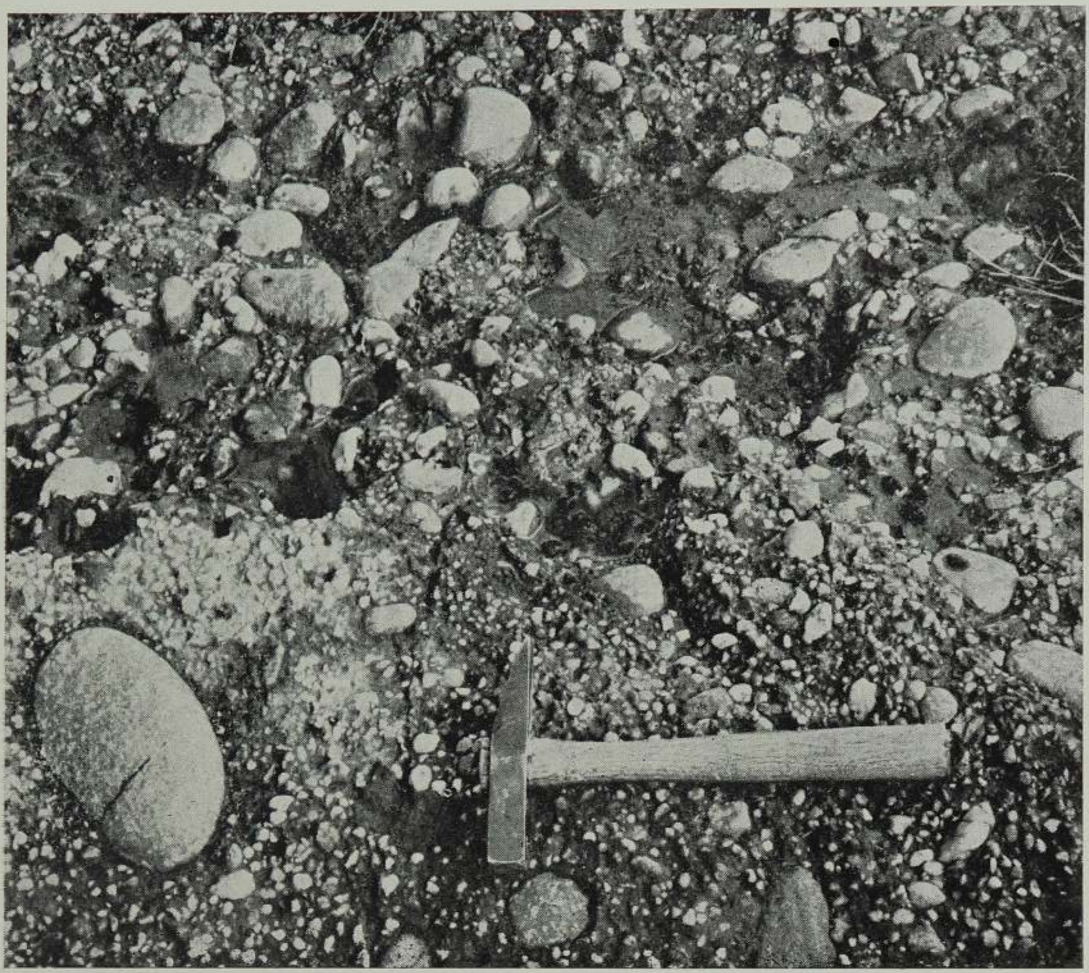


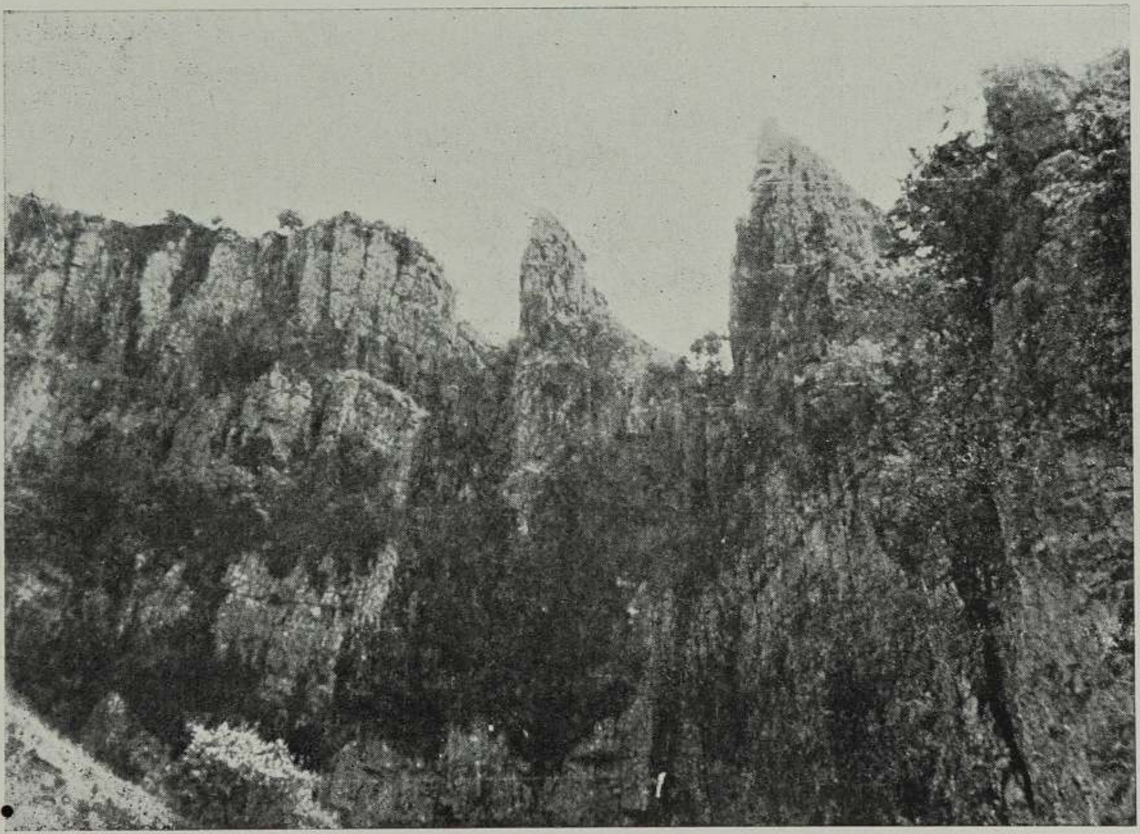
Fig. 5. Typical forms of igneous rocks.
1—volcano, 2—dyke, 3—sill, 4—laccolith, 5—stock with thermal aureole, 6—batholith.

The intrusive rocks have cooled more slowly than the extrusive ones, and are therefore coarser grained. They occur in a variety of forms (Fig. 5) such as *dykes* (vertical sheets), *sills* (sheets parallel to the bedding planes of the intruded rock), *volcanic plugs, batholiths or plutons* (large masses). The best known of these intrusive rocks are *dolerite, gabbro,* and *granite.*

Igneous rocks are classified according to the minerals in them, and this in turn is a reflection of the chemical composition of the magma from which they were formed. (Frequent reference should be made to Table 2 which gives the main rock-forming minerals). The **acid igneous rocks** (Table 3) contain much *quartz* (pure silica), enough silica being present in the magma to crystallise out by itself as quartz. *Granite* is the commonest rock in this group, and it is composed essentially of quartz and *potassum feldspar* (aluminium silicate with potassium) together with minor amounts of *mica* (magnesium-iron silicate), *hornblende* (magnesium-iron-calcium silicate), *magnetite* (iron oxide) *zircon* (zirconium oxide) and other accessory minerals. Granite is a coarse-grained rock, white, grey, or pink in colour, which forms the cores of many mountain ranges and also forms the bedrock of large areas of the crust, chiefly in its most ancient portions. Ore deposits are very often associated with granite, the tin-bearing lodes of Cornwall being an example. Very



A. Conglomerate. (*H. M. Geological Survey* (*London*) *Photographs*)



B. Thick beds of sedimentary limestone exposed in the gorges at Cheddar, England.

coarse granite is known as *pegmatite* and this rock type occurs, not as large masses, but as irregular patches and dykes (Pl. 1B). Pegmatites are important carriers of economic minerals like mica and beryl, and often contain beautifully formed crystals.

TABLE 3.—Classification of Igneous Rocks

FORM	MINERAL COMPOSITION			GRAIN SIZE
	Acid	**Intermediate**	**Basic and Ultrabasic**	
	Quartz *Feldspar* *Mica*	*Feldspar, Mica* *Amphibole* *Pyroxene, Quartz*	*Pyroxene* *Amphibole* *Olivine, Feldspar*	
Extrusive (*Volcanic*)	Obsidian Ryholite Trachyte	Andesite	Basalt	Glassy Fine-grained
Minor Intrusive (*Dyke, sill*)	Microgranite	Microdiorite	Dolerite	Medium-grained
Major Intrusive (*Stock,batholith*)	Granite Granodiorite	Diorite	Gabbro	Coarse-grained
COLOUR	Light		Dark	
SPECIFIC GRAVITY	Less than 2.7	2.7—2.9	More than 2.9	

The **basic igneous rocks** (*basalt, dolerite,* and *gabbro*) are all dark, heavy rocks, composed essentially of *plagioclase feldspar* (sodium-calcium feldspar) and silicate minerals rich in magnesium and iron like *olivine, pyroxene,* and *amphibole ;* such minerals are often referred to as ferromagnesian minerals. Little or no quartz is present in these rocks.

The **intermediate igneous rocks,** of which there are many types (see Table 3), have a composition between the basic and the acid rocks and are made up of *quartz, feldspars,* and *ferromagnesian minerals* (chiefly hornblende) in appreciable amounts. *Diorite* is the best known of this group.

Except in the glassy, extrusive rocks, the minerals of most other igneous rocks crystallise at the same time, interfering with each other's growth, and forming an interlocking mosaic of crystals (Fig. 6B).

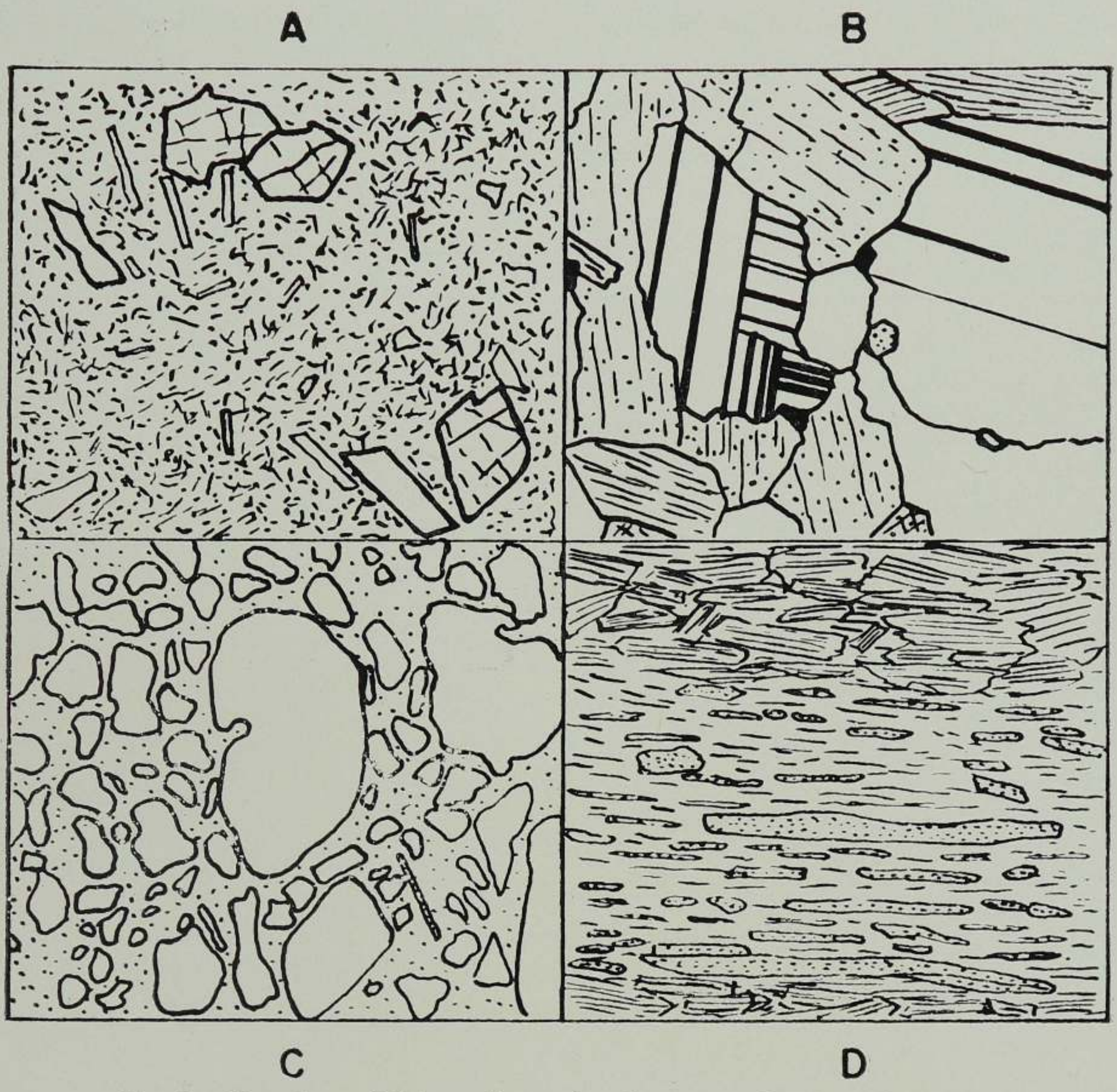


Fig. 6. Drawings of thin sections of rocks seen under the microscope. A — porphyritic texture in acid igneous rock, B — granite, C — sandstone, D — schist.

Sedimentary Rocks

As soon as lava from a volcano solidifies it is acted upon by great heat and cold, by frost action, and by dissolved acids in rain water, all of which tend to break up or disintegrate the rock into its constituent minerals. This process is known as *weathering* and it is acting all the time on rocks that are exposed to the atmosphere, whether igneous, sedimentary, or metamorphic. The disintegrated and weathered particles, once they are liberated from the parent rock, are then washed away and carried by water (rivers and streams), wind, moving ice (glaciers), or merely by gravity, until finally they are deposited elsewhere as horizontal layers of sand, clay and mixtures of both. Such deposition generally takes place in the ocean, but it may also occur in deltas and lakes or on the flood plains of rivers. These deposits are known as *sediments*.

When loosely held together they form the **unconsolidated deposits** such as *gravel, alluvium, beach sands,* and *sand dunes.* When, however, these loose deposits become compacted together by the weight of overlying material or are cemented together by silica, calcium carbonate, or iron oxide, they form the **consolidated rocks** (Table 4). Sands then become *sandstones,* gravels become *conglomerates,* and clays turn into *shales, siltstones,* and *mudstones.* All the types of deposits mentioned above belong to one of the major groups of sedimentary rocks, the fragmental or **clastic deposits.** They are made up chiefly of solid mineral or rock fragments formed by the break-up of pre-existing rocks, and have one common featrue which distinguishes them from igneous and metamorphic rocks. Whereas in the latter the mineral grains occur as interlocking crystals which have interfered with each other's growth, in the sediments the minerals are fragments or rounded grains of crystals which crystallised previously but now occur as clearly separate individuals surrounded by other grains or by some cementing material (Fig. 6C). The clastic rocks are classified according to the sizes of the individual grains, conglomerates (Pl. 2A) being coarse-grained (more than 2 mm. diam.), sandstones being medium-grained (2 mm. to 0.06 mm.) and shales being very fine-grained (less than 0.06 mm.).

In dry, arid regions, strong winds sometimes blow enormous quantities of fine clay and silt which settle on and cover very large areas of the surface, and which may remain unconsolidated for millions of years. The yellowish *loess* deposits of China, Central Asia and South America belong to this class.

Besides the major group of clastic deposits are two other important groups namely, the *chemical* and the *organic* sedimentary deposits. **Chemical deposits** are those formed directly by precipitation or crystallisation from solution, and they include the great group of *evaporites* or deposits of salt that have formed by evaporation of salt waters. These salts are mainly the chlorides and sulphates of sodium, magnesium, calcium, and potassium, and they form a large variety of minerals, among which may be mentioned *rock salt, sylvite, carnallite, anhydrite,* and *gypsum.* Evaporites are even now being formed in such inland seas as the Dead Sea and the Caspian Sea, and we can deduce that the great salt beds of Stassfurt in Germany, Alsace in France, and Cheshire in England, which today are buried at depth, were formed in past geological ages under similar conditions. In our own country we can see comparatively small accumulations of evaporites being formed by the same natural processes but under artificially controlled conditions in the salterns at Elephant Pass, Palavi, and Hambantota.

TABLE 4—Classification of Sedimentary Rocks

Mode of Formation	*Dominant Character*	*Unconsolidated*	*Consolidated*
MECHANICALLY	Pebbly	Gravel Scree	Conglomerate Breccia
	Sandy	Sand	Sandstone, grit (siliceous, ferruginous etc., depending on cement). Greywacke (with rock fragments) Arkose (with feldspar grains)
	Muddy	Mud and clay	Mudstone Siltstone Shale (when fissile)
ORGANICALLY	Calcareous	Shells Coral reefs Oozes Algal sands	Limestones : shelly, coral, crinoidal, foraminiferal, algal, dolomite
	Carbonaceous	Vegetable matter Peat	Coal, lignite
	Siliceous	Oozes (radiolarian, diatom) Sponge spicules	
	Ferruginous	Bog iron ore	Banded ironstones Oolitic ironstones
	Phosphatic	Guano Bones	Phosphorites
CHEMICALLY	Saline	Salt lake deposits	Gypsum Anhydrite Rock salt

Organic deposits are those formed by the accumulation of organic material such as the skeletons or tissues of animal or vegetable material, and they can be sub-divided according to whether they are predominantly *calcareous, carbonaceous,* or *siliceous* (Table 4).

The *calcareous* group includes most of the limestones (of which Chalk is a member) as well as coral reefs and modern shelly sands. Limestones, for example, are formed on the sea bed by the accumulation of the calcareous skeletons and shells of millions of marine creatures which died during a particular period ; they generally form thick beds (see Pl. 2B). Very often these complete shells and fragments of shells are cemented together with the mineral calcite (calcium carbonate). The Jaffna Limestone of Ceylon is such an organic deposit. Sedimentary limestones are often described by the dominant or characteristic organism found in them and so we get such names as *crinoidal limestone* and *nummulitic limestone.*

The *carbonaceous* deposits include *peat, coal, lignite,* and *natural oil.* Peat is formed by the accumulation of decaying vegetable matter in inland lakes (as in Muthurajawela, just north of Colombo) or seas where the water is fresh or slightly brackish, and it may ultimately be converted to pure carbon in the form of coal.

Sedimentary rocks, if they remain undisturbed from the time of their formation, remain in a horizontal position and give rise to enormous thicknesses of *strata* piled on top of each other.

Metamorphic Rocks

The third great class of rocks consists of igneous and sedimentary rocks that have been changed from their original form into something quite different by the action of great heat, great pressure, movement of the crust, or the chemical action of liquids and gases. The changes that take place to produce a metamorphic rock may be either in the mineral composition of the original rock, or in the texture, or in both. During metamorphism, the minerals in the original rock may undergo recrystallisation into larger crystals of the same mineral, or they may combine to form new minerals with a different chemical composition, such minerals being more stable under the new conditions of temperature and pressure than the original minerals.

There are many kinds of metamorphism each of which has its particular types of metamorphic rocks (see Table 5).

Thermal metamorphism is the result of the action of hot magma on the surrounding rocks and is due to the great heat and fluids given off by the magma (Fig. 5). The rocks formed in this way have a baked or glassy appearance, or they might be fine-grained, spotted rocks known as *hornfels.* When an impure limestone undergoes this type of metamorphism a host of new minerals may occur in the form of a skarn at the contact.

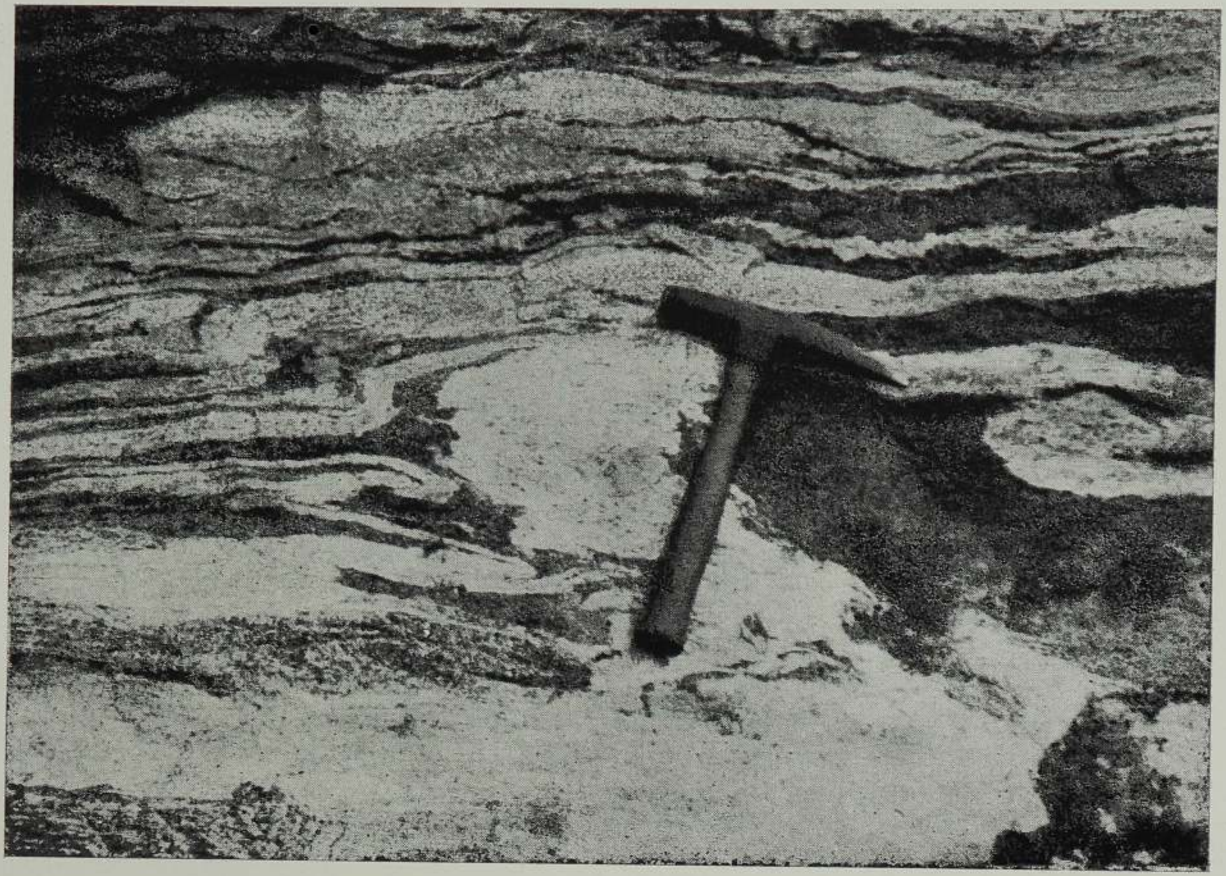
Dislocation Metamorphism is caused by the relative movement within the rocks on either side of a plane known as a fault, or within a zone of faults. In such instances the rocks suffering movement are ground down mechanically into angular blocks to form *breccia* or into mineral fragments and dust to form *mylonite.* Sometimes the great frictional heat generated during such movement may cause the rocks to melt and then recrystallise as fine-grained, glassy rocks known as *flinty crush rock.*

The most common type of metamorphism is, however, that which combines the action of great heat and pressure and acts over large areas ; this is known as **regional metamorphism.** The rocks produced are mainly schists and gneisses of various kinds (Table 5). Regional metamorphism is generally associated with mountain building, as we shall see below.

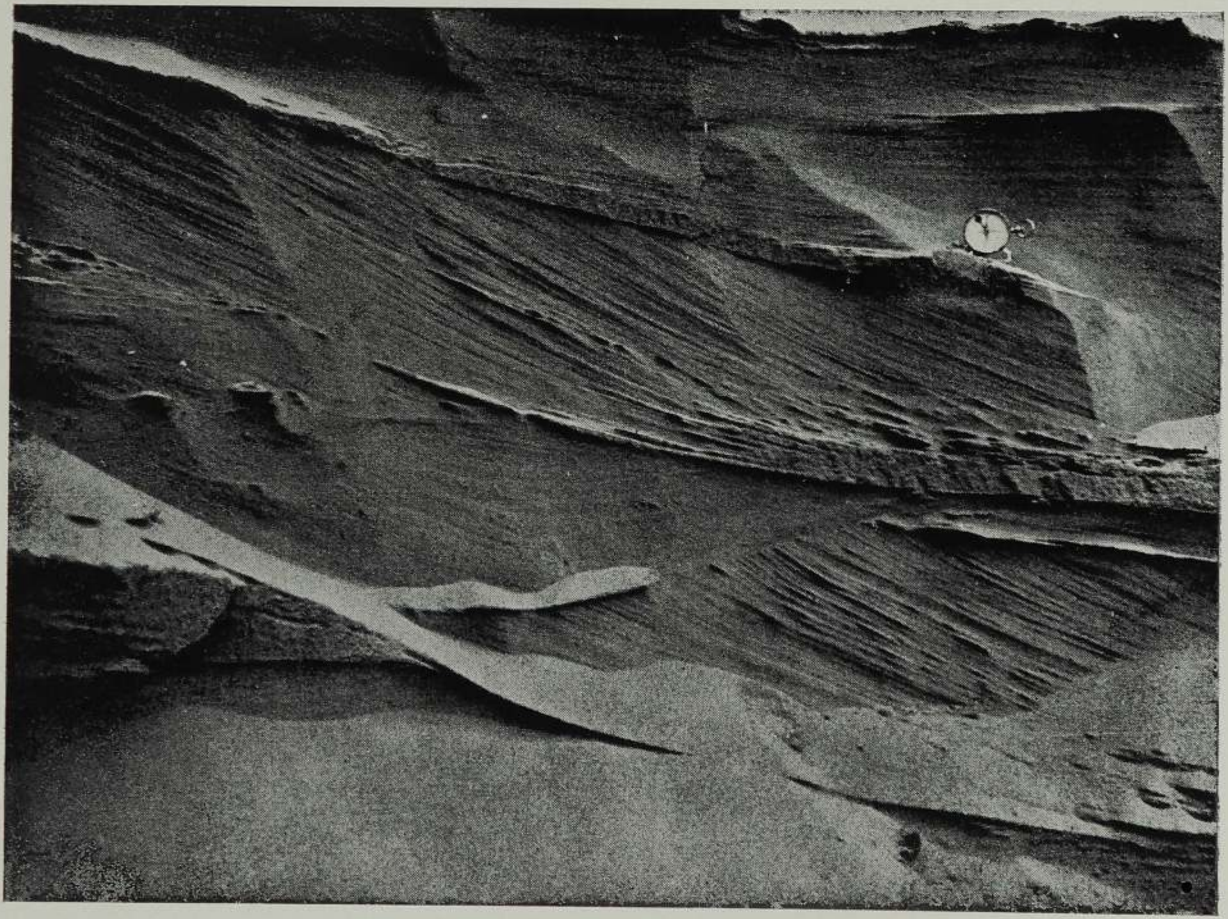
TABLE 5.—Classification of Metamorphic Rocks

Type of Metamorphism	*Unmetamorphosed rock*	*Metamorphosed rock*	*Distinctive minerals*
DISLOCATION METAMORPHISM	All rock types	Breccia, Mylonite, Flinty crush rock Augen gneiss Schist	Fragments of original minerals ; glass
THERMAL METAMORPHISM	Schists, slates	Spotted schists, slates Hornfels	Andalusite, cordierite, sillimanite, garnet
	Limestones	Marbles Skarns	Calcite, dolomite, diopside, mica Wollastonite, garnet, idocrase tremolite
REGIONAL METAMORPHISM	Shales	Slate Schist Gneiss	Quartz, feldspar, mica, garnet, sillimanite, kyanite, cordierite
	Sandstones	Quartzite Quartz schist	Quartz
	Limestone Impure limestone	Marble Calc gneiss	Calcite, dolomite, diopside, fosterite, mica Diopside, scapolite, wollastonite, sphene, tremolite
	Basic igneous rocks Acid igneous rocks	Amphibolite Schist, gneiss	Plagioclase, hornblende, pyroxene Quartz, feldspar, mica

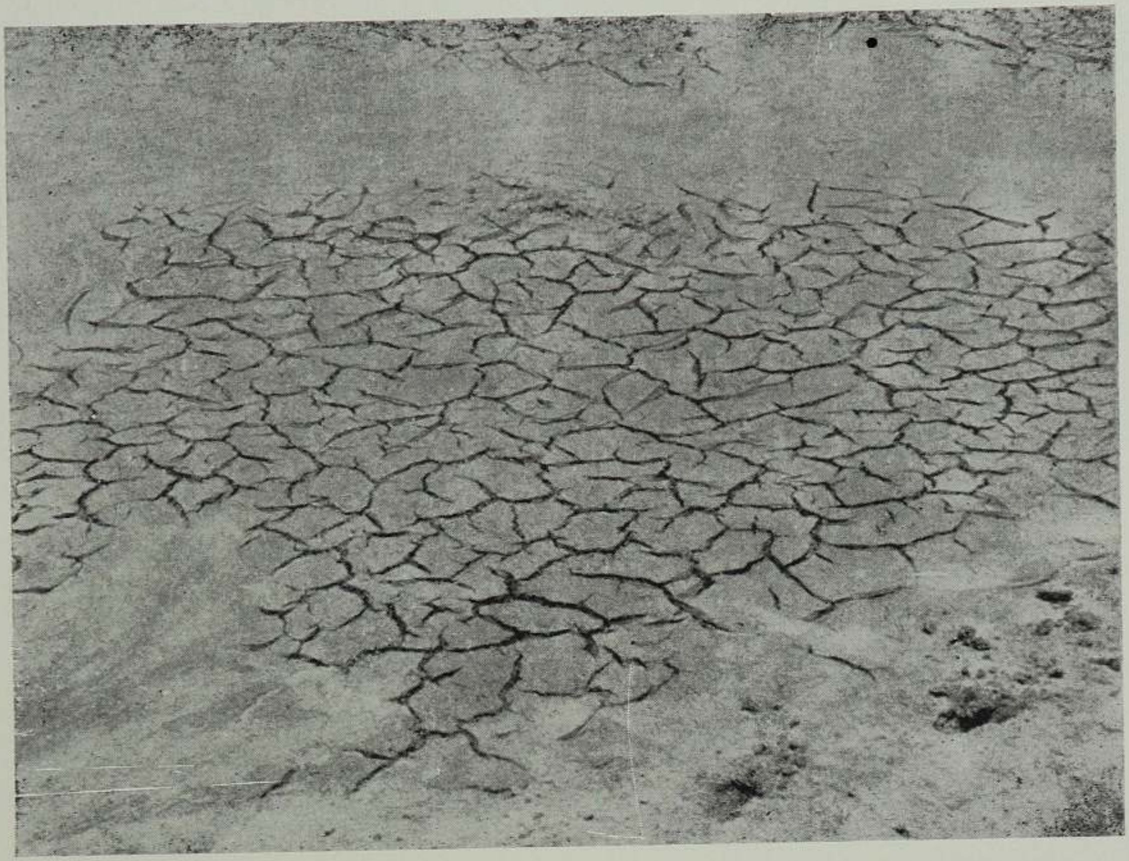
In the course of metamorphism, shale (composed mainly of clay minerals) is turned to *slate,* a rock composed mainly of *sericite* (fine white mica), *chlorite* (a flexible green mineral), *quartz, and graphite* or carbonaceous matter. Sandstone, when metamorphosed, turns to a massive rock called *quartzite* in which the original sand grains and the silica cement have recrystallised to new quartz grains ; quartzite, being hard and resistant to



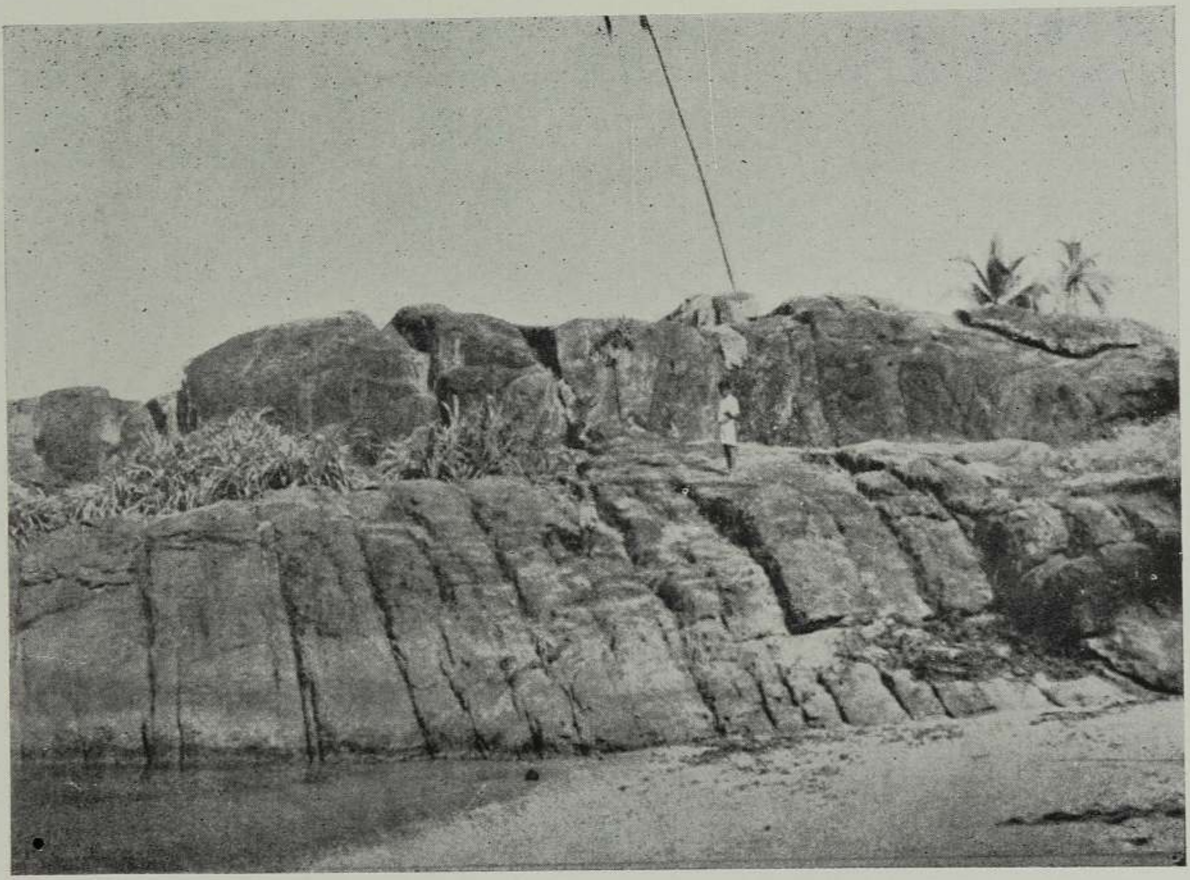
A. Gneiss with alternating bands of light-and dark-coloured minerals, Gampaha.
(*J. W. Herath*)



B. Current-bedded (or cross-bedded) sands, Cheshire.
(*H. M. Geological Survey* (*London*) *Photographs*)



A. Hexagonal mud cracks in dried tank bed.



B. Vertical joints in granitic gneiss, Ahungalla.

erosion, often forms prominent hills and ridges. When a pure sedimentary limestone is metamorphosed it is turned to *crystalline limestone* or *marble,* composed mainly of the minerals *calcite* (calcium carbonate) and *dolomite* (calcium-magnesium carbonate). When clayey or sandy impurities are however present in the original calcareous sediment this gives rise to numerous minerals such as *diopside, garnet, tremolite, scapolite,* and *wollastonite* in the crystalline limestone. All these minerals are silicate minerals rich in calcium, magnesium, iron, and aluminium. Traces of impurities in the calcareous sediment often give even the pure marbles their striking colour and intricate patterns as in the Connemara Marble of Ireland. Serpentinous marble is a particularly striking green variety of marble.

The commonest types of metamorphic rock are, however, *schist* and *gneiss* (pronounced ' nice ') and they occur in thousands of square miles in many parts of the world, particularly in the oldest parts of the crust. The mineral grains in these rocks are arranged in roughly parallel layers of different mineral composition (Fig. 6D), as for example, quartz and feldspars together in light-coloured bands and mica and hornblende together in dark-coloured to black bands (Pl. 3A). A gneiss is thus essentially a banded or streaky rock in which the layers of differing mineral composition are relatively thick. As the layers become thinner, gneiss grades into schist, in which the layers are extremely thin and can often be parted from each other with a thin edge. The commonest minerals in gneisses and schists are quartz, feldspars, mica, garnet, and hornblende, and these rocks are often named according to their mineral composition. We thus have names like *biotite gneiss, sillimanite gneiss* and *garnetiferous gneiss.* Less frequently they are named according to their appearance (*veined gneiss, streaky gneiss, augen gneiss,* the last being named after the ' eyes ' (German *augen*) of quartz and feldspar in them), or according to local place names (such as *Bintenne Gneiss* and *Wanni Gneiss* in Ceylon and *Lewisian Gneiss* in Scotland).

Rock Structures

All rocks, whether igneous, sedimentary, or metamorphic, have certain forms or *structures* which vary in scale and reflect the conditions under which they were formed. Those structures that can be seen only under a microscope are usually referred to as *textures*, but there are some that can be seen only in hand specimen, other structures that are visible only in quarries and large exposures of rock, and still others that cannot be seen except in maps.

The grains of all crystalline rocks (igneous and metamorphic) are seen under the microscope to have interfered with each other's growth and an interlocking network of lines is formed by the boundaries of such grains (Fig. 6B). On the other hand, the individual grains of sedimentary rocks are generally separated from each other by material that holds the grains together, or, in other words, the *matrix,* (Fig. 6C). The grain size of an igneous rock, as we have mentioned earlier, depends on the rate of cooling, a fact well seen in a dolerite dyke. The margins of the dyke, being in contact with relatively cold country rock, cool rapidly and are therefore fine-grained or glassy in appearance, whereas the central part of the dyke, taking more time to crystallise, has a coarser appearance. Sometimes the rock may cool rapidly at the beginning of its history but take more time to crystallise in the later stages of its history. It is in this way that a *porphyritic* texture develops in which certain minerals like feldspar and hornblende develop into large crystals (or *phenocrysts*) while the rest of the rock is in the form of a fine-grained groundmass (Fig. 6A.). When such large crystals have a spongy appearance due to the inclusion of smaller, earlier formed crystals, they are said to be *poikilitic.* (The corresponding terms in metamorphic rocks are *porphyroblastic* and *poikiloblastic*). At other times, when a molten magma flows in a particular direction before it finally solidifies, the crystals may be oriented in that particular direction ; the resulting rock is said to exhibit a *flow structure.*

The most important structure in sedimentary rocks is the *bedding plane* or the surface which separates one sedimentary band (*stratum*) from the other. Most sediments are originally laid down in a horizontal attitude but for some reason or other may be subsequently tilted in any direction and at any angle. When this happens the strata are said to possess a *dip*, the dip being the angle of inclination of the bed from the horizontal (Fig. 7A). The true *direction of dip* is that direction in which the inclination is greatest. The direction at right angles to the dip direction is said to be the *strike* of the strata (Fig. 7A) ; it is best measured along the intersection of an inclined bed and a horizontal plane such as a pool of water or a horizontal earth cut. Wind and water currents sometimes produce minor bedding planes within a single bed of sand or clay (Fig. 7B and Pl. 3B.). Such a structure is known as *cross bedding* or *false bedding* and it can often be seen in the small sand cliffs found on most beaches in Ceylon. *Graded bedding* is a structure caused by rapid settling of the larger, heavier grains at the bottom of the bed and the slower accumulation of the fine-grained, lighter material at the top (Fig. 7C). Bedding planes may sometimes preserve the imprints of rain drops, ripple marks, and mud cracks (Pl. 4A) especially when rapidly covered by later material. It is by these typical sedimentary structures that rocks millions of years old (and sometimes even metamorphosed), can be recognised as ancient sediments. Moreover, the attitudes of these minor structures can also tell us whether the rocks as we see them now are still in the positions in which they were originally deposited or whether they have subsequently been turned over.

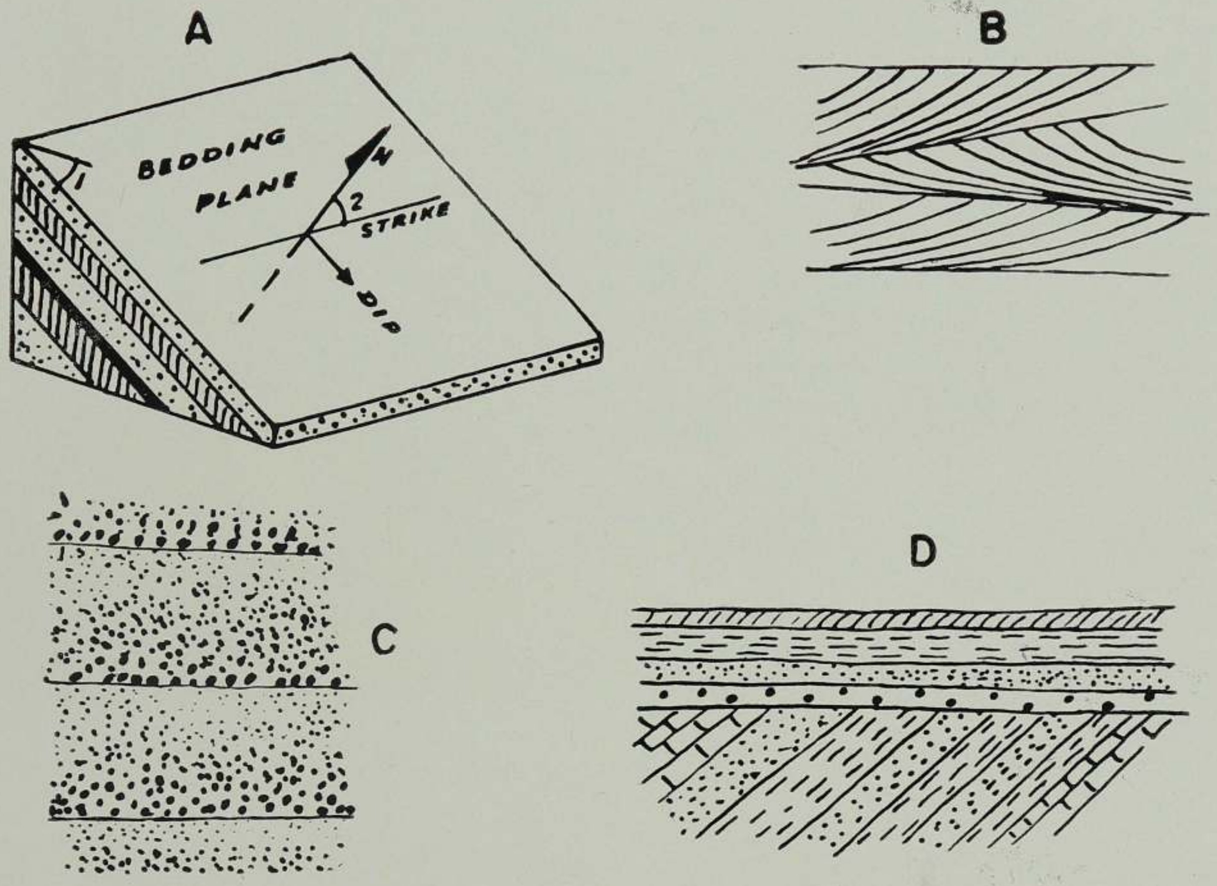
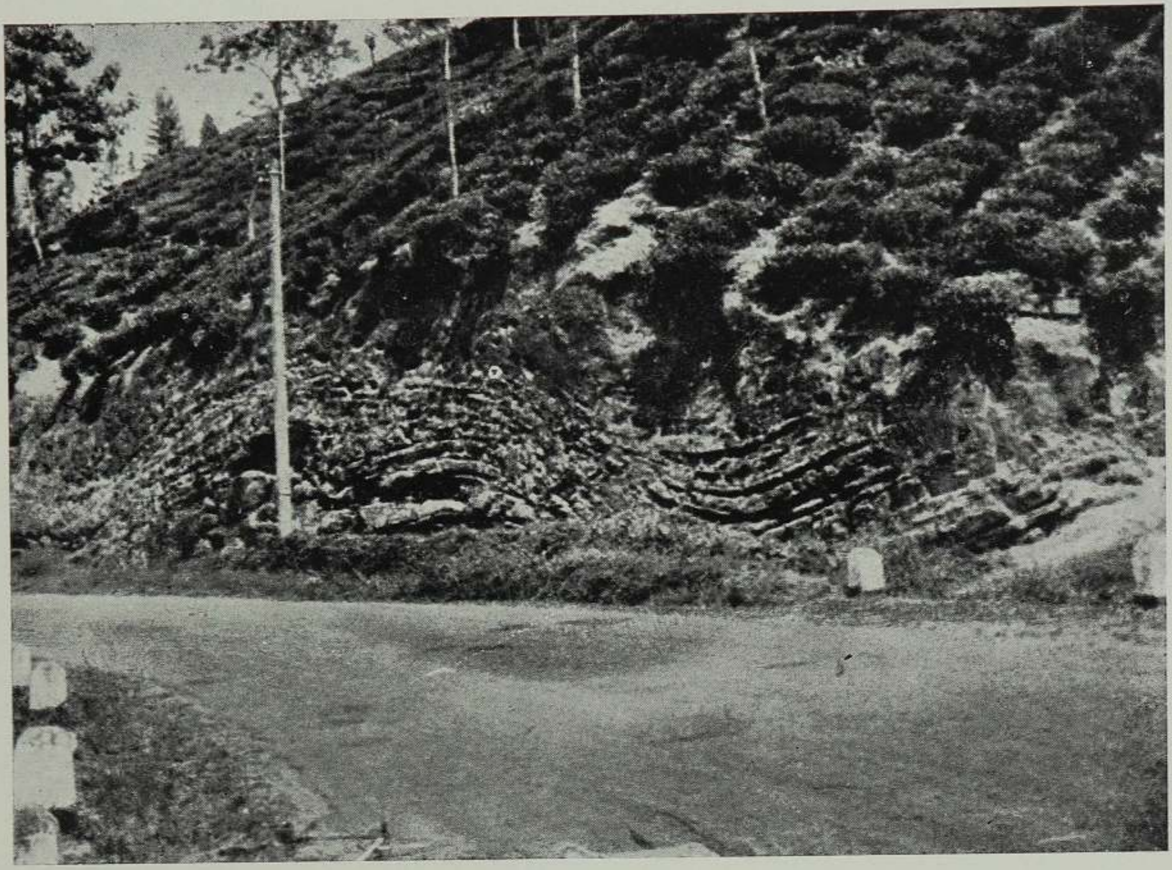


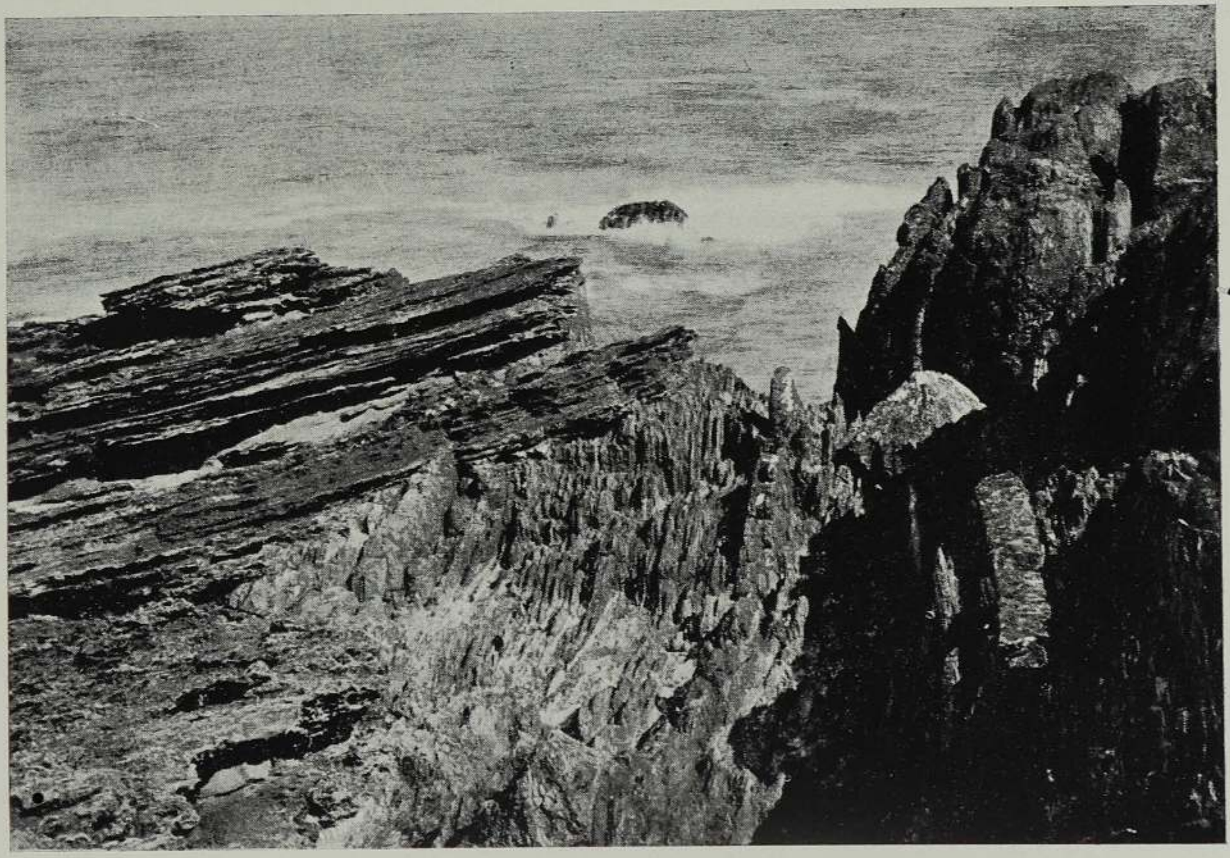
Fig. 7. Structures of sedimentary rocks.

A. Bedding. (1), Angle of dip, (2), Direction of strike.
B. Cross bedding or false bedding.
C. Graded bedding with coarse-grained sediment at bottom and fine-grained sediment at top.
D. Unconformity separating older, tilted beds from younger, horizontal beds.

In sedimentary rocks that have undergone only a little metamorphism (in comparatively low temperatures and pressures), the structures mentioned above may be preserved. In Finland and India, for example, ripple marks formed hundreds of millions of years ago on the bed of the sea are now seen in quartzites. In some slightly metamorphosed rocks, a minute splitting along closely spaced planes may develop ; this is known as *cleavage* and it is best seen in slates. In rocks that have undergone a high degree of metamorphism, such delicate structures as cross bedding and ripple marks are generally destroyed, as a result of the recrystallisation of the minerals that takes place. The most important structure in these high-grade metamorphic rocks is *foliation*. This is the layered arrangement of minerals, a foliation plane being the plane of parting between one layer of minerals and the next. When recrystallised minerals such as mica and



A. Folds in quartzite, near Talawakelle ; anticline on left syncline on right.



B. Uncomformity between flat-lying Old Red Sandstone Beds resting on eroded surface of vertical Silurian rocks, Siccar Point, Berwick, Scotland.
(*H.M. Geological Survey* (*London*) *Photographs*)

hornblende are oriented in the same direction and are closely packed together, the foliation planes become very closely spaced and the rock is said to be *schistose* (see Fig. 6D). When the rock is composed of broader layers than in a schist the rock is said to be *gneissic* (Pl. 3A). *Banding* is also a structure of metamorphic rocks and it reflects the presence of bands of varying chemical composition in the original rock, before it was metamorphosed. When a rock has been ground down into minute fragments by dislocation metamorphism (see p. 21) it is said to have a *cataclastic* texture.

In Ceylon, where the grade of metamorphism is very high, foliation is the commonest structure of the crystalline rocks ; gneisses and schists of various kinds are the predominant rock types. In addition to these types, however, a number of rocks, especially in the Highlands, have an equigranular texture, the mineral grains being more or less of equal size. Such rocks are called *granulites* and they are characteristic of the highest grade of metamorphism.

When sedimentary and metamorphic rocks are subjected to high pressures, they often buckle into *folds,* structures similar to those formed when the opposite sides of a table cloth are pushed together. Folds have been called, somewhat picturesquely, " waves of stone " by the German geologist Hans Cloos[1]. An upfold opening downwards, in which the sides (*or limbs*) dip away from the centre is called an *anticline ;* a downfold opening upwards, in which the limbs dip towards the centre, is called *syncline* (Fig. 8 and Pl. 5A). The *axial plane* of the fold bisects as nearly as possible the angle between the two limbs and the line of intersection between the axial plane and the bedding plane gives the direction in which the axis of the fold runs (Fig. 9). Folds in which the axial planes are vertical, inclined, or almost flat-lying are known as *vertical folds, overfolds,* or *recumbent folds* respectively (Fig. 8).

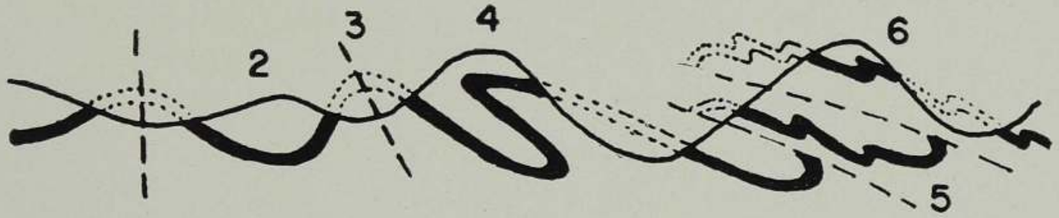


Fig. 8. Types of folds in rocks. (*After A. Holmes, 1965*)
(1) symmetrical anticline, (2) inclined syncline, (3) inclined anticline, (4) recumbent fold, (5) thrust plane, (6) nappe.

If the axis of the fold is horizontal, then the fold may continue for a very great distance, the outcrops of its limbs being parallel to each other for this distance. Generally, however, the axes of folds are inclined and

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[1] See list of References.

the folds themselves are said to be *plunging folds*. The shape of the outcrops of the limbs then tell us in which direction the fold plunges. In an anticline the beds converge in the direction of plunge and in a syncline they diverge in the direction of plunge (Fig. 9).

After a succession of rocks has been laid down, as flat-lying beds resting one on top of the other, the rocks may be tilted, folded, and sometimes metamorphosed as well, and then raised above sea level where they are exposed to the atmosphere. Weathering and erosion then take place and the beds are worn down gradually to a general level of erosion, steeply dipping beds being sharply cut off or *truncated* in the process. Such an eroded land surface may in time be submerged below the sea once again and a new succession of flat-lying beds deposited on the old truncated surface.

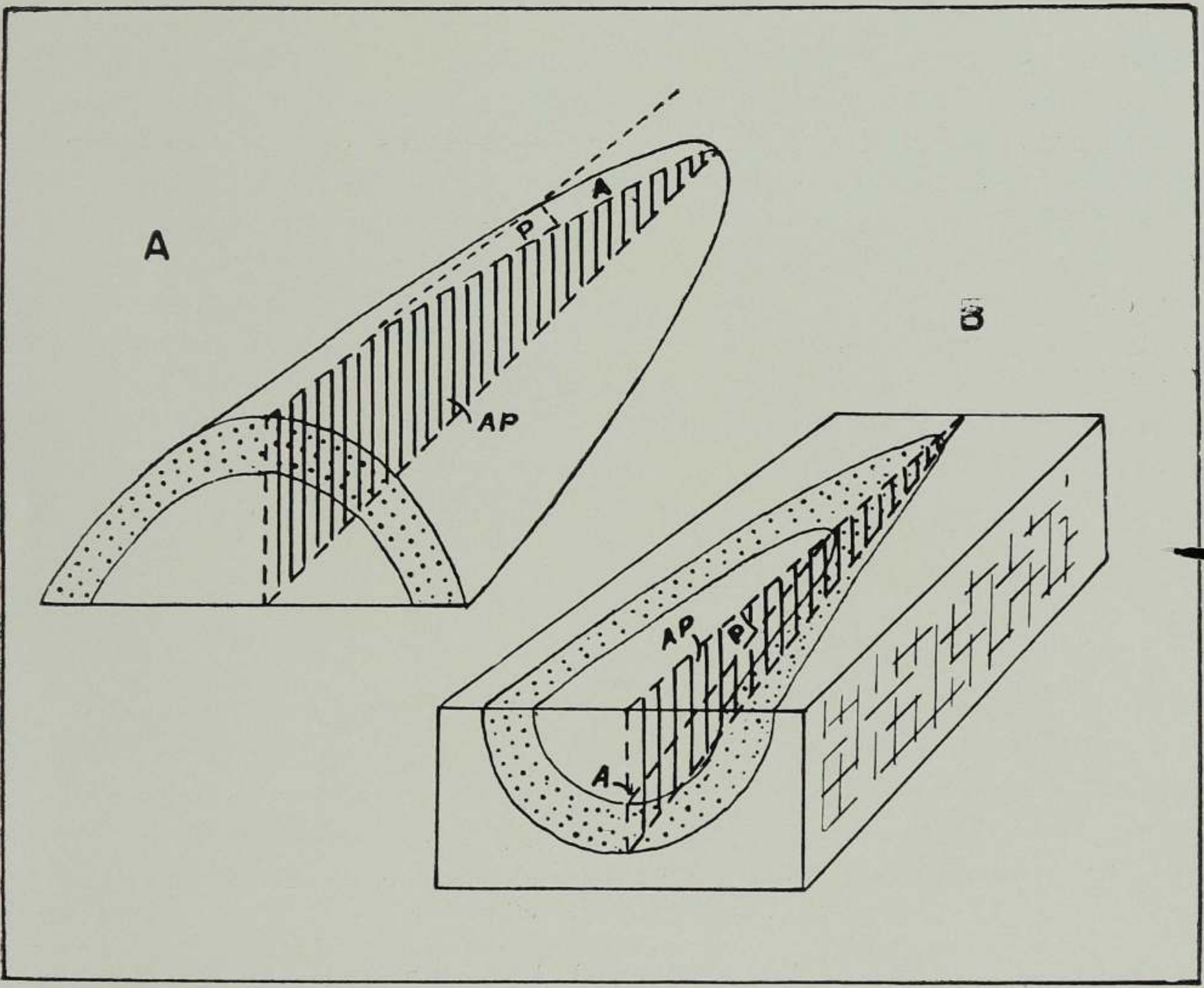

Fig. 9. Forms of plunging folds.
A. Anticline. B. Syncline.
(P) angle of plunge, (AP) axial plane, (A) axial trace (commonly called ' axis ').

The plane between two such sets of strata is known as an *unconformity* (Fig. 7D and Pl. 5B) and it is one of the most important planes in geology. Within each set of strata the beds are said to rest *conformably* on each other, but the younger set lies *unconformably* on the older, denuded set. An unconformity therefore represents a definite break in the continuity of the geological record, and it may also represent a very long interval of time.

It often happens that some rocks, owing to their rigid state, do not fold when subjected to high pressures but rather give way along planes, the rocks on either side of such planes moving relative to each other.

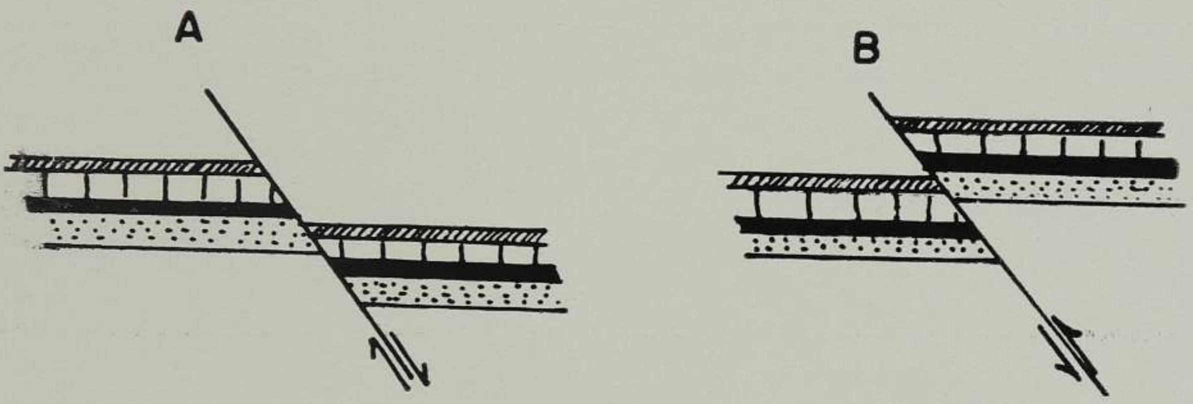

Fig. 10. Types of faults,
A. Normal fault. B. Reversed fault.

This movement is known as *faulting,* and the movement plane is called a *fault plane.* Several parallel faults may occur in a *fault zone.* Faults may be *normal faults* or *reverse faults* (Fig. 10) and in these types the fault plane as well as the relative movement is more or less vertical. Very often, however, the relative movement on either side of the fault is largely in a horizontal direction and the beds are laterally displaced. Such a fault is called a *tear fault* or a wrench fault (see Fig. 40). When the fault plane in a reverse fault is close to the horizontal it is called a *thrust* (Fig. 8). Thrusting very often takes place on a large scale and is frequently connected with the formation of large, recumbent folds. In such movements the lower limb of the recumbent fold may be stretched so much that the upper limb of the fold may be transported many miles from its original position. When this happens, the portion of the fold that has been detached and moved forward is known as a nappe (Fig. 8), nappe structures being very common in mountain chains like the Alps and the Himalayas.

In certain of the more stable parts of the earth's crust, faults may occur on a very large scale, the intervening land between sets of faults sinking to give *rift valleys* or rising to give *block mountains or horsts.* One of the finest examples of this is the African Rift Valley, a gigantic crack in the earth's crust which extends for several thousands of miles from the Red Sea down to the lower part of East Africa.

The third major structure that must be mentioned are *joints*. These are planes of weakness in all types of rocks, caused by tensional or compressional pressures ; the rock parts along joint planes but there is no movement. When a hot magmatic rock like basalt cools, for example, a certain pattern of jointing known as columnar jointing develops (Pl. 1A), the process and pattern being very similar to the mud cracks developing in a drying mud flat (see Pl. 4A). Each column in columnar jointing has a hexagonal cross section, and this results in some very spectacular forms, the best example being the Giant's Causeway in Antrim, Northern Ireland. Joints may be vertical (Pl. 4B), inclined, or horizontal, and they may be parallel to the dip and strike directions of the rocks (as in most Ceylon rocks) or oblique to them. Joints are important structures in that they often control the weathering of rocks, the drainage pattern, and the location of pegmatites and veins.

Mineral Deposits

The material resources of man are chiefly of two kinds—vegetable and mineral. The former are derived from the top few inches of the earth's crust known as the *soil* and they provide him with food and clothing. He must, however, cultivate and look after these uppermost inches of the earth's crust if he wants to get anything worthwhile out of them. The nature of the soil in any place is partly dependent on the rocks beneath, and we shall examine this aspect more closely in the last part of the book (see Chap. 14), but wherever the soil lacks any essential quality it can very often be supplied by man. In other words, man can make up deficiences in the soil or change its nature to suit his purposes. The mineral resources on the other hand, are a gift of nature and nothing he can do can alter their distribution. These mineral gifts of nature are sometimes hidden several hundreds or thousands of feet below the surface of the earth and man has to search carefully for them and devise ways and means of extracting them from the crust before he can use them. The mineral resources of the earth are of many kinds but they can be considered under broad general groups.

There is first the group of *fuels*, mainly *oil* and *coal*. Natural oil, from which we obtain petroleum, is thought by some to be the distillation product of organic or vegetable matter which accumulated in the sediments while they were being laid down ; others consider it of primary origin

Oil is chiefly found in gently folded foothills on the flanks or sides of the great mountain chains of the world, especially those formed during the Tertiary Period (20-70 million years ago) like the Alps, Rockies, and Andes. During the building of these mountain chains, when the rocks were subjected to great pressures, drops of oil distilled from the vegetable organic matter and were forced through the rocks to the margins of these mountain chains. Here they collected in porous material such as sands, sandstones and limestones (with cavities), filling the spaces or pores in these rocks in the same way as water fills a sponge. Within these oil-bearing rocks oil tends to concentrate most at the crests of upward folds or domes (Fig. 11A), and the search for oil is really the search for such structures as these.

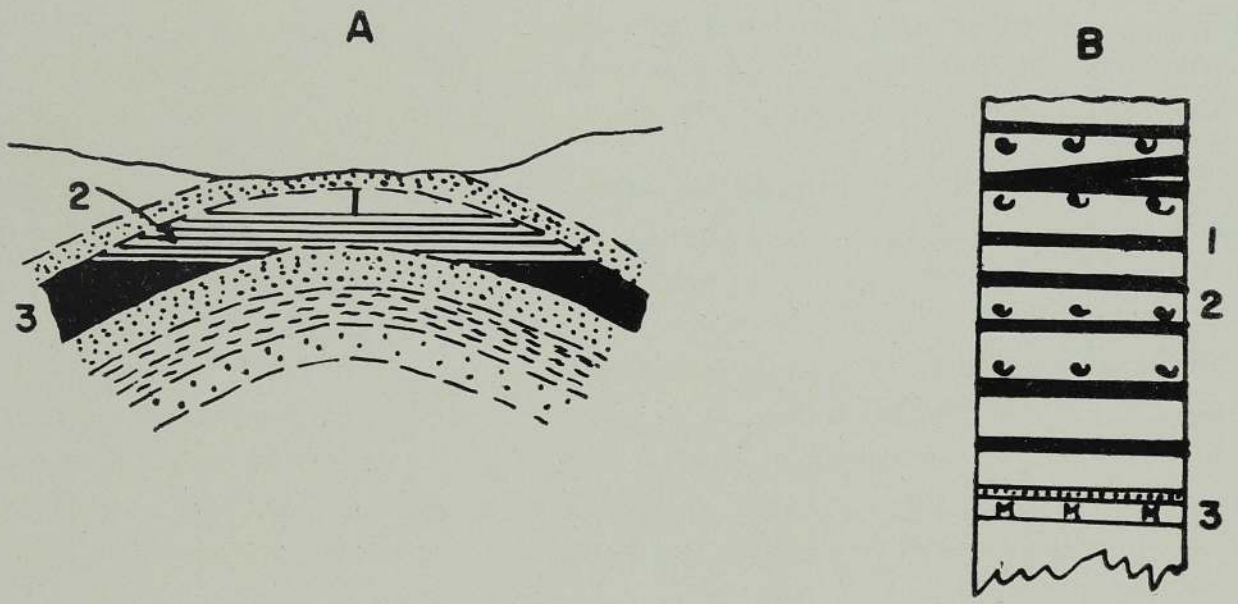

Fig. 11.

A. Diagrammatic section showing an anticline with accumulation of oil at crest. (*D. Leitch*, 1945). (1) gas, (2) water, (3) oil.

B. Generalised section through coal-bearing strata of Central Scotland. (*D. Leitch, 1945.*) (1) coal seams, (2) mussel bands, (3) marine bands ; height of section about 600 feet

Coal, as we have seen, is the ' fossil remains of organic matter ' that has accumulated in equatorial swamps and jungles in past geological ages. The compression of this vegetables matter has turned it first into peat, which still consists largely of vegetable matter, then into lignite, and finally into coal. Coal is brownish black or jet black in colour and occurs in seams together with beds of *fireclay*. The latter contain roots which pass upwards into the coal, and fireclays thus appear to be the original soils in which trees grew. Coal seams are found in great basins, as in S. Wales, where they are interbedded with a variety of other rocks, some of which are bands containing vegetable matter, fresh-water mussels, or marine shells (Fig. 11B). The latter are very important for they often lie above the coal seams, thus representing an encroachment of the sea on the land. By tracing these marine bands (or 'marker horizons') laterally, it has often been possible to discover new coalfields or extensions of old ones.

The industrial development of any country depends primarily on the availability of fuel for power, and it is no accident that the greatest industrial countries of the world have hitherto been those which have large resources of coal and oil. Where such resources are absent, as in the Scandinavian countries, other forms of power like hydro-electric power have been developed in order to assist industrial development. In the future, with the development of atomic power and the use of radio-active minerals (such as uranium and thorium) as sources of energy, man may not be so dependent on these sources of power as he has been in the past. He will however have to rely on them for many years to come.

The second group of mineral resources consists of the metallic and non-metallic **ores,** and here we have to consider a number of different substances formed in a variety of ways. The *primary ores* are those found in the positions in which they were originally formed. For example, nickel ores have formed as minute grains during the crystallisation of hot, molten magma, and are found today as rich concentrations in some igneous rocks. Similarly, many of the diamonds of South Africa occur as crystals in solid volcanic rocks which once filled the necks of ancient volcanoes. The diamonds are easily extracted because the solid rocks are now highly weathered and soft.

Some ores have formed by crystallisation from hot liquids and gases which rose from the depths of the earth's crust and circulated through fissures and cracks in it. Others are the result of cold percolating rain-water leaching out minute quantities of ore minerals from the same rocks and depositing them in cavities and cracks in others. In both instances the ores so formed are found in veins and pockets, where they are associated with *gangue* material, a miner's term given to the useless mineral matter (such as quartz and calcite) that often accompanies ore material in veins. The world's resources of gold, silver, and copper, and our own resources of graphite and mica occur in this manner (see Figs 69, 71 & 72). Many of these ore-bearing veins go down into the crust for thousands of feet and run along the surface of several miles. The Mother Lode of California, for example, has been traced for about 70 miles.

Such primary ores, however, are subject to the normal processes of weathering and erosion, and they are broken down and carried away mechanically or in chemical solution. As they are much heavier than sand and mud, the ore minerals are often deposited in river beds, flood plains, river mouths and beaches. These are the *secondary ores* and they are of great importance because of the ease with which they can be mined. For example, gold used to be mined by panning the sandy beds of rivers, just as our own gems are obtained by panning the old river gravels of the Ratnapura District. Another name for this type of deposit is the term *placer deposit,* and in S. India and Ceylon the most interesting placer deposits are the millions of tons of mineral sands which have been concentrated on the beaches.

One of the most valuable of the minerals in the earth's crust is water, though this might seem surprising at first. The source of all water is, of course, rain, but while much of this rain-water flows away on the earth's surface as rivers and streams or evaporates into the air, a good part of it sinks into the ground and is stored in the earth's crust, saturating the rocks in a zone which is sometimes deep ; the surface of this zone is called the water-table. The depth of the water-table below the surface of the land varies from place to place and from month to month so that a knowledge of the water-table and the manner in which it varies is an important factor in the location of all wells, and ultimately of all human settlement. The best rocks for the underground storage of water are those which have a large proportion of air space (or pore space), such as sands and gravels. Limestones too, with their fissures, solution caves, channels, and underground streams, are good for the storage of water.

CHAPTER 3

GEOLOGICAL TIME AND LIFE

I see no prospect of an end, no signs of a beginning.

James Hutton, 1783

The Age of the Crust

THERE were two ways, before the present century, of estimating the earth's age, and both were based on one of the fundamental laws of geology, namely the *Law of Uniformitarianism*. This states that the processes going on at the present time have operated throughout the earth's history and at roughly the same rate. In other words, ' the present is the key to the past '. To take a simple example, modern glaciers, when they melt and retreat, leave behind a thick assortment of sand, clay, and boulders known collectively as *glacial till*. The recognition of similar looking deposits in ancient rocks, for example the Dwyka Tillite of S. Africa or the Talchir boulder bed of India, indicates that such areas were covered by glaciers during the Palaeozoic Era.

In the same way, the first method of estimating the earth's age was by assuming that the weathering of the rocks at the surface and the accumulation of sediments both have gone on at an average rate throughout geological time. Geologists therefore thought that by dividing the total thickness of the sedimentary rocks by the annual rate of deposition of sediments an estimate of the age of the crust could be arrived at.

The second method was by using the total amount of sodium in the sea. It was assumed that the oceans were originally of ' fresh ' water and that t[illegible]odium now found in them was brought into the sea by all the river systems of the world. Hence, by dividing the total amount of salt in the oceans by the rate of discharge of salt by the rivers, an estimate of the earth's age was arrived at. By these two methods the oldest sediments found in the crust were reckoned to be 100 to 175 million years old.

Both methods, we can now see, are subject to the same errors and limitations, chief among them being (*a*) that it is quite impossible to make an accurate estimate of the amount of sediment or salt carried into the sea, (*b*) that the rates of deposition have varied enormously during geological time, and (*c*) that when estimating the total thickness of the sediments, no adequate allowance can be made for the many gaps in the succession when rocks were being eroded away not being deposited.

GEOLOGICAL PROCESSES AND PRINCIPLES

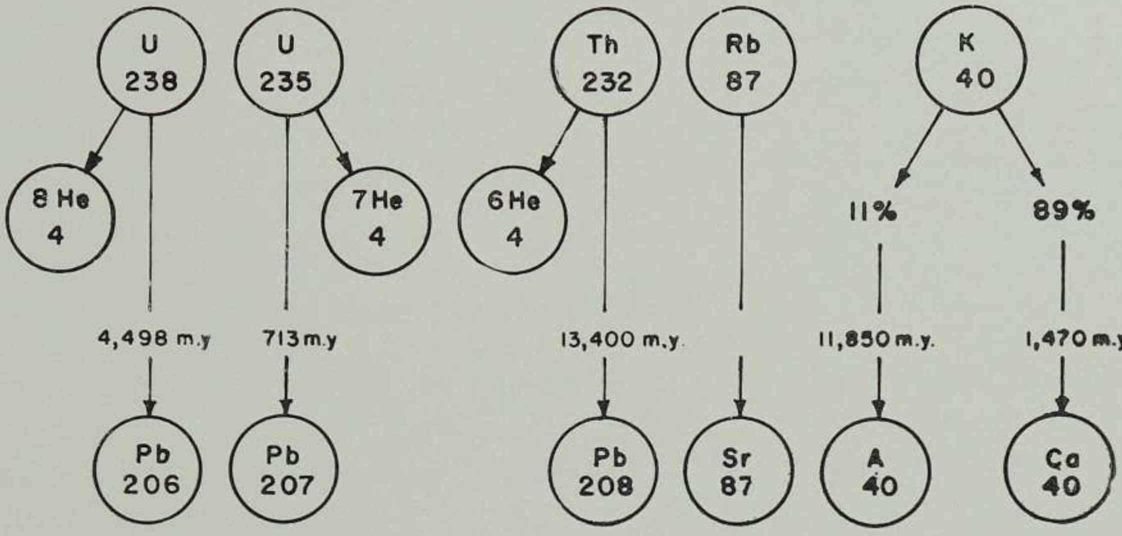

Fig. 12. Radioactive timekeepers ; diagram showing the parent isotopes, their half-lives (in millions of years) and their end products. (*A. Holmes*, 1965)

It was only at the end of the last century that the discovery of radioactivity in minerals (see Pl. 32A) gave men a more precise method of calculating the age of the crust in terms of years, a method known as *radioactive dating.* The principle of the method is this. Certain elements such as uranium and thorium have unstable atomic nuclei which disintegrate spontaneously to form more stable end products (Fig. 12). Uranium, for example, breaks down to give helium (a gas which escapes) and lead (which accumulates). The rate of this radioactive decay is constant for any element and differs from one element to the other and these rates have been measured with a high degree of accuracy. For example, after 5 million years, half the atoms in a piece of uranium change to lead ; the *half-life* of uranium is therefore said to be 5 m.y. Thus, by measuring the ratio of disintegrated lead to undisintegrated uranium (the uranium/lead ratio) the *isotopic age* of the uranium-bearing rock or mineral can be measured in years. Uranium and other radioactive minerals are fairly widely distributed in many rock types, though in small amounts, and by measuring the uranium/lead, thorium/lead, potassium/argon, or rubidium/strontium ratios, a fairly reliable geological time scale has been set up.

The oldest dated rocks by this method are lepidolite (lithium-mica) pegmatites in Rhodesia (C. Africa), Wyoming (U. S. A.), and Manitoba (Canada), which are about 3,300 million years old. These pegmatites, however, are themselves intruded into considerable thicknesses of still older rocks whose ages are as yet not known. The most recent estimates of the consolidation of the earth's crust, that is, the cooling and solidification of the original molten skin, is 4,200 million years ; the earth itself is believed to have originated 4,500 to 5,000 million years ago (see Table 6).

GEOLOGICAL TIME AND LIFE

The Sub-division of Geological Time

Geological history, like human history, can be subdivided into a number of ERAS, based on the general character of life during these subdivisions. Thus we speak of the Egyptian era and the Greek era in human history whereas in geological history we speak of the *Cryptozoic* (hidden life), the *Palaeozoic* (ancient life), the *Mesozoic* (middle or mediaeval life) and the *Cenozoic* (recent life, eras. Each era is subdivided into several PERIODS and every period has its particular association of living organisms (now preserved in the rocks as fossils) and a particular group of rocks which reflect the climatic and physical conditions under which the sediments were laid down. The periods are named either after the localities where they were first recognised or by some distinctive feature of the period. This succession of Eras and Periods is generally represented by the *standard geological column* which, in fact, is a composite picture of the history of the earth's crust built up from individual successions in various parts of the world.

Let us look at this geological column or *geological time scale,* shown in Table 6, a little more closely. The most important dividing line in the column occurs about 600 million years ago at the base of the Cambrian Period, when it is first possible to use fossils to subdivide geological time. Everything before this, representing nearly 6/7ths of geological time is known as the Cryptozoic era or the Pre-Cambrian period. Although once called the Azoic (lifeless) era there is increasing evidence of the existence of forms of life in the Pre-Cambrian not different from those in the Cambrian and later periods. In the absence of good fossil evidence, however, the Pre-Cambrian has to be subdivided into *geological cycles* whose ages are known from radioactive dating.

The Palaeozoic Era extended from 600 to 225 million years ago and is subdivided into six periods known as the *Cambrian* (after Cambria, the ancient name for Wales), the *Ordovician* (after Ordovices, a Celtic tribe), *Silurian* (after Silures, another Celtic tribe), *Devonian* (from Devonshire), *Carboniferous* (the great coal-bearing period) and *Permian* (from Perm, a kingdom of old Russia). The Palaeozoic Era saw the origin and development of a variety of living forms such as the invertebrate animals, fishes, amphibians, and primitive plants.

The next era, the Mesozoic, lasted from 225 to 70 million years ago and it is subdivided into three Periods, namely, the *Triassic* (after the threefold development of rock types in Germany), the *Jurassic* (from the Jura Mountains) and the *Cretaceous* (the system containing extensive chalk deposits). This was the great period of the reptiles when monstrous creatures like the dinosaurs roamed the earth.

TABLE 6—The Geological Time Scale

(Revised A. Holmes, 1959)

ERA		PERIODS AND SYSTEMS		**Maximum known thickness** (*Thousands of feet*)	**Began m.y. ago**	**Duration**	LIFE	
					(*Millions of years*)		**Animal**	**Plant**
CENOZOIC (70 m.y. to present)		QUATERNARY	Holocene (or Recent) Pleistocene	6	2 or 3	2 or 3	Mammals, birds	Modern seed plants
		TERTIARY	Pliocene	15	12	9 or 10		
			Miocene	21	25	13		
			Oligocene	26	40	25		
			Eocene	30	60	20		
			Palaeocene	12	70	10		
MESOZOIC (225 to 70 m.y. ago)		CRETACEOUS		51	135	65	Reptiles and Ammonites	Ancient seed plants
		JURASSIC		44	180	45		
		TRIASSIC		30	225	45		
PALAEOZOIC (600 to 225 m.y. ago)	UPPER	PERMIAN		19	270	45	Amphibians	Spore-bearing plants
		CARBONIFEROUS		46	350	80	Age of fishes	
		DEVONIAN		38	400	50	Invertebrates	Seaweeds
	LOWER	SILURIAN		34	440	40		
		ORDOVICIAN		40	500	60		
		CAMBRIAN		40	600	100	Abundant fossils first appear	

PRE-CAMBRIAN*	Late	See Table 13	Scanty remains of sponges, algae worms, and bacteria.
	Early		Rare algae, bacteria, 3000 m. y ago.
OLDEST DATED ROCK		3,400	
Undated interval		3,400–4,500	
ORIGIN OF CONTINENTAL CRUST		4,500	
ORIGIN OF THE EARTH			

* Formerly known as *Proterozoic*, *Archaeozoic*, or *Eozoic*.

The last era, in which we are living, is the Cenozoic, subdivided into the *Tertiary* and *Quaternary* Periods. The Tertiary Period is itself further subdivided into several EPOCHS and these are named after the proportions of modern marine shells occurring as fossils in each. They are the *Palaeocene* (ancient dawn of the recent), *Eocene* (dawn of the recent), *Oligocene* (few of the recent), *Miocene* (less recent), *Pliocene* (more recent). The Quaternary Period is subdivided into the *Pleistocene* (most recent) and the *Holocene* (wholly recent) and it has occupied only the last million years. Mammals (including man) and flowering plants evolved during the Cenozoic era.

Geological time, like the distance of the stars from the earth, is so immense that it is really quite difficult to comprehend or appreciate its magnitude. We can, however, understand something of its comparative length if we represent the earth's history by a calendar year in which January 1 is the origin of the earth 5,000 million years ago and December 31 the present day. Each second would then represent 167 years and each minute would be equivalent to 10,000 years. In such a calendar the lower Cambrian world would begin on November 18, and the appearance of man would take place on December 31, at 11.50 p.m., that is, 10 minutes before midnight!

Life in the Rocks

We have seen that the most important dividing line in geological time lies at the beginning of the Cambrian Period, when several forms of animal life were preserved in abundance as fossils in the rocks of this period. What exactly are fossils? Fossils (from the Latin word *fossilis* meaning something dug up) are the actual remains or the direct indications of life in the past which are preserved in the rocks formed at the time these creatures lived. The processes by which fossils are preserved is termed *fossilisation.*

As one would expect, the soft bodies of animals, or even the hard parts such as bone and teeth, would normally decay in a very short time, so that only in exceptional circumstances would they be preserved. The woolly mammoth, for example, was completely preserved for 25,000 years by being ' deep frozen ' in ice immediately after it had died. Most fossil remains, however, are due to the infilling of the cavities once occupied by the soft parts of the animal by some mineral such as silica, calcite, or pyrite ; in others even the hard parts are dissolved or decay away but the moulds are filled with these same minerals, thus forming *fossil casts.* Sometimes the *impressions* of fossils are left in the soft materials which subsequently cover them. In such ways even the most delicate structures such as muscle scars and leaf structures may be preserved after millions of years (see Pl. 18).

Fossils have attracted attention from the time of primitive men, being used mostly as charms and curios, but it was the Greeks like Herodotus (484-425 B.C.) and Aristotle (384-322 B.C.) who first recognised their true nature. This knowledge was lost during the ignorance and superstition of the Dark and Middle Ages and it was only in the Renaissance of the 15th and 16th centuries that it was rediscovered that fossils were in fact the remains of organisms that once lived. Leonardo da Vinci (1452-1519) was one of those who rediscovered this truth ; but so literally was the Biblical story of the Creation interpreted that most people up to the 19th century believed that the presence of fossils in the rocks was due to the Great Flood and to other catastrophes.

In the late 18th century, a mining surveyor called William Smith (1769-1838) now known as the 'Father of English Geology', kept a careful record of the fossils collected by him from the many canal cuttings he surveyed. By carefully recording his observations, William Smith discovered two very important and fundamental facts. These were (1) that each layer or stratum of rock had its own particular assemblage of fossils, and (2) that widely separated rocks, if they had the same assemblage, must be of the same age. William Smith applied his new-found knowledge to produce the first geological map of England and Wales in 1815. Further, his discoveries made possible the dating of each stratum of rock and the construction of the detailed geological column, described in the earlier section, which tells the continuous story of life on the earth's crust.

The Palaeozoic Era was the age predominantly of the invertebrate animals or 'animals without backbones', the most abundant and highly developed of which during the Cambrian period were the **trilobites** (Fig. 13). These fascinating, segmented creatures are the ancient relatives of the lobster and the crab, and their evolutionary development is so clearly recorded in fossils that they are used to subdivide the Cambrian into a number of smaller time divisions. About 100 million years later the **graptolites** (Fig. 14) became an important form. They are called by this name because they look like pencil lines on the slates in which they are best preserved. The graptolites floated on the surface of the Palaeozoic seas and when they died they sank to the sea bottom and were preserved in the black, muddy deposits of the ocean deeps. Graptolites have two characteristics which make any group of fossils valuable to the geologist. Firstly, they were floating organisms and therefore had a wide distribution ; in this way members of the same species

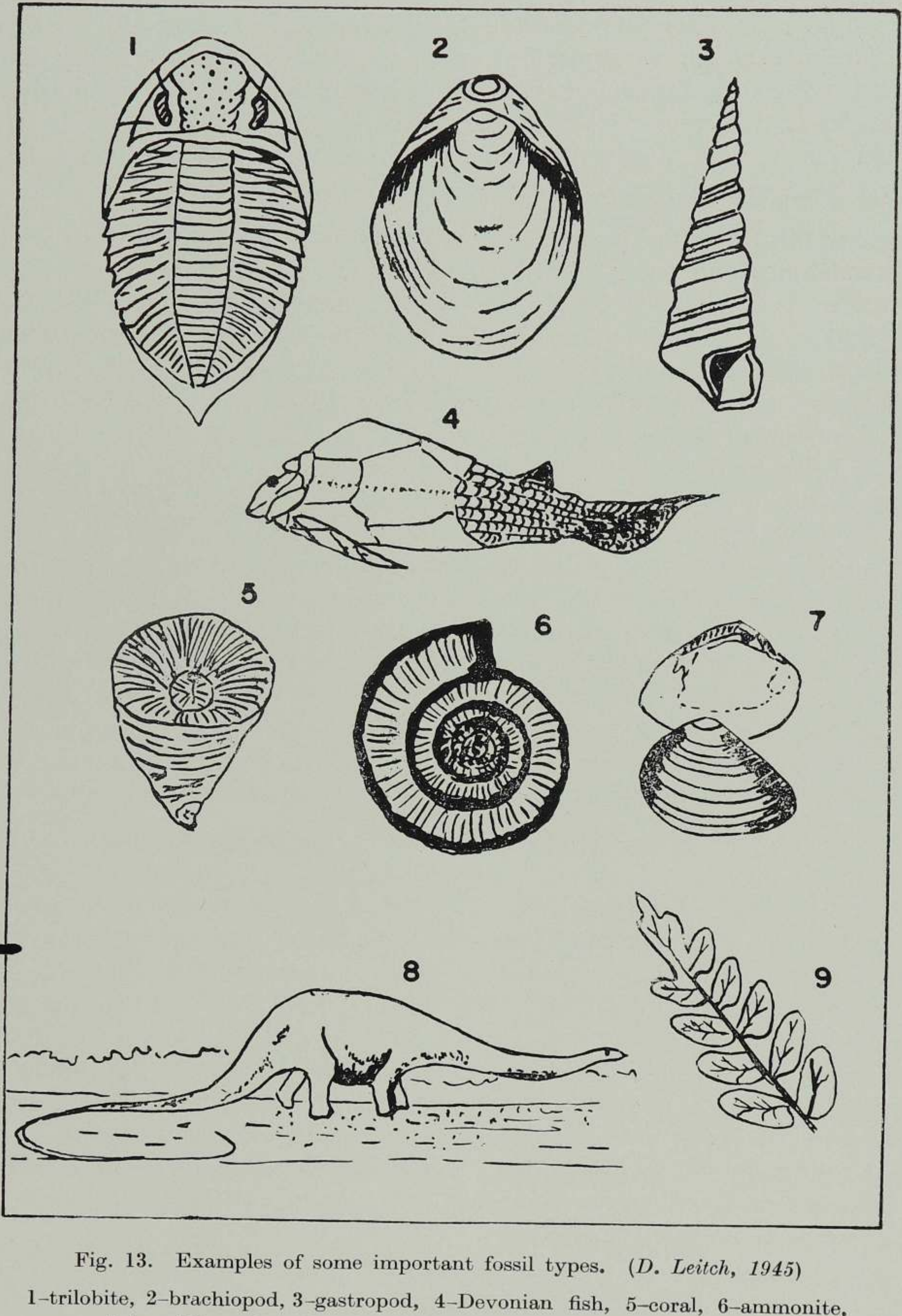

Fig. 13. Examples of some important fossil types. (*D. Leitch, 1945*)
1–trilobite, 2–brachiopod, 3–gastropod, 4–Devonian fish, 5–coral, 6–ammonite, 7–lamellibranch, 8–dinosaur (*Diplodocus*), 9–Carboniferous plant.

living at the same time would be found hundreds or even thousands of miles apart, thus making possible the correlation of rocks in Scotland and N. America, for example. Secondly, they evolved very rapidly, each species living only for a short time ; as a result it is possible to subdivide the Ordovician period into a large number of narrow zones, each with its unique association of graptolites. Other common forms which existed during the Paeozoic Era were **corals** and **brachiopods** (Fig. 13).

During the Devonian period, part of Britain was a semi-desert in which red sandstones and coarse detrital deposits were laid down. These rocks are called the Old Red Sandstone (to distinguish them from the New Red Sandstone, formed under similar conditions in the Triassic period), and in this formation are found large numbers of **primitive fish.** The fish are heavily armoured with thick plates (Fig. 13) but have no bony jaws, and the way in which they are preserved suggests that they lived in inland lakes and pools which dried up suddenly, causing hundreds of them to die together. During the Carboniferous period which followed the Devonian, a warm, probably shallow sea covered the land, and corals of many kinds are fossilized in the great limestone beds which formed at the time. Even coral reefs, with a rich and varied association of marine forms as in modern coral reefs, have also been found in the Carboniferous limestones. There were at the same time large areas of swamps and deltas in which a dense, luxuriant, equatorial vegetation flourished, with gigantic trees carrying palm-like fronds growing in these swamps. This rich vegetation in time decayed to form the great Coal Measures, and their stems, roots, leaves, and even pollen are preserved as fossils.

The Mesozoic Era is sometimes known as the Age of Reptiles owing to the fact that these creatures dominated the land, sea, and air during this time, finally dying out as rapidly as they began. The weird, monstrous, spectacular beats, known collectively as the **dinosaurs** or 'terrible lizards' had a number of interesting genera. Tyrrannosaurus, for example, stood 20 feet high, had scimitar-like fangs, and was the most powerful flesh-eater of them all ; *Brontosaurus,* 65 feet long, was a herbiverous creature ; *Diplodocus* (Fig. 13), the largest of the dinosaurs, sometimes attained a length of 80 feet, and *Stegosaurus* had bony plates and powerful spikes on his back. In spite of their great size the dinosaurs had tiny brains, and they quickly died out when they failed to adapt themselves to rapidly changing environmental conditions.

One group of reptiles, the Pterodactyls, took to the air, but they all had teeth and four legs, and the largest had a wing spread of 24 feet. The pterodactyls evolved finally into the birds, the connecting link being *Archaeopteryx* which was both bird and reptile, with rows of long teeth and a long tail.

The Jurassic period saw the special development of the **ammonites** (Fig. 13), relatives of the present day *Nautilus,* squid, and octopus. Like the graptolites in the Ordovician, the ammonites evolved rapidly, each species being restricted to a thin stratum in the geological column and to a short period of time. The Jurassic period also can be subdivided into a large number of zones, each with its characteristic ammonite.

During the Tertiary Period many of the present day forms such as the **oysters** and **molluscs** were increasing ; it also saw the rise of mammals and **flowering plants.** The Pleistocene and Holocene witnessed the evolution of Modern Man.

Fossils and Evolution

The researches of men like William Smith, his two French contemporaries Lamarck and Cuvier, and Charles Darwin showed that the fossil record is a continuous one extending over almost an infinity of time. It gradually came to be realized therefore that the final answer to the principles of evolution lay in the detailed study of the fossil evidence, inch by inch, over continuous successions of rock strata.

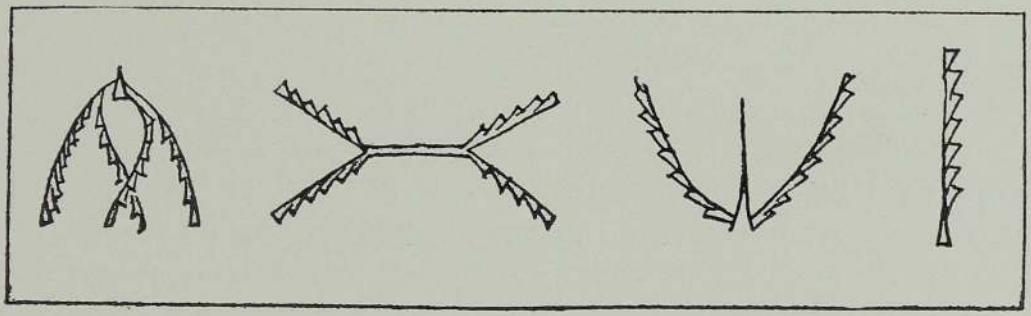

Fig. 14.—The evolutionary trend in graptolites, showing (from left to right) the reduction in the number of branches and the change in direction of growth. (*After D. Leitch, 1945*)

Take the graptolites for example. They were small colonies of floating organisms, rather like the present day sea firs, each colony consisting of rows of small cups connected by a common canal, each cup occupied in life by one animal. Studies of large numbers of graptolites from successions of Ordovician strata showed that there was a rapid change of character from the early to the late types. The early types had many branches hanging downwards, the middle types had branches which spread out flat, and the later types were reduced to one or two branches which stood upright (Fig. 14). There were other changes as well, but the important thing is that the changes were gradual, taking place over millions of years and giving rise to a procession of ever-changing species.

Another good example is that of the sea urchin, *Micraster,* found in the Chalk deposits of the Tertiary era. The study of thousands of fossils, carefully collected from layer upon layer of the Chalk, disclosed an almost imperceptible but continuous change from one species into another, by an infinite number of intermediate links. Here in fact was the perfect case of "evolution caught in the act."

The knowledge gained by geologists from these and many other similar studies has had great practical importance. By knowing the series of changes in the history of certain fossils it has been possible to correlate rocks whose ages are unknown with those whose ages are known ; in this way the existence of important oil and coal fields in America has been successfully proved.

The Geological Cycle

We have seen how geological time is subdivided into Eras, Periods, and even smaller units, and how, by studying the fossil record, we have been able to build up a story of successive strata being laid down on top of each other under varying conditions to give us the history of the earth. But the history is still not complete and we must, in this final section, attempt to fill the gaps.

In the early 18th century it was still not realized that fossils were the remains of forms of life living in the sea which, when they died, sank into the ocean bed, to be covered by later sediment. It was a man named James Hutton who, wandering around the coast of his native Scotland in the 1780's, realized that the beach deposits he saw lying high above the existing shoreline, must once have been at sea level and been subsequently raised to their present heights. This was one of the major steps forward in geological thinking, and it ultimately led to the recognition that rocks containing marine fossils, now found at such great heights as 16,000 feet above sea level in the Himalayas, must once have been laid down at the bottom of a sea.

The next step was a short one, namely, the recognition that the earth throughout its history has been undergoing continuous elevation or subsidence. These so-called earth movements are of two kinds—*epeirogenic* and *orogenic*. Epeirogenic movements are vertical movements, either up or down, affecting large portions of the crust. It has been found, for example, that Scandinavia is undergoing a slow tilting movement and that in the north of Sweden the coast is rising at the rate of 3 feet every 100 years. We can see the same process in our own island where the Jaffna

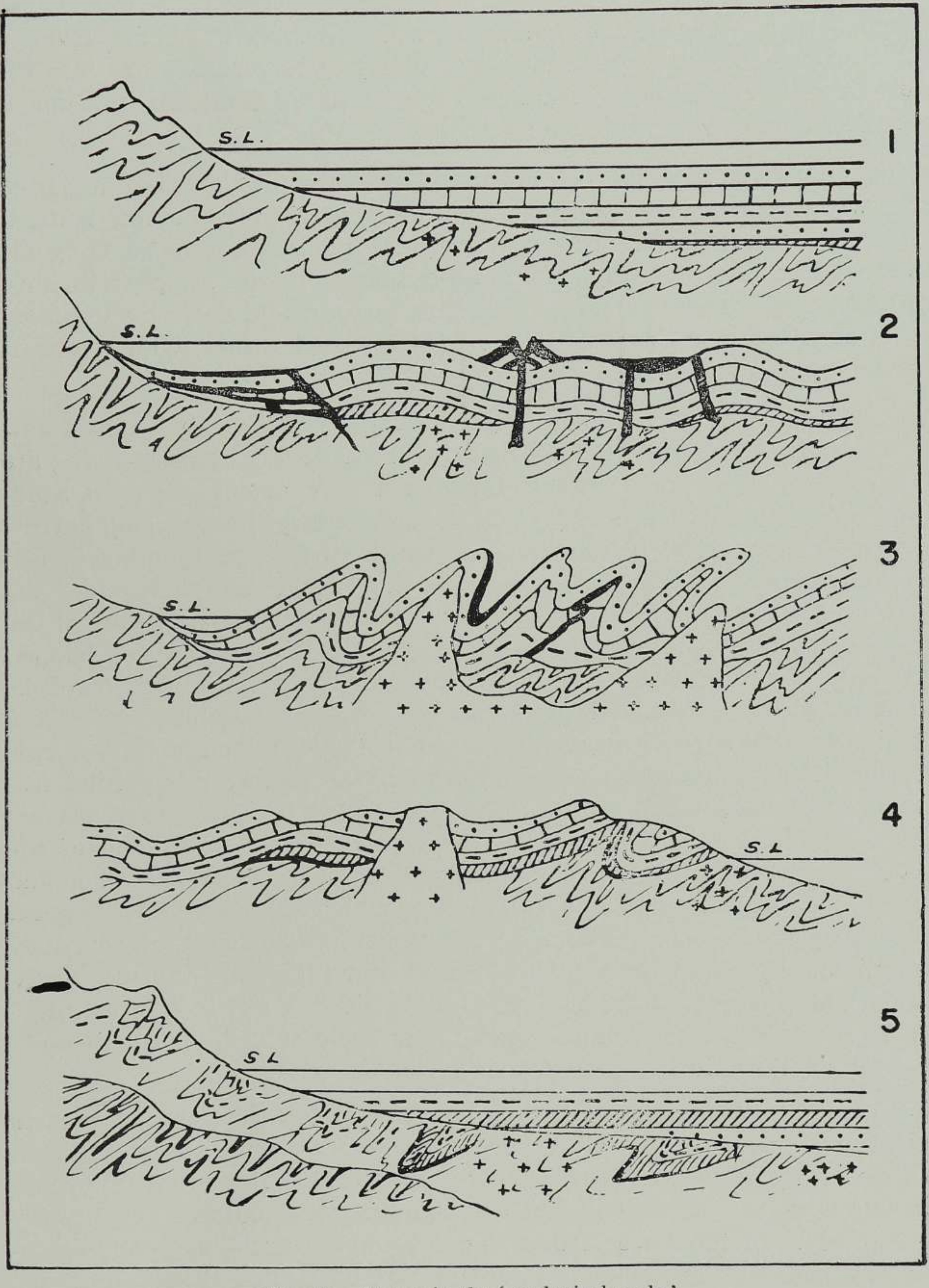

Fig. 15. Stages in the 'geological cycle'.

1. Deposition of sediments in geosyncline.
2. Gentle folding and extrusion of volcanic rocks (solid).
3. Intense folding and mountain building, with intrusion of granite (crosses).
4. Weathering and erosion of mountain chain.
5. Deposition of sediments in new geosyncline.

limestone which was formed below the sea now rises above sea level in cliffs that are 50 feet high. Many rift valleys and plateaus are also the result of such movements in which large blocks of land are uplifted or depressed between gigantic faults.

Orogenic movements, on the other hand, are brought about by tangential forces within the crust and are confined to comparatively narrow belts. It is these movements that give rise to great mountain ranges. Orogenic movements or, more simply, mountain-building episodes, appear to have occurred several times during the earth's history, and each such episode can be seen to be an essential part of a cycle of events which repeats itself over and over again.

The beginning of such a cycle is sedimentation (Fig. 15). When a new land surface is exposed to weathering, the products of such weathering are carried down, as we have seen, to form great thicknesses of shales, sandstones, limestones, and a variety of other sedimentary rocks in long narrow basins or troughs of deposition in the ocean known as *geosynclines*. Such great thicknesses of sediments could not, however, accumulate under the sea on the floor of a geosyncline unless the floor itself keeps sinking at the same rate as the sediments are being deposited. If this did not happen the trough would soon fill up and no more deposition would take place. The sinking of the trough is probably due to the down-buckling of the earth's crust below the geosyncline, brought about by compressive forces in the crust, but it may also be due to the weight of the overlying sediments. As a result, the sediments begin to be folded and at the same time volcanic rocks are poured out through volcanoes and fissures. The folding of the rocks is accompanied by uplift, the folded rocks being pushed higher and higher to form mountain chains, the cores of which are often filled by great masses of granitic rock. As soon as the rocks emerge from the sea, they are immediately acted upon by the forces of weathering, the weathered material being carried down and deposited on the flanks of the mountain chain as new sediments. Thus begins a new cycle of sedimentation—folding—uplift and erosion.

The geological (or orogenic) cycle, though it takes a few minutes to describe, takes tens, even hundreds of millions of years to complete itself, and the history of the earth is a record of several major orogenic cycles, each following the other and building up the continents in the process (see Fig. 16). In the lower Palaeozoic Era, for example, a great geosyncline extended through what is now the eastern United States, northern Scotland, and Norway ; the sediments and volcanic rocks laid down in this geosyncline were folded and uplifted to form the Caledonian mountain chain, only the roots or remnants of which we now see in the Highlands of Scotland and in Norway. Again, during the Tertiary Period, a great geosyncline known as Tethys Sea extended across Europe and Asia, separating a northern landmass know as Laurasia from a southern landmass known as Gondwanaland. The sediments of this geosyncline were folded and uplifted at the end of the Tertiary Period to form the folded mountain belt containing the Alps, the Carpathians, and the Himalayas. The Himalayas are still rising, even today, and this uplift can be seen in the tremendous gorges that are being cut in it. The vast amount of material being

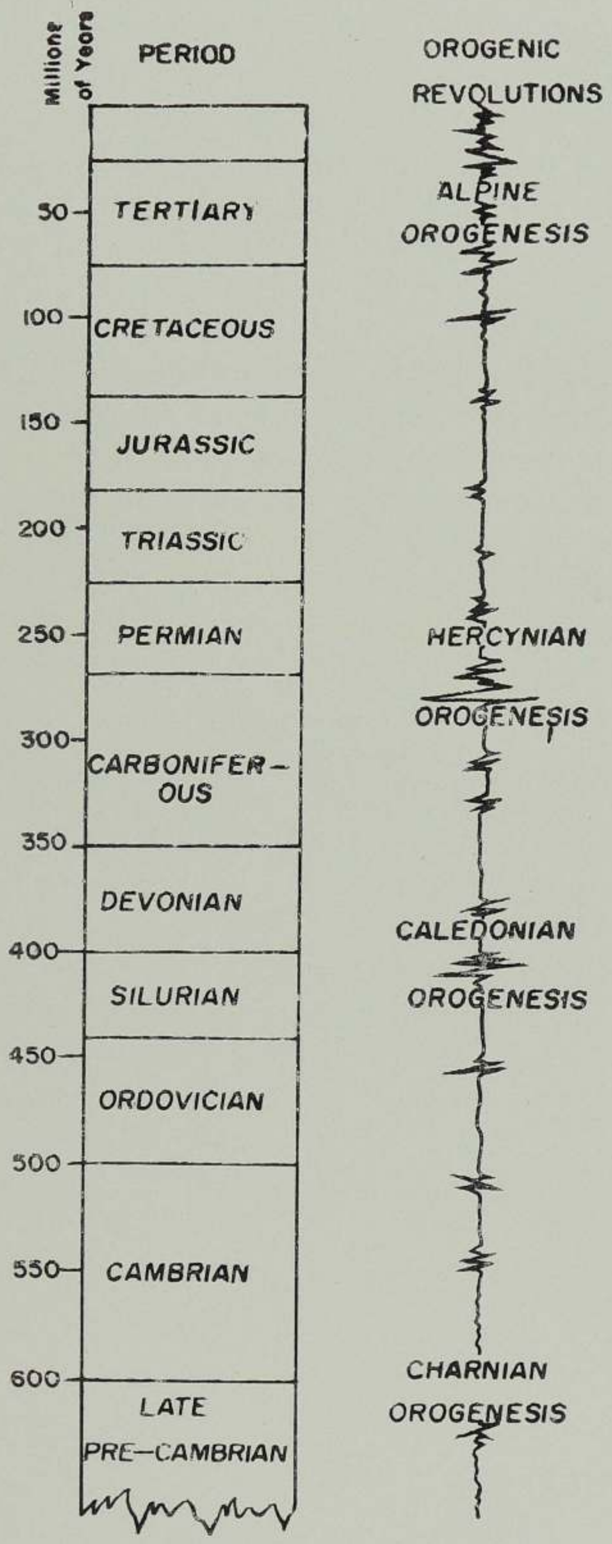

Fig. 16. Diagram showing the main orogenies that affected Europe after Pre-Cambrian times.
(*A. Holmes*, 1965)

denuded from the rising mountain chain is brought down by the countless streams and rivers flowing from the Himalayas and is being deposited in the long narrow Indo-Gangetic plain on its southern flank.

Several orogenic cycles have been recognized in Western Europe from the time of the Cambrian Period, each of which has been carefully dated by its fossils (Fig. 16). This is true of other parts of the world as well. Moreover, it is now known that similar cycles took place through Pre-Cambrian time, the roots of one dissected mountain chain often forming the floor of a new cycle of sedimentation. In fact, in the absence of fossils, Pre-Cambrian history is subdivided into ' orogenic cycles ' which have been dated by radio-active methods. In the Pre-Cambrian of Central Equatorial Africa, for example, four cycles have been recognized ; several orogenic belts are now known to occur in the Indian Shield (see Fig. 30). In Ceylon, as we shall see later, we can recognize one such geological cycle, the Taprobanian, which evolved in a geosyncline stretching from Ceylon to the east coast of India, now occupied by the Eastern Ghats.

We shall, at this point, leave our introduction of the reader to geological principles and processes * and take a look at the geology of our own island more closely.

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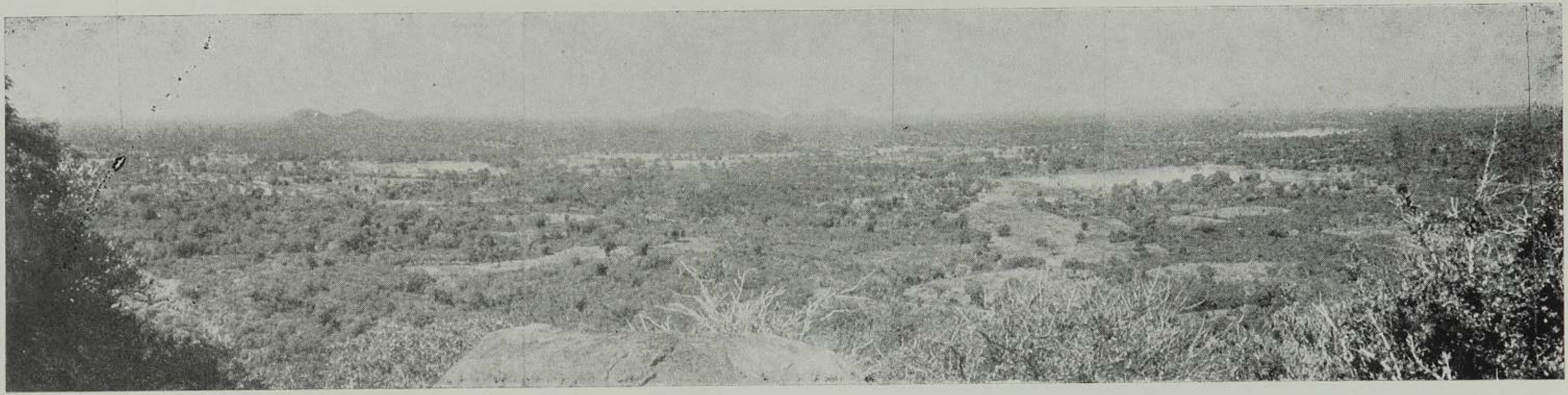
* Anyone interested in knowing more about the geological principles and processes briefly outlined in this part of the book should read the excellent new (1965) edition of *Principles of Physical Geology* by Arthur Holmes, D.Sc., Ll.D., F.R.S. It is a mine of information on most topics.

PART TWO

THE GEOLOGY OF CEYLON



Panoramic view of the lowest peneplain south-west of Anuradhapura; view looking north-westwards from Tambutakanda, near Galgamuwa. Note the granitic erosion remnants of Sangakparle, 738′ (on extreme left) and Sangilimala, 888′. Tambutta Wewa is in middle of picture and Giribawa Wewa behind it.

(Length of horizon about 20 miles)

CHAPTER 4

PHYSICAL FEATURES

I want you to understand that the Island of Ceylon is for its size the finest island in the world.

Marco Polo, 13th Century.

Introduction

EVEN though Marco Polo may have been guilty of some exaggeration, many travellers throughout the centuries have described Ceylon (variously designated as Ceilan, Serendib, Taprobane, Sielediva and other names) as one of the most beautiful islands in the world. The reason for this clear, for within its 25,332 square miles (the island is 270 miles long and 140 miles at its widest) can be seen wide plains and high mountains, gentle slopes and steep precipices, white sandy beaches, green forested hills, scrubland, grassland, and semi-desert in combinations that are particularly delightful to the eye and satisfying to the aesthetic sense. All this wonderful scenery is the result of the interplay of many factors such as climate, natural and man-made vegetation, human culture, physical features, rock type, and geological structure. The last three factors are among the most important and the fact that they influence each other to a considerable extent will be seen in this chapter.

The physiography of Ceylon can best be described briefly as consisting of a central mountainous mass, the Central Highlands, rising in a series of tiers or ramparts from a low, flat plain surrounding it on all sides and extending to the sea (Figs. 17 and 18). Robert Knox was aware of this in 1681 when he described the Kingdom of Kandy as being[2]

> ' strongly fortified by nature. For which way soever you enter into it, you must ascend vast and high mountains and descend very little or nothing. '

Most of us, too, are consciously or unconsciously aware of this main fact about the island's physical features, but it was the Canadian geologist, Frank Dawson Adams who, in 1929, first recognised and described the ' three well-marked plains of erosion (*or peneplains*) cut in the rocky framework of the island '[3]. A peneplain is defined as being ' almost a plain ' produced by long periods of weathering and erosion. Peneplains can exist at all levels, their main characteristics being that the hills, ridges, and plateaus within them are all at the same general level; for this reason they are often referred to as *erosion levels*

THE GEOLOGY OF CEYLON

Fig. 17. Sketch map of the relief of Ceylon.
(The two small blank spaces in the south-west should have a close stipple, i.e., 3,000′—5,000′)

PHYSICAL FEATURES

The lowest peneplain of Ceylon surrounds the central Hill Country on all sides and is a flat, sometimes gently undulating, plain stretching down to the coast (Fig. 18). It has an average height of less than 100 feet but rises inland to 300 or 400 feet above sea level. Rising from this inner edge in a steep step of about 1,000 feet is the middle peneplain (see Figs. 19 and 20) with a maximum elevation of 2,500 feet above sea level, best seen on the south and east of the island. Within it and rising from it in another steep step of 3,000 to 4,000 feet is the highest peneplain at a general level of 5,000 to 6,000 feet, but rising in places to 7,000, or 8,000 feet. Though deeply dissected by river valleys, these peneplains are recognized as such by the fact that the summits of the hills and ridges show a general accordance of level ; remnants of higher erosion levels sometimes rise above them.

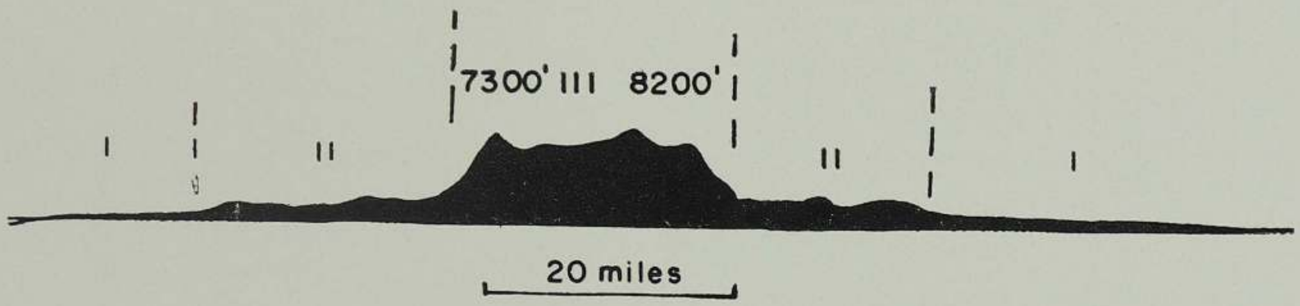


Fig. 18. Diagrammatic section across Ceylon showing the three peneplains. (*D. N. Wadia*, 1942
I—lowest, II—middle, III—highest.

The best place from which to see the three peneplains of Ceylon is Haputale (Fig. 19A). As one looks southwards from this point on the rim of the highest peneplain, the *Uva Basin* and *High Plains* (see below) lie behind and to the right respectively, and before one the land falls away steeply in a mighty escarpment to the plateau-like region, around Haldumulla, which is part of the middle peneplain. Beyond this is still another sharp drop to the coastal peneplain stretching out almost endlessly, with here and there a few isolated hills rising almost disconsolately from it.

Adams thought that the highest peneplain was the oldest of the three and that the island had been rising throughout its geological history in a slow, vertical movement, exposing more and more land to atmospheric erosion and denudation. In 1941, however, the Indian geologist Dr. D. N. Wadia, who was the Government Mineralogist of Ceylon at the time, suggested that the Highlands were formed comparatively recently by the vertical uplift of large blocks of the crust along very large faults, that is ' by ' block uplift '[4]. If this were so, then the highest peneplain is the youngest, and not the oldest, as Adams suggested. These theories of

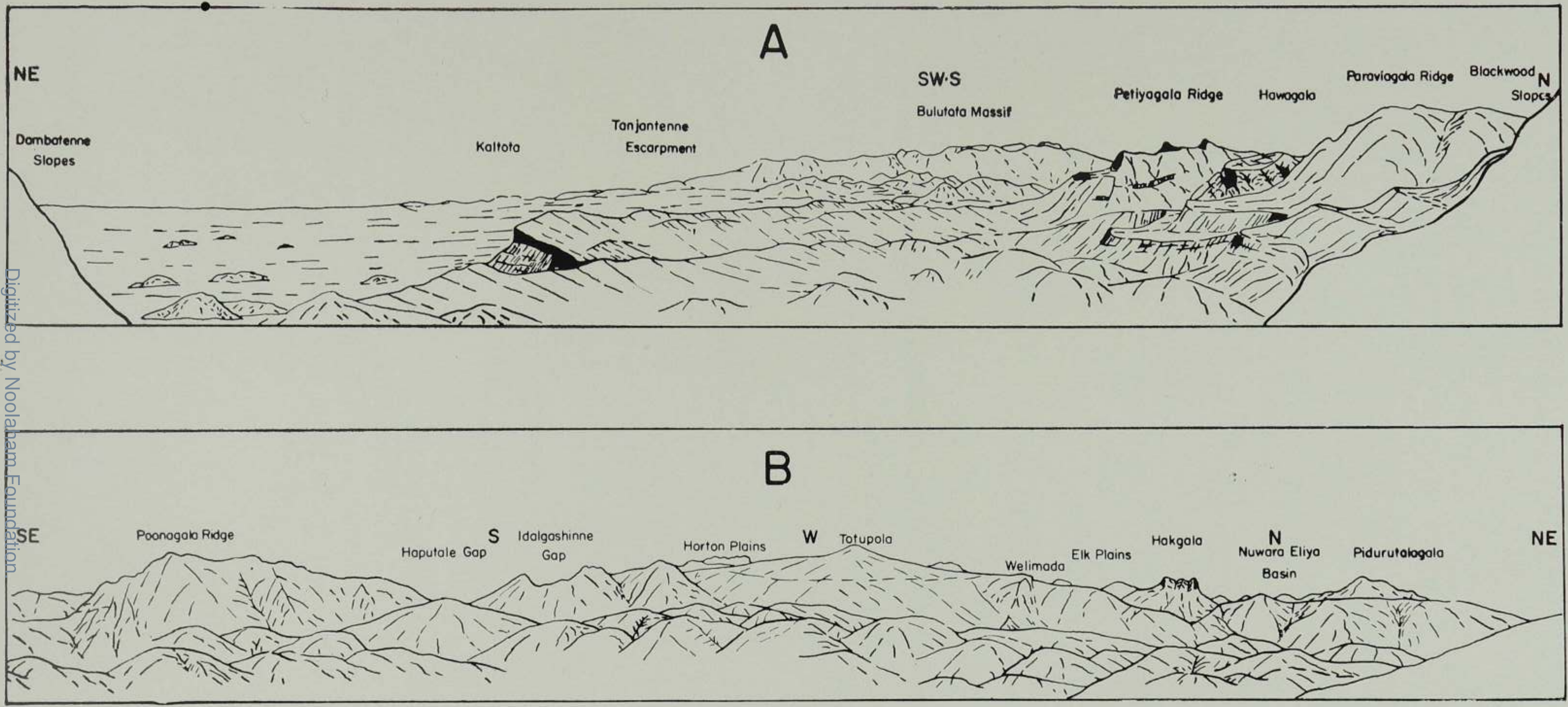


Fig. 19.

A. Sketch of the panoramic view from Haputale Gap showing the middle peneplain and the lowest peneplain separated by the Kaltota escarpment. Note the Rakwana (or Bulutota) Massif in the background.

B. Sketch of the panoramic view of the Uva Basin as seen from near Bandarawela.

origin do not concern us here, and much hard but interesting field work has still to be done before the way in which these peneplains originated is known. We can, however, recognize peneplains (in a broad sense) as essential parts of our landscape and examine them in more detail.

The Lowest Peneplain

The lowest peneplain stretches from coast to coast in the north of Ceylon and from Trincomalee to Hambantota on the east and south. On the west too, a general impression of flatness is present, though the peneplain is here at a somewhat higher level and rather narrower in

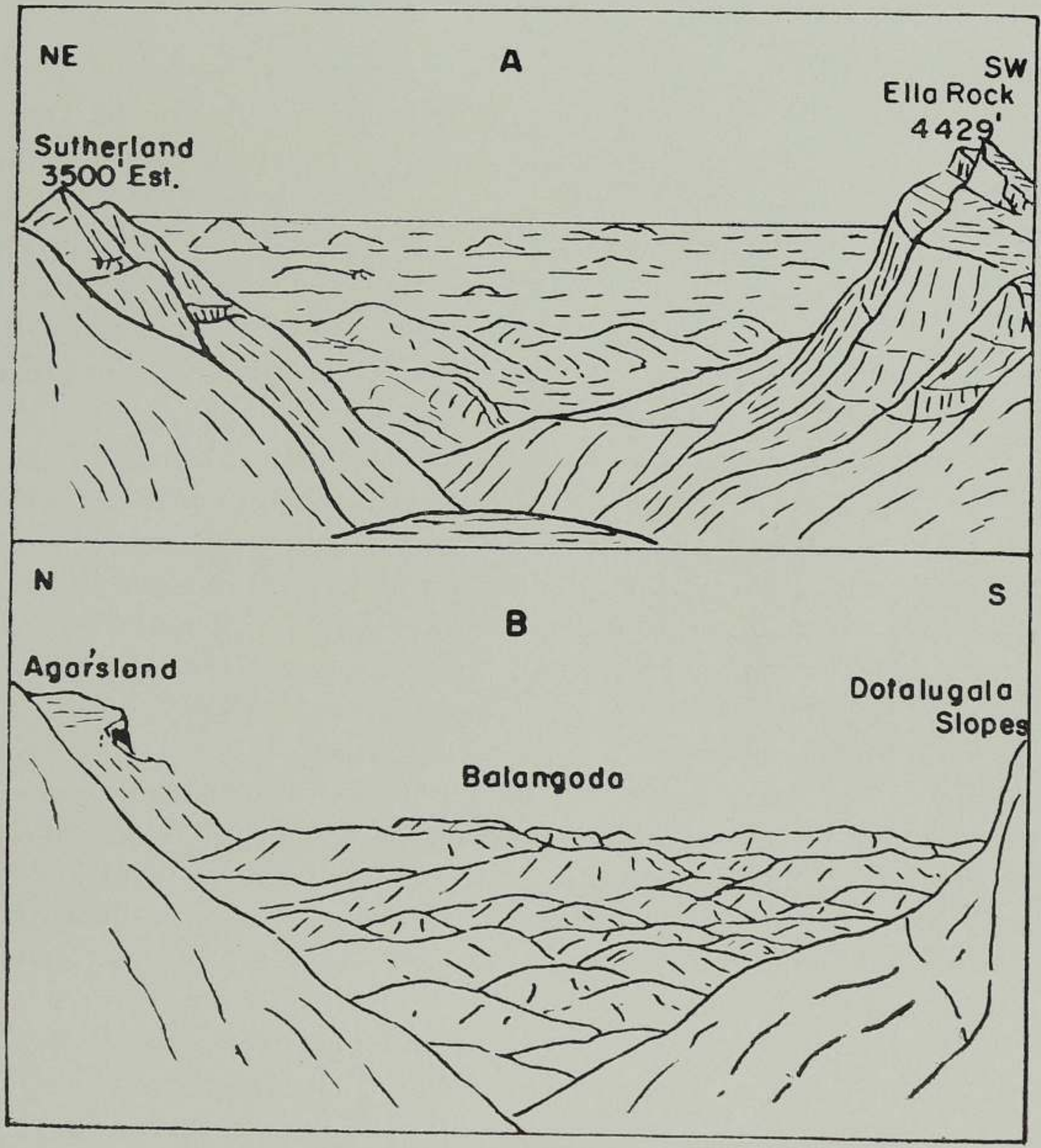


Fig. 20.

A. View of the lowest peneplain from Ella Gap.

B. View of the Southern platform around Balangoda.

extent. This vast plain is the result of millions of years of subaerial weathering of the ancient, highly folded landmass of crystalline rocks which must have been very different in appearance from what we see now. During this time, tens of thousands of feet of crystalline material were removed and only the roots of the great mountain chains that once existed now remain. This planing-down process is evident from the sharp manner in which the steeply-dipping or vertical foliation planes of the gneisses that underlie the plain are truncated or cut off (see Fig. 43B). Further, the processes of erosion have not only destroyed most of the hills but have also filled up the intervening valleys with the detrital material produced. The inequalities of the original landscape have thus been levelled out, except for the isolated hills and hill ranges which lie scattered about.

The remarkable flatness of the lowest peneplain can be seen from many points, and one of the best that the author knows is the top of Tambutakande rock, 7 miles from Galgamuwa and just north of the Ranjangane ruins (Pl. 6). Standing on this rock, at a height of 900 feet, a sweeping panorama of forests, dotted with glistening tanks and villages is spread out before one. On the immediate west are the granite hills of Sangaparle and Sangilimala, rising sharply to more than 900 feet above the plain ; 20 miles to the north of Tambutakande, only the glistening white dome of the Ruwanwelisaya Dagoba at Anuradhapura breaks the monotony of the flat horizon. Another good view is down Ella Gap, from Ella Rest House (Fig. 20A). Throughout the length and breadth of the lowest peneplain, like lone sentinels, rise a number of scattered steep-sided rock hills and knobs such as Sigiriya, Yapahuwa, Gunner's Quoin, and Westminister Abbey, to mention only a few (see Pls. 6 and 30A). These *erosion remnants* (or *monadnocks*, as they are sometimes called), have stood out against the levelling process of nature largely because they are made of resistant granitic rocks containing large proportions of quartz, one of the most indestructible of rock-forming minerals. Their present heights give us only an indication of the original height of the land, for even erosion remnants have suffered much levelling down. Because of the steepness of the sides of these erosion remnants, and because of the commanding views they provide, many of them, like Sigiriya and Yapahuwa, have become famous in Ceylon history as the sites of fortresses, palaces, and temples. Even today, nearly all the more prominent rock hills are the sites of ancient and modern shrines and temples ; these are one of the most striking elements of the cultural landscape of the country. Where such resistant rocks form ridges they have frequently been made use of by the ancient engineers as portions of bunds for the large irrigation tanks of the Dry Zone (see Chap. 12).

There are also, in the lowest peneplain, thousands of low, bare rock mounds or *turtle backs,* whose form is due largely to a weathering process known as *exfoliation* (see Pl. 7A). In this process, as a result of alternate cooling and heating during the cool nights and the hot days and of 'rotting' by the chemical action of water, the rock peels off from the surface in thin layers, rather like the skins of an onion. Turtle backs are important in the Dry Zone (into which most of the lowest peneplain falls), as they form the abutments to the numerous small irrigation tanks which abound here and on which the people of the Dry Zone depend so largely for their livelihood. The frequency with which names bearing the prefix *gal* (rock) appear on the topographic maps (for example, Galgoda, Gallewa, Gallewela) is ample evidence that these small rock outcrops are, in fact, numerous.

The Middle Peneplain

Inland from the coast, especially on the eastern and southern sides of the island, the land rises very gradually to about 300 or 400 feet until it reaches the foot of an escarpment, generally about 1,000 feet high, which separates the lowest peneplain from the middle peneplain. This escarpment is continuous in many places, as in the Minipe and Kongala areas, but elsewhere it is deeply indented and irregular where rivers have cut back into the wall and destroyed its continuity while enlarging their drainage basins.

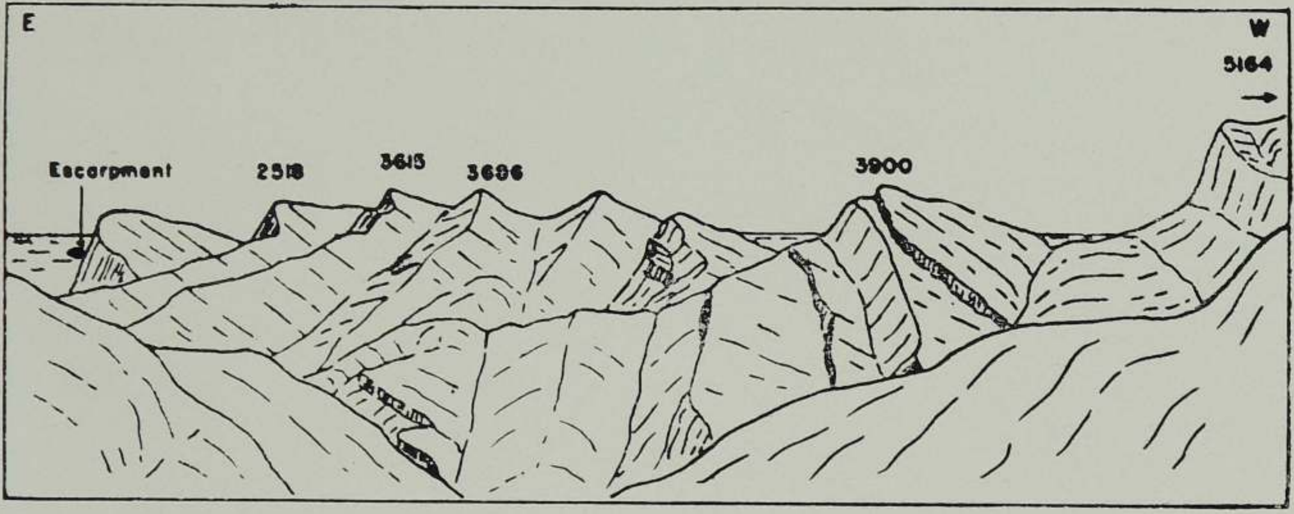


Fig. 21. Sketch of the middle peneplain above Weragantota, looking south-eastwards from near Hunnesgiriya ; heights in feet.

On the east, between Minipe and Wilgomuwa, this steep wall of hills rises sharply from a flat plain with no intervening foothills, and overlooks the Mahaweli Ganga for 20 miles. The road from Weragantota to Kandy climbs the escarpment in a number of hairpin bends and then

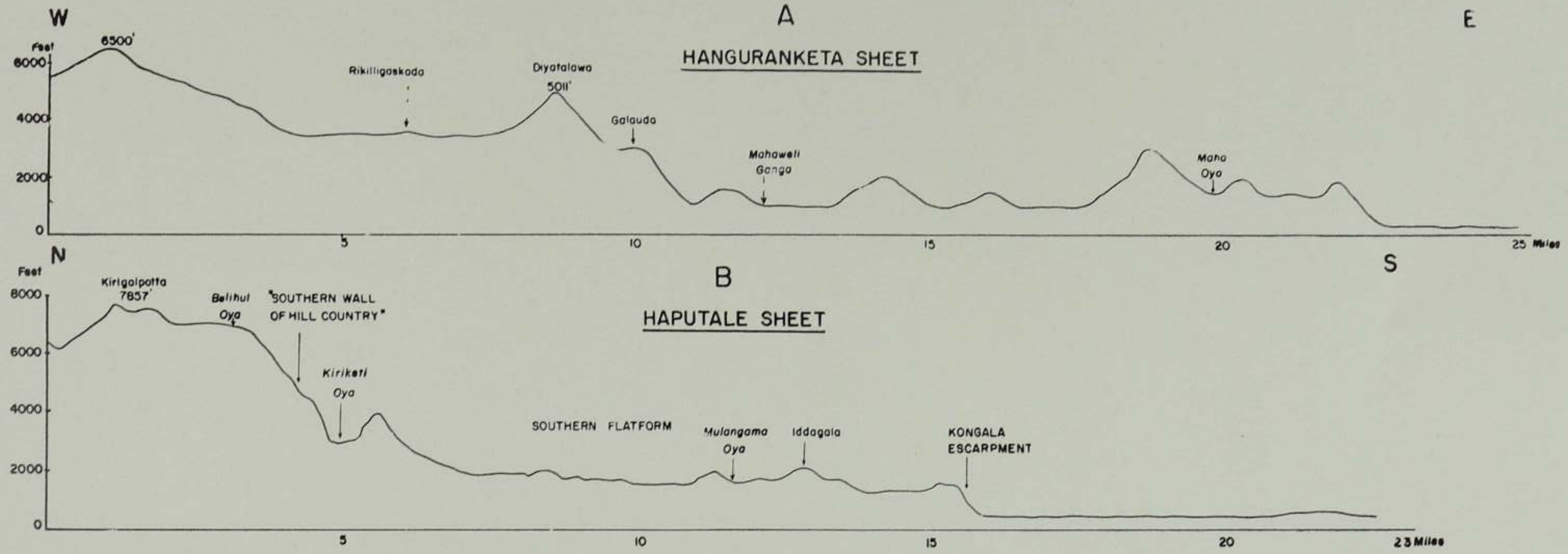


Fig. 22. Cross sections showing erosion levels.
A. Hanguranketa sheet. B. Haputale sheet.
(Vertical scale is 2½ times horizontal scale)

wanders about in a region of parallel ridges (all at a general level of between 2,500 to 4,000 feet above sea level) which is part of the middle peneplain (see Fig. 21); the steep east-facing scarps of the Knuckles Massif limit it on the west. The same succession of escarpment, peneplain and escarpment can be seen further south, in the Hanguranketa area (Fig. 22A).

The Kongala escarpment, south-east of Balangoda, is very marked (Fig. 22B), being 1,000 feet high ; it forms the boundary of a wide, undulating plateau which Elsie Cook[5] has called the ' Southern Platform ' (see Figs. 20B and 23 also).

On the western side of the island, the steep rock-face of the Alagalla range, dominated by the dark, foreboding traingular peak of Alagalla, separates the Kandy Plateau from the lowest peneplain. The railway line from Colombo begins to climb this escarpment at Rambukkana and goes through it by way of the conspicuous cleft in the rock wall at Kadugannawa, wandering about thereafter as far as Nawalapitiya on a portion of the middle peneplain.

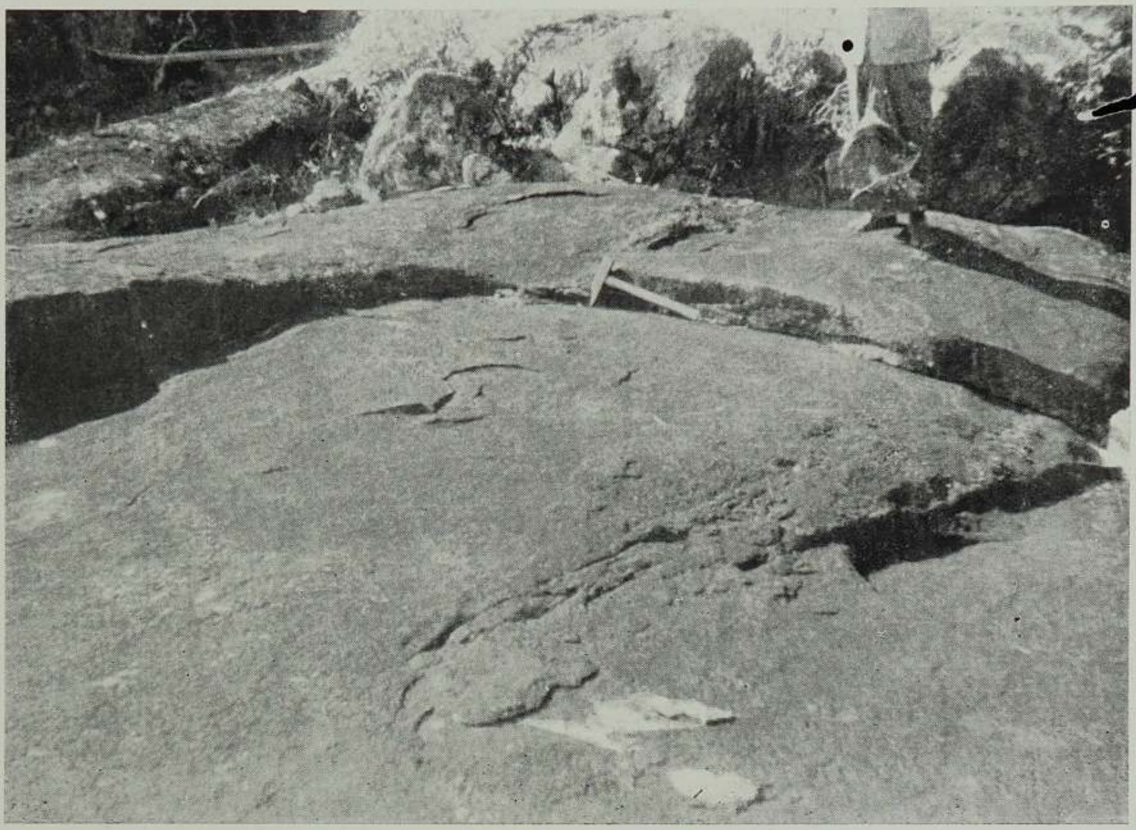
The Highest Peneplain

Unlike the lowest and middle peneplains, the so-called highest peneplain is least like a peneplain and is more a complex of plateaus, mountain chains, massifs, and basins, within each of which a general erosion level can be recognized (Fig. 23).

The southern margin of the highest peneplain is the magnificent *Southern Wall of the Hill Country*[5], stretching for more than 50 miles from Adam's Peak or Sri Pada (7,360 feet) on the west to the ' nine peaked mountain ' Namunukula (6,360 feet) on the east, and rising from a little over 1,000 feet to more than 5,000 feet in some places, as at World's End (see Fig. 22B).

This almost impenetrable barrier up which the magnificent road from Balangoda to Bandarawela climbs, is one of the most imposing natural features in Ceylon and is made up largely of resistant charnockites. A number of fine waterfalls like Diyaluma, Bambarakanda, and Galagama Falls drop over its edges and two tremendous clefs cut it, namely Haputale Gap and Ella Gap (Fig. 20A); the latter has resulted from the strong erosive action of the headwaters of the Kirindi Oya.

Running northwards from the centre of the Southern Wall is the highest of the plateau regions, the *High Plains*, stretching from Kirigalpotta (7,857′) to Pidurutalagala (8,292′), Ceylon's highest mountain (Fig. 23).



A. Turtle-backed outcrop caused by exfoliation

B. An incised meander of the Kotmale Oya below Talawakelle.

This bare, gently undulating grassland includes the picturesque Horton Plains, Elk Plains, Moon Plains, and Kandepola-Sita Eliya Plains, all at a general elevation of 6,000 to 7,000 feet.

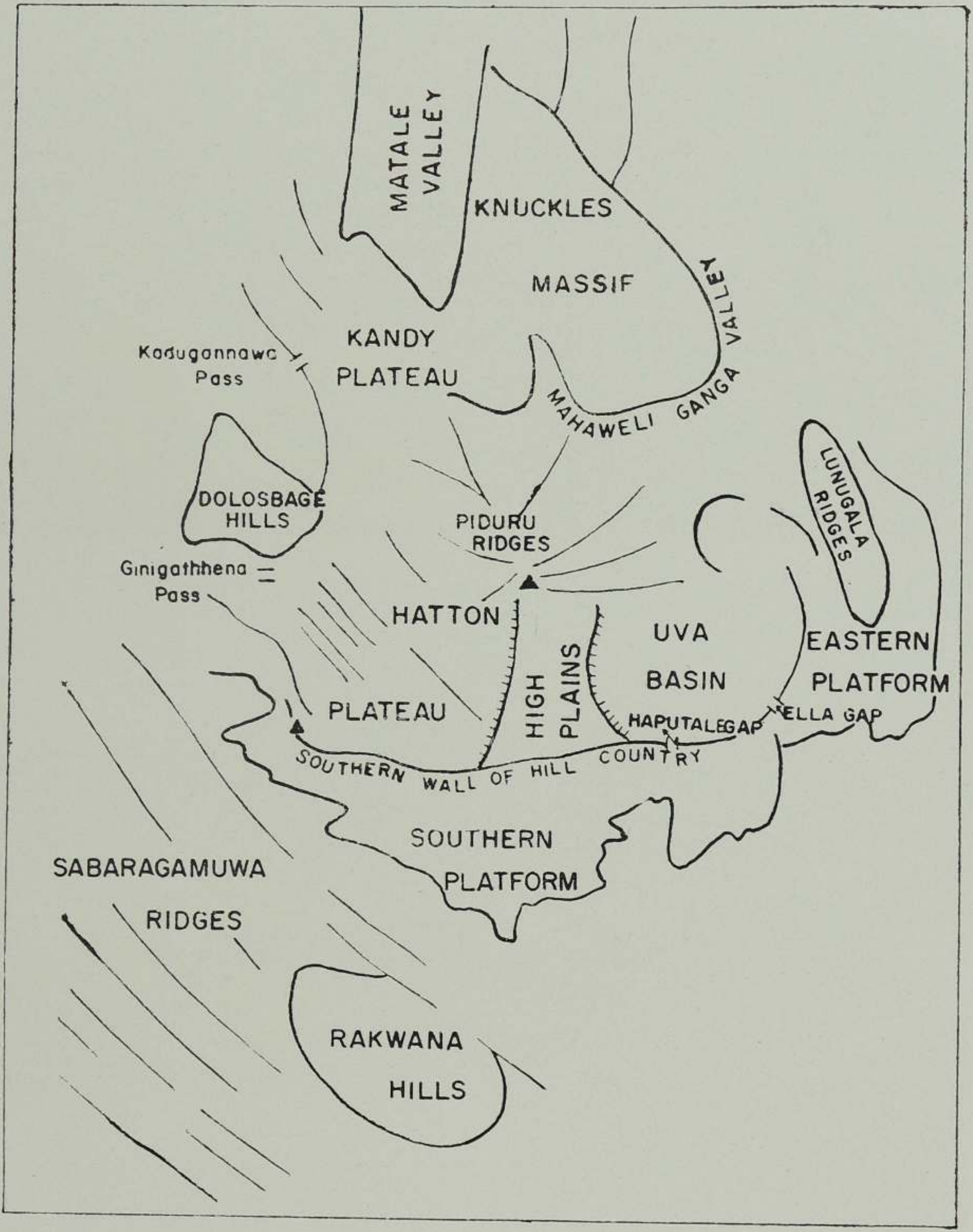
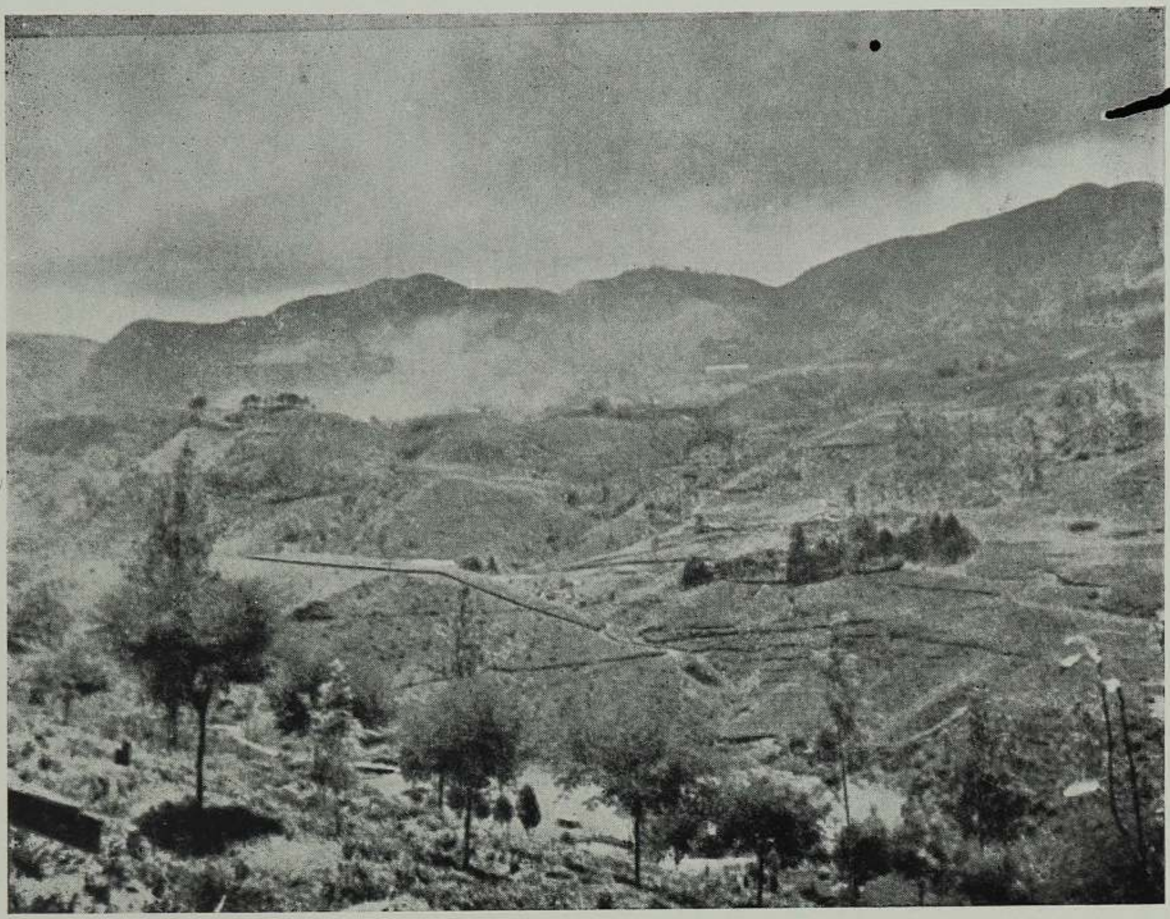
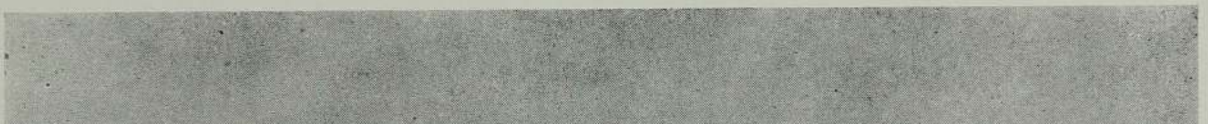


Fig. 23. Physiographic regions of the Hill Country. (*E. K. Cook*, 1931)

East of the High Plans is the 'magnificent amphitheatre' of the *Uva Basin,* a basin-like depression surrounded on nearly all sides by a rim of mountains which includes Hakgala (7,127′), Totupola (7,741′), Tungoda (6,051 feet), Beragala (5,832′) and Namunukula (6,679′) (Fig. 19B).



A. Part of the Hatton Plateau near Radella, with the Great Western escarpment in the background.



B. Udalaxapanagala escarpment, overlooking the valley of the Maskeliya Oya.

In the centre of the basin, at a general elevation of 3,000 feet, are rolling grasslands or *patanas* which, owing to their resemblance to the Chalk Downs of Southern England, have been called the Uva Downs. The Basin is drained by two rivers, the Badulla Oya and the Uma Oya, the latter flowing northwards in a deep, gorge-like valley which increases in height to about 300 feet as it nears the Mahaweli Ganga. Everywhere in the Uva Basin are signs of violent earth movements in the form of steep to vertical folds, recumbent folds, faults, and thrusts (see Fig. 41). Both the High Plains and the Uva Basin are made up predominantly of easily-weatherable feldspathic metamorphic rocks and this is the cause of the soft, rounded forms, and the deep, clayey soils found here.

On the west of the High Plains is the *Hatton Plateau* (see Pl. 8A), a deeply dissected area with strong relief, unlike the plateau regions described above. The remarkable appearance of 'flatness' in the Hatton Plateau is largely due to the nearly horizontal attitude of the rocks within much of the area. The average level of erosion in the Hatton Plateau is between 3,500 and 4,500 feet, but a complexity is introduced by several higher parallel ridges running N.W.-S.E. Here too are numerous waterfalls like Aberdeen, Laxapana, St. Clair, and Devon Falls, and the rivers flow in gorges or steep-sided valleys. The incised meanders of the Kotmale Oya near Talawakele are good example of this (Pl. 7B).

A number of ridges radiate in all directions from the centre of the highest peneplain, near Pidurutalagala, and these extend into the general level of the middle peneplain. The Ramboda-Hantane range, for example, extends north-westwards into the heart of the Kandy Plateau.

Two massifs, separated from the main part of the Central Highlands, also form part of the highest peneplain. On the southwest is the *Rakwana Massif*, bounded on the north by as escarpment similar to the Southern Wall of the Hill Country but much smaller in scale and lower in height. The road from Rakwana to Deniyaya climbs this escarpment by way of the Bulutota Pass, crossing it at the only break in it for miles. Several of the peaks on this escarpment are over 3,500 feet high. The highest parts of the massif are a series of high plains such as the Handapan Ella Plains and the Tangamale Plains, at a general elevation of 3,500 to 4,000 feet; they are surrounded by several fine peaks and escarpments such as Beralagala (4,545′), Gongala (4,416′), Suriyakande (4,300) and Abbey Rock (4,268′). The Bulutota escarpment and much of the massif are made up largely of gently-dipping, resistant charnockites.

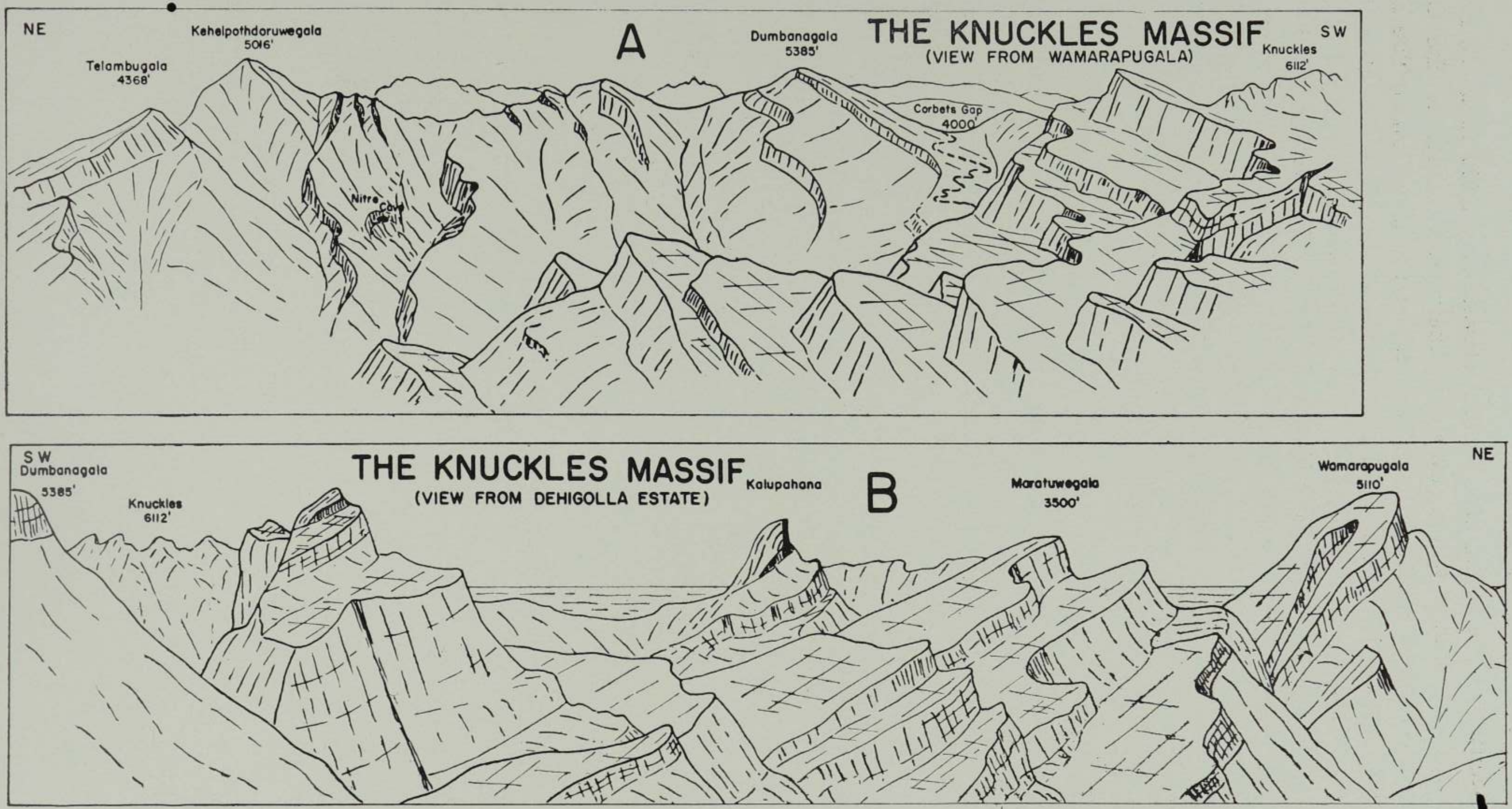


Fig. 24. Sketches of parts of the Knuckles Massif.

North-east of the Kandy Plateau is the *Knuckles Massif,* with several fine mountains over 5,000 feet (Fig. 24) ; its highest peaks are Gombaniya (6,248′) and Knuckles (6,112′). Many spectacular escarpments on the eastern margin of the massif overlook the middle peneplain, which here is rather well-defined. The Knuckles Massif is really a complex of ranges resulting from a large recumbent fold, and some of Ceylon's finest and most rugged mountains are to be found in this comparatively inaccessible and little known region". (A new road from Hunasgiriya to Corbet's Gap will soon bring this fascinating region within the reach of many people).

The main part of the Knuckles Massif extends for over 30 miles from near Rattota to Medamahanuwera and throughout this length there are only three places where the main range can be crossed. One is at Laggala, north-east of Matale, the second is Corbet's Gap, near Rangala which is the head of a tremendous cleft in the massif, and the third is the Hunasgiriya Gap which takes the road from Kandy to Weragantota.

There are, in most of the regions of the highest peneplain just described, several physiographic features which have their origin in geological causes. One of the commonest of these is the long, parallel strike ridges and valleys with their gentle dip slopes and steep scrap slopes, well seen in the area around Ratnapura and Rakwana (Pl. 9A). They are the result of erosion along the less-resistant strata in a succession of rocks folded into long continuous folds. The more resistant charnockites and quartzites frequently form the vertical escarpments, the less resistant feldspathic rocks providing the intervening valleys and flats. A trellis-like drainage pattern is common in these areas (Fig. 25), the rivers flowing alternatively along the strike valleys and across the ridges, in the latter instances along major joint planes.

Long escarpments, some rising thousands of feet in sheer rock walls are also common, particularly in the Hatton and Knuckles areas (Pl. 8). These escarpments may be the result of faults but more often they are the result of jointing. Some escarpments have resulted from the breaching of long anticlinal folds, as, for example, the Ramboda escarpments (Fig. 39) and the Kaipoogala-Great Western scarps.

Waterfalls are another common feature of the Central Highlands both on its margin and within it as D. N. Wadia noted. For example, in the area of about 2,000 square miles he counted 24 major falls; most of the waterfalls are named on the topographic maps, but a larger number of unmarked and unnumbered falls must also be present. The presence of these waterfalls, unusual in an area subject to long-continued erosion and denudation, was one factor which led Wadia to suggest that the highest peneplain was uplifted in recent geological times by block faulting.

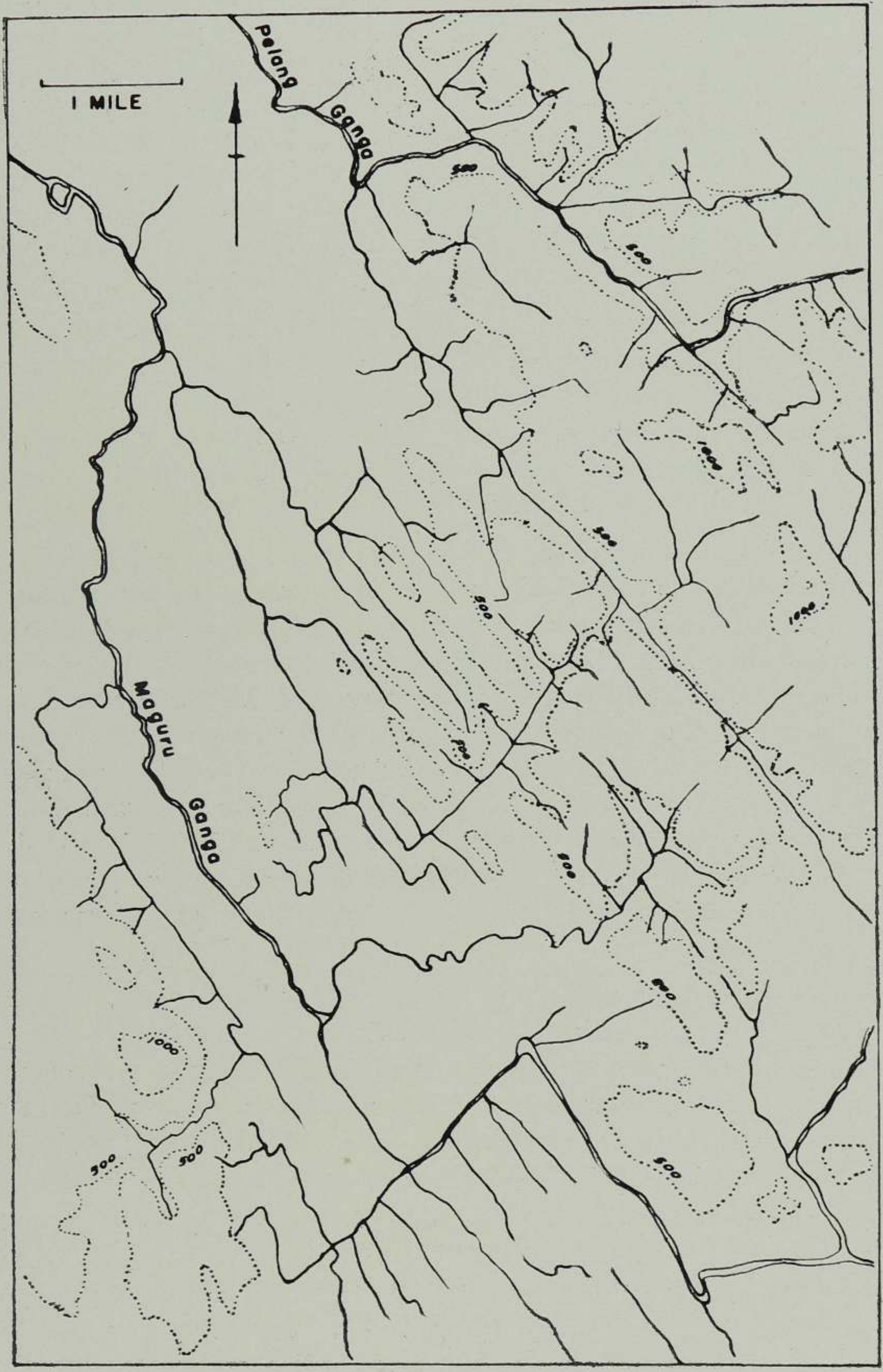


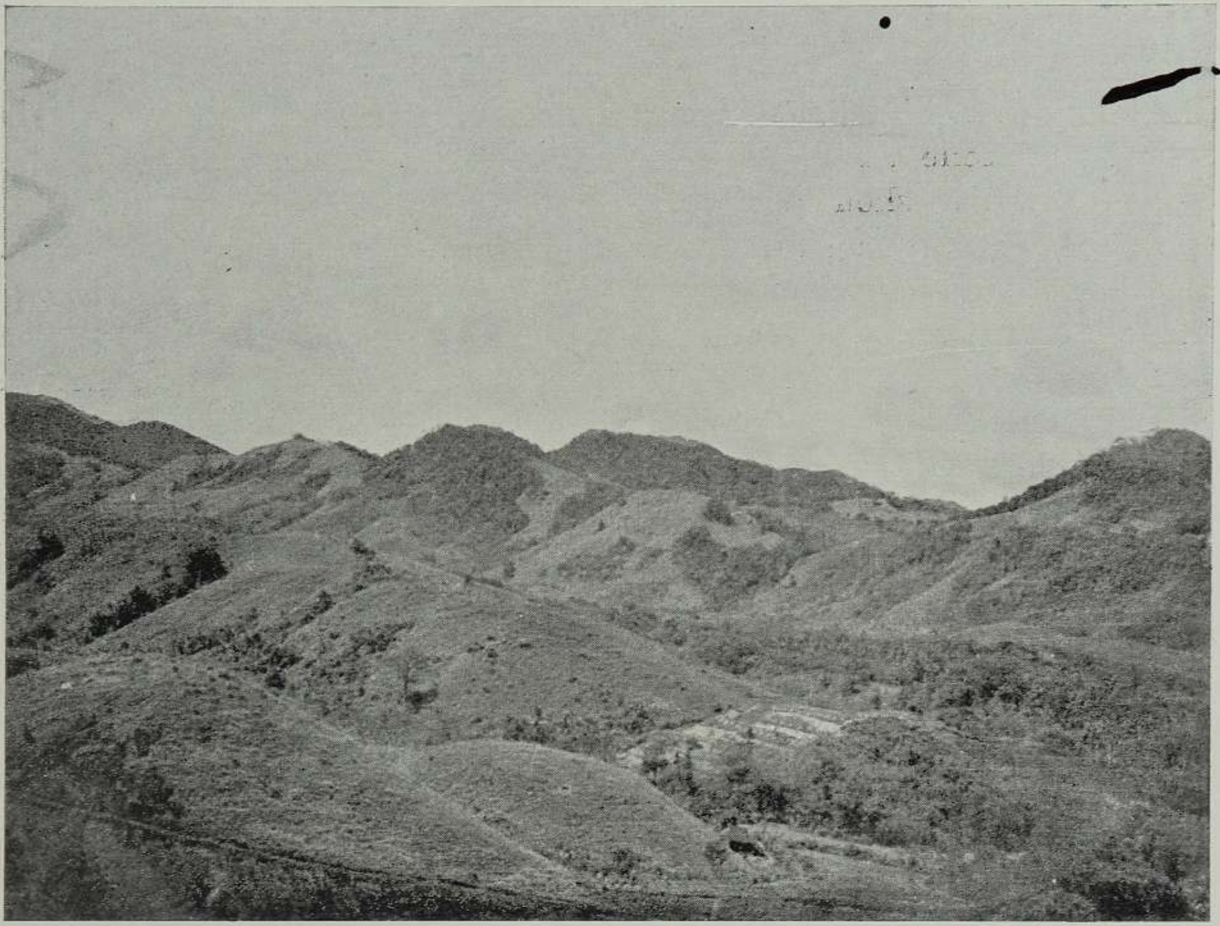
Fig. 25. Map showing a trellis pattern of drainage, largely controlled by dip and strike joints ; dotted lines are contours.

One final comment about the peneplains of Ceylon must be made. Ceylon has, until Miocene times, been a part of the South Indian shield (see Chap. 11), and we should expect to see similarities in the physiographic features of the two regions. These were recognized by both Adams and Wadia. The highest peaks of the Nilgiri and Palni Hills, which are over 8,000 feet, correspond to the highest peaks of the highest peneplain in Ceylon. Like the latter, the Nilgiri-Palni massifs are bounded on the west and south-east by gigantic scarps, 3,500 to 6,000 feet high; waterfalls are also common in the Indian area. The Deccan Plateau probably represents a continuation of the middle peneplain of Ceylon and the lowest peneplain has its exact counterpart in the coastal plain around Madras, with its scattered erosion remnants.

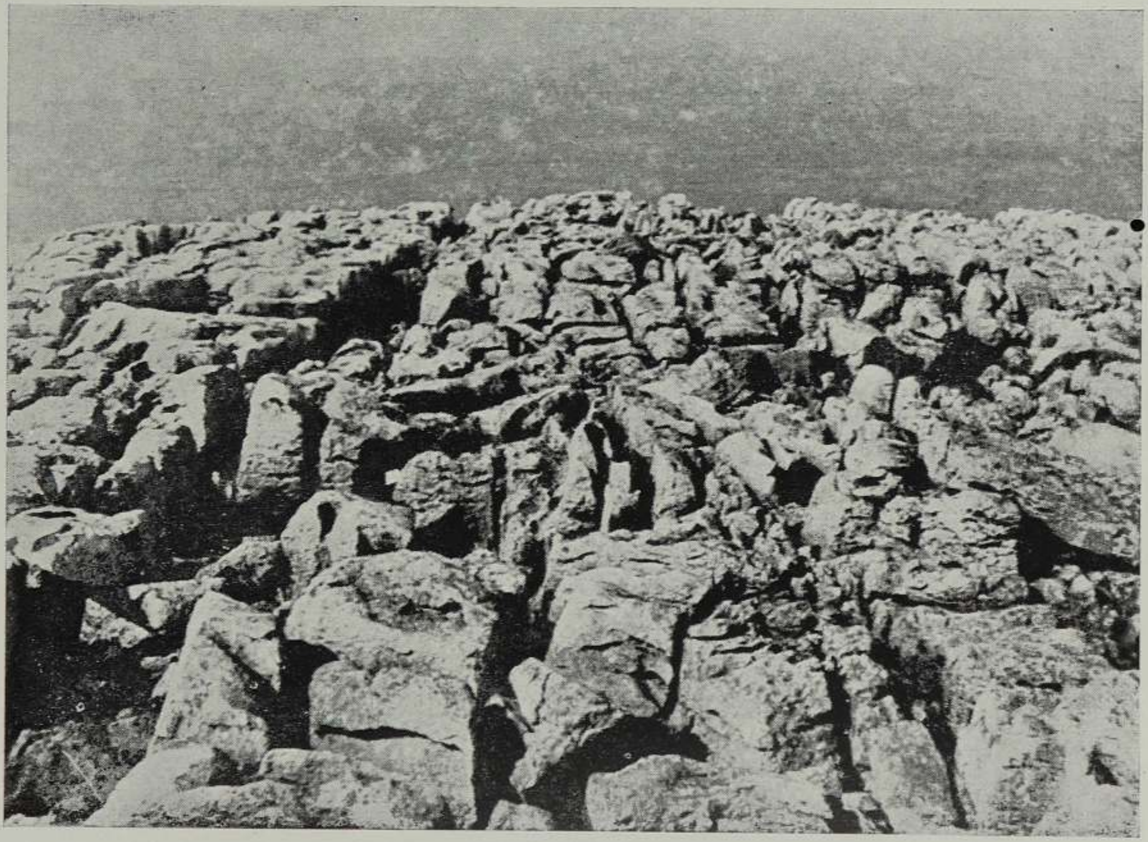
Coastal Plain, Coastline, and Continental Shelf

Many parts of the **coastal plain** owe their flatness not to erosion or peneplantation of the crystalline rocks but to the presence of extensive flat-lying sedimentary deposits of more recent age lying on a peneplained basement of crystalline rocks or on flat Miocene limestone. In the coastal belt between Chilaw and Colombo, for example, long stretches of flat country have, in recent times, been formed by sandy beaches, lagoonal silt and clay, blown sand, and river alluvium. North of Chilaw such stretches are bounded on the east by low, elongated, dome-like structures which extend for several miles in a north-south direction and rise to 100 feet or more above the surrounding areas. The domes, clearly visible from the Kalpitiya road on the west or from any high point 10 or 15 miles east of the coast, are ridges of the Red Earth formation (see Chap. 8) generally resting on top of low, elongate ridges of limestone or gneiss. They form distinctive features in an otherwise featureless plain.

The flood plains and estuaries of the island's major rivers also form many square miles of flat, alluvium-covered land (see Pl. 28). Ceylon's rivers carry a large amount of sand, silt, and clay, and when they leave the hilly country the velocity of their flow decreases and they drop some of this load, as can be seen in numerous sand banks that occur in rivers of the Dry Zone. These rivers often overflow their banks or change their courses during periods of flood and the finer sediment is deposited as thin layers over the flooded areas. The lower reaches of the Deduru Oya, the Mi Oya, and the Mahaweli Ganga are particularly good examples of this. Such alluvial stretches are generally planted with rice, and the changing shades of green, seen as the wind caresses the slender, pliable paddy stalks, is one of the loveliest sights in the lowlands.



A. Typical strike ridge and valley, east of Hiniduma.



B. Grikes in limestone caused by chemical weathering along joints, Malham Cove, Yorkshire.

The monotonous, flat landscape of the **Jaffna Peninsula** and the surrounding islands results from the horizontal beds of limestone which have but recently been uplifted above the level of the sea. Very little vegetation grows here, except for clumps of palmyrah palms, some scrub, and patches of cultivated crops. The land looks bare and stony, and where a soil is present, it is generally thin.

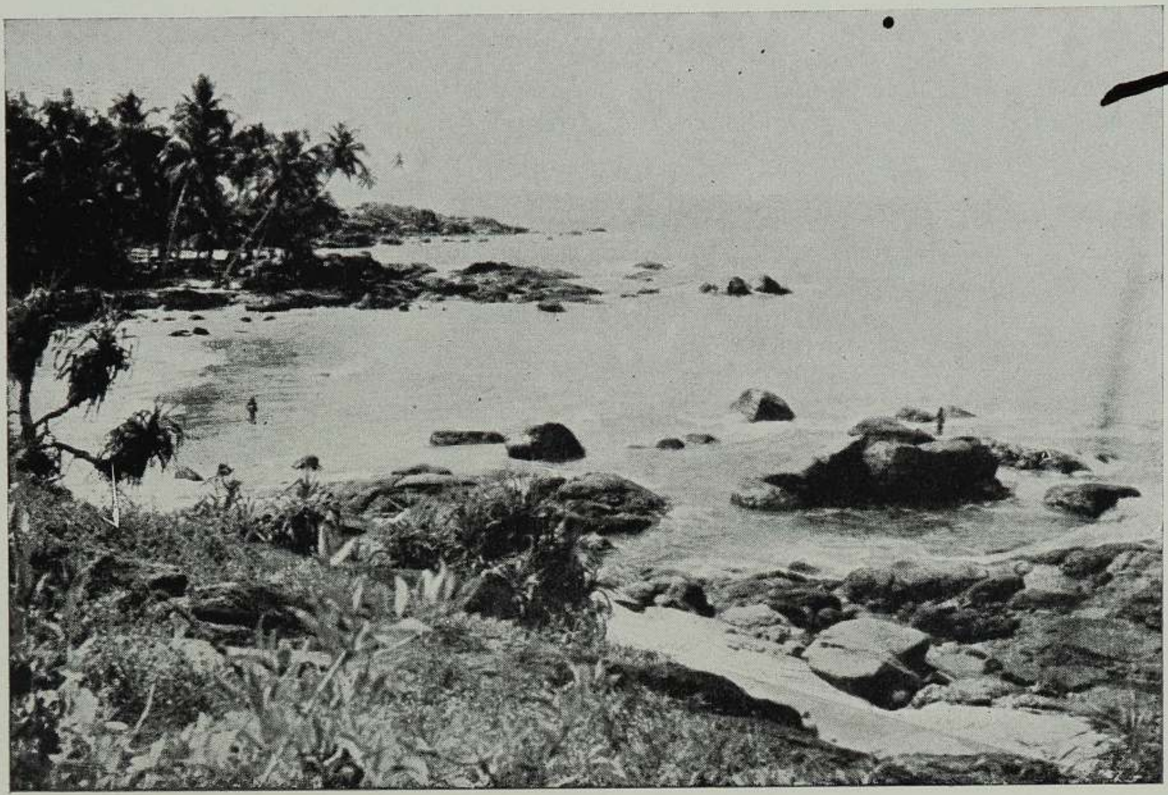
The Jaffna Peninsula displays many of the physical features characteristic of limestone regions, such as *caverns, sink holes, swallow holes,* and *grikes* (Pl. 9B). All of them have been brought about by the solution of the limestone along joints and fissures. The following eyewitness's account of the formation of a swallow hole at Manipay in 1905 is of interest in this connection[7]:

> 'At dawn on that same day (20th April, 1905) the villagers living near the Kirai fields heard a strange sound which was found to have been caused by the collapse of the surface soil over an area about 10 feet in diameter. The pit thus formed contained a pool of salt water which gradually widened till about 4 p.m. when the pool was about 40 feet in diameter ; soil from the sides continued to fall in for a time. The depth of water was about 30 feet, and its surface about 1 foot below the surface of the field. Salt water, passing through underground passages, gradually undermined a place where the subsoil was more than usually friable. Similar occurrences are said to have taken place in the past in Jaffna.'

Elsewhere, as for example between Kudremalai and Puttalam on the mainland, the limestone has the appearance of a typical karst region, with 'weathered pinnacles, hollows and fissures in all directions, making walking over them a torture'[8].

There is no surface drainage in the Jaffna Peninsula, all the water which falls on the surface passing downwards along fissures formed by solution of the limestone and flowing in underground channels. The 'bottomless' well at Puttur and the fresh-water spring at Keerimalai are both parts of this subterranean drainage system (see Fig. 93).

The lowest peneplain and the coastal plain extend outwards from the island and under the sea as a submarine shelf, the **Continental Shelf,** for a distance varying from 5 to 25 miles and at an average depth of 36 fathoms (216 feet) below sea level (Figs. 26 and 27). The outer edge of this shelf is a comparatively steep cliff (the *Continental Slope*) falling 6,000 feet or more in about 12 miles to the general level of the Indian Ocean. Notched in this cliff are several 'submarine valleys' where deep water comes to within a few miles of the coast. Four of the valleys have been located opposite the



A. Rocky headlands along the south-west coast, near Alutgama, where the strike of the rocks is oblique to the coastline.

B. A headland and small bay in laterite, Beruwela. Note the intensive erosion and the small cave in soft laterite at the foot of the cliff.

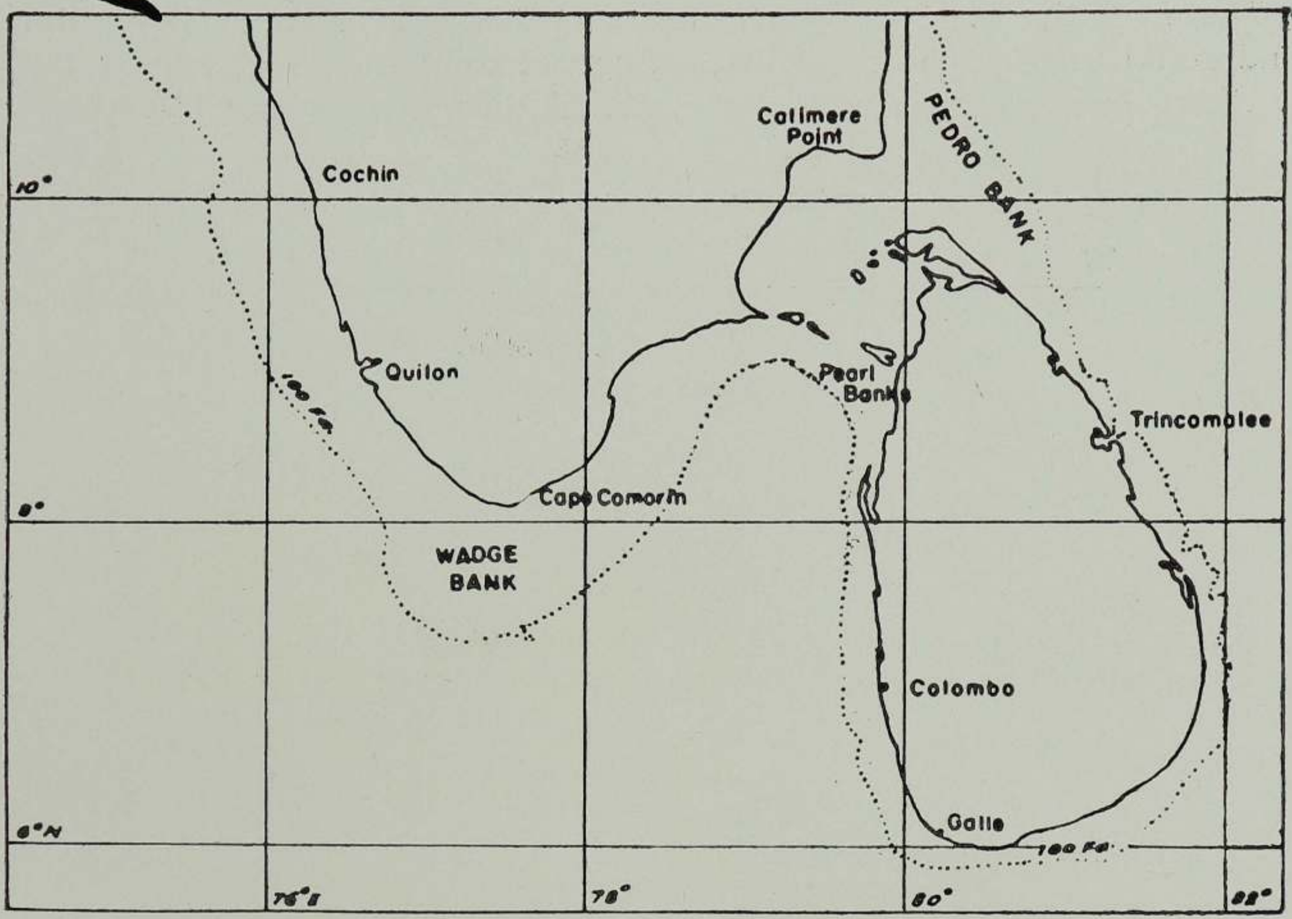


Fig. 26. Map of the continental shelf around S. India and Ceylon.

mouths of the Mahaweli Ganga (near Trincomalee), the Kumbukkan Oya (near Kumana), the Nilwala Ganga (near Matara) and what may have been the outlet of the combined Kelani-Kalu Ganga drainage system, near Panadura[9]. The 100-fathom line comes nearest to the coastline at these points (see Fig. 26). A fifth submarine valley appears to be present about 5 miles north of Batticaloa.

The continental shelf is narrow around the southern part of the island, but towards the north it widens out and merges with the platform that surrounds India (Fig. 26). On this northern part of the shelf are three elevated portions, namely, (1) *Pedro Bank,* stretching northwards from the Jaffna Peninsula to the coast of India, (2) the *Pearl Banks* and *Adam's Bridge,* the latter a narrow but long sandbank between Mannar in Ceylon and Danushkodi, India which makes the Palk Strait impassable for ships, and (3) *Wadge Bank,* around the southern extremity of India.

The presence of this continental shelf with shallow water above it has led to the formation of numerous coral reefs around the coast of Ceylon, with 'corals, sea ferns and sponges of many sizes shapes and colours . . . . . so thick as to form a diminutive submarine forest'[10].

Those off the coast at Mt. Lavinia and Hikkaduwa are well known, and aerial protographs show that an almost continuous reef fringes the northern coast of the Jaffna Peninsula. Although bare rock is exposed in some parts of the shelf, a large variety of sands and muds cover the greater portion of it. As we can see from Fig. 28 sandy deposits predominate in the south and muds in the extreme north.

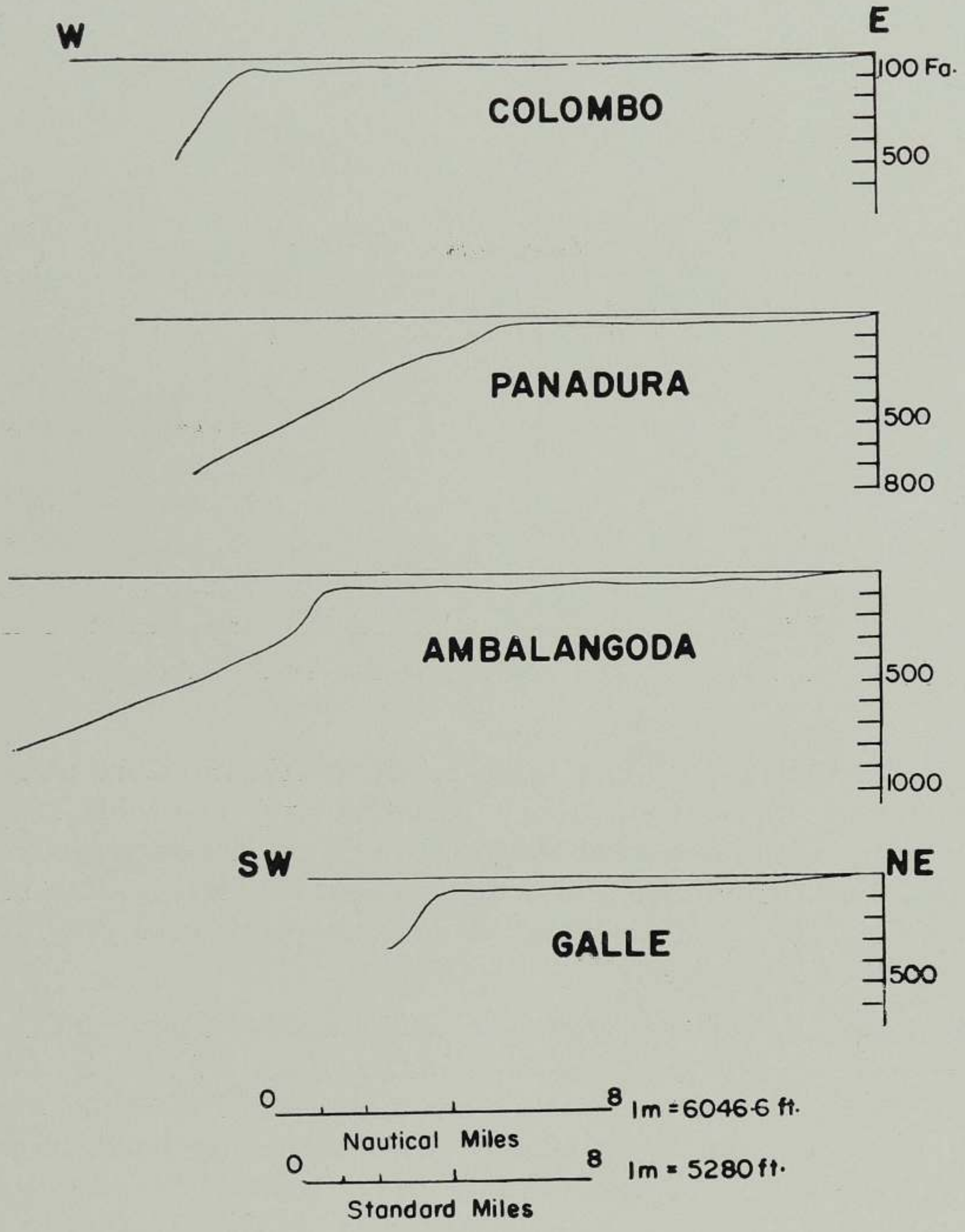


Fig. 27. Sections across the Continental Shelf and Slope off southern-western Ceylon. Note the head of the submarine valley off Panadura relatively close to the coastline.

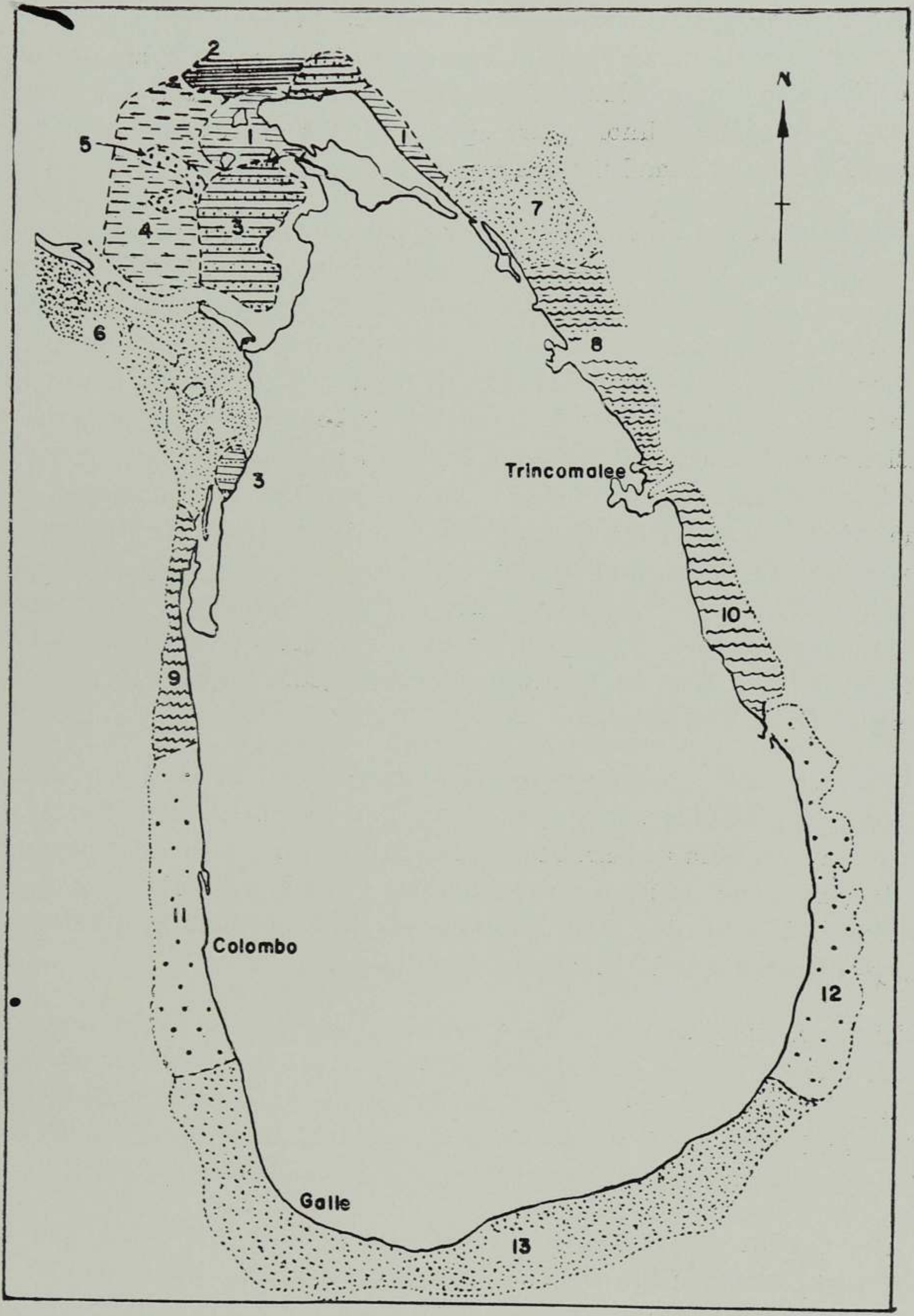


Fig. 28. Map of the bottom deposits on the Continental Shelf around Ceylon. (*After A. H. Malpas*, 1920)

(1) firm, black mud, (2) black ooze, (3) firm, grey mud and sand, (4) soft, grey mud, (5) coarse, yellow sand, (6) yellow-grey sand, (7) firm, white sand, (8) flat rock with firm, dark mud and sand ; Gorgonoids and sponges abundant, (9) flat rock and living coral, (10) flat rock; Gorgonoids and sponges abundant, (11) coarse, white sand with outcrops of rock and living coral, (12) coarse, red and yellow sand ; frequent outcrops of rock and living coral; Gorgonoids and sponges abundant, (13) firm, grey sand with frequent outcrops of rock and living coral.

We can see that the continental shelf is the submerged portion of a continental mass of which both Peninsular India and Ceylon are a part. We shall also see (in Chap. 11) that Ceylon became a distinctive physical entity only a few million years ago, when the encroachment of the sea turned it into an island detached from the mainland of India.

The continental shelf and the lowest peneplain meet in the coastline of Ceylon, and here, as elsewhere, geological factors have had a profound influence on the landscape. Along the south-western and north-eastern coastlines we find a succession of beautiful sandy bays, each protected on either side by rocky headlands. Such coastlines are known as *transverse* coastlines, running as they do across the strike of the rocks; here the more resistant rocks stand out for a little while longer against the never-ending destructive action of the sea. At Trincomalee, for example, where the rocks strike NE-SW and the coastline runs NW-SE at right angles to the strike, high rocky cliffs alternate with deep inlets. In the south-west, where the rocks strike slightly obliquely to the coastline, the same succession of bays and headlands can still be seen, in the beautiful examples of Bentota, Beruwala, Ambalangoda, Hikkaduwa and Closenberg in Galle (Pl. 10).

Another feature common to transverse coastlines is the presence of many rocky islands which lie a short distance offshore, as for example between Beruwala and Ambalangoda. All of these have once been a part of the mainland, but the erosive action of the sea has removed the land between, thus turning them into islands. The coastline mentioned so far may be said said to be *retreating* coastlines ”.

The south-west coast also has many complex systems of lakes and lagoons with sinuous shapes, quite unlike the open expanses of water on the east and north-west of the island. Such systems as Ratgama, Bolgoda, and Koggala Lakes are *drowned river valleys* that have been submerged by the sea and subsequently cut off from it by sand bars and spits.

The north-western and south-eastern coastlines present a completely different picture. This is clearly seen in the fact that whereas on the road from Colombo to Galle one can see the sea for most of the way, on the journey from Colombo to Puttalam the sea is never visible from the main road and is often several miles west of it. The reason for this is that the constructive action of the sea is extending the land surface westwards

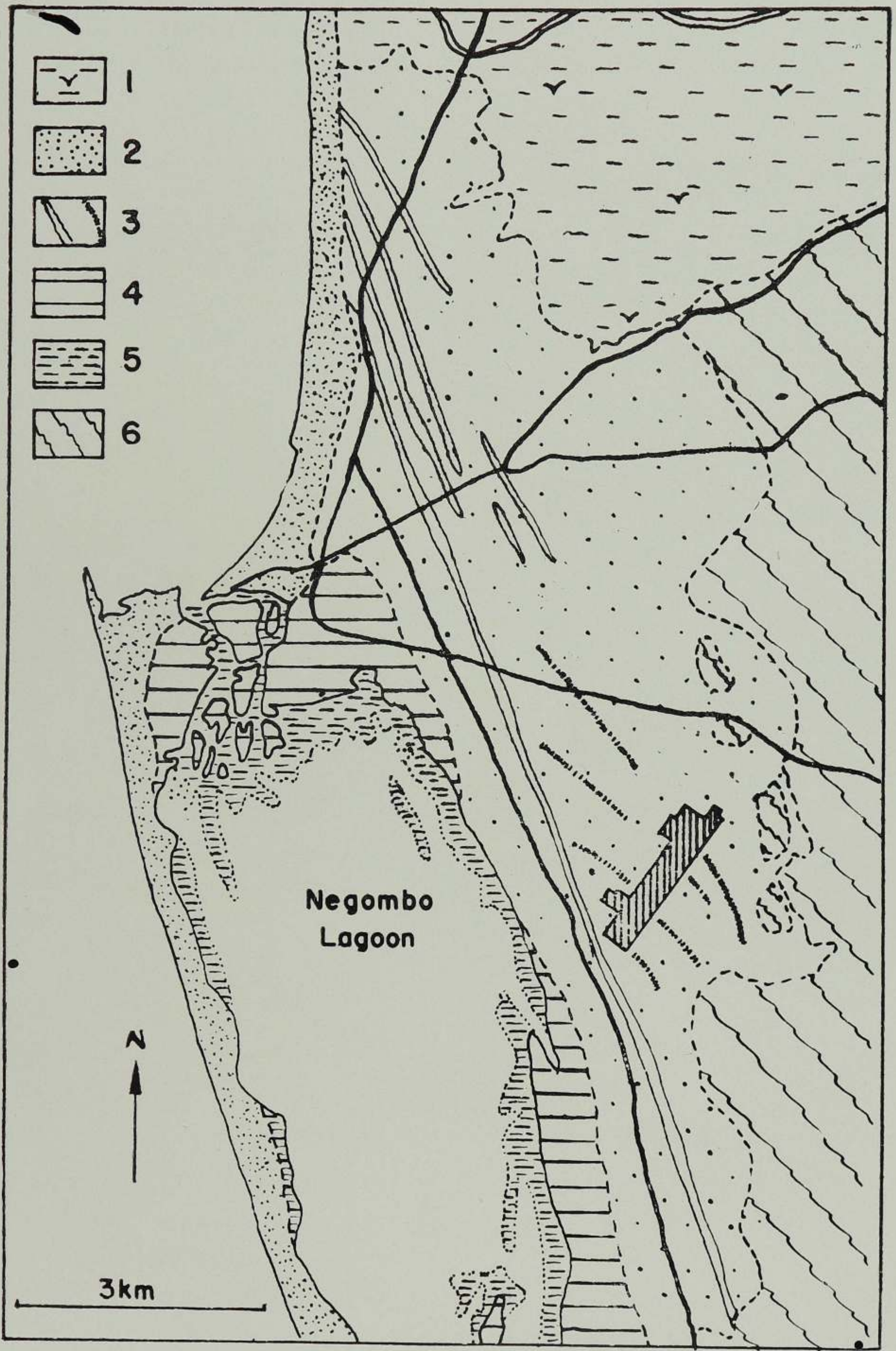


Fig. 29. Sketch map of the Negombo area showig the outward growth of the coastline. (*After L. Herath*, 1962)

(1) alluvium, (2) barrier spit and beach, (3) old beach plain with ridges and swales (or runnels). (4) lagoon flats, (5) submerged lagoon flats, (6) crystalline basement.

Aerial photograph of the barrier spit north of Kalpitiya Peninsula. Note the complex nature of the barrier, with recurved spits and cuspate forelands.

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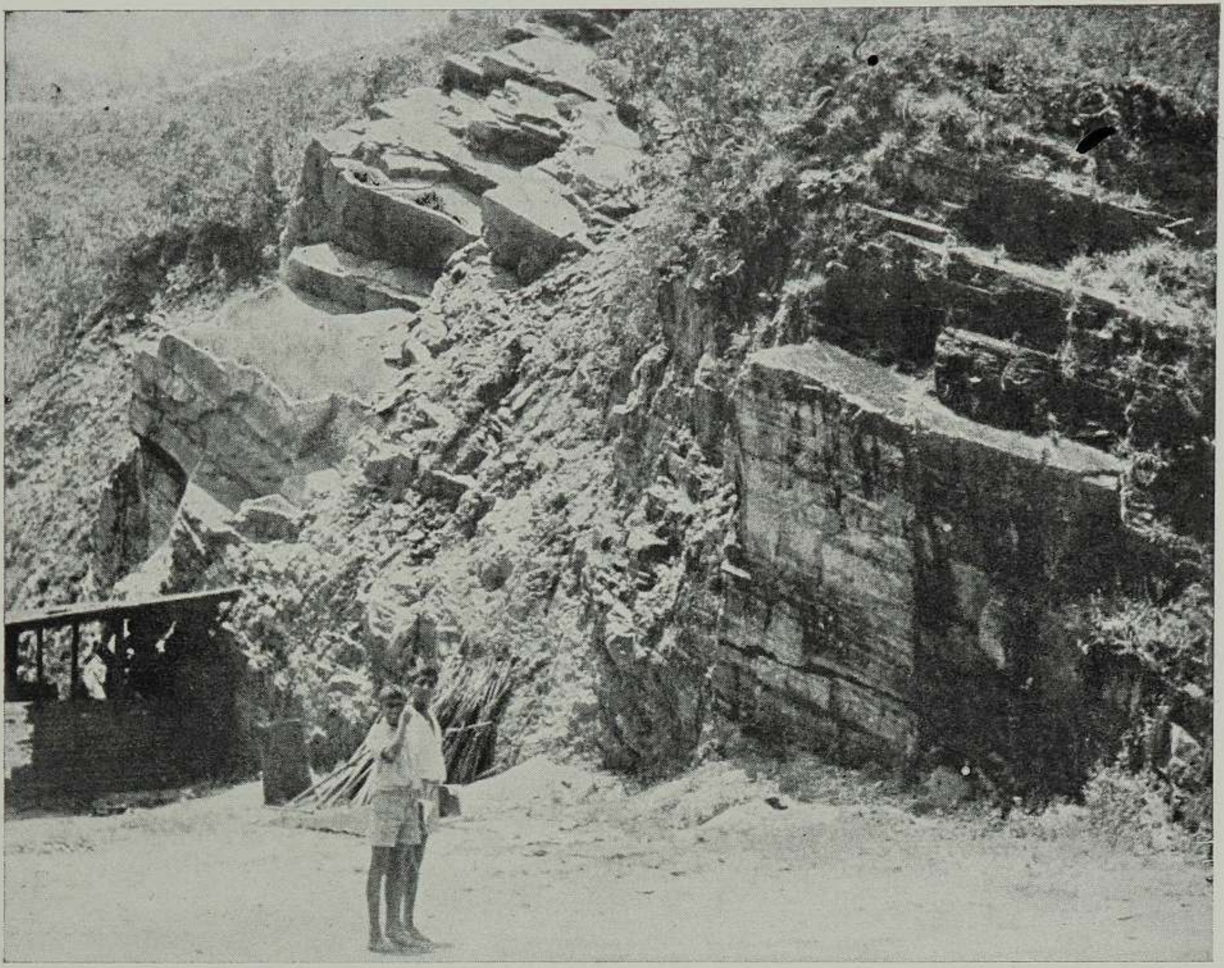
from the ancient shorelines which were probably close to where the road now runs, as at Negombo (Fig. 29). Such a coast is said to be an *advancing* coast. The present shoreline of the north-western coast is, in fact, the seaward margin of a continuous line of barrier beaches and spits, some over 25 miles long, whose growth can be measured even within historical times. The coastline is remarkably straight on the east coast as well, as between Batticaloa and Komari, where no solid rocks are seen for about 60 miles.

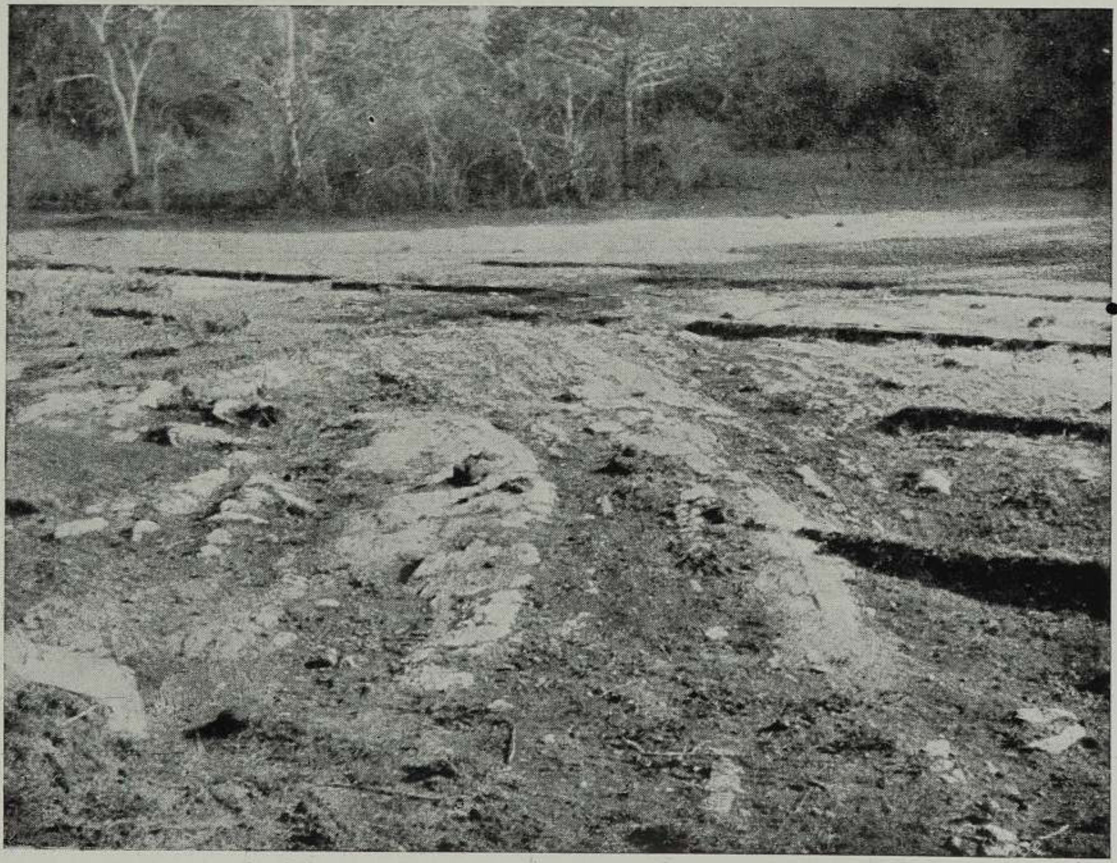
These vast deposits of sand, thrown up by the waves on the relatively shallow floor of the sea here, enclose a succession of lagoons, lakes, swamps, and tidal flats which separate them from the mainland, but which will ultimately become dry land, adding a few square miles here and there to the total land surface of Ceylon.

Although the history of the north-western coast is very complex, we can recognise a cycle with several stages in its development. The first stage is the formation of a barrier beach, or, if attached to the land at one end, a barrier spit, which grows in length as more sand is added to its seaward end. The complex Dutch Bay spit, growing northwards from the Kalpitiya Peninsula, is one of the finest examples in Ceylon of this phenomenon (Pl. 11); almost every step in sand-spit development can be seen on aerial photographs. As the spit grows, a lagoon forms between it and the mainland (as, for example, Puttalam Lagoon), and in time the outlet of the lagoon may be wholly or partly closed, converting it into a lake. Mundel Lake, once the southerly extension of Puttalam Lagoon, is such a lake. The rivers flowing into the lagoon or lake deposit layers of fine silt and mud which cannot be carried out into the sea, and these gradually fill up the lake to form mud flats and swamps, as in the southern and eastern parts of Mundel Lake (see Pl. 26A). The lake may finally be turned into a swamp or peat bog in which dead and decaying vegetation accumulates to form peat. Muthurajawela, to the south of Chilaw Lake, is an example of such a swamp which must have begun life as a lagoon. Thus, along the north-west coast of Ceylon, can be seen all the stages of the cycle of the sea's constructive action.

The same coastal features are evident along the south-eastern and eastern coasts. A drive along the road from Arugam Bay to Batticaloa for example, is one along straight roads through open flat country with an everchanging kaleidescope of land, lagoon, river, and sky. Here, too, the development of numerous lagoons is evidence of a growing shoreline.



A. Well bedded and jointed quartzite, near Norton Bridge ; beds dip to bottom right of photograph.



B. Crystalline limestone exposed at the surface, near Moragollagama.

Barrier beaches and sand spits have enclosed portions of the sea behind them or have diverted the mouths of rivers for miles, thus forming vast stretches of water. The sizes of some barriers and spits is an indication of the great quantities of sand that are being drifted along the coasts of Ceylon by ocean currents. The barrier enclosing the middle portion of Batticaloa Lagoon, for example, is 25 miles long, and barriers and spits stretch almost continuously for a hundred miles northwards from Colombo.

Many parts of the coast of the island are dominated by the presence of sand dunes, which, in spite of their barren and desolate appearance, become fascinating elements of the landscape once their formation and history are considered. Sand dunes are very common along the whole of the south coast, most of the east coast and the west coast northwards from Chilaw. In all these areas the dunes are strongly oriented in a SW-NE direction, the direction of the monsoonal winds in Ceylon. This explains why sand dunes in the Kalpitiya and Jaffna areas run almost at right angles to the coast but in the Hambantota area are almost parallel to it.

Two zones of dunes can generally be recognized, namely, an older zone of high dunes with trees and shrubs, and a younger zone of low dunes with only grasess; the high-dune zone is further inland. (See Chap. 7 for a detailed description of the sand dunes in the Kalpitiya Peninsula.)

CHAPTER 5

OUTLINE OF GEOLOGY

GEOLOGICALLY, nine-tenths of Ceylon is made up of highly crystalline, non-fossiliferous rocks belonging to one of the most ancient and stable parts of the earth's crust, the South Indian shield. The rest of the Island, mainly the north-western portion, is formed of Mesozoic (Jurassic), Tertiary (Miocene) and Quarternary sedimentary formations, some of which are fossiliferous. The main formations present in the Island and their ages are shown in the table below (Table 7).

The crystalline rocks are exposed south of a line running in a north-north-east direction from Negombo to Mankulam (Fig. 30) and they make up a great *complex* of granulites, schists, gneisses, migmatites, and granites of infinite variety and more than one age. We are still far from a complete knowledge of the detailed distribution, origin, age, and interrelations of these cystalline rocks, but for the purpose of this book they can be sub-divided into three groups, each with its characteristic rock types, structures, and well defined distribution. The sub-divisions are (*a*) the Highland Series,* (*b*) the South-western group, and (*c*) the Vijayan Series. It was thought, until recently, that all the crystalline rocks were Pre-Cambrian in age, but there has been increasing evidence that they were probably formed during two widely separated metamorphisms, the first in middle Pre-Cambrian times, the second during early to middle Palaeozoic times. The former produced the Highland Series (and the Kataragama Complex) and the latter the Vijayan Series about 1000 million years later; the south-western group contains rocks of both metamorphisms.

The Highland Series is composed of (*a*) the Khondalite Group of metamorphosed sediments and (*b*) charnockites, and it occupies a broad belt running across the centre of the Island from south-west to north-east. It thus includes the whole of the central Hill Country of Ceylon. The South-western group, which is found in the coastal belt of the south-west sector of the Island, consists of metasediments and charnockites similar to those in the Highland Series, of which it may have formed a part, as well as granitic and migmatitic gneisses. The Vijayan Series, a varied

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* See Appendix I on the use of the term *Highland Series.*

THE GEOLOGY OF CEYLON

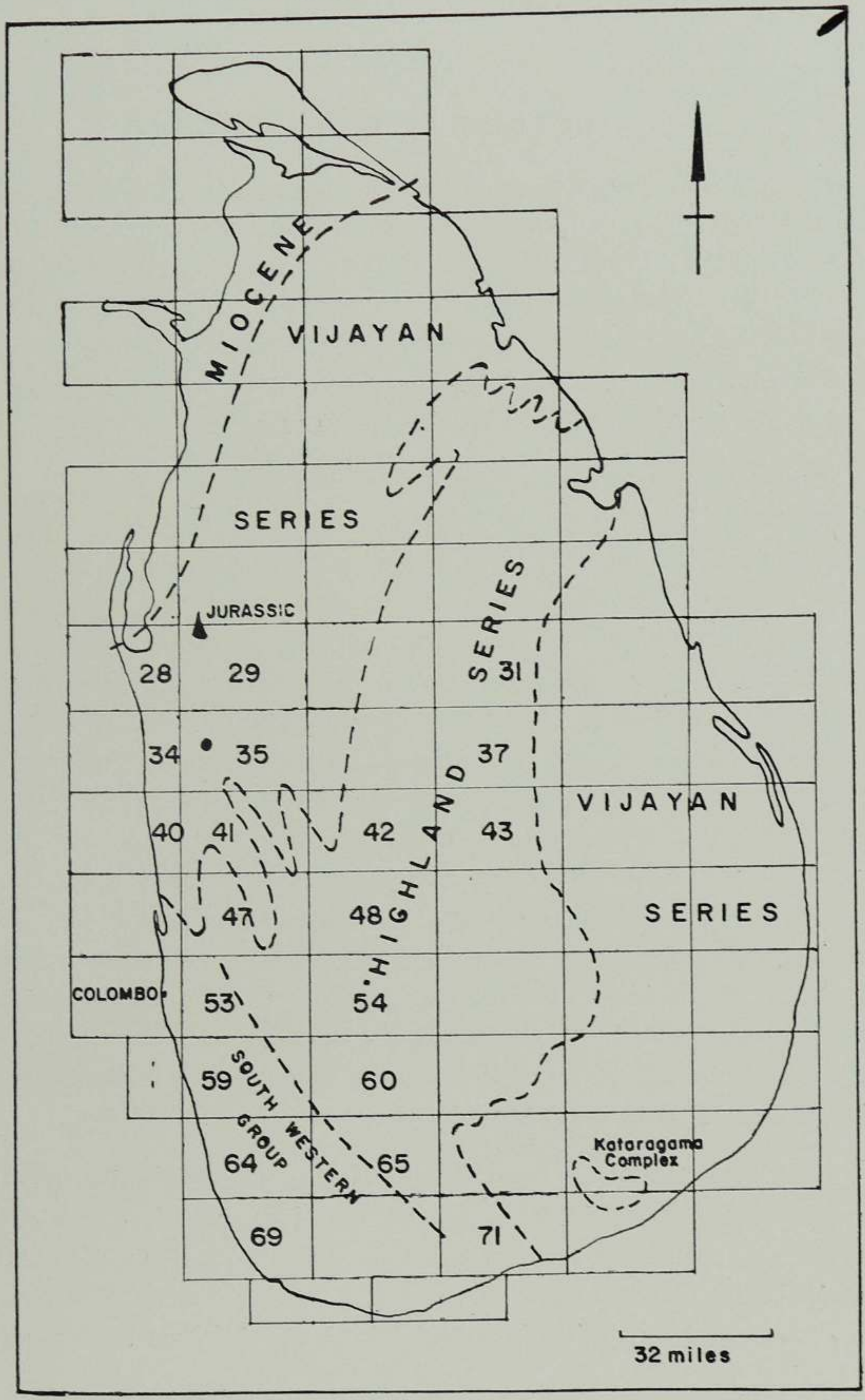

Fig. 30. Map of Ceylon showing the main geological divisions and locations of one-inch geological sheets that had been or were being mapped at the end of 1965.

(28) Puttalam, (29) Galgamuwa, (31) Polonnaruwa, (34) Battulu Oya, (35) Wariyapola, (37) Elahera, (40) Chilaw, (41) Dandagamuwa, (42) Kurunegala, (43) Rangala, (47) Gampaha, (48) Kandy, (53) Avissawella, (54) Hatton, (58) Panadura, (59) Horana, (60) Ratnapura, (64) Alutgama, (65) Rakwana, (69) Ambalangoda, (71) Ambalantota.

group of gneisses, granites, and mixtures of the two, occupies the lowlands on the north-west and south-east of the Highland Series belt. Numerous pegmatite dykes and veins, small bodies of granite, and dolerite dykes have been intruded into the crystalline rocks at various times between the Pre-Cambrian and the Tertiary eras.

Very small extents of Mesozoic rocks, mainly sandstones, shales and mudstones of Jurassic age, are found at Tabbowa and Andigama, near Puttalam where they are preserved in basins which have been faulted into the Vijayan Series. The base of this formation has not been seen, but a major unconformity lies between it and the underlying cystalline basement.

TABLE 7.— Formations Present in Ceylon

ERA	PERIOD	EPOCH	FORMATION
CENOZOIC	QUATERNARY	'Younger Group'	*Secondary formations :—* Laterite, nodular ironstone, chert, travertine, kankar Coral reefs Alluvium ; lake deposits Lagoonal and Estuarine beds Unconsolidated sands (beach and dune) Littoral sandstone
		'Older Group'	Red Earth Group Terrace Gravels Basal ferruginous gravel Ratnapura Beds
	TERTIARY	Miocene	**Jaffna Limestone: Minihagalkanda Beds**
MESOZOIC	?CRETACEOUS		Dolerite dykes
	JURASSIC (Upper Gondwana)		**Tabbowa Beds ; Andigama Beds**
PALAEOZOIC	UPPER		Granites and granite gneisses of South-western region Pegmatitities
	LOWER		**VIJAYAN SERIES**—Bintenne Gneisses, Wanni Gneisses, Tonigala Complex Pegmatites
PRE-CAMBRIAN			**HIGHLAND SERIES**—Khondalite Group, Charnockites, Kadugannawa Gneiss, Kataragama Complex ? Basement rocks (not seen)

North-west of the Negombo-Mankulam line is the largest extent of Tertiary sedimentary rocks in Ceylon. This is the Jaffna Limestone of Miocene age, consisting of a thick limestone together with calcareous sands and muds. The Miocene rocks, like the Jurassic, rest unconformably on an eroded basement of the crystalline complex. A much smaller outcrop of Miocene rocks (mainly sandstone) occurs in the extreme south-east of the Island, at Minihagalkande.

The Quaternary deposits are mostly unconsolidated and partly consolidated clays, sands, and gravels occupying the coastal tracts and the flood plains of the major rivers. Some of these deposits are wind blown, others have been deposited by rivers, some are old lake and lagoon deposits, and some are of marine origin. Coastal sandstones and coral reefs are also found in many places along the coast.

The Highland Series rocks are folded into a system of long, parallel folds which may be called the *Taprobanian* fold system[12]. The general direction of these folds lies between north to south and north-west to south-east, although in the southern part of the Central Highlands they veer to almost west-east and near Trincomalee they run north-east to south-west (see Fig. 37). These varying trends, however, are part of the same fold system. The folding of the Vijayan Series, in contrast to that of the Highland Series, is irregular, and there is no clear pattern of continuous, parallel folds. The latter can only be traced for relatively short distances and they vary in direction within small areas. The sedimentary rocks are not folded.

The crystalline rocks appear to have undergone much faulting, and several faults have been mapped in the field or determined by photogeology (that is, geological interpretation from aerial photographs). Many of them run for 10 to 20 miles across the crystalline rocks in an intersecting pattern of north-east to south-west and north-west to south-east trending faults; a large proportion of them are tear faults.

The crystalline rocks as well as the Jurassic and Miocene sedimentary rocks are well jointed.

The geological evolution of Ceylon began with the deposition of a thick pile of sediments in a Pre-Cambrian geosyncline. The sediments were subsequently buried at great depth in the earth's crust where they were subjected to regional metamorphism at great heat and pressure, and pushed into folds of great magnitude. The resulting rocks were the granulites, schists, and gneisses of the Highland Series. Many hundreds of millions of years later, these rocks underwent a second metamorphism when vast quantities of granitic material invaded them and turned them into the gneisses and migmatites of the Vijayan Series. The rocks were then pushed up into a mountain belt which remained above sea level for another large interval of time, during which they were continuously worn down by erosion.

It was not until the middle of the Mesozoic Era that the sea approached the margins of Ceylon (itself only a small portion of a vast continent called Gondwanaland); the Jurassic sediments of Tabbowa were deposited in deltas on the margins of that sea. After this episode, the landmass rose above sea level and remained so for another long period, until the middle of the Tertiary period. Once more the borders of Ceylon (now probably an island for the first time) were submerged below the sea and the thick Miocene limestone were deposited on its floor. A second, slow emergence followed, and the last few millions of years have been ones of comparative stability, with only slight changes in the boundary between land and sea occurring around the Island's coastline.

CHAPTER 6

THE CRYSTALLINE COMPLEX

The hills are covered with wood and great Rocks.

Robert Knox, 1681.

THE HIGHLAND SERIES*

ROCKS of the Highland Series occupy nearly all of the Hill Country of Ceylon, including the Southern Platform, the Rakwana and Knuckles massifs, the Matale Hills, and the narrow belt of low ridges that stretches into the lowlands towards Trincomalee (see Fig. 17). The eastern boundary of the Highland Series more or less follows the valley of the Mahaweli Ganga as far as Minipe and then curves outwards in a bulge to take in the Passara Hills. From here it runs westwards, following the foot of the Kongala escarpment which separates the Southern Platform from the lowest peneplain between Wellawaya and Mahawalatenne (see p. 53). The boundary then takes a sharp turn to the south-east, approximately along the road from Timbolketiya to Hambantota, and finally runs out to the sea near Ambalantota.

The western boundary of the Highland Series is much less well defined, but may be said to run roughly east of a line joining Habarana and Kurunegala. On the south-west side, the approximate limit of undoubted Highland Series rocks appears to be the zone of basic rocks that runs through the Sinharajah Forest and extends northwards to the vicinity of Labugama.

The Highland Series is, as we have seen, composed of two major groups of rocks, namely, the *Khondalite Group* (metamorphosed sediments) and *Charnockites* (metamorphosed sediments, metamorphosed basic volcanic rocks, or both). Representatives of both groups occur in very close association with each other in the field as can be seen in the Polonnaruwa area (Fig. 31). Nowhere, except in one area, is any single lithological type predominant, the exception being the Kadugannawa area where basic rocks are so prominent that they have been given the special name of 'Kadugannawa Gneisses'[13].

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* Detailed descriptions of Highland Series rocks can be found in the two published Memoirs of the Geological Survey Department on the Polonnaruwa and Rangala areas respectively.

THE GEOLOGY OF CEYLON

Khondalite Group

The Khondalite Group of rocks is made up of a variety of granulites, schists, and gneisses, all of which can be seen anywhere in the Hill Country as a well bedded series of strata (Figs. 31,32). These rocks are the metamorphosed equivalents of sedimentary rocks such as shales, sandstones, limestones, sandy clays, calcareous sands, and similar intermediate types. They can be subdivided according to their mineralogical composition, which is in turn a reflection of their chemical composition and the degree of metamorphism that they have undergone. The main rock types are—

(i) garnet-sillimanite schists and gneisses,
(ii) quartzites and quartz schists,
(iii) quartz-feldspar granulites and garnetiferous gneisses,
(iv) crystalline limestones and calc granulites,
(v) graphitiferous schists.

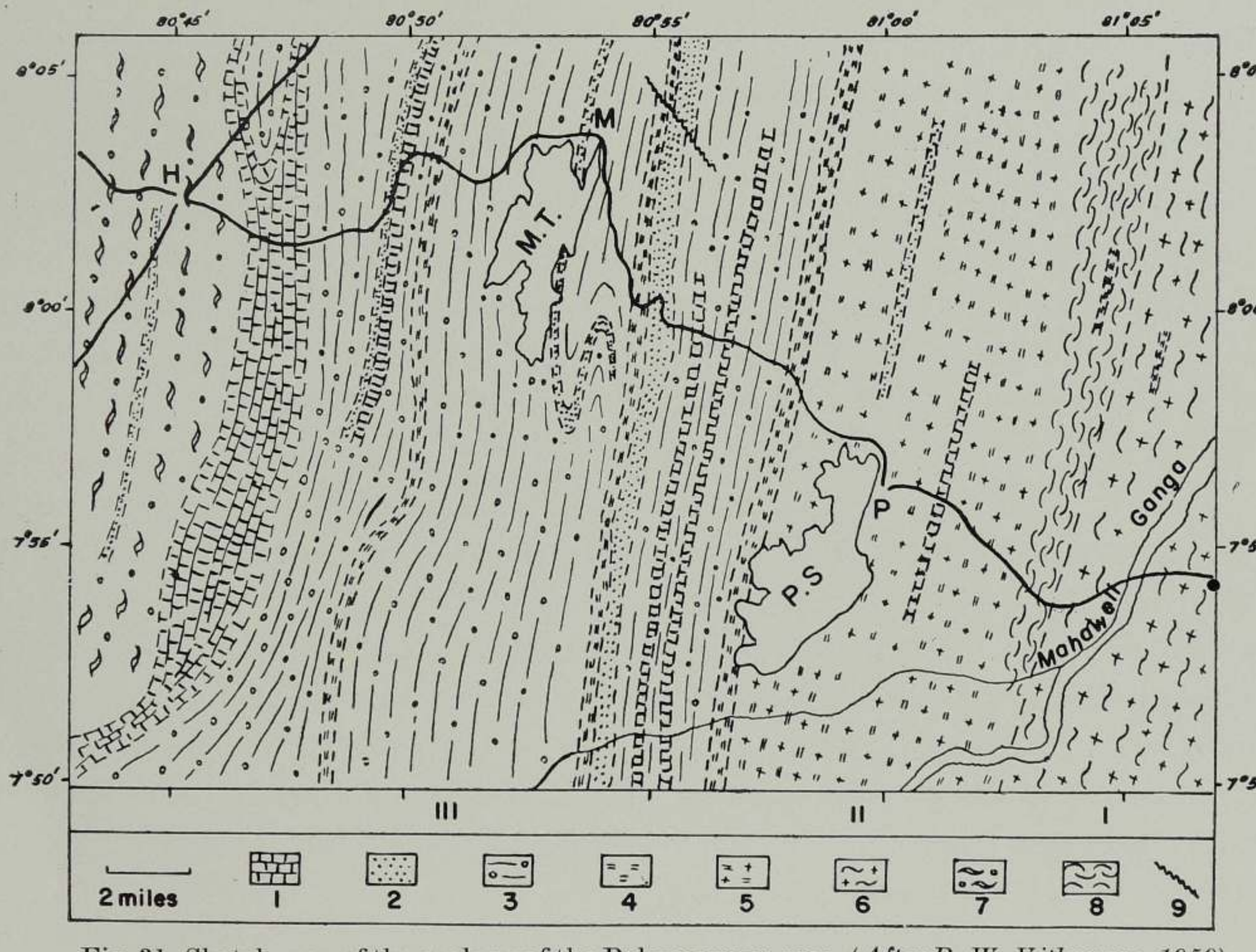


Fig. 31. Sketch map of the geology of the Polonnaruwa area. (*After P. W. Vithanage, 1959*).

(I) Vijayan Series, (II) Transitional Zone, (III) Highland Series.

(1) crystalline limestone, (2) quartzite, (3) metasedimentary gneiss and schist, (4) charnockites, (5) charnockitic biotite gneiss and schist, (6) granitic gneiss, (7) migmatitic gneiss, (8) crush zone, (9) fault.

(H) Habarana, (M) Minneriya, (M. T.) Minneriya Tank, (P) Polonnaruwa, (P. S.) Parakrama Samudra.

THE CRYSTALLINE COMPLEX

We have necessarily to describe these rocks individually rather than according to regional distribution because it has not been possible, so far, to recognise any significant pattern in their occurrence.

Garnet-sillimanite schists and gneisses

The most striking rocks of the Khondalite Group are the garnet-sillimanite rocks, someties called *khondalites,* after which the Group is named. The name 'khondalite' comes from the Khonds, a hill tribe in India who live in the area where these rocks were first noted. The khondalites are metamorphosed clays or shales (sediments rich in alumina), and they are characterised by the presence of such alumina-rich minerals as *sillimanite* (a colourless, needle-like form of aluminium oxide seen in Pl. 13A) and reddish to pinkish *garnet* called almandine (see Tables 2 and 5). The garnets are very large, often over an inch in diameter, and their presence

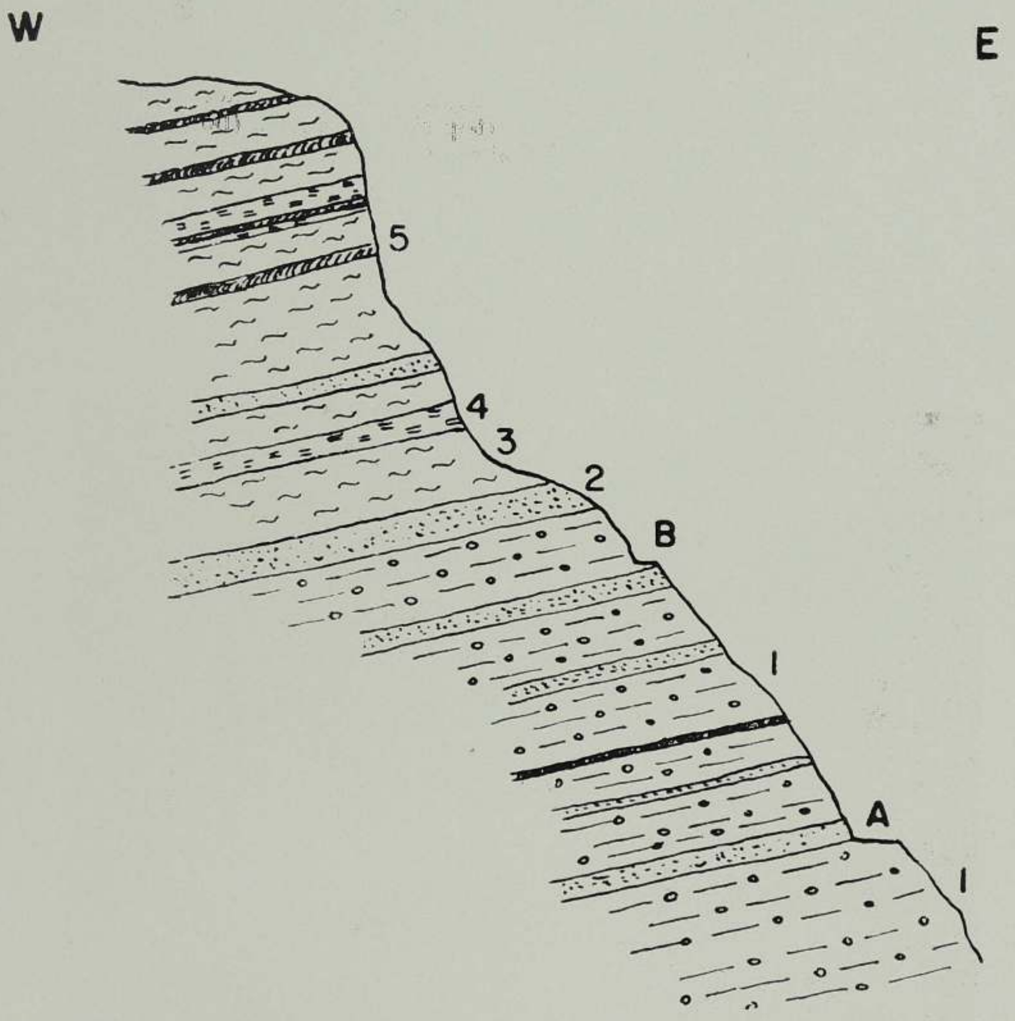
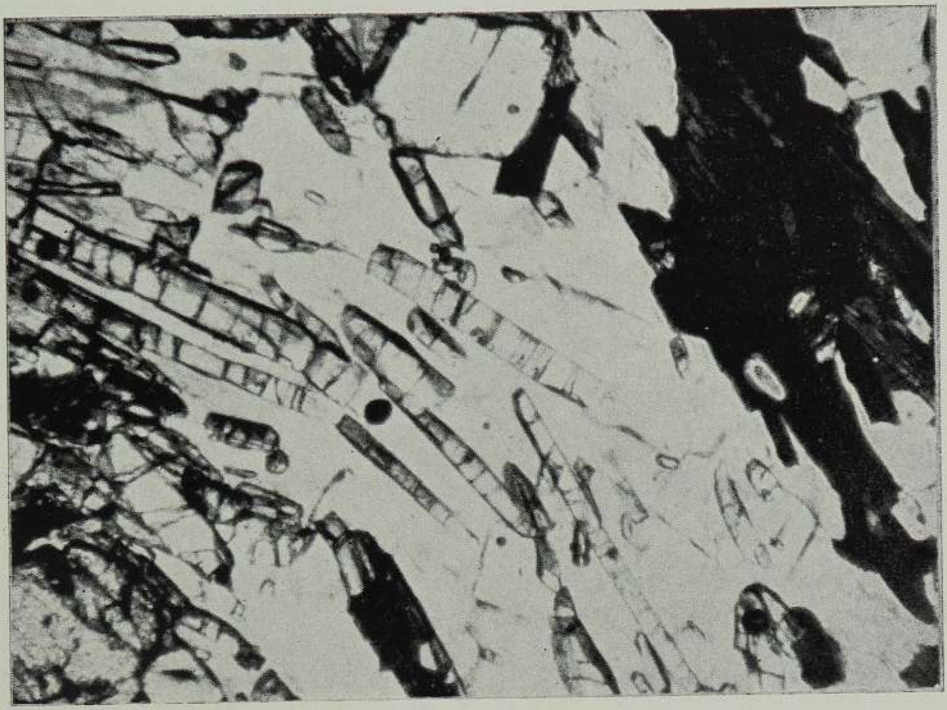


Fig. 32. Generalised section showing interbedded garnet-sillimanite schists (*Khondalite*), quartzites and other metasediments near Madulkelle.

(A) milestone 16 on Kandy-Madulkelle Road, (B) Hatale Estate road ; (1) garnet-sillimanite schist, (2) quartzite, (3) quartz-feldspar gneiss, (4) charnockite, (5) basic rock. Height of section about 1,000 feet.



A. Photomicrograph of garnet-sillimanite gneiss. Note bladed crystals of sillimanite, dark colour of mica (top right), garnet (bottom left corner) and quartz and feldspar (colourless). X35

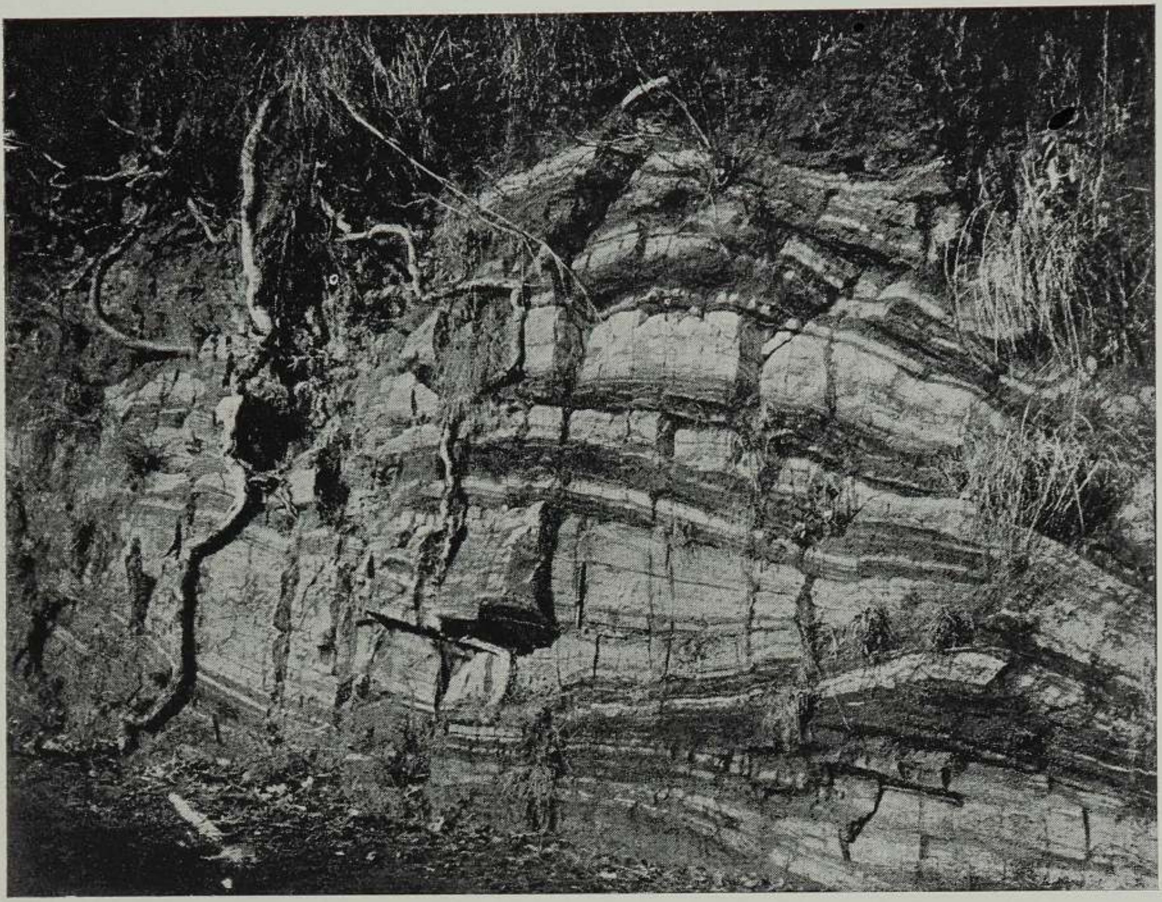
B. Photomicrograph of calc granulite with pyroxene and scapolite. Note the typical equigranular texture of granulites. X 35 gives the rocks a 'plum-pudding' appearance; when weathered, the garnets turn into rounded concretions of iron oxide. The term 'khondalite' should be used only for this specific type of garnet-sillimanite schist with the large garnets which can be seen in many parts of the Hill Country, particularly around Bandarawela (on the Welimada and Uva Highlands roads), Passara, Madulkelle (Fig. 32), and Nalanda.

Many other gneisses and schists rich in garnet and sillimanite but containing biotite mica, quartz, and feldspar as well also belong to this group. They are essentially metamorphosed sandy clays and are generally medium-grained rocks with small, purplish-pink garnets. The garnet-sillimanite rocks nearly always contain tiny flakes of graphite, probably derived from organic plant remains in the original sediments. This is one reason why it is believed that primitive forms of life existed in Pre-Cambrian times. The garnet-sillimanite rocks are usually stained brown on the surface, owing to the garnets being rich in iron. They weather easily into a clayey product known as *lithomarge* which is variously coloured in shades of red, brown, purple, and orange, with reddish-brown spots to mark where the garnets were; fresh specimens of the rock are therefore difficult to collect.

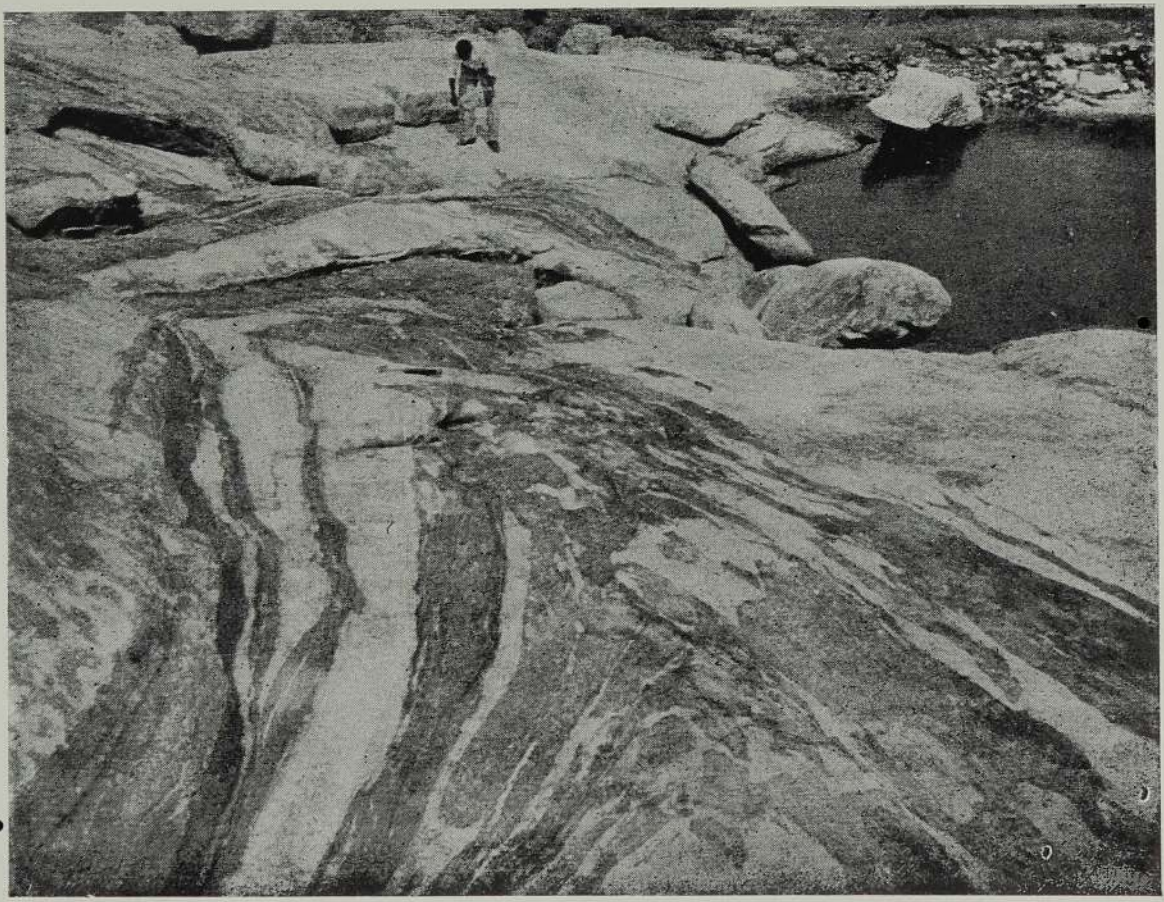
Quartzites and quartz schists

Quartzites are metamorphosed sandstones, and, as their name suggests, are made up almost wholly of shapeless crystals of *quartz* which have recrystallised from the detrital quartz grains in the original sandstone into an interlocking mosaic. *Sillimanite, garnet,* and *magnetite,* may also be present, either scattered through the rock or concentrated in thin layers, if the original sandstone contained small amounts of clay and iron. The quartz grains may at times be highly elongated and the rock may contain a fair proportion of *feldspar*; such rocks are called *quartz schists*. When weathered they crumble easily between the fingers, and for this reason the quartz schists are often quarried and used for road-dressing material on tea estates in the Hill Country.

The quartzites are coarse-grained or medium-grained rocks, whitish in colour and glassy in appearance, and highly jointed and fissured (Pl. 12A). They are easy to recognise owing to their distinctive appearance; where-ever they occur the hill slopes are covered with white sandy soil and debris which can be seen from a distance. It should be mentioned here that quartzites are not to be confused with vein quartz which is more massive (see Pl. 31B), does not have minerals like garnet and sillimanite, occurs in narrow zones generally running across the strike, and which has a different mode of origin (see Chap. 9).



A. Interbedded charnockites (dark) and quartz-feldspar gneisses (light) in the Highland Series ; between milestones 128 and 129 on the road from Koslanda to Wellawaya. (*D.K. Erb; Crown Copyright Reserved*)



B. Folded, thick amphibolitic layers in hornblende-biotite gneiss, Vijayan Series ; Kirinda Rock. (*D. K. Erb ; Crown Copyright Reserved*)

Quartzites are found in all parts of the Highland Series belt, especially around Nuwara Eliya, Hatton, Norton Bridge, Maskeliya, Namunukula, Madulsima, Rangala, Madulkele, Teldeniya, Peradeniya, and Trincomalee. Parallel bands can sometimes be traced for miles along the strike and quartzites frequently form prominent escarpments and ridges. One of the most striking of these is the Sudukande Quartzite which forms a hill range running in an almost straight line from Giritale Tank, near Polonnaruwa (Fig. 31), almost up to Alutnuwara. The Sudukande Quartzite is 200 to 300 feet thick and runs for nearly fifty miles ; the Minneriya quartzite band west of it is 50 to 75 feet thick and about thirty miles long[14]. In other parts of the Hill Country the quartzites may be a few inches to a few feet thick, and several narrow bands may be interbedded with charnockites and other metasediments in comparatively narrow zones (Figs. 32 and 33). The quartzites of the Trincomalee area form long, low ranges and run out to the sea in such cliffs as Swami Rock and Fort Frederick. The closest quartzite occurrence to Colombo is at Panagoda, near the bridge over the railway line at milesstone 16½ on the road to Avissawella.

Quartzites, because they are highly jointed, are very permeable and can carry much water which issues in numerous springs from the sides of the hills they form (see Chap. 12).

Quartz-feldspar granulites and gneisses

These are a group of light-coloured rocks (Pl. 14A), sometimes gneissic but more often equigranular, which are made up chiefly of *quartz* and *feldspar,* with varying amounts of *mica* and *garnet.* The garnets are scattered through the rock and the quartz grains may be in elongate leaves or ribbons. *Sillimanite* and *graphite* are also sometimes present and this suggests that the quartz-feldspar granulites are metasediments. The typical rock in this group is a white, sugary-textured granular rock with small scattered garnets which was formerly known as 'acid granulite' but is now called 'quartz-feldspar granulite.'

The quartz-feldspar granulites and gneisses probably are metamorphosed sandy clays or clayey sands, intermediate in composition between the garnet-sillimanite gneisses and the quartzites (see Table 5) ; they may grade either into the former by an increase of garnet and sillimanite, or into quartzites by an increase of quartz.

Crystalline limestones and calc granulites

Crystalline limestones, the pure varieties of which are called *marbles,* are metamorphosed sedimentary limestones. They vary from coarse-grained to fine-grained in texture and though usually white (Pl. 12B), are sometimes greyish, pinkish, or greenish, depending on the colour of the carbonate or silicate mineral found in them. Crystalline limestones are striking rocks when fresh and have often been used as a building stone in the past, as at Polonnaruwa. Their weathered surfaces are generally black and for this reason they are less easy to recognise than quartzites. Soils developed on limestones are usually dark chocolate brown or red in colour.

Calcite and *dolomite,* carbonates of calcium and magnesium, are the two main constituents of these rocks, but the original sediments generally contained small amounts of silica (in the form of sand), alumina (as clay), and iron oxide (as grains of ilmenite and magnetite). Consequently, most crystalline limestone have a variety of silicate minerals in greater or lesser amounts. Among the most common of these are a greyish olivine called *forsterite* (magnesium-iron silicate), green *diopside* (calcium-magnesium-iron silicate), *phlogopite* (a brown mica containing calcium and magnesium), blue or green *apatite* (a calcium phosphate resembling light blue sapphire), purplish and blue *spinels* (aluminium oxides with magnesium and calcium), brassy-looking *pyrite* and *pyrrhotite* (sulphide minerals), and *graphite* (see Table 5). Some crystalline limestones contain a striking orange-coloured mineral known as *chondrodite,* and others, such as the Rupaha marble, are green owing to the presence of the hydrated mineral *serpentine.*

It is interesting to note that the silicate minerals very often occur in bands in the crystalline limestones, and this suggests that the quiet seas in which the calcareous sediments were laid down were from time to time inundated with sand and clay, perhaps brought down by flood waters. Owing to the different degrees of resistance of the several bands to weathering it is not uncommon to find grooved and fluted surfaces on the crystalline limestone bands.

Crystalline limestones occur in all parts of the Highlands, some of the best known occurrences being near Matale, Nalanda, Habarana, Kandy, (see Fig. 36) Badulla and Welimada. Their presence is often given away by the numerous lime-burning kilns in the vicinity. One of the longest bands of crystalline limestone is the one running northwards from Matale to Nalanda and beyond that to Habarana (see Fig. 31), a total distance of about 60 miles. Parts of this band can probably be traced in scattered outcrops through Kaudulla and Kantalai, and even up to Trincomalee. The thickness of the Matale-Nalanda limestone band varies from 100 to about 2,000 feet[14]; but most limestones are between 5 and 50 feet thick.

Calcium carbonate is an easily soluble mineral so that *solution caves* reaching up to 10 or 20 feet in height are sometimes found in crystalline limestone bands. The caves are generally in rather inaccessible spots, unfortunately, often on the sides of steep cliffs, as in the instance of Nitre Cave in the Rangala area. To reach this cave is difficult but well worth the effort, and when one gets there eventually one finds a large cave with a mouth almost twelve feet high, in an almost vertical cliff face. A platform within the main cave forms the floor of an inner, smaller cave, about 8 feet high, the floor of which is covered with a soft, powdery, brown deposit like saw-dust. This is the 'nitre' after which the cave is named; it is really the droppings (*guano*) of hundreds of bats which infest this and all such caves and give them their obnoxious smell. Tradition has it that the nitre or saltpetere (potassium nitrate) was collected and used for the manufacture of gunpowder during the days of the Sinhalese kings.

Other caves in crystalline limestone are found at Ella (Ravana's Cave), Maturata (near Padiyapelella), Wellawaya, Hakgala, Istripura (near Welimada), Padanwela (near Wilson's Bungalow), Patanagedera (near Laggala), and Kudawa (near Gilimale)[15]. A large substerranean chamber with good *stalagmites* and *stalactites* as well as a large lake, 120 yards long, 50 yards wide, and 20 feet deep is present at Istripura; *hydromagnesite* (*Maturata makul*) from Maturata cave is used for painting the walls of vihares and as paint for pottery.

Two other caves, both in the Norton Bridge area, might be mentioned. One goes by the intriguing name of 'Cave of the Seven Virgins' and can be seen from the road to Maskeliya occupying a small cliff face overlooking the valley of the Maskeliya Oya. The other is at the foot of Laxapana Falls and to reach it involves a steep but rewarding descent. This is a magnificent cave, partly occupied by a large pool, and what can be seen of it is thirty to forty feet in height. It is not possible to get into this cave, or even very near to it. One can only stand at a distance on the huge, rather slippery boulders that lie strewn about, and catch a glimpse through falling spray of a scene as awe-inspiring and silently majestic as something from a Rider Haggard story.

Calc granulites and gneisses are very impure calcareous rocks formed by the metamorphism of calcareous muds (or marls) and calcareous sands. They are of minor importance in the Central Highlands, being completely subordinate to the crystalline limestones. Those that are present are dark greenish to blackish-green rocks composed mainly of *diopside, scapolite,* and *hornblende,* with abundant *sulphide minerals*;

some of these rocks also contain much *mica*. Calc granulites are much more important in the South-western region, and they will be described more fully in that section.

Graphitiferous schists

Graphitiferous schists occur as very narrow and relatively scarce bands, rich in graphite and sulphide minerals[6]. The presence of these two minerals in such high proportions suggests that the original sediments from which they were formed were accumulations of mud, sand, and decayed vegetable matter in stagnant water, similar to the present-day accumulations in inland lakes and ponds. The floors of such inland lakes, where little or no aeration takes place, are covered with thick deposits of blackish mud rich in decaying organic matter ; there is a strong smell of sulphurreted hydrogen in the vicinity of these lakes.

Graphitiferous schists were first noted in the Rangala area but it is likely that they occur elsewhere in the Central Highlands. It is important that their presence should be noted because, being distinctive rocks, they can be used as 'marker' bands to determine the relative positions of other rock types.

Charnockites

The charnockites are less easy to describe than members of the Khondalite Group, but they can be quickly recognised once one is familiar with what they look like. All charnockites are greenish-grey or bluish-grey in colour, are generally very fresh and somewhat glassy-looking on newly broken surfaces, but have a dull, greasy appearance when exposed to the atmosphere for any length of time. Their characteristic dark colour is due to the fact the quartz and feldspar crystals are greenish or greyish in colour, unlike in other rocks where these same minerals are white or colourless. It is for this reason that charnockites are generally known by the all-embracing term *kalu gal* (= black rock).

There are several varieties of charnockites. They range from fine-grained to coarse-grained in the size of the constituent minerals, from acid to basic in composition, and from equigranular to gneissic in texture. The **acid** types contain more than 65 per cent silica and are made up mostly of *quartz* and *feldspar,* together with small amounts of *pyroxene ;* the **intermediate** types, with 55 to 65 per cent silica, have all these minerals as well as some *mica* and *hornblende ;* the **basic** charnockites, with less that 55 per cent silica, are generally finer grained than the others, and are composed mainly of *plagioclase, pyroxene,* and some *hornblende. Garnet* may be present in all varieties and *graphite* in some. The acid and intermediate charnockites are the predominant types in most areas, basic charnockites generally occurring as comparatively narrow bands within them. The gneissic varieties, like other gneisses, may be banded, streaky, or augened, and all of them have a well marked foliation. In spite of this wide variety, however, all charnockites have one common property, namely, the presence of a dark pyroxene called *hypersthene* (a magneiusm-iron-calcium silicate). This mineral cannot be seen easily with the naked eye but it is always present when thin sections of charnockites are looked at under the microscope.

It was this characteristic feature that led Sir Thomas Holland, a former Director of the Geological Survey of India, to name them the ' Charnockite Series ', after Job Charnock, the engineer who founded modern Calcutta on the mudflats of the Hoogli River and whose tombstone is of this rock. This Holland did in 1900, in a Memoir that has now become a classic of geological literature[16]. Since that time charnockites have been discovered all over the world, in such widely scattered places as the United States, Scotland, Sweden, Finland, Russia, Central and East Africa, South India, Ceylon, Australia, and Antartica. The locality from which charnockites were first described by Holland is St. Thomas' Mount, a small hill outside Madras which one passes on the way from the airport to the city.

Charnockites are the commonest rock types of the Highland Series and can be seen almost anywhere in the Central Highlands of Ceylon. They occur generally as narrow or medium-sized bands (2 or 3 feet to 30 or 40 feet thick) regularly interbanded or interbedded with quartzites, crystalline limestones, and garnet-bearing gneisses of the Khondalite Group

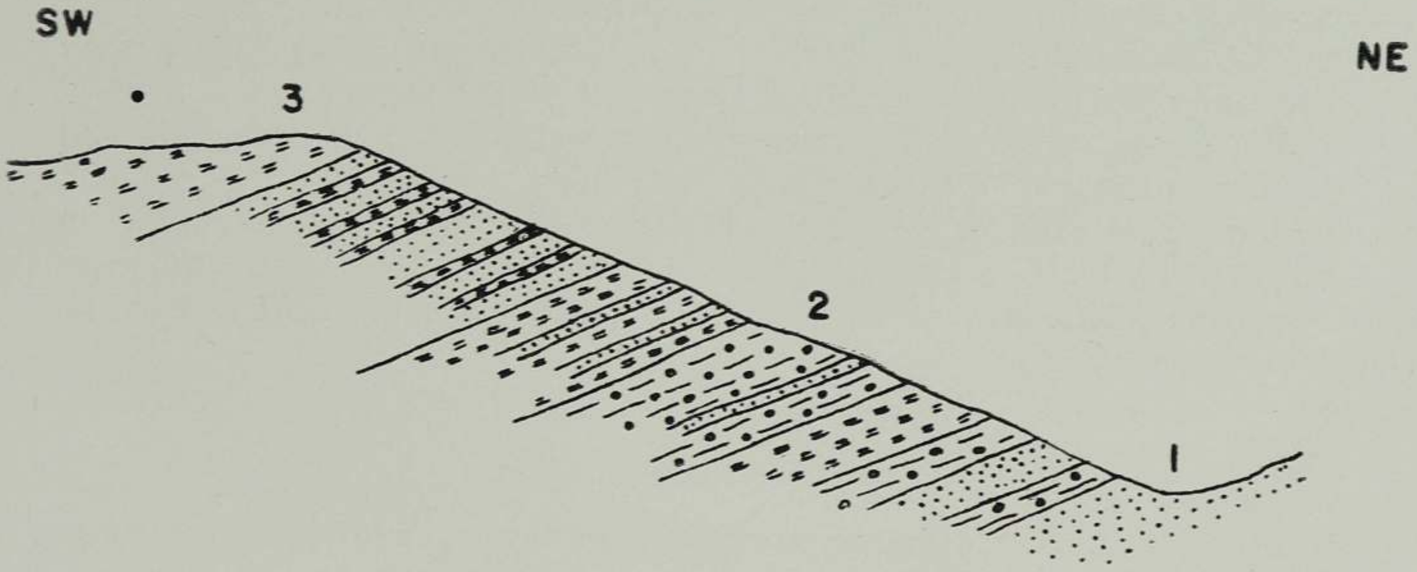


Fig. 33. Generalised section showing interbanding of charnockites with quartzites and other metasediments between Rangala Estate and Corbet's Gap.

(1) quartzite, (2) garnet-sillimanite gneiss, (3) charnockite. Length of section about 1½ miles; height about 600 feet.

(Fig. 33). Charnockites sometimes occur as large masses, often hundreds of feet thick. The Bulutota escarpment on the north side of the Rakwana Massif, for example, is made up entirely of charnockites, as can be seen when climbing up Bulutota Pass. Standing at the top of this pass and looking north, one sees the Haputale escarpment where perhaps the largest mass of charnockite in Ceylon is found ; it is several hundreds of feet thick. Most of the Dimbula valley (as the area around Talawakelle is known) is also made up of charnockites, and one cannot but help notice this on the road from Dimbula to Nanu Oya.

One very significant fact about the occurrence of charnockites in Ceylon is that wherever metamorphosed sediments are present, charnockites are also found. The opposite also seems true, namely, that where metasedriments are rare or absent, as in the Vijayan Series, charnockites seldom occur. A good example of this phenomenon is seen in the Kataragama Complex (see p. 117). Here, like an island in the sea, are a few square miles of charnockites interbanded with crystalline limestones and other metasediments (exactly as in the Central Highlands), surrounded completely by the Vijayan gneisses completely lacking in charnockites (see Fig. 30).

The rocks of the 'Charnockite Series' were considered by Sir Thomas Holland to have crystalised from a magma ; according to him therefore, charnockites were igneous rocks intruded into the surrounding gneisses and schists. Within the last twenty years, however, there has been increasing evidence from many parts of the world (especially Finland, Central Africa, Australia, India, and Ceylon) that charnockites are metamorphic rocks formed at the same time and by the same processes as the metasediments with which they are so closely associated. What is still uncertain is the original nature of these rocks. Were they originally sediments or igneous rocks, and if the former, what kind of sediments were they ? Or were the original rocks both sediments and igneous (volcanic ?) rocks which have been converted to a common metamorphic product by the conditions of high-grade metamorphism in which they were formed ? We are still far from the answers to these questions which only patient, careful work both in the field and in the laboratory can solve.

Kadugannawa Gneisses

THE Kadugannawa Gneisses are black, lustrous *amphibolites* (or hornblende-plagioclase schists) which are found extensively around Kadugannawa, Nawalapitiya and Dolosbage, but are also found north of Kandy, especially in the Kurunegala area. Good exposures can be seen on the

Kadugannawa Pass (Fig. 34), in the Kabaragala Range between Nawalapitiya and Dolosbage, as well as on the roads from Kandy to Matale and to Galagedera.

Although amphibolites occur elsewhere in the Central Highlands as narrow bands and lenses associated with charnockites and other metasediments, in the Kadugannawa area they form a large body, lens-like in shape, about 8 to 10 miles wide and stretching from north to south for about 30 miles[13]. The rocks within this area may be massive, schistose, or banded, but they are all composed essentially of *hornblende, plagioclase feldspar, mica,* and some *pyroxene.* Within the amphibolites are narrow bands of calc gneiss, a fact which suggests that the Kadugannawa Gneisses may themselves be metaphorphosed impure calcareous rocks of a special character. They may, on the other hand, be igneous rocks such as lava flows or volcanic dust which have been changed into hornblende schists by high-grade metamorphism.

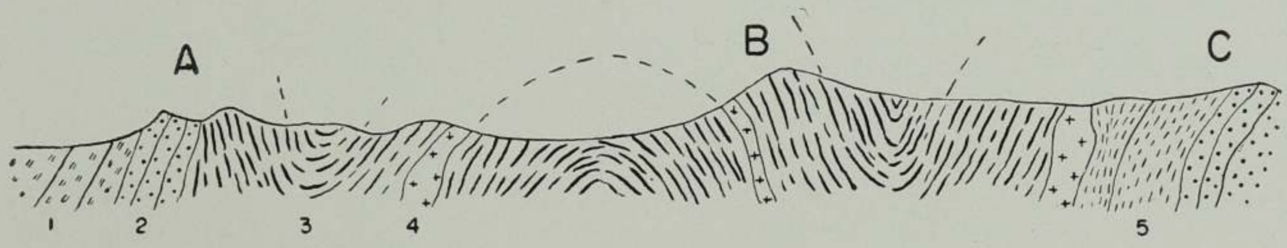


Fig. 34. Diagrammatic section along the Kadugannawa Pass. (*J. S. Coates, 1935*)
A—Pelpatha, B—Kadugannawa, C—Peradeniya.
(1) charnockite, (3) metasediments, (3) Kadugannawa Gneiss, (4) pink granite, (5) biotite gneiss.

Geological Structure

THE most important structural elements in the metasediments and charnockites of the Highland Series are foliation and bedding, the former being characteristic of gneissic rocks like charnockites and garnetiferous gneisses, the latter being recognisable in some quartzites and crystalline limestones. In the quartzites, thin layers of clay within the original sandstones are now marked by the presence of aluminous minerals like sillimanite and garnet, and such rocks split easily along these bedding planes (see Pl. 38A). In the crystalline limestones the original impure sandy and clayey layers are now occupied by dark, narrow bands of calc silicate minerals, these bands contrasting strongly with the whiteness of the rest of the rock. True schistosity is seldom met with, except in some hornblende schists of the Kadugannawa Gneisses. Among the minor structures, mineral elongation, especially of quartz, is a common feature (Fig. 35 A,B.), and rodding (where the rock appears to be made up of columns) is seen in some quartzites, especially around Hatton and Norton Bridge. Small folds are sometimes present but are not common (Fig. 35 C, D.).

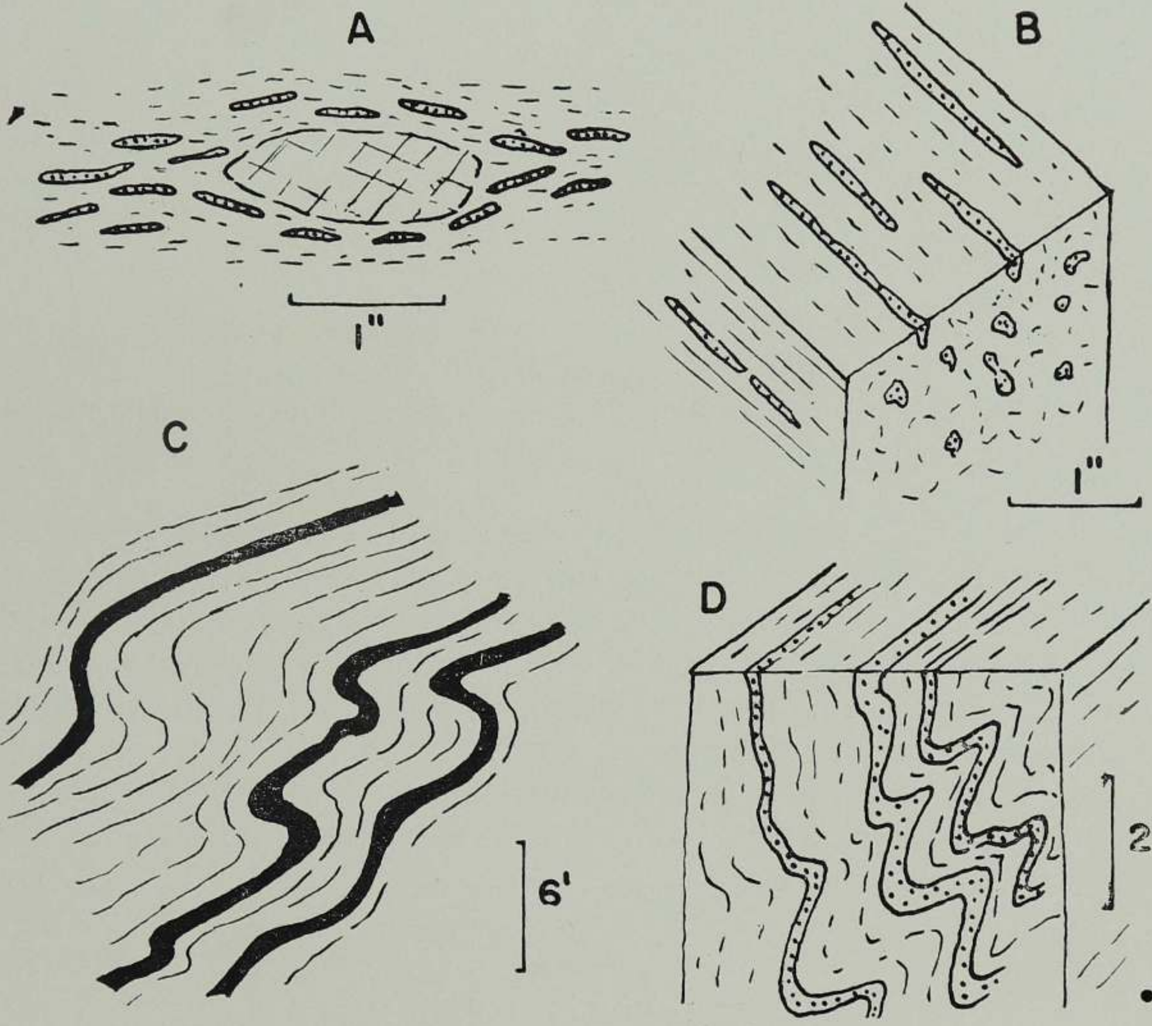


Fig. 35. Minor structures in Highland Series rocks.
A. Elongate quartz leaves. B. Elongate feldspar rods. C and D. Small folds.

Geological mapping, together with the study of aerial photographs, has led to the recognition of a very large number of folds in the Highland Series. The first person to map one of those large folds was Ananda Coomaraswamy who, by mapping the outcrops and attitudes of the foliation and bedding planes of the crystalline limestones east of Kandy, determined the form of the Dumbara Syncline (Fig. 36) [12]. This is a classic type of syncline, and because the outcrops close on the south-east side (see Pl. 16A), we know that the axis of the fold plunges to the north-west. The majority of the folds in the Highland Series have the same trend and

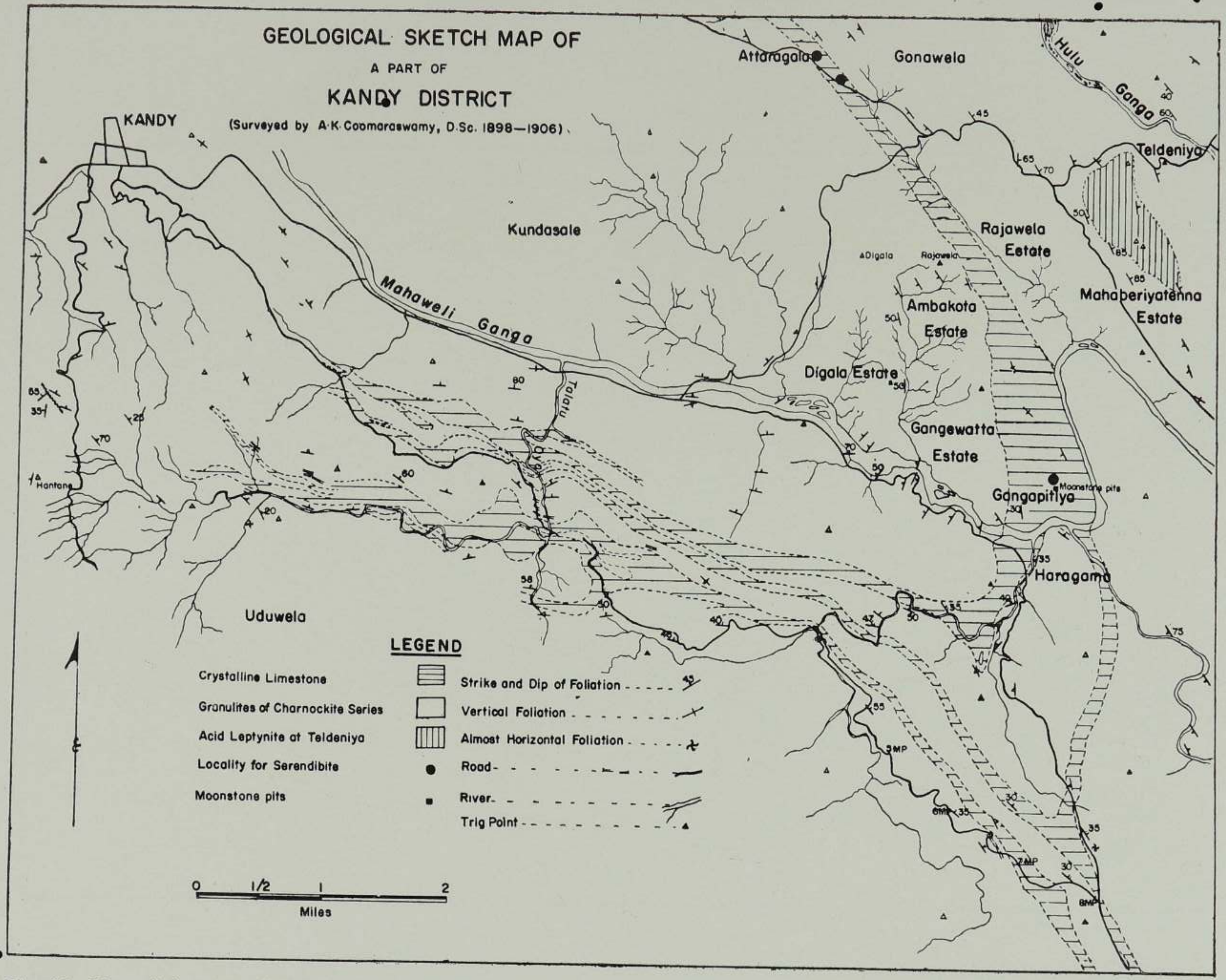


Fig. 36. Map of the crystalline limestones east of Kandy which are folded into the north-west plunging Dumbara Syncline. (*A. K. Coomaraswamy, 1906*)

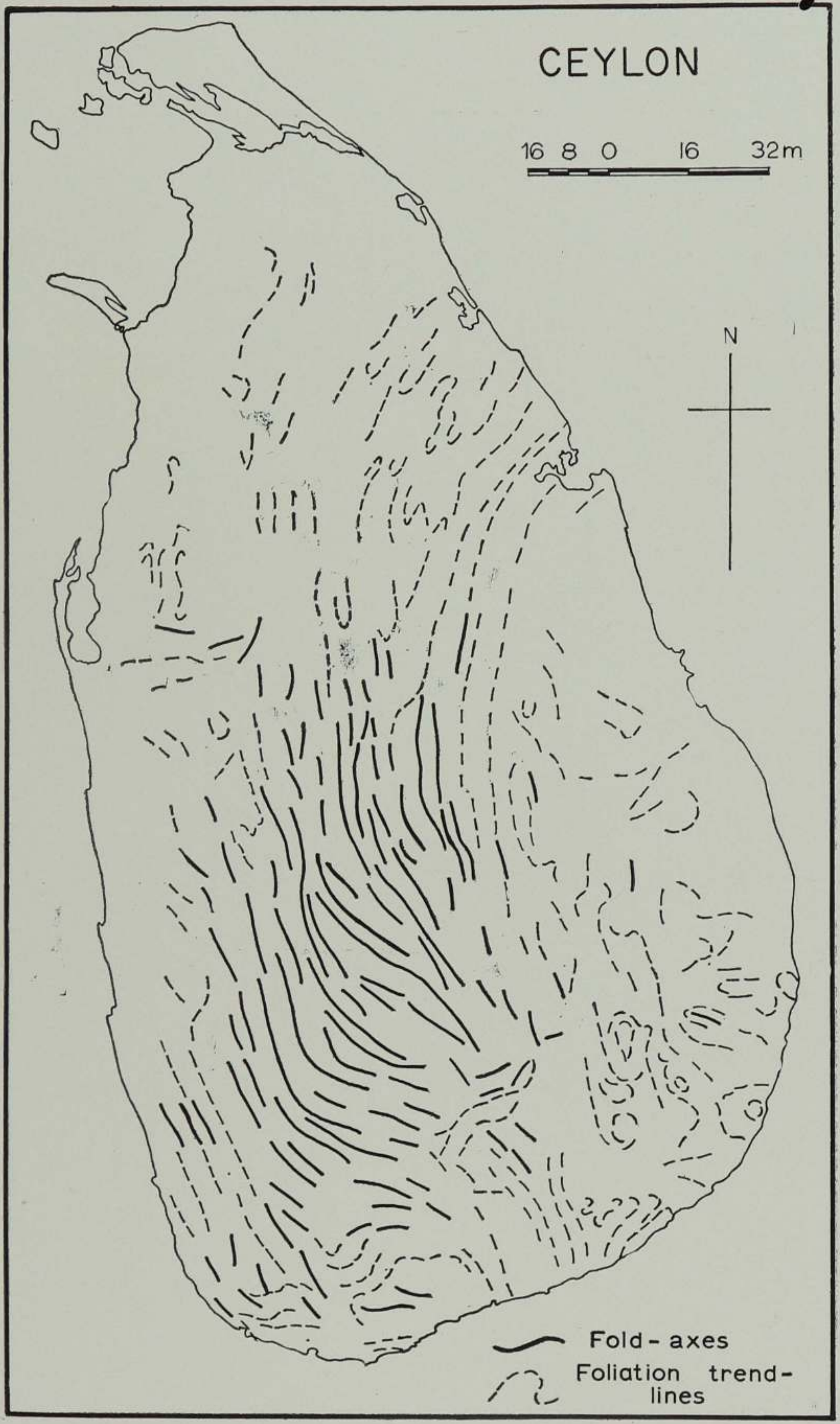


Fig. 37. Simplified Tectonic Map of Ceylon showing the Taprobanian fold system and variable trend lines of the Vijayan Series.
(*After R. L. Oliver, 1957*)

most of them plunge in the same directions (Fig. 37). Departures from this dominant trend are found in the southern part of the belt, for example, in the Haputale area where they run almost E-W, and northwards from Matale where they vary from N-S to NNE-SSW. The axes of all those folds are more or less parallel to each other, and they form a regular pattern of synclines and anticlines known as the Taprobanian fold system.

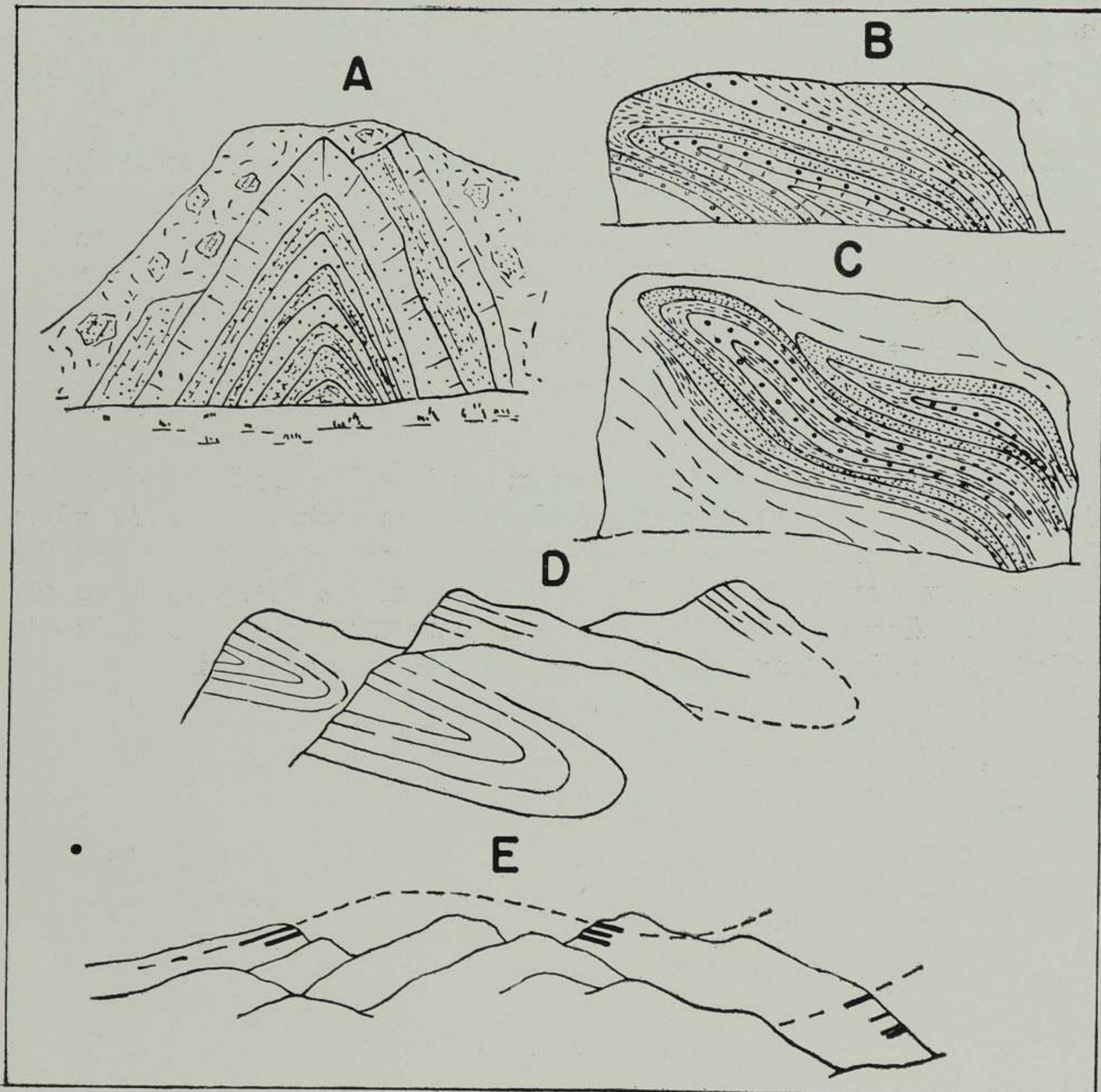


Fig. 38. Types of folds in the Central Highlands.

A. Symmetrical fold in quartzites and quartz schists, Nyanza Estate, Maskeliya. (Height of section, 7½ feet)

B. Small recumbent fold in Khondalite Group, Bindunuwewa Farm road, Bandarawela. (Length of section, 40 feet)

C. Small recumbent folds in Khondalite Group, 3¾ miles from Bandarawela on Uva Highlands road. (Length of section, 100 yards)

D. Large recumbent fold, Andirigala, Knuckles Massif; looking south-westwards from Mimure.

E. Katugahakande folds, Uva Basin; looking north-eastwards from the Poonagala road, Bandarawela.

The folds vary in attitude and size (Fig. 38). Medium-scale folds have amplitudes varying from 10 to 100 feet and can often be seen in road cuttings and quarries (see Pl. 5A). The large-scale folds may be from 10 to 50 miles in length, or even more, and their amplitudes are of the order of 2 to 6 miles. Such folds can only be seen on geological maps, as in the example of the Dumbara Syncline, mentioned above (Fig. 36 and Pl. 16A). The folds may be symmetrical and vertical, overturned, or even recumbent, the axial planes of the latter folds being generally overturned to the east. Some of the E-W trending folds in the southern part of the Hill Country are overturned to the south.

Although the majority of the fold axes plunge to the north, some plunge to the south, and others plunge in both directions. One example of the latter type is the Hatton syncline. The town of Hatton is located on the highest point (or *culmination*) of the fold axis, and from here it plunges north-westwards towards Ginigathhena and south-eastwards towards Dickoya. When the same fold axis plunges in both directions, it leads to the formation of *domes* (in the case of an anticline) and *basins* or *arenas* (in the case of a syncline).

Running almost through the centre of the island is the Ramboda anticline, a broad, open fold, now breached along the centre by a wide valley (Fig. 39) ; this fold can be traced for several miles northwards into the Kadugannawa anticline (see Fig. 34). Some of the major folds on the east of the Ramboda anticline are the Dumbara syncline, the Rajawela anticline, the Huluganga syncline and the Knuckles overfold.

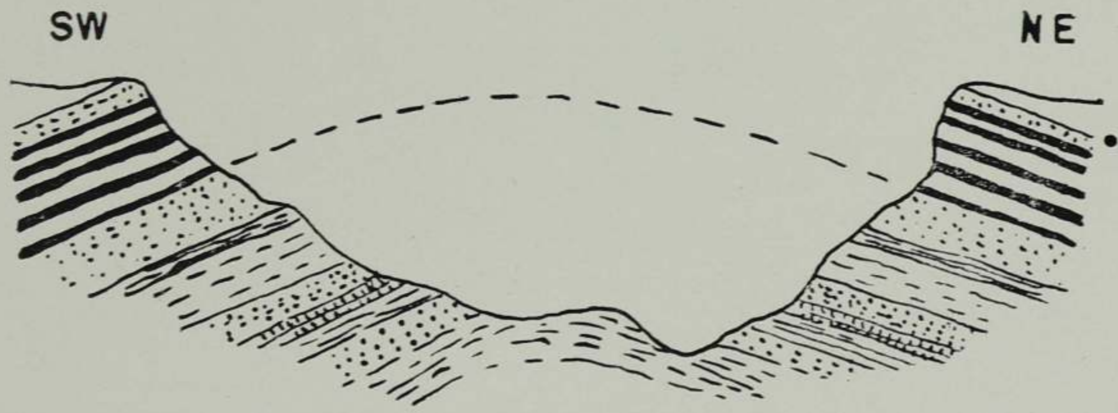


Fig. 39. Diagrammatic section across the Ramboda anticline; looking north-westwards from top of Ramboda Pass. (*D. N. Wadia*, field notebook)

On the south-west side of the Ramboda anticline are the Pundaluoya syncline, the Belton-Meddacombra anticline, the Hatton syncline (occupied by the valley of the Mahaweli Ganga), the Massena anticline, and the Kiribathgalla syncline.

Jointing is well developed in most rock types, strike joints and dip joints being the commonest. This can be illustrated in the Polonnaruwa area where the majority of joints are either N-S or E-W, these being the directions of strike and dip respectively of the rocks of the area (see Fig. 31). As we have noted earlier, joints have a strong influence on the landscape, and nowhere is this better seen than in the Hill Country. Weathering and erosion take place easily along joint planes, and this results in vertical rock faces, land slides and rock falls, gorges, and rectangular drainage patterns.

The commonest type of fault in Highland Series rock is the tear fault, where opposing horizontal movement takes place on either side of the fault plane. Such a fault can be seen near Minneriya in the Polonnaruwa area, where the gap formed by the displacement of a quartzite ridge is utilised by the railroad (Fig. 40), and in the Rangala area where rocks on one side of a fault are not seen on the other (see Geological Map). Faulting is not always easy to recognize in the crystalline rocks, but its presence can sometimes be deduced from the occurrence of dark coloured, fine-grained to glassy mylonitic rocks that have obviously been crushed, or by

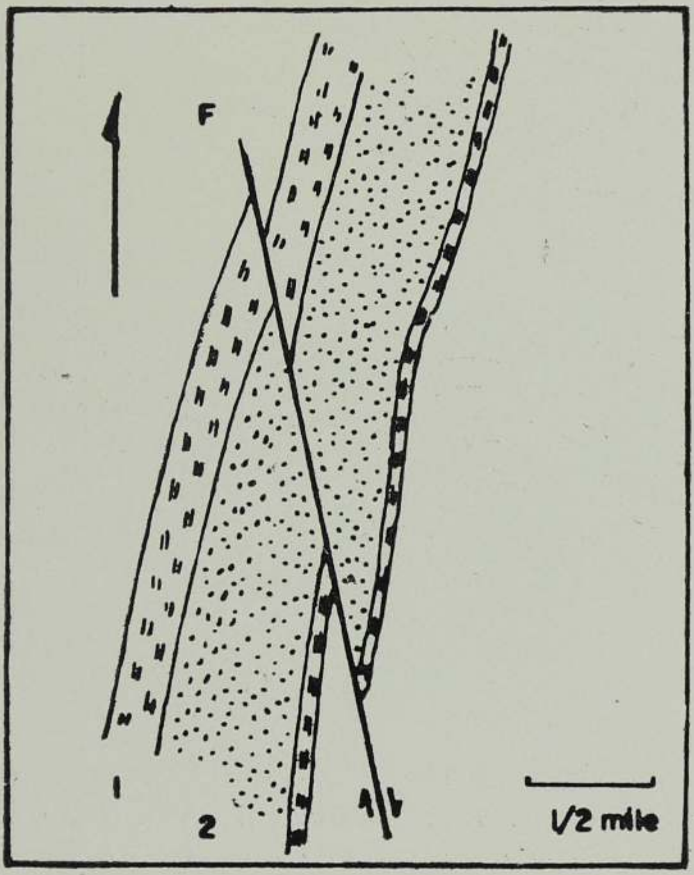


Fig. 40. Sketch of tear fault near Minneriya, showing horizontal displacement of quartzite band (dotted).

the presence of vein quartz in fractures in the rocks. Medium-scale faults can often be seen in road cuttings and in quarries, as for example along many of the roads in the Uva Basin (Fig. 41), where violent earth movements appear to have taken place.

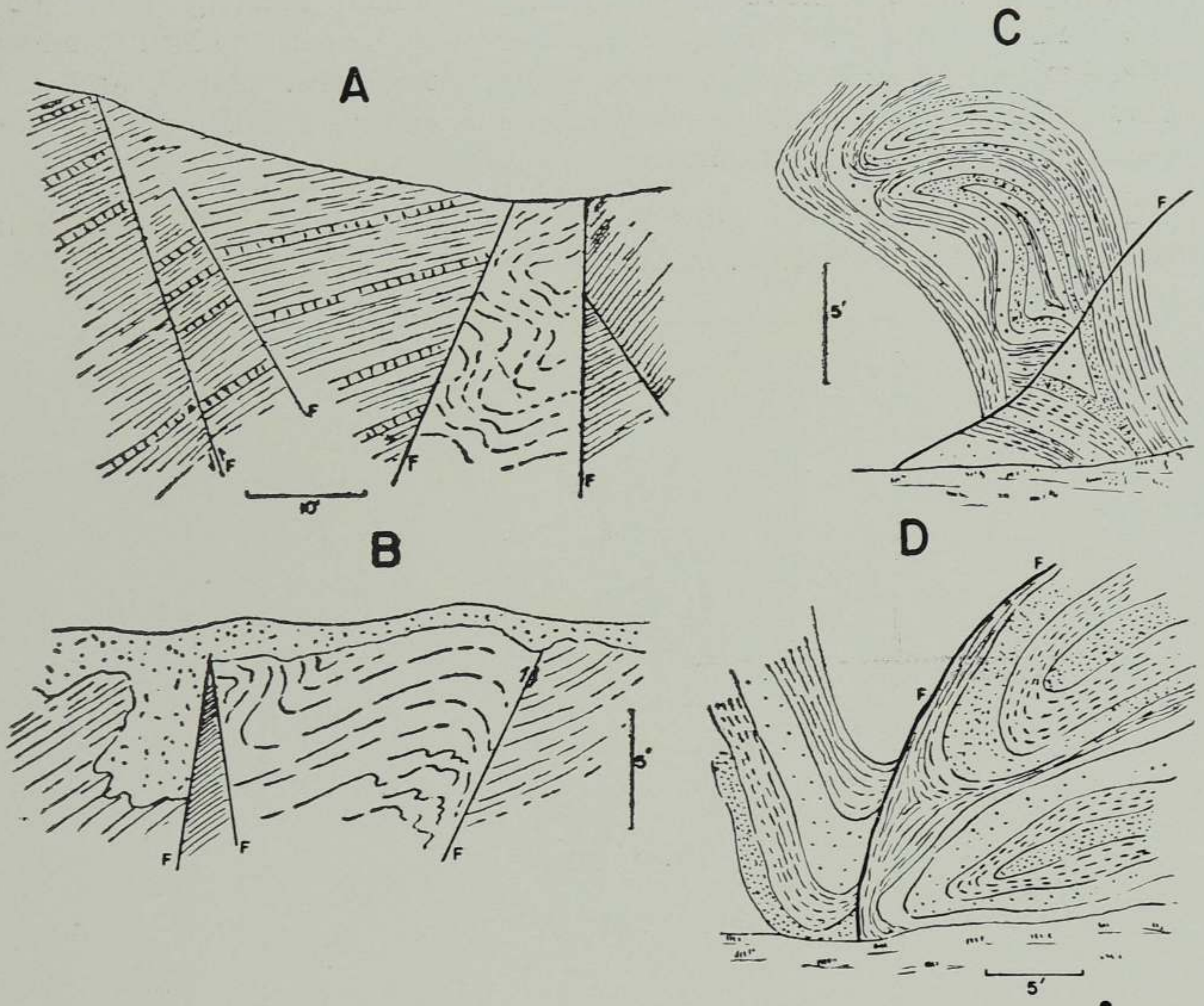


Fig. 41. Sketch sections showing faults and thrusts in the Uva Basin.

A. Bandarawela-Welimada road, culvert 3/7. (*D. N. Wadia*, field notebook)
B. Cemetery on Bandarawela-Welimada road. (*D. N. Wadia*, field notebook)
C and D. Between milestones 4 and 5 on Bandarawela-Welimada road.

THE SOUTH-WESTERN GROUP *

The rocks to be described in this section occupy the strip of country running from about the latitude of Hettipola in the north to Galle in the south, and extending for about 15 to 20 miles inland from the coast. They

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* The material for this section has been obtained from Memoir No. 3 of the Geological Survey Department, on the Alutgama area, and from the 'Brief Descriptions of the Geology' which accompany the geological maps of Gampaha, Avissawella, Ratnapura, and Rakwana; the latter are in press.

occupy the western portions of the Dandagamuwa, Avissawella, and Horana sheets, and most of the Alutgama and Ambalangoda sheets (see Fig. 30). The region is bounded on the eastern side by a prominent band of basic rocks which separates it from the Highland Series belt in the Rakwana, Ratnapura, Hatton and Kandy sheets.

Some of the rocks in this group are similar to those in the Highland Series, and others are similar to Vijayan gneisses on the south-east and north of the belt. But there are certain distinctive rock types that have so far not been recorded from anywhere else in the Island, and it is for this reason that it seems preferable to treat the south-west region as a unit by itself.

The major rock types in the region are :—

(i) Metasediments
(ii) Charnockites and allied rocks
(iii) Basic rocks
(iv) Migmatitic and granitic gnesses
(v) Granites and pegmatites

The predominant rocks are charnockites and gneisses which occur in alternating zones of varying width. The metasediments occur as narrow bands and are subordinate in amount to the other types. Small granitic bodies and pegmatites are intrusive into these rocks. These relationships are typically displayed in the area around Kurunegala (Fig. 42).

Metasediments

Quartzites and quartz schists, garnet-sillimanite gneisses, and quartz-feldspar granulites are all found throughout the south-western region. Of these, the quartzites and quartz schists appear most frequently, especially in the Dandagamuwa, Gampaha, and Avissawella sheets; their apparent frequency may, however, be due to the repetition of a few bands by folding. The above metasedimentary types are little different from similar rocks in the Central Highlands and we need not consider them any further. The metasediments that make this region distinctive are the calc granulites, the cordierite-bearing gneisses, and the banded ironstones.

The **calc granulities and gneisses** are generally banded, and are either equigranular rocks or streaky, gneissic ones varying in colour between greyish, greenish white, or "dirty" white. Their mineral composition is characterised by the presence of *wollastonite* (a white, fibrous, silky-looking calcium silicate), white, equigranular *scapolite* (a sodium-calcium silicate, Pl. 13B), green *diopside,* and the accessory mineral *sphene* (a calcium-titanium silicate) with its honey brown colour and wedge shape. Dark greenish *hornblende* is sometimes present and *graphite* as well as the sulphide minerals *pyrite* and *pyrrhotite* are commonly found. The presence of the sulphide minerals in appreciable amounts gives the weathered surfaces of these calc rocks a rusty, sulphurous appearance, and it is by this feature that they can often be recognised in the field.

Calc granulites and gneisses occur mostly as narrow bands, a few feet thick, or as narrow ribs, a few inches thick, in a variety of other rock types. They can, however, be traced for long distances and several continuous bands are present in the Alutgama and Ambalangoda areas. The best known of these bands are found near Migahatenne, Bussa (near Galle), and Kotagoda (near Baddegama) ; a good exposure is seen in a quarry at Kaikawalagala, a few miles south of Beruwela.

The calc granulites and gneisses are almost the only recognisable rocks of calcareous composition in the south-western region, a fact which seems to be of some significance. Crystalline limestones appear for the first time about 15 miles east of the coastline, near Ingiriya. Ananda Coomaraswamy recognised the special nature of these wollastonite-bearing calc rocks of the south-west in 1902 when he named them the 'Point-de-Galle Group "[17].

The **cordierite-bearing rocks** are closely allied in composition to the garnet-sillimanite gneisses of the Highland Series, both being rich in alumina. They owe their distinctiveness to the presence of the blue mineral *cordierite* (a magnesium-iron-aluminium silicate) and it is this mineral that gives the rocks their characteristic bluish colour. The rocks are either granulitic or gneissic in texture, the latter being more common. Cordierite gneisses occur as well defined bands in the Gampaha, Avissawella, and Horana sheets, and good exposures can be seen at Walpita, Mirigama, Panagoda, Homagama, Horana, Ingiriya, and Matugama [18], [47].

The mineral composition of the cordierite granulites and gneisses is fairly constant. Besides *quartz, feldspar*, and *cordierite,* they contain *garnet* and *biotite* nearly always, and *sillimanite, magnetite, spinel,* and *graphite* often. Such an association of minerals suggests that the cordierite-bearing rocks were formed by the metamorphism of clayey sediments rich in iron and magnesium.

Banded ironstones do not occur at the surface but have been recorded in drill holes in the Tambakanda-Panirendawa area, east of Chilaw. They are interbedded with calc granulites and basic rocks in a succession that is about 700 feet thick in places, and they form an important source of iron ore. The mineral composition of the banded ironstones is simple ; apart from *magnetite* and *hematite* (iron oxides), they contain only small amounts of feldspar and pyroxene[58].

Charnockites

Charnockites and rocks allied to charnockites are found extensively throughout the south-western region and in certain areas (for example, the Alutgama sheet) form nearly fifty per cent. of the rocks present. The charnockites of this region are similar in many respects to those of the Central Highlands, but differ from the latter in their greater variety of appearance, composition, and manner of occurrence. For example, mica is a common constituent; as a result the charnockites here appear to be more gneissic, and even schistose, in texture. Besides the normal acid, intermediate, and basic varieties, coarse-grained varieties of charnockites are common and occur as cross-cutting dykes, veins, and irregular patches. There are even a few charnockitic granites which are intrusive into the surrounding rocks.

There are also several streaky types of charnockites as well as greyish rocks that are not strictly charnockites but have the appearance of being so. Such rocks are said to be " charnockitic " and whereas they are frequently met with in the south-west they are of limited and local occurrence in the Highland Series. It is of interest to note that similar charnockitic rocks are present in the Transitional Zone between the Highland Series and the Vijayan Series on the eastern side of the island (see p. 117).

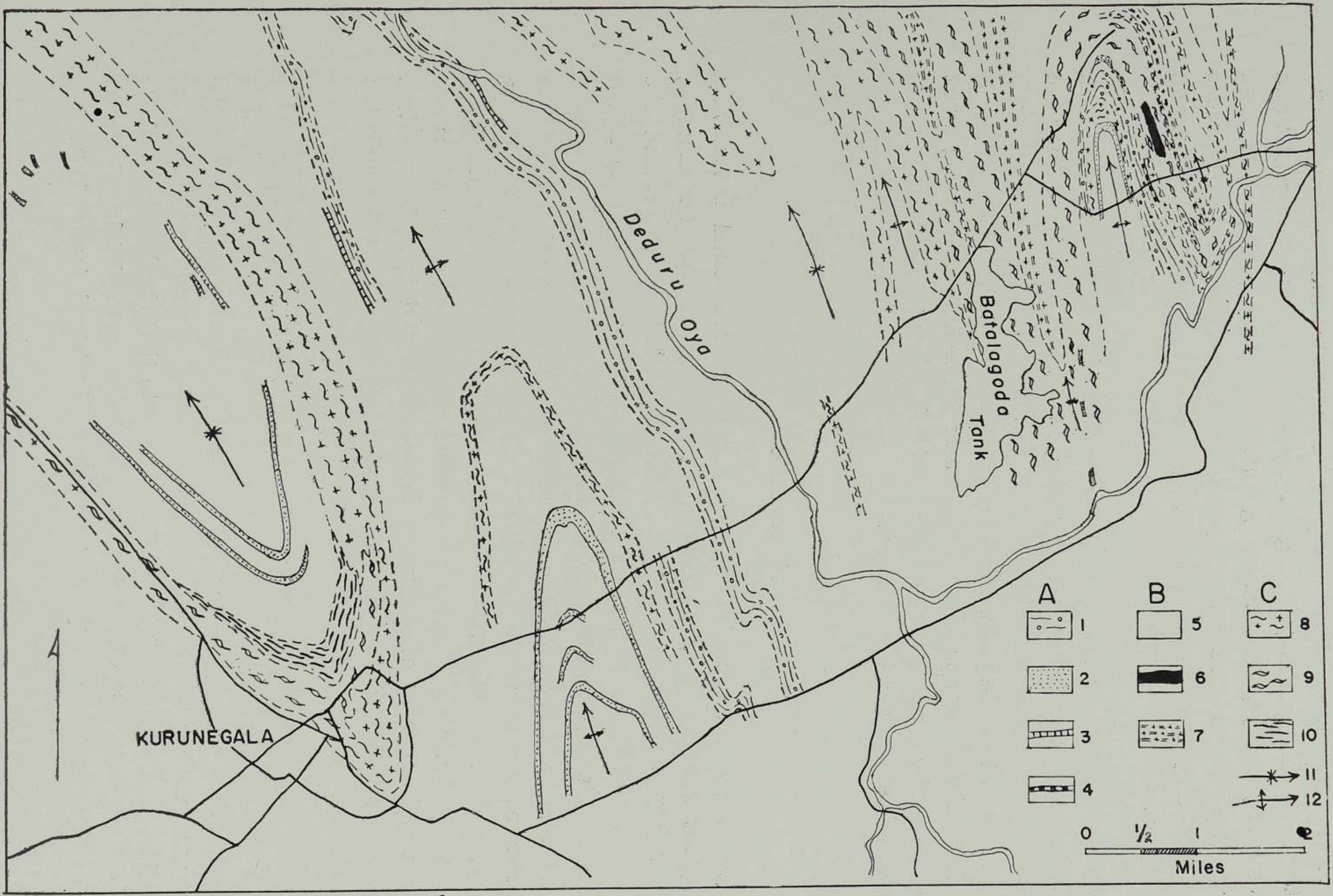


Fig. 42. Geological Map of the Kurunegala area. (*P. S. Kumarapeli*, 1965)

A—**Metasediments** : 1—garnet-biotite-sillimanite gneiss, 2—quartzite and quartz schist, 3—crystalline limestone, 4—calc granulite.
B—**Charnockites and allied rocks:** 5—acid and intermediate charnockite, 6—basic charnockite and amphibolitic rock, 7—charnockitic rock with streaks and patches of biotite gneiss.
C—**Granites and associated gneisses** : 8—granite and granitic gneiss, 9—biotite gneiss with foliae of pink granite, 10—biotite-hornblende gneiss, 11—synform, 12—antiform.

Basic rocks

A zone of basic rocks, which might be called the Sinharajah Basic Zone, extends from Denuwakanda in the south to Labugama in the north ; it is about three miles wide and extends for about fifty miles. The actual thickness of the belt may be much less owing to the presence of several folds within it.

The basic rocks that make up the zone are mainly black amphibolites (as in the Kadugannawa Gneisses) and basic charnockites. The former are either *hornblende-plagioclase* or *hornblende-pyroxene-plagioclase* schists and the latter are *pyroxene-plagioclase* granulites. Narrow quartzites and charnockites are interbedded with the basic types. The main accessory mineral in the basic rocks is *magnetite,* as a result of which the zone shows up on the aero-magnetic maps of this part of the island as having a relatively high magnetic intensity. (Other zones of relatively high magnetic intensity are shown by the cordierite-bearing rocks and by the banded ironstones.)

Migmatitic and Granitic Gneisses

A large variety of gneisses of granitic or migmatitic appearance are present in the south-western region and, next to the charnockites, are the most common rock types. In the Alutgama and Ambalangoda sheets these gneisses are generally light coloured *quartz-feldspar-biotite-garnet* rocks of streaky or veined appearance; their foliation planes are often irregular and contorted. Some of the gneisses have remnant patches of greyish-green charnockite in them and from this fact it can be deduced that they have been formed by the action of granitic material on pre-existing charnockites. Another feature of these gneisses is that they frequently contain radio-active *monazite* as an accessory mineral (see Pl. 32A). This golden-brown mineral is a rare-earth oxide with cerium and thorium (see Table 22) and is therefore important economically. The weathering of the monazite-bearing gneisses has led to the release of grains of monazite from the rocks and to their transport to the sea and accumulation on the beaches near Beruwala and Induruwa (see p. 211).

Further north, in the Dandagamuwa, Gampaha, and Avissawella areas, greyish gneisses with hornblende and biotite as well as black-and-white biotite gneisses are common. The latter appear to have been formed by the action of granitic material on basic rocks. The relationships of the various gneisses to each other are complex, as can be seen in the Kurunegala area (Fig. 42).

Intrusive Rocks

The south-western region differs from the Central Highlands in one other important aspect, namely, the presence of intrusive rocks of several types in the former. Among them may be mentioned the small granitic bodies at Ambagaspitiya, Ruwanwella, Loluwa, and Arangala, intrusive charnockite granites and pegmatites and allanite-bearing pegmatites as at Alutepola. Some of these rocks are described more fully in Chapter 9. Granitic pegmatites and granitic gneisses are generally much in evidence in the south-west, unlike in the Central Highlands where such rocks are only seldom met with.

Geological Structure

As in the Highland Series, foliation, bedding, and mineral elongation are important structural elements in the south-west. At the same time, streakiness and small folding as well as oriented inclusions become increasingly important in the gneisses that form a large proportion of the rock types present.

The Taprobanian pattern of parallel, NW-SE trending folds continues into this region, the folds being symmetrical or overturned to the east (see Fig. 43A). Several major folds are present, among which might be mentioned the Hiniduma and Beruwela Antiforms and the Matugama Dome in the Alutgama sheet (Fig. 43A), and the Botale Antiform in the Gampaha sheet. A number of narrow folds in quartzites are present near Avissawella. Folding in the gneisses is much more plastic than in the other rocks, and the foliation planes become increasingly contorted into small folds and corrugations. The plasticity of the rocks increases northwards until, in the Dandagamuwa sheet, a complex pattern of folds of several sizes is developed; an almost text-book type of dome can be seen here (see Geological Map).

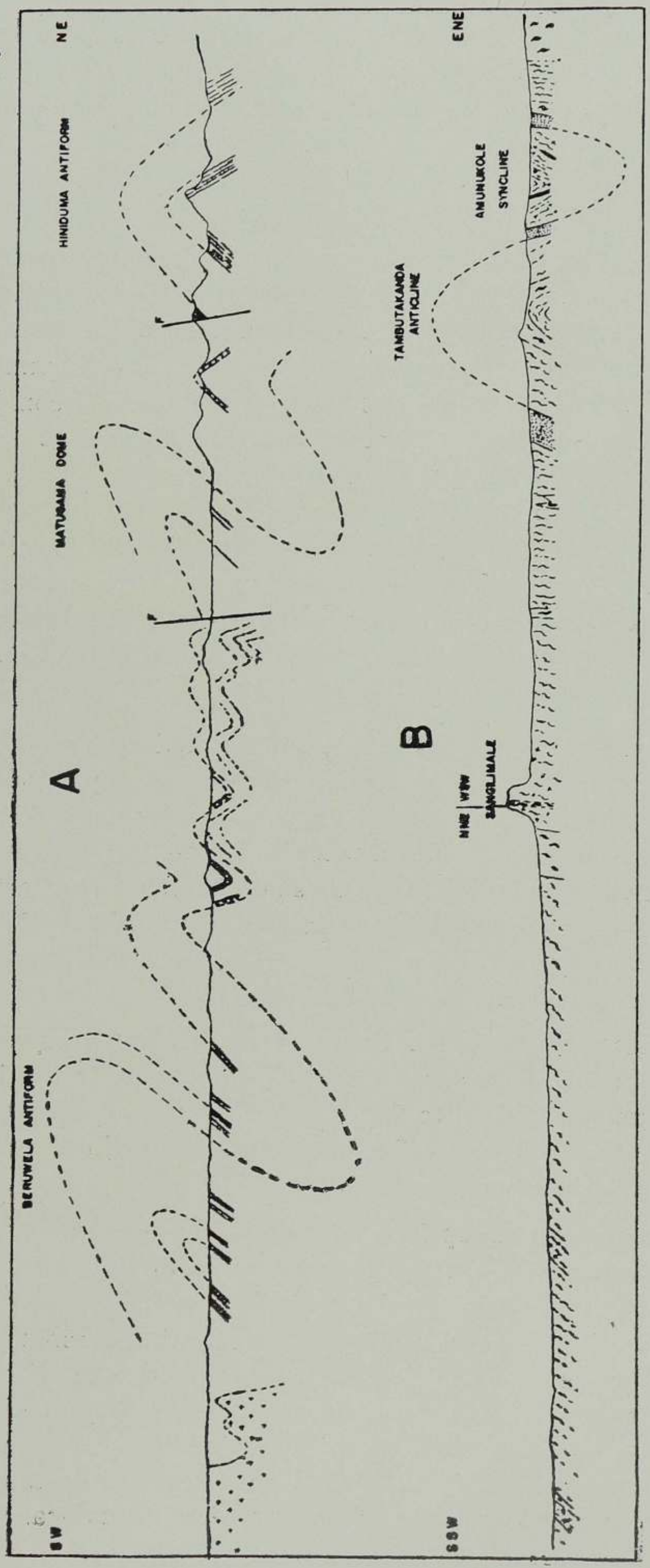


Fig. 43. Geological cross sections showing types of folds in the South-western region (A) and in the Vijayan Series (B).

A. Alutgama sheet. B. Galgamuwa sheet.

Joints are common in the south-west, but there appears to be less faulting than in the Highlands. One very large tear fault runs in a NW-SE direction for a distance of about 60 miles, through the Alutgama, Ambalangoda, and Morawaka sheets.

THE VIJAYAN SERIES

Rocks of the Vijayan Series occupy most of the lowest peneplain, the series being named after Prince Vijaya who landed on the west coast of Ceylon in 534 B.C. and founded the Sinhalese race. Gneisses, gneissic granites, granitic gneisses, granites, augen gneisses, and migmatites make up this complex groups of rocks, but they are nearly all composed of a limited number of minerals, namely, *quartz, microcline* (potassium feldspar), *plagioclase, biotite,* and *hornblende.* These minerals occur with monotonous regularity in the Vijayan rocks, relieved only sometimes by the presence of pyroxene, and sometimes garnet. Variations in the rock types are due largely to differences in colour and to the proportions of minerals between one rock and another. Minerals like sillimanite, graphite, cordierite, hypersthene, and garnet, so typical of the Highland Series rocks, are seldom or never found in the Vijayan Series.

The Vijayan Series has so far not been studied in detail, except in limited areas, largely because the rocks occur in the least populated and most inaccessible and heavily forested parts of the country. We do know, however, that there are broad differences between the Vijayan rocks of the eastern and southern lowlands and those of the north-western lowlands and we shall follow this broad division in the description to follow.

South-eastern Lowlands

The south-eastern lowlands are occupied mainly by a broad group of gneissess known as the Bintenne Gneisses[13], named after the local name of the region. They extend from the coast right up to the southern and eastern escarpments of the Hill Country, and from Hambantota in the south to Kalkudah in the north.

The typical rock of the group is a well banded black-and-white rock in which *quartz* and *feldspar* are concentrated in the light-coloured bands and *hornblende* and *biotite* in the dark bands. Such banded gneisses can be seen near Welikande and Vakaneri east of Polonnaruwa, near Batticaloa, and between the Walawe Ganga and the Kirindi Oya; excellent exposures can also be seen in the quarries around Hambantota (Pl. 14B). Banded gneisses often pass into veined and streaky gneisses with varying amounts of granitic material, and finally into more uniform granitic rocks, as in the Dambane area easy of Alutnuwara.

Other rock types in the south-eastern region include a group of reddish gneisses and a coarse granitic rock. The former are found along the coastal belt between Kirinda and Komari, the colour of the Kirinda gneisses being due to the pink colouration of the feldspars which is caused by the presence in them of minute flakes of reddish iron oxide (hematite). Reddish gneisses are also found at Kalkudah and Kathiraveli on the east coast. All these pink gneisses are similar in appearance to the Wanni gneisses of the north-western region which we shall describe presently.

The Moneragala hills, rising to 5,000 feet, are formed largely of coarse-grained, prophyritic granitoid rocks rich in biotite; they form a lens-like body of rock several hundreds of feet thick [13]. Granitoid rocks are also found in the Okkampitiya range, east of Moneragala on the road to Arugam Bay. Several circular or oval structure can be seen in the aerial photographs of the south-eastern region (see Fig. 45), and it is possible that the centres of these structures are also occupied by coarse granitic rocks or by augen gneisses.

Foliation is the common structure in the Vijayan rocks and the foliation planes of the Bintenne gneisses may be either regular or highly folded and contorted. The rocks contain a profusion of pegmatites and granitic veins which may be parallel to the foliation planes or cut across them. Large bodies of augen gneiss are also present, as at Magulmaha Vihara Pokuna, south-east of Kataragama, and around Bambowa Wewa, east of Tissamaharama [20].

Associated with the granitic gneisses, but in comparatively minor amounts, are narrow amphibolites and metasediments. The amphibolites (hornblende-plagioclase schists without pyroxene) occur as discontinuous bands and lenses which are often injected by granitic material and converted to streaky biotite-hornblende gneisses (Pl. 14B). The metasediments are chiefly greenish calc gneisses occurring in scattered, narrow bands. Charnockites and charnockitic rocks are more or less absent from the Vijayan Series of the south-eastern lowlands.

Within the region, in the area around Kataragama, is a group of rocks occupying an area of a few square miles, which resemble closely those of the Highland Series of the Central Highlands. The Kataragama Complex, as it is called, consists of closely folded charnockites and crystalline limestones together with some pegmatites, and appears to be a large remnant of the once extensive Highland Series that has escaped the processes that formed the granitic gneisses of the Vijayan Series. The Kataragama Complex is completely surrounded by Vijayan rocks.

The boundary between the Vijayan Series of the south-eastern lowlands and the Highland Series of the Central Highlands is a zone containing rocks characteristic of both groups and known as the *Transitional Zone* 6,77. It is about 6 or 7 miles wide and runs continuously through the Polonnaruwa, Elahera, and Rangala sheets for a distance of about fifty miles. A similar transitional zone is also known to occur within the Kirindi Oya and Walawe Ganga basins on the south. The typical rocks in the zone are greyish charnockitic rocks (like those of the south-western region), charnockites, and granitic and migmatitic gneisses in which are found narrow, scattered quartzites, calc gneisses and graphite-bearing schists.

The relationship between the Vijayan Series, the Highland Series, and the Transitional Zone can best be seen in the Rangala and Polonnaruwa sheets. In the Polonnaruwa sheet, for example (Fig. 31), the extreme east is occupied by Vijayan microcline gneisses of the Welikande-Vakaneri zone, and most of the western half by Highland Series charnokites, crystlline limestones, garnet-sillimanite gneisses, and quartzites within the Batuoyakande-Sudukande belt[14]. Between them is the Dambutulugala-Viharagala transitional zone in which charnockitic biotite gneisses are predominant ; highly crushed calc gneisses occur in the Gallela-Pudur belt along the eastern margin of this zone, and narrow quartzites within it.

A similar three-fold division is present in the Rangala sheet (see Geological Map). On the extreme east is the Dambane belt of Vijayan gneisses and on the west are charnockites and metasediments of the Highland Series; between the two is the transitional Wilgomuwa belt of charnockitic gneisses, granitic gneisses and rare metasediments.

North-western Lowlands

Banded gneisses are present in this region too, especially towards the north, but they are overshadowed in the southern parts by a variety of pinkish to reddish gneisses and granitic rocks known collectively as the 'Wanni Gneisses' (again after the local name of the region)[12]. The pinkish gneisses are best developed within the *Tonigala Complex*, an area of nearly 3,000 square miles between Chilaw, Kurunegala, Anuradhapura, and Puttalam, but similar rocks are found as far away as Madhu, Vavuniya, Mankulam, and Kuchchaveli on the north-east coast. A coarse, reddish pegmatite forms the prominent headland of Koduwakattumalai at the last-named locality ; it juts far out into the sea and forms one end of a beautiful bay. Pinkish gneisses and pegmatites belonging to the Wanni Gneiss group can also be seen as far south as the Panadura-Horana area, and there are several quarries in these rocks at Kaduwela and other places around Colombo.

The dominant rocks within the Tonigala Complex are veined gneisses (with thin veins of pink granite), banded gneisses, streaky gneisses, granitic gneisses, augen gneisses, migmatites, and granites (Fig. 44 and Plate 15), most of which possess this characteristic reddish colour in

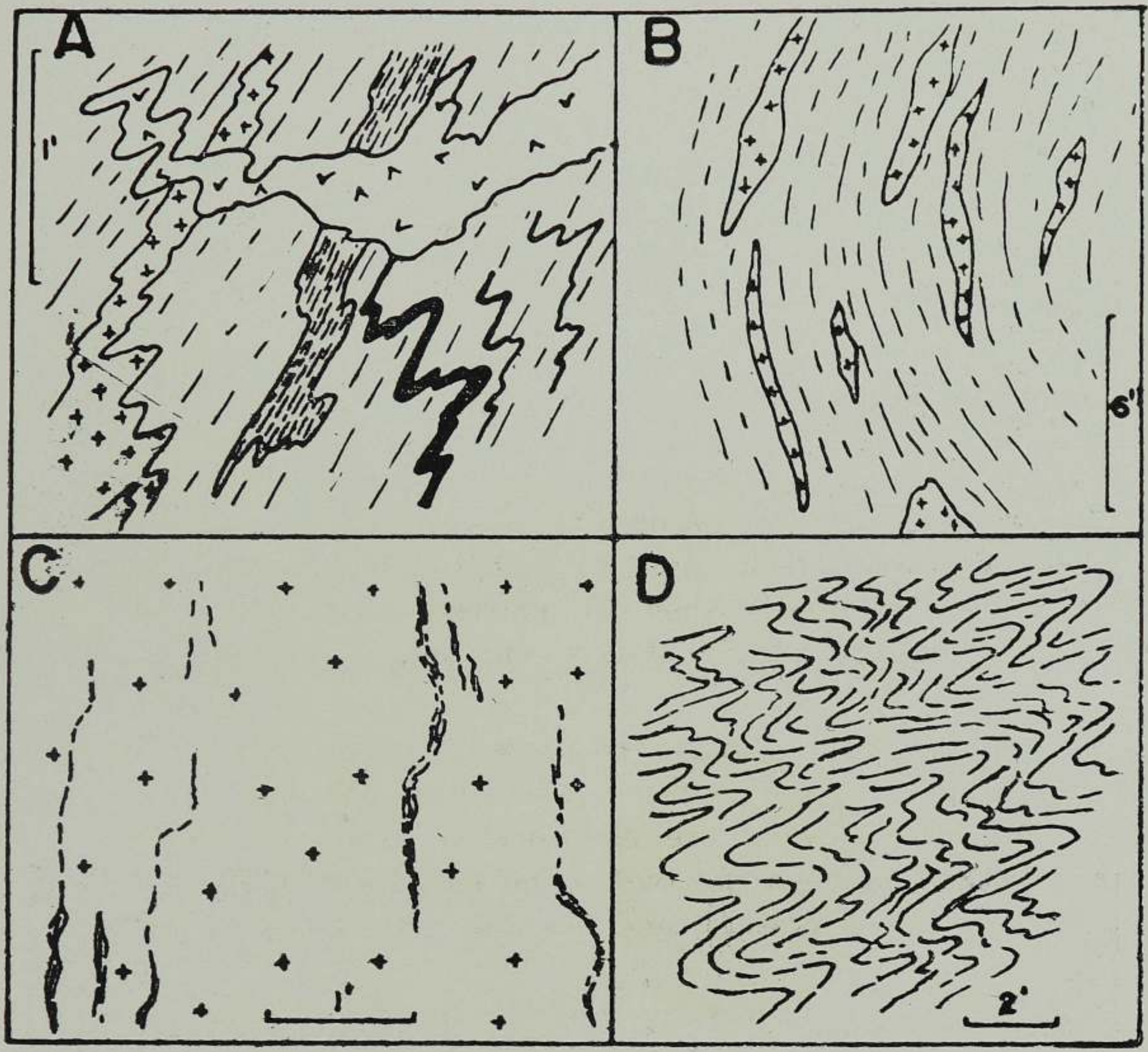
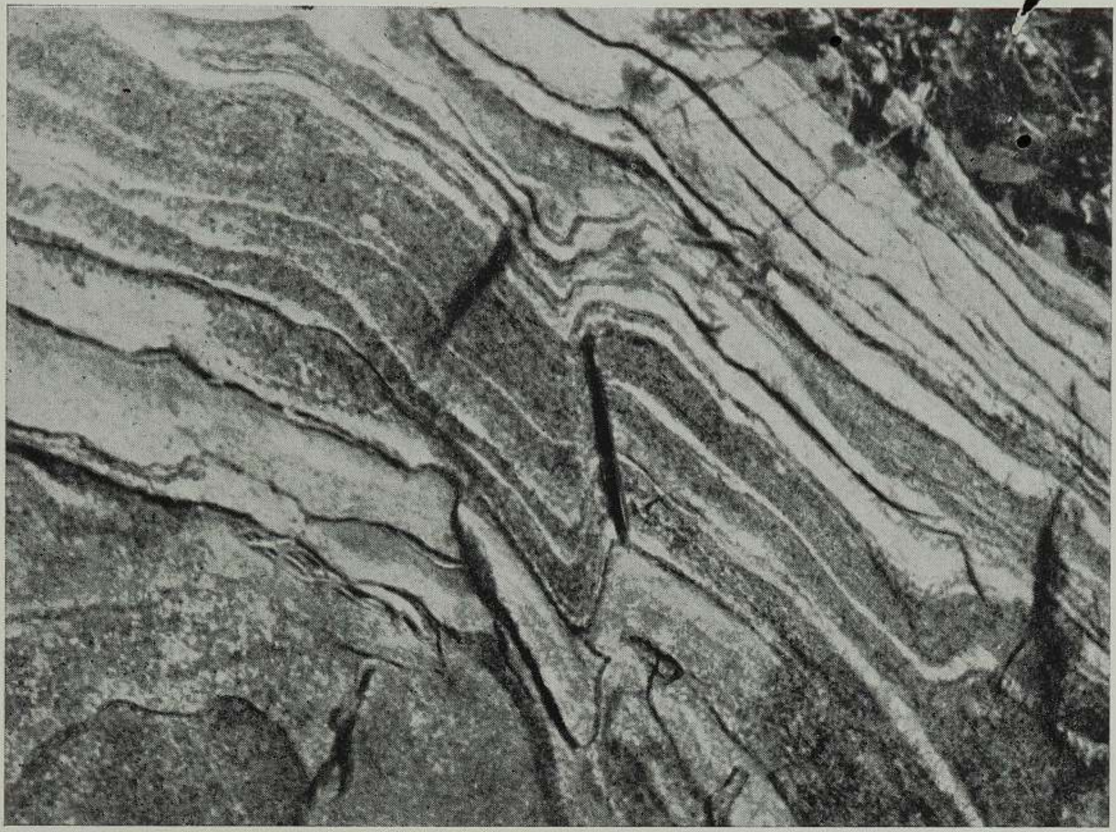


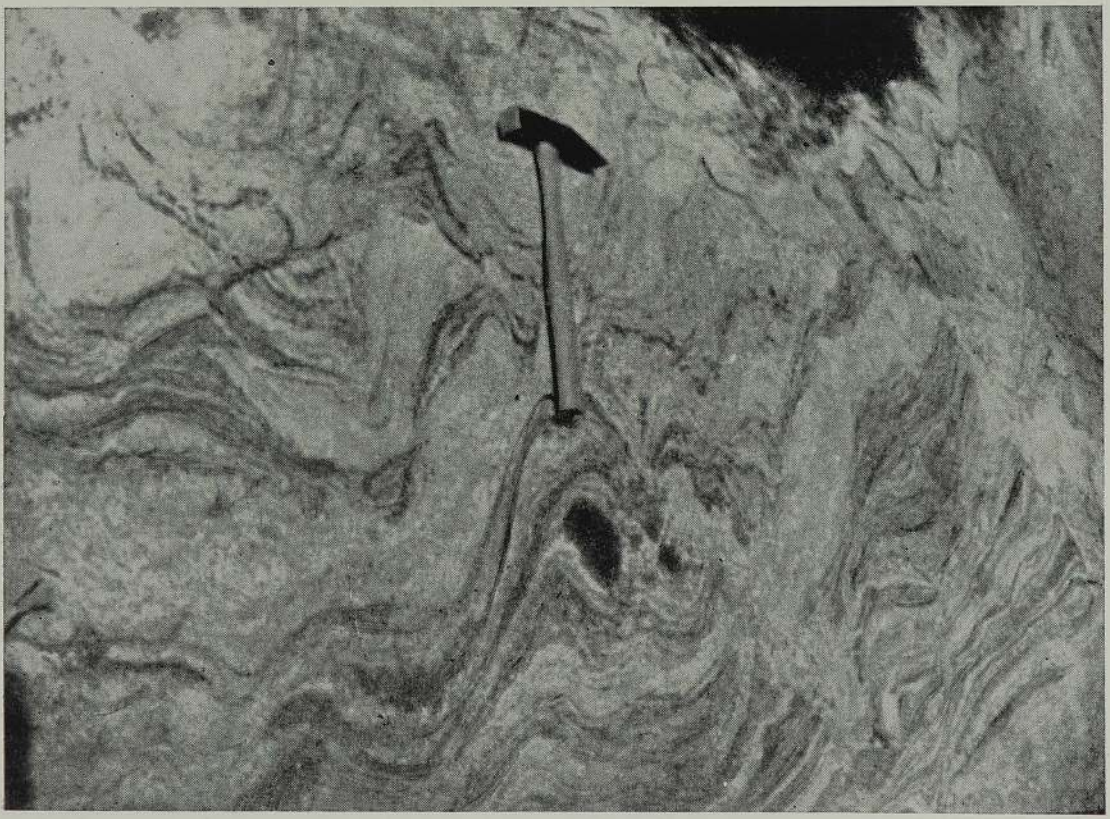
Fig. 44. Features typical of gneisses in the Tonigala Complex.
A. Biotite gneiss with shear-folded bands of pegmatite, schist, and basic rock.
B. Gneiss with elongate veins and lenses of pegmatite.
C. Pink granite with thin streaks of biotite schist.
D. Highly contorted gneiss.

different degrees. The Complex is named after the pink granite at Tonigala, about 14 miles from Puttalam on the road to Kurunegala (see Fig. 63). The Tonigala Granite is well exposed in a number of quarries by the side of the road.

Another common rock type in the Tonigala Complex is really a variation of the granite. It is a gneissic granite which is best exposed in the rocky ridge that runs for several miles by the side of the road from Galgamuwa to the Kala Oya ford. The rock is dark pinkish in colour and has small, elongate crystals of black hornblende all oriented in the same direction as that in which the rock strikes. The vihare at Galgamuwa is built on top of this ridge, and a very large quarry has been opened in it at Amunukole Wewa, a few miles north of Galgamuwa.



A. Thinly veined gneiss with small fold, Tonigala Complex.



B. Gneissic granite with remnants of folded gneiss bands, Tonigala Complex.

Alternating with the pinkish gneisses within the Tonigala Complex are strips of light coloured to greyish granitic and gneissic rocks. These are occasionally veined with pink feldspars, the rocks having been formed before the reddish Tonigala rocks. Pegmatites of several types are common in the Complex. There are also some charnockites, calc gneisses, crystalline limestones, and amphibolites in relatively minor amounts. As in the south-eastern region, the metasediments are in narrow, scattered bands and the amphibolites are invaded by granitic material changing them into streaky biotite-hornblende gneisses with remnants of the original amphibolites. The total area occupied by metasediments, charnockites, and basic rocks is extremely small, as can be seen in the Galgamuwa sheet where, in an area of about 500 square miles, such rocks occupy less than two or three square miles.

Geological Structure

In the Vijayan gneisses, mineral elongation, oriented inclusions (see Pl. 15B), and small folds are as important as foliation; bedding is very rare.

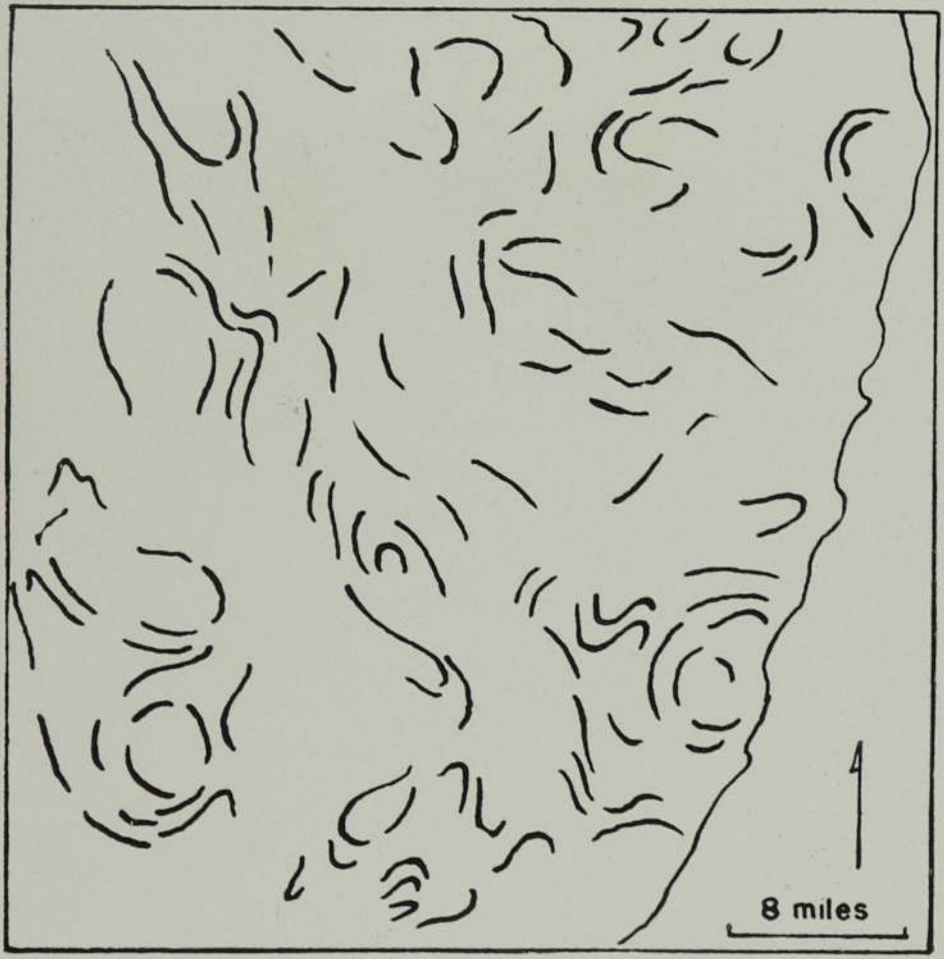
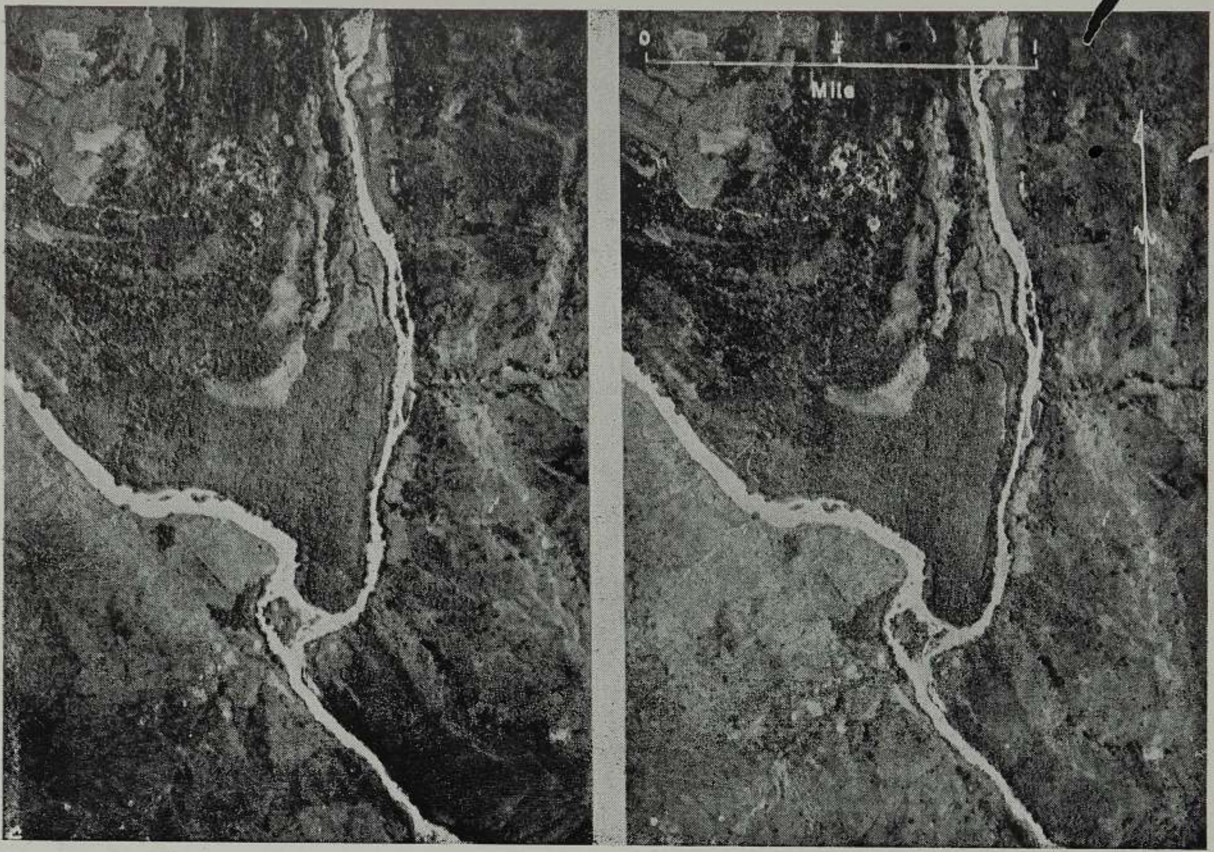
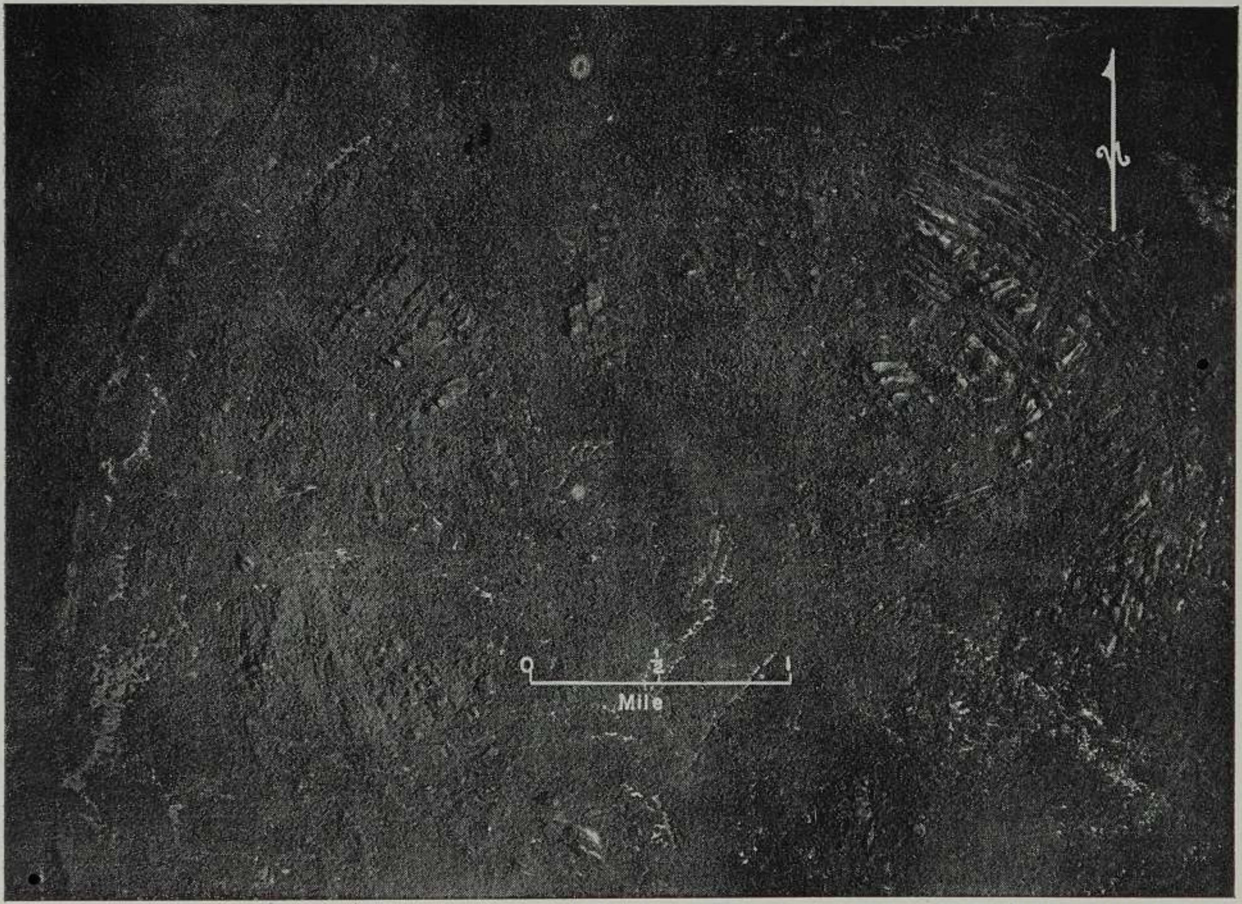


Fig. 45. Circular structures in gneisses and granitic rocks of the Vijayan Series, south-east Ceylon. (*Tectonic Map of Ceylon*, 1965)

PLATE 16



A. Stereo-paired aerial photographs of the southern end of the Huluganga synclinal basin, south of Teldeniya; a fold in Highland Series rocks. Note the N-S trending strike valley, the 'nose' of the fold, and control of drainage by geological structure.
(*Ceylon Survey Department. Crown Copyright Reserved*)



B. Aerial photograph of a circular structure in Vijayan Series gneisses near Panama, S. E. Ceylon.

(*Hunting Survey (now Lockwood Survey) Corporation, Canada. Crown Copyright Reserved*)

Those folds near the Highland Series boundary appear to maintain the Taprobanian trend, but away from it the folds become more and more irregular, and fold axes change in direction from N-S to E-W within a short distance. As a result, strike directions tend to vary considerably, and in the extreme south-east, circular and oval structures are common (Fig. 45 and Pl. 16B). Such structures appear to have resulted from the doming up of the gneisses by the intrusion of granitic material. Foliation in the Vijayan gneisses is very often vertical (Fig. 43B).

The gneisses exhibit a very plastic type of folding, brought about by what is known as *shear folding*. In this type of folding a relatively straight vein cutting across the foliation may be intensely deformed by horizontal movement along very closely spaced planes, called *shear planes,* in the rock (Fig. 46).

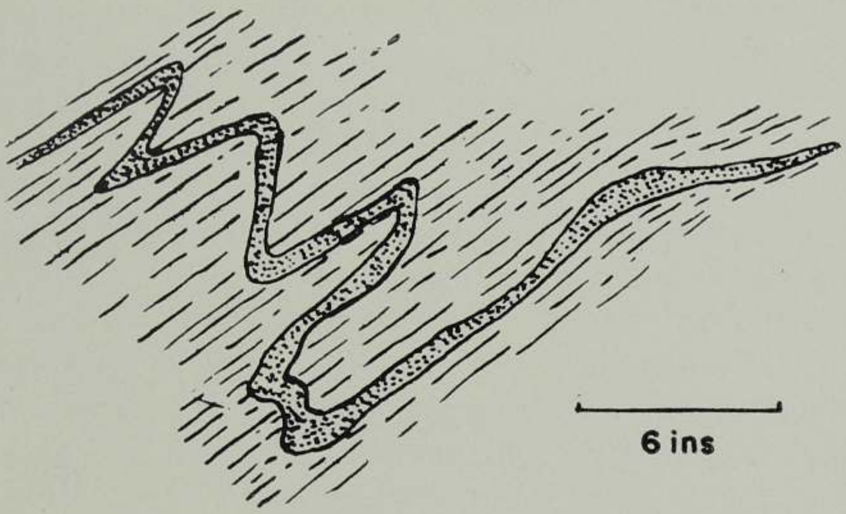


Fig. 46. Shear-folded vein in gneiss.

Jointing is well developed, but the joints are often wide apart, as can be seen on aerial photographs (Pl. 16B). Joints in the more granitic rocks like the Tonigala Granite facilitate quarrying into large blocks, and have controlled the shape of outcrops of granite. They have also led to the development of numerous narrow, elongate, boat-shaped rock pools within it.

The aerial photographs suggest that there are several faults in the Vijayan Series, but these have not been mapped yet. On the other hand, localised zones of fracturing are common, as in the Galgamuwa sheet. In these fracture zones or *shear zones*, movement has taken place along several nearly parallel faults, and as a result the rocks have a shattered (or brecciated) appearance. Glassy, fragmented mylonitic rocks are common, and the shear zones are criss-crossed by numerous small veins of quartz and calcite. Good examples of such shear zones can be seen east of Polonnaruwa, beyond the north end of the bund of Tabbowa Wewa, and at the western end of Kottukachchiya tank bund.

Origin of the Vijayan Series

We can see from the foregoing description of the rocks of the Vijayan Series that the latter is made up of a very mixed group of rocks that have been formed in different ways, from varying parent materials, and probably at different times. Many of the black-and-white biotite-hornblende gneisses have clearly been formed by the injection and invasion of pre-existing basic rocks by granitic material. Others, containing calcium-rich minerals like diopside and sphene, are probably impure calcareous rocks that have recrystallised. Still others may be earlier granites which have been changed to gneisses by the effects of pressure. Lastly, the presence of scattered charnockites and metasedimentary rocks within the Vijayan Series leads us to suspect that the former are only the remnants of a much more extensive series of rocks similar to the present Highland Series. These must have existed before the Vijayan gneisses but were altered to the latter by the action of heat, pressure, and water vapour accompanying the invasive action of the granitic rocks. We can therefore say that the Vijayan Series are, in fact, *polymetamorphic rocks,* or rocks that have undergone more than one metamorphism—an earlier regional metamorphism and at least one later metamorphism that changed the earlier formed rocks into gneisses and granitic rocks.

Unlike in the Highland Series, where well banded rocks run continuously for miles along the strike with little variation and hardly any distortion, the Vijayan rocks are seldom uniform for any length, are highly contorted and folded, and are largely streaky in appearance. These Vijayan rocks give the impression, in fact, of having been, at the time of their formation, in a highly plastic state. They seem to have been ‘ pushed and shoved about ’ in several directions by the forces of pressure, and invaded along the foliation planes by vast quantities of granitic material. The rocks and minerals were drawn out or elongated into lenses, streaks, and foliae in the process, giving them their characteristic gneissic appearance.

CHAPTER 7

JURASSIC AND TERTIARY SYSTEM

These rocks, these bones, these fossil ferns and shells, shall yet be touched with beauty, and reveal the secrets of the book of earth to man.

Alfred Noyes.

JURASSIC

SEDIMENTARY rocks of Upper Jurassic age are preserved in at least two faulted basins within the crystalline Vijayan Series in north-west Ceylon. Only one of these basins, that on the west of Tabbowa Wewa and about eight miles from Puttalam on the road to Anuradhapura, is exposed at the surface. The other, which is at Andigama and about 20 miles due south of Tabbowa, is completely covered by more recent deposits. The two known occurrences lie almost in a straight line with similar faulted basins near Madras on the east coast of Peninsular India, nearly 2,000 miles to the north, and it is probable that all these Jurassic sediments were deposited at the same time (see Fig. 84). They form part of a thick series of formations known in India as the GONDWANA SYSTEM (about which we shall hear more in Chapter 11), which extended in time from the Permian to the Cretaceous Periods (see Table 5). The sediments were laid down on the margins of an ancient landmass known as *Gondwanaland* which included parts of what are now known as India, Australia, Antarctica, South America, Africa and Madagascar.

Tabbowa Beds

Location and Extent

The Jurassic sediments at Tabbowa, known as the Tabbowa Beds, were first described in 1925 by E. J. Wayland, Assistant Mineral Surveyor at the time[21]. They form the relatively high ground around milestone 8 on the road from Puttalam to Anuradhapura (Fig. 47), where massive sandstones are exposed by the side of the road. The total width of the basin-like outcrop is about 1½ miles here, extending from mst. 7½ to mst. 9. More sandstones occur as boulders by the side of the road to Tabbowa Wewa. The best exposures of the Tabbowa Beds are below the left spillway of the tank (see Pl. 17A), but these can only be seen when the water in the tank is below spillway level, during the Dry Season.

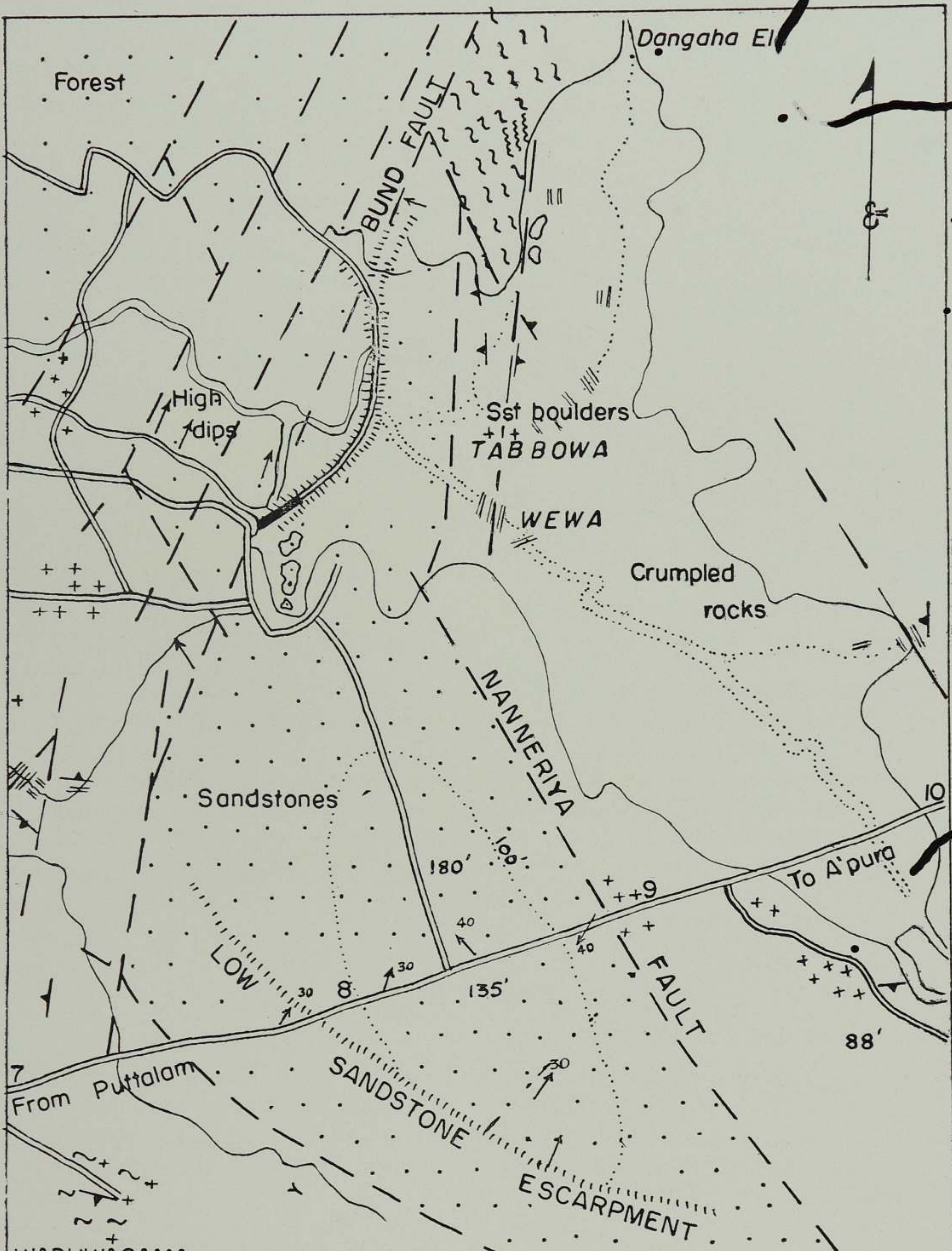


Fig. 47. Map of Jurassic Rocks at Tabbowa Wewa. (*E. J. Wayland*, 1925)

Dots—Tabbowa Beds, blank—crystalline rocks and alluvium, crosses—granitic rocks, double dash—pegmatite arrows—dip of bedding, dashed lines—faults, solid bar—spillway.

Specimens of this small but interesting group of rocks can be collected and the succession closely examined at this locality. The total extent of the Tabbowa Beds is about 2 or 3 square miles, and it is surrounded on almost all sides by granites and gneisses of the Tonigala Complex.

Lithology

The Tabbowa Beds consist mainly of a well bedded series of feldspathic sandstones, *arkoses* (feldspathic sandstone with over 30 per cent. feldspar), *siltstones,* and *mudstones,* the last three being the more modern terms for what Wayland described earlier as 'grit', 'shaly beds' and 'pipeclay'[22]. A few thin beds of nodular limestone are also present. The sediments vary in colour from white or light grey to dark brown and purplish red, and in texture from coarse-grained to fine-grained.

Arkose is the main rock type and is made up of angular to sub-angular grains of quartz and feldspar; it is almost granitic in appearance (Pl. 17B). The large grains and the small pebbles sometimes present form a framework, the intervening spaces being filled with finer grained quartz and feldspar. The grains are generally fused together by pressure and very little cementing material is present. Where this arkose outcrops at the surface the weathering and removal of the feldspar grains makes it porous.

Feldspathic sandstone is a finer grained variety of arkose with somewhat less feldspar and a more even texture (Pl. 17). Some of the sandstones are purplish red in colour and in these the grains are cemented together with hematitic iron such sandstones are therefore ferruginous sandstones.

Siltstones are light brownish in colour and are composed of fine quartz grains, chloritic mica, and clay (Pl. 20A); they are generally soft and easily crumbled. Some of the siltstones are cemented together with hematite and are then dark reddish brown and extremely hard with an iron-rich crust. Some curious and striking concentric structures are present in these ironstone bands.

Mudstone is made up wholly of white clay and is somewhat indurated. A few laminations are present, the fossil plant impressions being seen when the rock is split along such layers.

The detailed succession of beds seen near the left spillway of the tank, by the side of the 'summer house', is shown in Fig. 48. Other successions can be seen about 100 yards of this point but still below the spillway. Leading away from the latter is a channel, the bed of which is made up

A. Well jointed and bedded feldspathic sandstone, Tabbowa Wewa.

B. Detail of feldspathic sandstone with bands of coarser arkose, Tabbowa Wewa. Whitish grains are feldspars.

of massive, well jointed ferruginous sandstone, dark purplish red in colour, which dip to the north-west at about 10°. At the end of the channel is a small cliff, about 10 feet high, made up of light greyish arkoses and feldspathic sandstones (Pl. 17A).

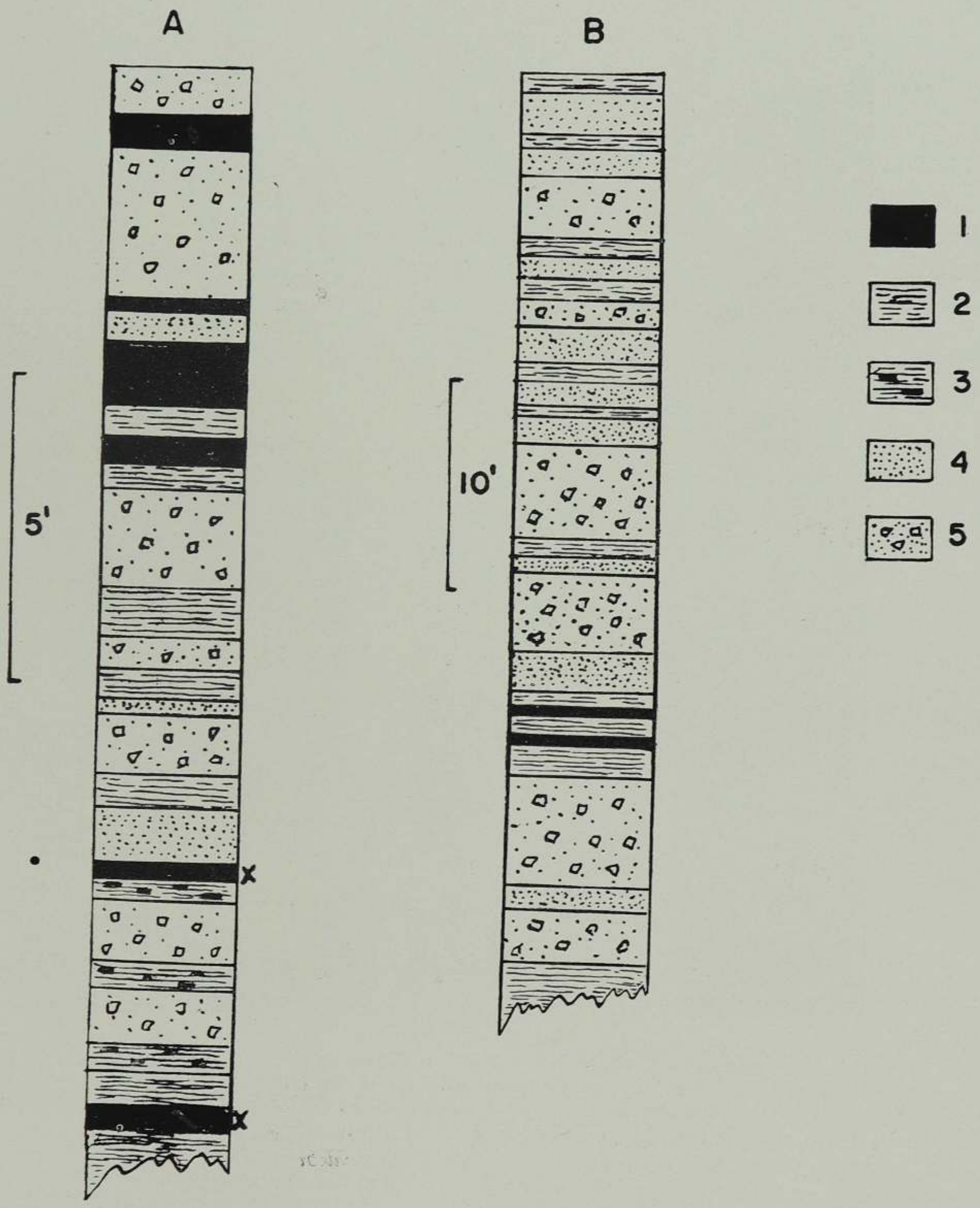
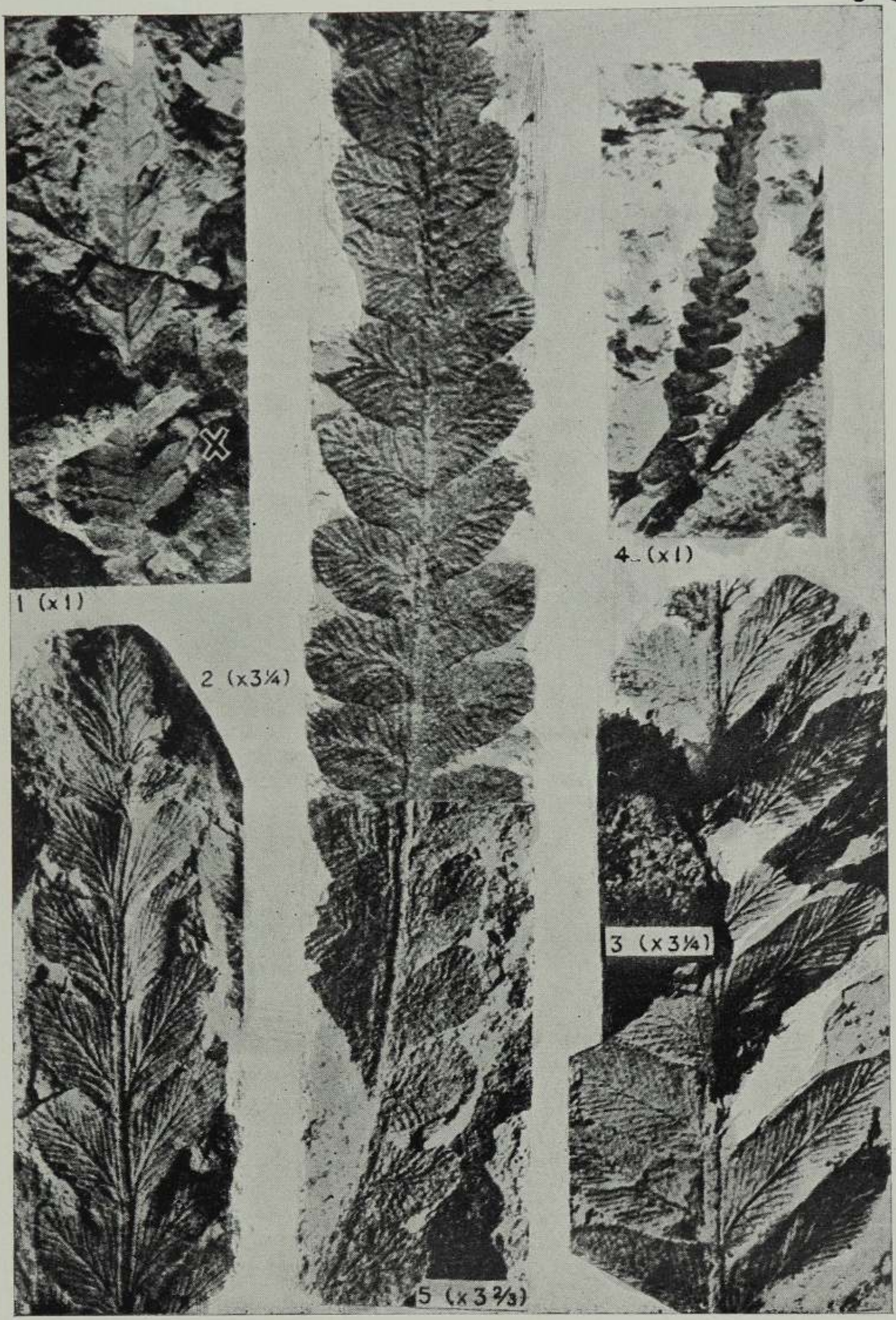


Fig. 48. Detailed sections, Tabbowa Beds.

A. Below spillway. B. Stream running north below bund.
(1) mudstone, (2) siltstone, (3) siltstone with hematite,
(4) feldspathic sandstone, (5) arkose, (X) plant bed.

PLATE 18



Photographs of *Cladophlebis zeylanica* Sitholey (Nos. 1–3) and of *Cladophlebis reversa* (Feist.) Seward and Holttum (Nos. 4 & 5) from the Jurassic Tabbowa Beds. (*R. V. Sitholey*)

1—a pinna of *Cladophlebis zeylanica*, 2—part of dista lhalf of same, 3—proximal half of same, 4—a pinna of *Cladophlebis reversa*, 5—part of same magnified to show form of pinnules and venation.

According to Wayland, who examined the Tabbowa outcrops when the tank bund was breached, the rocks present could be broadly grouped as follows (from top to bottom):—

3. Massive grits and sandstones (forming minor surface features).
2. Shaly beds with inconstant bands of nodular limestone.
1. Loosely consolidated argillaceous sandstones and grits.

Wayland estimated the total thickness of the Tabbowa Beds to be 2,000 feet, but this was not based on actual measurements, and it may possibly be more than this figure. The base of the succession rests on a floor of decomposed crystalline rocks of the Tonigala Complex.

Sedimentary Features[22]

If the section shown in Fig. 48A is examined it will be seen that although there is a rapid variation in the types of deposits laid down, a distinct pattern can be recognized in the succession, the beds generally repeating themselves in a regular sequence. Such a feature is known as *cyclic sedimentation* and each unit or cycle is called a *cyclothem*. All the beds of the unit may not be present in every cyclothem but there is a regular repetition of coarse sandy beds and fine clayey beds throughout the section.

Cross or false bedding is a common feature, especially in the sandstones at Tabbowa ; only rarely is it met with in the siltstones, and never in the mudstones. The attitude of the current bedding shows that the Tabbowa Beds are the 'right way up' and have not been inverted since their deposition.

Perhaps the most interesting sedimentary feature at Tabbowa is an example of 'channel fill' which can be seen in the cliff section below the spillway (Fig. 49). The dimensions of the channel are: *width* 12 feet and *maximum depth* 20 inches ; its floor, which is concave upwards, cuts sharply through the horizontal beds on either side. This feature would have formed in the following manner. After the horizontal beds were laid down in shallow water, a sudden flood stream flowed over them and cut a channel through the beds ; subsequently, more coarse sediments were deposited within the newly-cut channel until it was filled up, and horizontal beds were once again deposited.

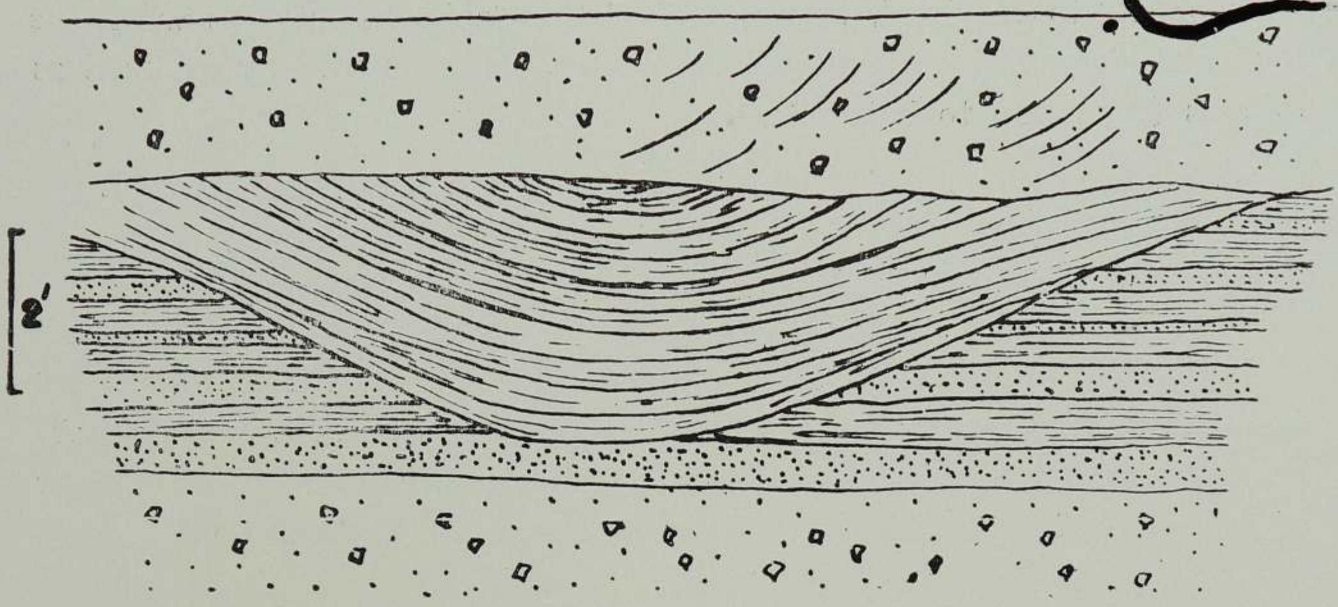


Fig. 49. Sketch of the channel fill in small cliff below spillway. Ornament as in Fig. 48.

Structure

Although the arenaceous beds at Tabbowa are massive, the series as a whole is well bedded. Dips are variable, being 20° to 40° east or west along the road and about 10° north near the spillway. This variation in the dips may be due to faulting within the basin and consequent tilting. Joints are well developed, especially in the coarse-grained arkose, the joints running north-west and north-east, at right angles to each other. As a result of this, the rock weathers into large rectangular or squarish blocks which are scattered in profusion in the bed of the channel leading from the spillway and below the cliff (Pl. 24A).

Evidence of faulting is very clear in the gneisses surrounding the Tabbowa Beds. About half a mile north-east of the tank bund, for example, the granites and gneisses have a shattered look and black mylonitic streaks are frequent. The latter are seen under the microscope to be made up of large, broken fragments of quartz set in a glassy matrix of fine, dust-like fragments of quartz and feldspar, clearly brought about by the grinding action within the rocks. The same shattered appearance is evident in the pink granite south-east of Tabbowa, about a mile along the road to Tamanawetiya.

Fossils

The only fossils in the Tabbowa Beds are those preserved in the mudstone horizons and in the brownish siltstones within the sandstones. Here are found the fossilized impressions of a large variety of plant remains such as the leaves, stem fragments, and shoots of coniferous trees, cycads, and ferns (*Pteridophyta*). A full list of the fossil species found at Tabbowa and Andigama is given in Appendix III but we might mention here some of the interesting and more important forms recorded at Tabbowa (Fig. 50). Among the pteridophytes are *Cladophlebis zeylanica* and *Sphenopteris wadiai,* both new species of Jurassic plants, first described from Tabbowa[23]; the second of these is named after D. N. Wadia (Pl. 18). Another fern *Cladophlebis reversa* and the cycads *Taeniopteris spatulata* and *Nilssonia fissa* are known Jurassic forms in India. The species of *Ptilophyllum* found at Tabbowa is significant in that it is a characteristic species of all Upper Gondwana formations.

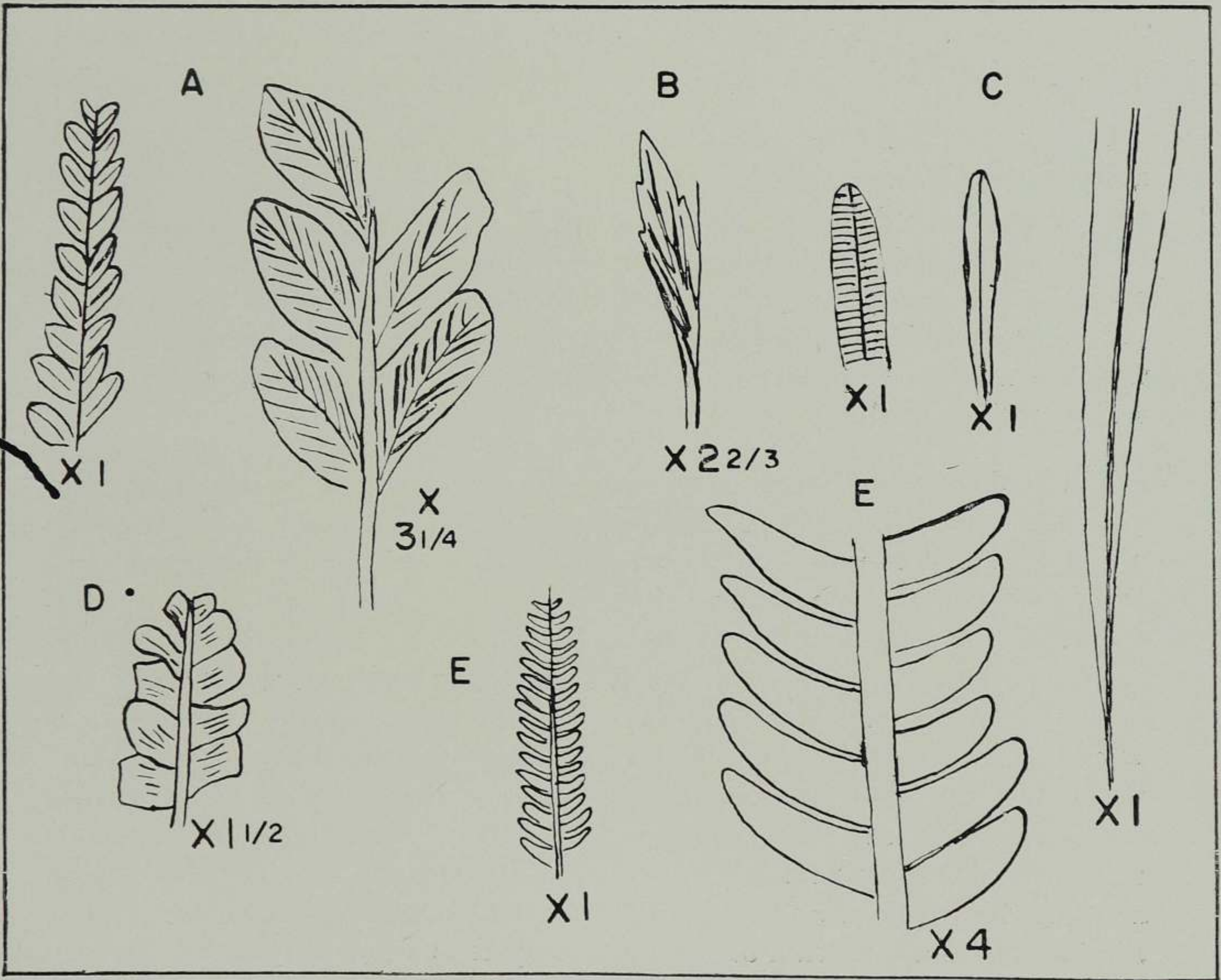


Fig. 50. Jurassic plants from the Tabbowa Beds. (*After R. V. Sitholey*, 1944)

A, *Cladophlebis zeylanica* Sitholey. B, *Sphenopteris wadiai* Sitholey. C, *Taeniopteris spatulate* McClell. D, *Nilssonia fissa* (Feist.) Seward and Sahni. E, *Otozomites* sp.

Several of the species at Tabbowa are identical with those found in the Upper Gondwana deposits of Rajmahal in the Damodar Valley and of the Madras basins, in all of which the cycad *Ptilophyllum* is present. The Tabbowa Beds, therefore, on the basis of their fossil plants, are dated as belonging to the Upper Gondwana System of Upper Jurassic age.

Conditions of Formation

The types of sediments that make up the Tabbowa Beds as well as the sedimentary features seen in them lead us to the conclusion that they were shallow-water deposits, laid down in a rapidly subsiding fresh-water or brackish-water delta where thousands of feet of sands and clays could accumulate in a relatively short time. Occasional changes of sea level caused an influx of sea water and thin limestones were laid down during these periods. The weight of this great thickness of sediment caused a compaction of the material and a fusing together of the sand grains.

Owing to the relative scarcity of plant impressions and to the total absence of coal-bearing, or even carbonaceous, beds at Tabbowa, it would appear that very little vegetation grew in the actual region where these beds were deposited. This may have been due largely to semi-arid climatic conditions in the area. The plants that were carried down to the delta probably grew in a cooler and wetter mountainous region nearby, and it was the weathered products of these mountains that were brought down and deposited in the delta.

The rapid alternation of coarse-grained and fine-grained sediments, the poor sorting of the grains, and the presence of angular quartz and feldspar all suggest that the environmental conditions under which the rocks were laid down varied from time to time. Periods when coarse, sandy detrital material was rapidly deposited by flood waters and turbulent rivers must have alternated with periods when fine clayey material was slowly and quietly laid down. Any vegetation carried along by the flood waters would be destroyed by the coarse, sandy detritus carried along at the same time. On the other hand, when quieter conditions existed and when no coarse material was being transported, the leaves and stems of the cycads and ferns growing in the cooler mountain regions would have floated along in the streams and been deposited and preserved in the soft clays. Similarly, the alternation of predominantly reddish or brownish beds with greyish-white rocks in which the feldspars are slightly kaolinised indicates that the degrees of atmospheric weathering and oxidation changed from time to time.

The sediments of the Gondwana System were brought down by large rivers which drained the Gondwana continent and deposited by them in great deltas and bays along the margin of the sea or in inland basins and lakes. The Tabbowa Beds of Ceylon must have once formed part of such a deltaic or basinal succession ; they have been preserved from subsequent erosion by being faulted down into the Pre-Cambrian basement during or after their deposition. What we see now is only a small portion of a much greater thickness of sandstones and siltstones that must once have covered this part of Ceylon.

Andigama Beds

A small basin of Jurassic sediments, somewhat similar to those at Tabbowa, is known to be present at Andigama, a small village 8 miles east of Kiriyankali which is near milestone 63½ on the Colombo-Puttalam road.

These beds do not, however, outcrop at the surface, but can be seen in well cuttings over an area of about 3 square miles. They consist mainly of black carbonaceous shale and some concretionary hematite in which fossils of a coniferous leaf, a poorly preserved fern, and plant spores and cuticles have been found (see Appendix III). Though the fossil evidence is meagre, it does suggest a Jurassic age for the Andigama Beds. The species identified resemble closely those occurring in the Upper-Gondwana (Upper Jurassic) beds of Madras, and the Andigama and Tabbowa Beds are therefore probably of about the same age.

Sediments similar to those at Tabbowa were recently found to be present in drill cores in the Mannar area, lying below 250 feet of Miocene limestone. It is thus possible that still other deposits of Jurassic age may exist in faulted basins within the crystalline basement in this north-western part of the Island, hidden by latter deposits of Miocene and Quaternary age.

TERTIARY (MIOCENE)

Tertiary rocks of Miocene age occur in two widely-separated areas of Ceylon, namely, in the Jaffna Peninsula in the extreme north, and at Minihagalkande in the extreme south-east ”.

Jaffna Limestone

Extent

The dominant member in the north is the thick Jaffna Limestone which underlies the whole of the Jaffna Peninsula and the surrounding islands, and also extends southwards along the west coast of the mainland as a gradually narrowing belt. Its total extent is about 800 square miles, and the limestone is at least 250 feet thick, as shown by borings.

The most southerly exposures of the Jaffna Limestone are seen in low cliffs near Karativu, 15 miles north of Puttalam.* Although probably underlying all this coastal belt, most of the limestone here is covered by later Quaternary deposits, scattered outcrops of limestone being seen along the coast, on the sides of ridges like Aruakalu (north of Karativu), or in stream sections where erosion has removed the overlying deposits.

The eastern boundary of the Jaffna Limestone has not been mapped but it must lie north-west of a line running through Karativu, Madhu Road, and Mankulam where Pre-Cambrian crystalline rocks of the Vijayan Series are exposed. In the extreme south this boundary cannot be more than 4 or 5 miles from the coast, but elsewhere the limestone belt may be up to 10 miles wide.

The Jaffna Limestone thins out eastwards on the floor of Pre-Cambrian rocks on which it lies unconformably[25]. It passes westwards under the sea, forming the bed of the Palk Strait at a depth of only 20 fathoms (120 feet). Tertiary rocks outcrop again on the south-east coast of India, at Warkalli and Cuddalore (see Fig. 84) where Miocene limestones, similar in age to those of the Jaffna Limestone, possibly lie below the Pliocene sandstones and other formations that appear on the surface. This suggests that the Jaffna Limestone formation is a continuous one extending from north-west Ceylon to South India.

Overlying the limestone in the Jaffna Peninsula are recent sand dunes (as at Point Pedro and Mannar) and coral reefs (along the northern coast) ; on the mainland it is covered by Quaternary Red Earth and gravels as well as by alluvium (see Chap. 8).

Mottled, coloured sandstones and sands are well exposed in small cliffs along the coast near Kudremalai, and these lie between the Miocene limestone below and Quaternary beds above. The age of these deposits is uncertain and they may be Miocene or later in age.

Structure

The Jaffna Limestone is flat-bedded over nearly all the area in which it occurs, though here and there a slight dip to the west may be present. It is generally at surface level or a little below it, but at Kirimalai (on

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* A small outcrop of what is probably Miocene limestone was noted, in 1964, near Villuke just south of the Mi Oya and about 3 miles north of Puttalam. The alluvium of the Mi Oya north of Puttalam also probably rests on Miocene limestone.

the north coast of Jaffna), Kolankanatta (6 miles south of Kudremalai), and on the Moderagam Aar (near the ancient stone anicut) it forms cliffs about 50 feet high (Pl. 19A). The limestone beds are extremely well jointed and the aerial photographs of the Peninsula reveal a marked rectangular pattern of closely spaced joints running NW-SE and NE-SW.

Lithology

The typical Jaffna Limestone is a hard, partly crystalline, compact, indistinctly bedded, creamy coloured rock.

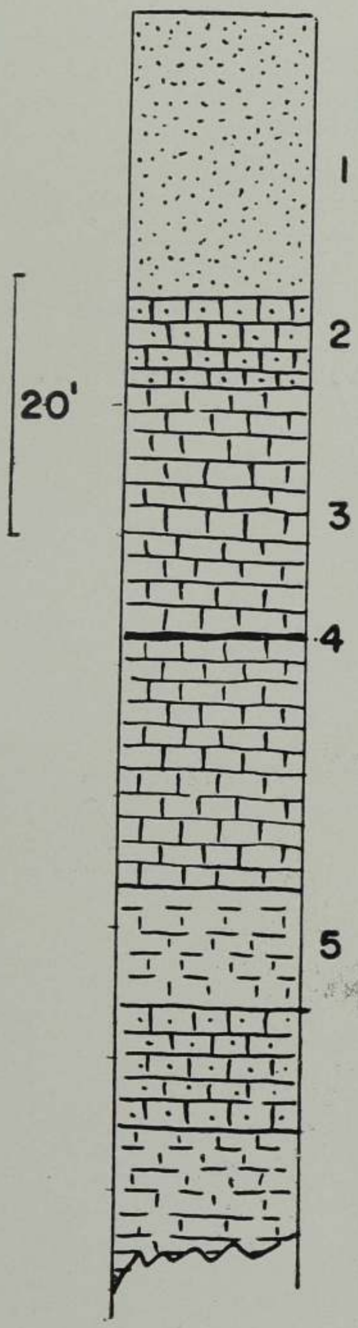
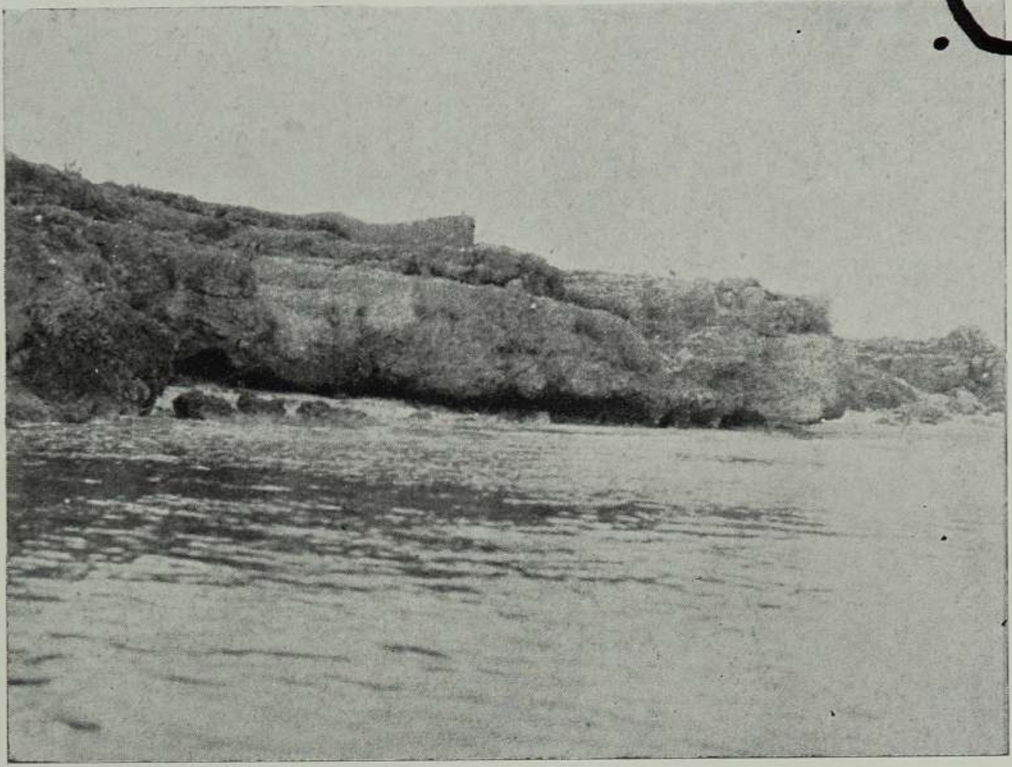


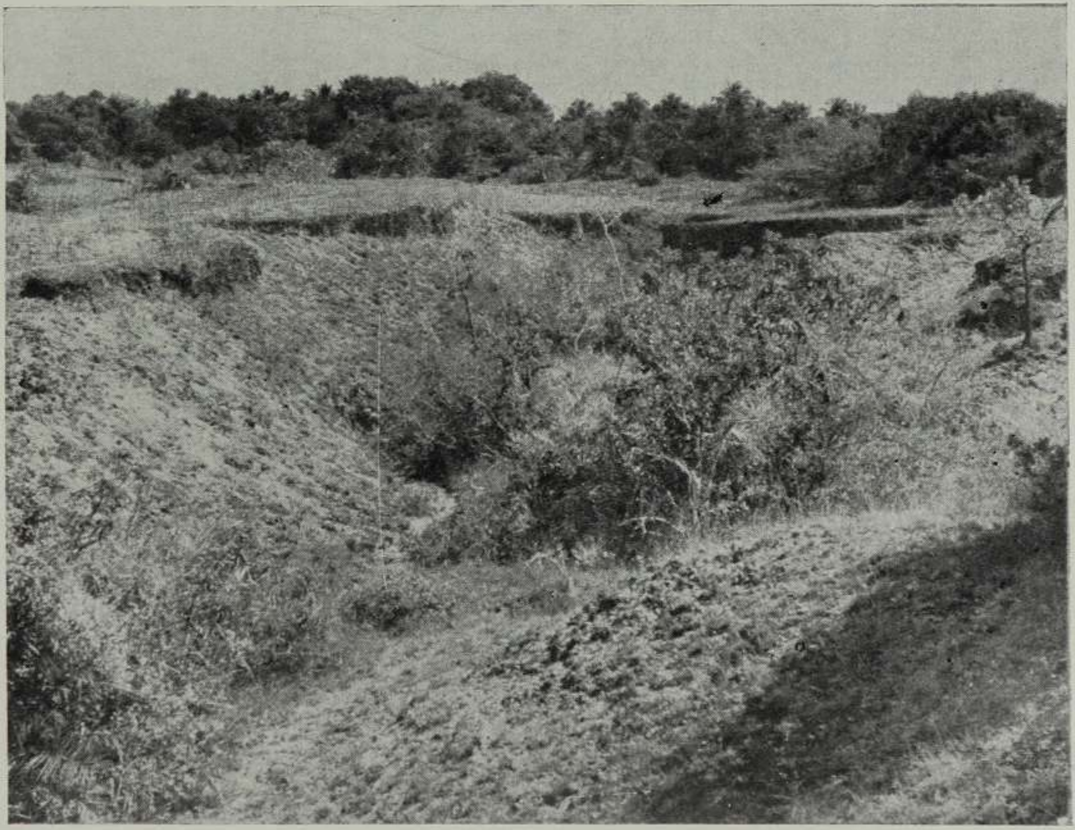
Fig. 51. Borehole section through the Miocene limestone, Aruakalu Hill. (*After J. W. Herath, D. B. Pattiaratchi, and L. J. D. Fernando*, 1961)

(1) Red Earth, (2) siliceous limestone, (3) pure, hard limestone, (4) siliceous band in limestone, (5) soft, powdery limestone with quartz grains.

It is massive in parts but some layers are richly fossiliferous and weather into a honeycombed mass. Sandy beds containing grains of magnetite, garnet, zircon, monazite, and mica are also present. These minerals are



A. Low cliffs in Jaffna Limestone, Jaffna. Note caves at sea level.
(*D. N. Wadia*)



B. A *vembu*, showing ironstone cap resting on gravel, near Vanathivillu.
(*K. S. O. Perera*)

found in the crystalline Vijayan gneisses to the east of the limestone and were probably derived from the gneisses by weathering and erosion. The limestone is much more variable south of Karativu. At Aruakalu Hill, for example, soft powdery limestone and calcareous clay (or *marl*) overlie the typical hard limestone, and calcareous sandstones and siliceous limestones (with sand grains and small quartz pebbles) are present in addition to the hard, pure limestone (Fig. 51)[26].

Fossils

A varied assemblage of fossils (see Appendix III) is found in the Jaffna Limestone (Pl. 20B), and it includes *foraminifera,* lamellibranchs, gastropods, echinoids, corals, calcareous algae, *bryozoa,* and *anthozoa*[24] The *foraminifera* (or 'forams' as they are popularly known) are important microfossils by which the Tertiary System has been subdivided into a number of 'stages', thus enabling formations in one part of the world to be correlated with those in another. The characteristic foraminifer in the Jaffna Limestone is *Taberina Malabarica* (Carter)* which, together with the association of other forms, dates the Jaffna Limestone as belonging to the upper part of the lower Miocene[27, 28]. This is equivalent to the Burdigalian stage of Western Europe and elsewhere, and to the Upper Gaj of India. Beds of the same age occur at several localities on the coasts of India, notably the *Orbiculina shales* of Gaj in the Kutch Peninsula and the *Quilon Limestone* of Quilon in Travancore. Limestone of similar age also occur in Persia (*the Asmari Limestone*), Syria, and Indonesia.

Such a varied assemblage of marine forms as is seen in the Jaffna Limestone is characteristic of modern coral reefs. It is thus probable that the marine creatures whose fossilized remains are found in the Jaffna Limestone lived in and around coral reefs of the Miocene sea in which the limestone beds were laid down. (Ancient coral reefs have also been found in limestones of Carboniferous age in England). We know too that the water of this sea must have been warm and shallow because it is only in such conditions that coral reefs can grow. Occasional storms would have led to the destruction of the reefs from time to time and to the bringing in of coarse sand and grit containing quartz, magnetite, zircon, and other minerals by the flood waters of rivers, exactly as they do today.

Although the oil-bearing formations of the Punjab, Burma, and Assam are in Tertiary rocks, they belong to the lower part of the Tertiary, particularly to the Eocene and lower part of the Lower Miocene. The Jaffna Limestone is unlikely to carry oil unless there is a continuous succession

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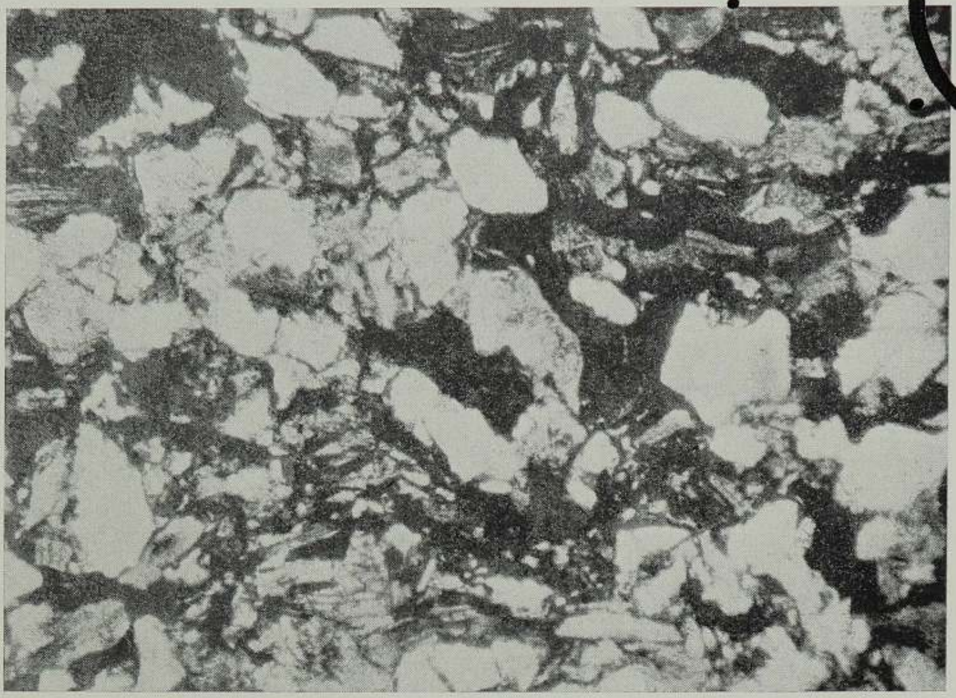
* Previously known as *Orbiculina malabarica* and *Archais malabaricvs.*



A. Photomicrograph of siltstone with flakes of mica and sub-angular to sub-rounded grains of quartz and feldspar, Tabbowa Wewa. X 35

B. Photomicrograph of fossiliferous Miocene limestone with foraminifera, sponge spicules, and part of a large unidentified fossil on right. X 35 of rocks below it going down to the lower part of the Lower Miocene and even to the Eocene, and then only if there are suitable structures for the accumulation of oil. If the limestone thickens westwards, then such a succession, if present, is likely to occur somewhere in the Palk Strait, but if the limestone is faulted against the Pre-Cambrian on the east, then such a succession may be present anywhere in the Miocene belt. We need, therefore, to know the true thickness of the Miocene formation, its age throughout, its relation to the underlying rocks, and the structures present, before we can even speculate about the presence of oil in Ceylon.

The Jaffna Limestone is the main raw material for the manufacture of cement in Ceylon.

Minihagalkande Beds

A small outcrop of Lower Miocene beds occurs on the south coast of Ceylon at Minihagalkande ('rock shaped like a man'), 40 miles east of Hambantota, where the beds are exposed in small semi-circular cliff-like exposures or 'amphitheatres'. They consist of an unfossiliferous basal bed of ferruginous grit and sandstone, 4 to 6 feet thick, above which are about 50 feet of brownish and yellowish sandy and clayey beds[29]. Within the latter are thin layers of nodular limestone with fossil sponges, echinoids, corals, and purplish concretions similar to the fossil remains in the Jaffna Limestone (see Appendix III). The uppermost beds are limestone containing fossil shells and echinoids. The most characteristic fossil is the mollusc *Ostrea* (*opha*) *virleti* Deshayes[24].

These beds may be of the same age as the Jaffna Limestone but only detailed work on the fossils will make this clear. We do know, however, that the conditions under which the Minihagalkande Beds were formed were different from those in which the Jaffna Limestone were laid down. The predominance of sands, grits, and clays suggests that they were laid down fairly close to the shoreline, where detrital material from the land was being brought in constantly. Limestone reefs could not have formed in such disturbed conditions except occasionally, during periods when no detritus was being brought in. We see here either the beginning or the end of another cycle, the *sedimentary cycle*, where coarse sediments laid down at the beginning of the cycle are succeeded by limestones and clays deposited during a period of quiet in the middle of the cycle; these are overlaid by coarse deposits again, at the end of the cycle.

The high land formed by the Minihagalkande beds extends inland for about a quarter of a mile, and then descends steeply to plains covered by recent alluvium through which crystalline rocks appear. The exact relation between the Miocene and the crystalline rocks here is not known.

CHAPTER 8

QUATERNARY SYSTEM

Introduction

RESTING on the Miocene and crystalline rocks in many parts of the Island are a variety of unconsolidated or partly consolidated deposits consisting largely of gravels, sands, and clays. These belong to the Quaternary System and among them are to be found many of the important economic minerals of Ceylon. Information about the Quaternary deposits is, however, of a fragmentary nature, and it is still not possible to give a reasoned account of the Quaternary System in Ceylon ; all that can be done is to summarise the information available at the present time.

The sedimentary deposits formed during the last million years of the Island's history occur mainly within a coastal belt that is narrow in the southern half of the island but widens considerably northwards of Negombo on the west coast and of Batticaloa on the east. Unconsolidated deposits also occur in a number of river valleys in the interior of the Island, particularly in the Sabaragamuwa Province. Owing to minor fluctuations of sea level after the Miocene epoch, a few of these Quaternary deposits are possibly of marine origin, but the majority of them are continental deposits. They have been laid down by wind and water on beaches and in lagoons and estuaries along the coast, or in lakes and on the flood plains of rivers further inland.

Also included in the Quaternary System are several formations that are classed as 'secondary'. These have resulted from the action of later processes (such as weathering and solution) on pre-existing formations. The most important of the secondary formations are laterite and nodular ironstone, both of which are fairly widespread, but in different parts of the country ; the others, such as chert, flint, travertine, and kankar are of restricted occurrence.

Although some of these Quaternary deposits have been dated as belonging to the Pleistocene epoch[30], the evidence for this is not conclusive enough and it is preferable, at present, to use the wider term Quaternary. In the north-western coastal region where these deposits have been studied, it has been possible to recognise two main groups, namely, an Older Group and a Younger group (see Table 7), a subdivision that can probably be extended to other parts of the Island's coasts.

We shall, in the following pages, first describe the Quaternary deposits of the Ratnapura region and then those of the coastal areas, confining our description mostly to the north-west coastal tract.

RATNAPURA REGION

Ratnapura Beds

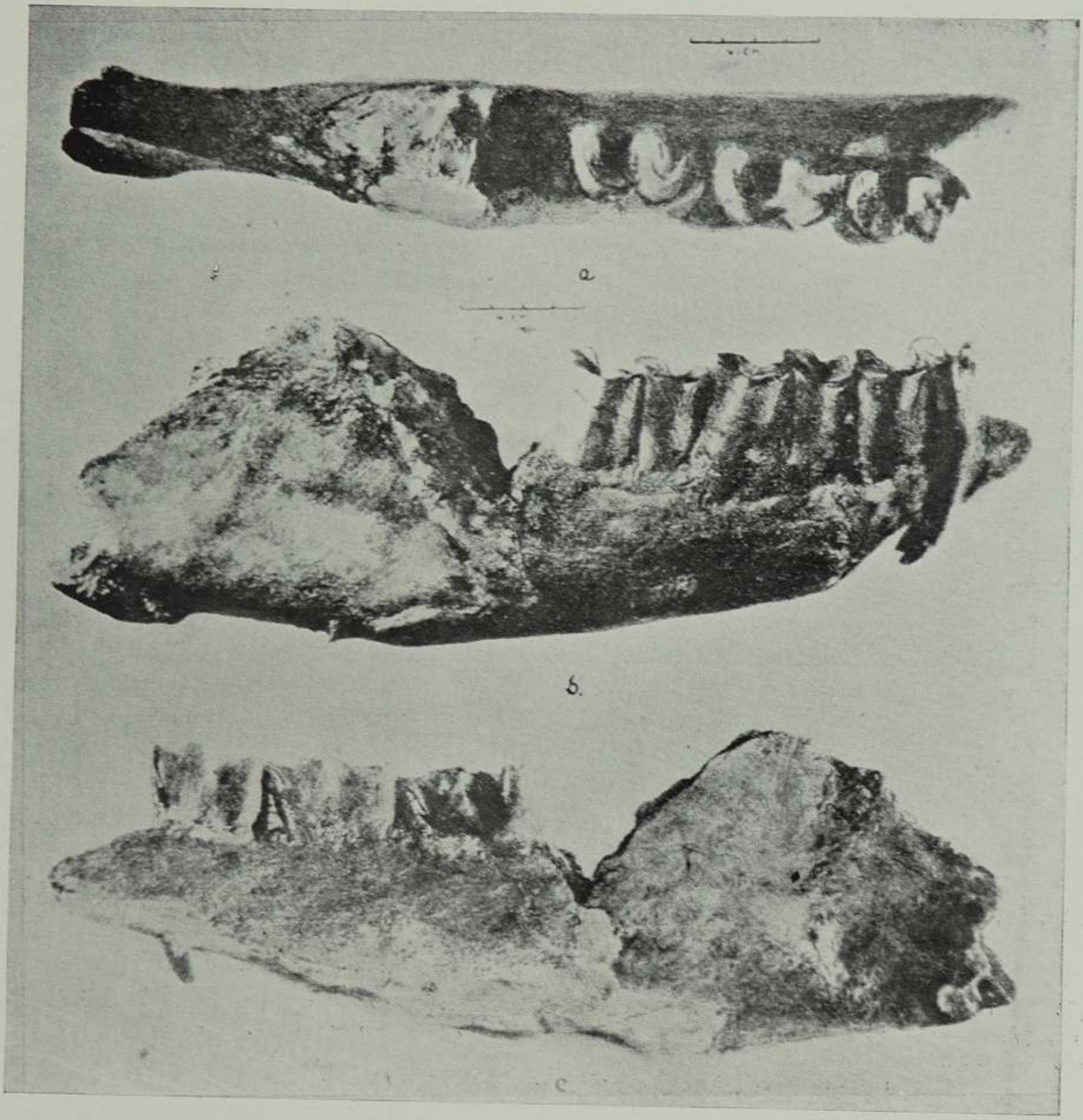
Extent

The name 'Ratnapura Series' has been given to a group of river and lake deposits that have accumulated in the strike valleys of the Sabaragamuwa Province around Ratnapura[15], but owing to their comparatively limited occurrence it is preferable to call them the Ratnapura Beds. These deposits have been recorded in the valleys around Kuruwita, Kamarangapitiya, Getahetta, Ratnapura, Hangamuwa, Kalawana, Pelmadulla, and Balangoda (see Fig. 66). Similar deposits may possibly be present in many other valleys of the Hill Country.

Lithology

The different members of the Ratnapura Beds are best seen in the innumerable gem pits opened up in the area mentioned above, where a large number of sections have been recorded. A few typical sections are shown in Fig. 52, from which it is seen that the deposits are all gravels, sands, and clays but of great variety The same succession hardly occurs even in pits close to each other. Several types of deposits have been recognized and these reflect the constantly changing conditions of weathering, transport, and deposition that have existed in the area during Quaternary times. Among the beds that have been noted in gem pits are[15] :—

(i) Gravel (*borälla*)..transported nodular ironstone.
(ii) Coloured clay, yellow, red purple or variegated (*nava nīla mäṭṭa*)..river silt or lake clay.
(iii) Leaf bed (*kola mäṭṭa*)..lake deposit.
(iv) Plant remains with bituminous clay (*däli pas*)..lake or swamp deposit.
(v) Grit (*väli katuwa*). .coarse river sand
(vi) Blue clay (*nil mäṭṭa*)..lake deposit
(vii) Fine white sand (*séni vali*)..fine river sand
(vii) Pebble bed (*bōla gal*) ..river deposit, possibly re-sorted terrace gravel
(ix) Green sand with fossils (*nil välla*)..river sand
(x) Grey gem-bearing sand with pebbles, boulders, and fossils (*iḷlama*)..river deposit



Three views of the mandible (jaw) of *Rhinoceros sinhaleyus* Deraniyagala, a fossil from the Pleistocene Ratnapura Beds. (*National Museums Department*)

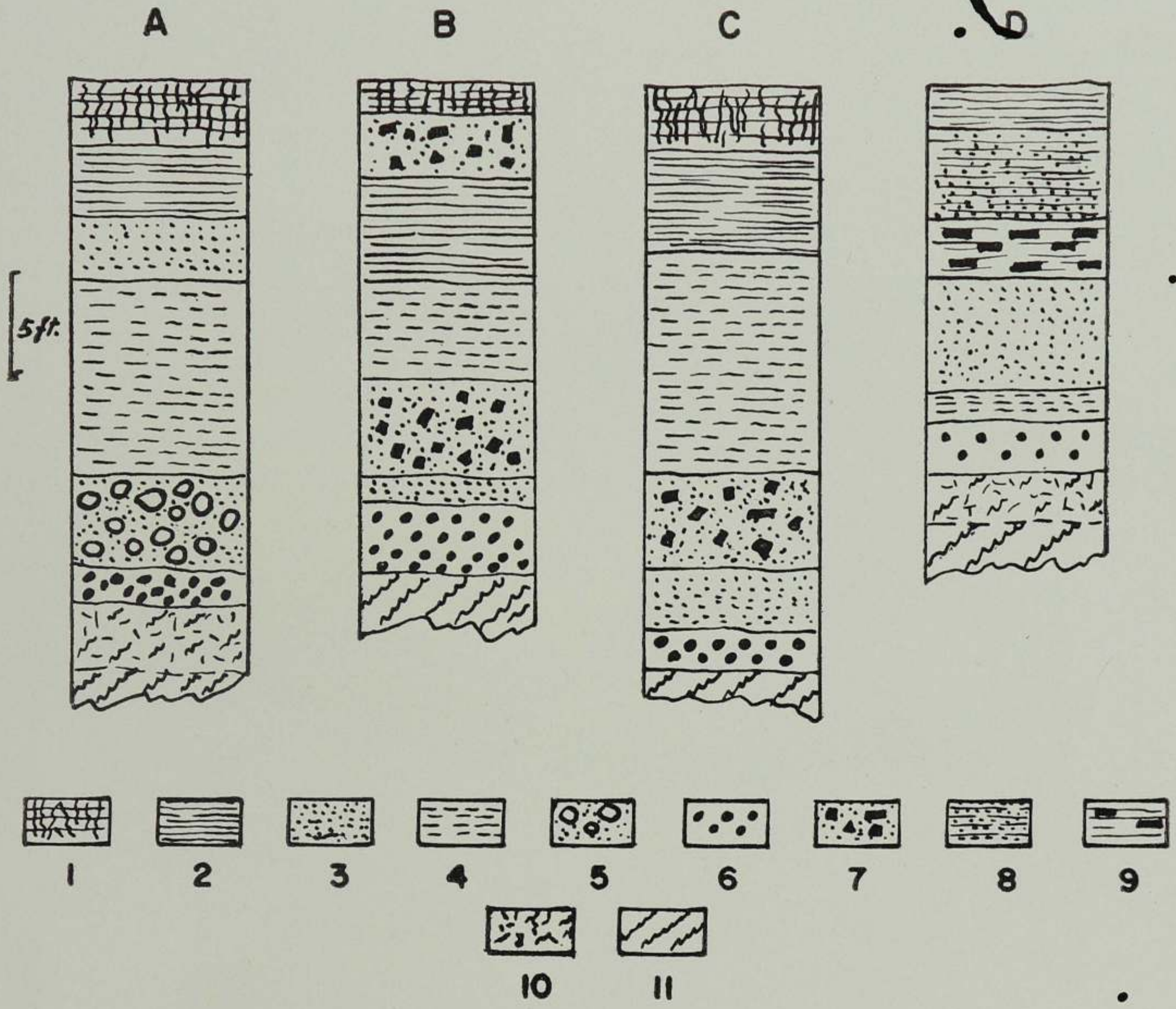


Fig. 52. Cross-sections showing typical successions in the Ratnapura Beds. (*Drawn from data in P. E. P. Deraniyagala*, 1958)

A, B, and C, pits around Kāmarangpitiya. D, pit in Hangamu Oya valley

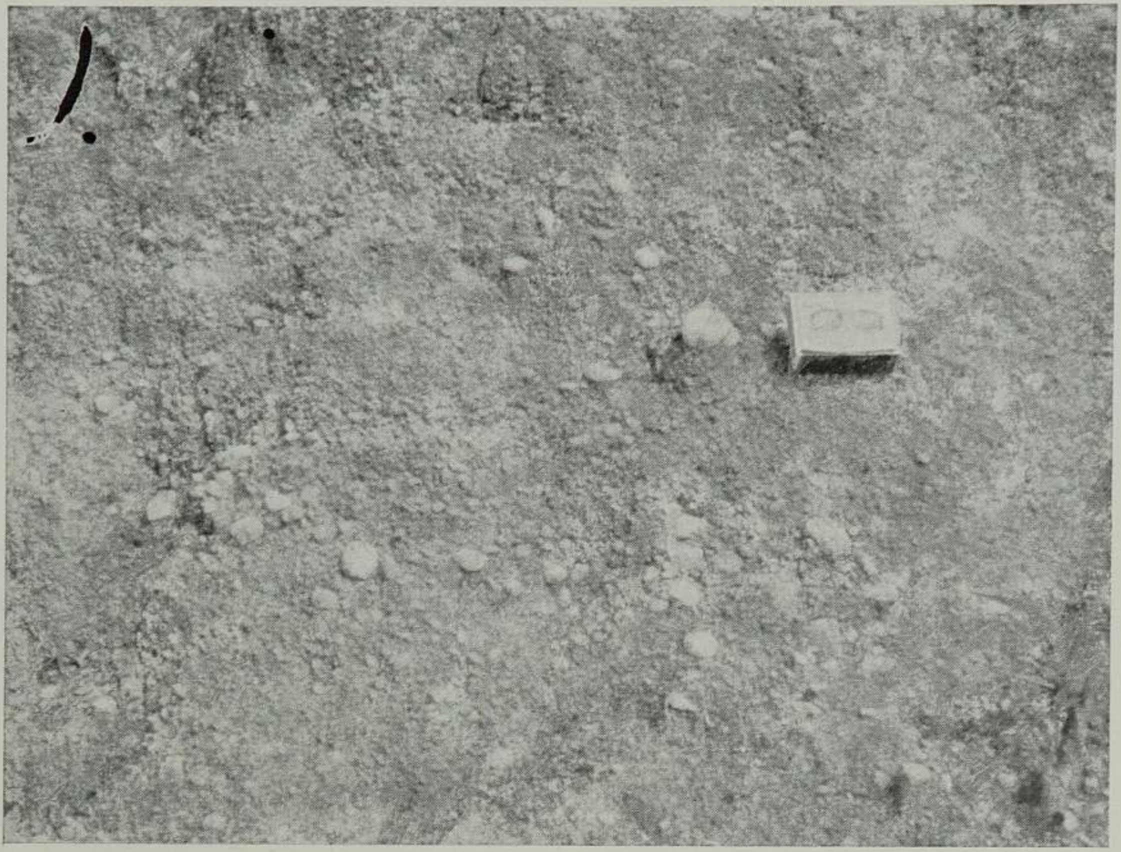
(1) humus, (2) black mud, (3) sand, (4) grey clay, (5) boulders and sand, (6) gem gravel and sand, (7) lateritized gravel, (8) lateritized mud, (9) leaf mud, (10) weathered bedrock, (11 fresh bedrock.

(In pit D, sand and clay are black, and gem sand is fossiliferous.)

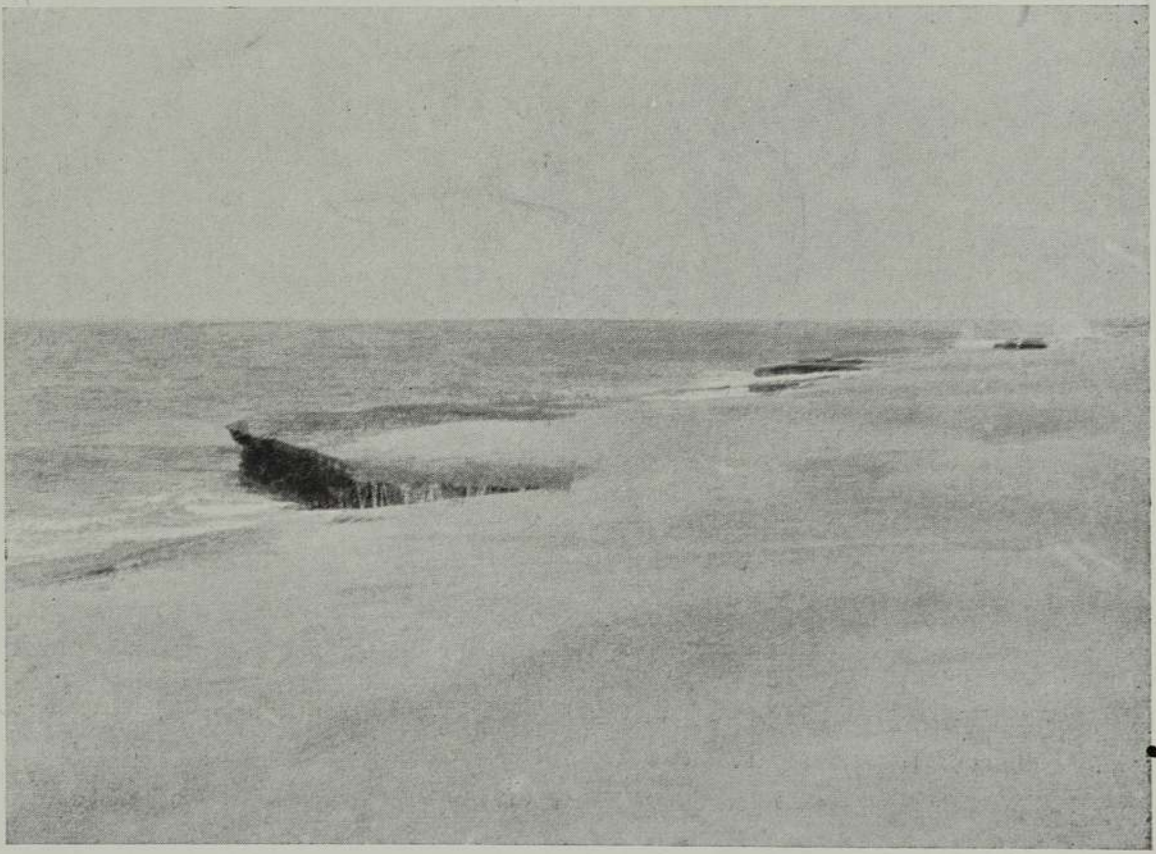
The maximum thickness of the beds is about 40 feet but occasionally, as in the Kuruwita valley, 85 feet of lake deposits have been recorded. The fossil-bearing sands are 6 inches to 3 feet thick and lie at depths of 12 to 40 feet below the surface. Below these sedimentary deposits, in nearly every instance, is a horizon of kaolinsed or decomposed bed rock.

Fossils

It is from the gem-bearing horizons that the fossilised bones and teeth of an extinct vertebrate fauna have been recovered. This *Ratnapura Fauna* is a branch of the great Siwalik fauna in India and consists of



A. Detail of the terrace gravel at Erunwala showing mixture of pebbles, sand, and clay; note rude stratification of pebbly layers.



B. Littoral sandstone reef, Chilaw.

forms ranging from the Pleistocene to the Recent[15]. A full list of these fossils is given in Appendix III but it is interesting to note here the presence of fossils of the hippopotamus (*Hexaprotodon*), the ridge-browed elephant (*Hypselephas* and *Palaeoloxodon*), the Asian elephant (*Elephas maximus*), the buffalo (*Bubalus*), the gaur (*Bibos*), and the rhinoceros (Pl. 21) together with freshwater shells. Fragmentary remains of an extinct race of neanderthaloid man, *Homo sinhaleyus*, as well as stone implements of several cultures have also been found in these beds.

The fossil remains recorded in the Ratnapura Beds range from middle Pleistocene to Recent in age, and the fact that they are found together in the same horizons suggests that the Ratnapura Beds are really post-Pleistocene in age; they have been formed by the re-working and re-deposition of earlier beds of which no traces are seen now. This re-working may have been brought about by recent earth movements which disturbed the existing drainage systems; the resulting swiftly-flowing streams eroded the deposits in which the fossil remains were originally preserved. Such a suggestion is borne out by the presence of layers of large water-worn pebbles and boulders (representing former river channels) at the base of the Ratnapura Beds.

Quaternary Climate

On the basis of several lines of evidence, chiefly faunal, an interesting picture of the climatic changes during the Quaternary has been drawn by Deraniyagala[15]. He has enumerated the following phases:—

(*a*) *Ratnapura phase*: a cool, pluvial phase marked by moderate to heavy rainfall; tropical rain forest and savannah vegetation; large lakes and swamps supported the hippopotamus, rhinoceros and Palaeoloxodon.

(*b*) *Palagahaturai phase*: an arid phase; colour of sediments was predominantly reddish as in laterite and Red Earth, due to high degree of oxidation.

(*c*) *Colombo phase*: present climate.

COASTAL REGIONS

(chiefly the North-West)

The Quaternary deposits of the north-west coastal region between Negombo and Puttalam have recently been recognised as belonging to two major groups.[30a] These are a *Younger Group* occupying the belt of barrier beaches and bars, sand dunes, lagoons, and estuaries adjacent to the coastline, and an *Older Group* forming the slightly higher land immediately east of this belt. The two groups are made up as follows :—

Younger Group	Alluvium, lagoonal and estuarine deposits Unconsolidated sands of beaches and dunes Littoral sandstone
Older Group	Red Earth Basal ferruginous gravel ; Terrace gravels

OLDER GROUP

Basal ferruginous Gravel

The basal ferruginous gravel occurs within a broad belt extending from Negombo to Mannar, and in scattered outcrops northwards from there. It is not well exposed in the southern part of the belt, being mostly covered by extensive stretches of unconsolidated white sands, but it can be seen in many of the excavations for wells around Negombo and Chilaw. The gravel can also be seen in some of the stream sections that dissect the area north of Puttalam.

The ferruginous angular gravel is made up of a mixture of coarse sand grains, fragments of chert, and pellets of ironstone partly cemented together with ferruginous material. The sand grains are mostly angular to sub-angular in shape but small, rounded to sub-rounded pebbles are sometimes present in it. A little clay is also present and the gravel, generally grey in colour, is partly mottled in shades of red and brown. In places it is friable and can easily be crushed but most often the gravel is hard. One clue to the presence of the gravel, when it is concealed, is the brownish colour of the water in the wells that penetrate the formation.

The fact that the ferruginous gravel lies below the Red Earth formation (see below) and the fact that gravels sometimes occupy relatively high ground led Wayland to group the two formations together as the 'Plateau Deposits'[30]. According to him, these 'plateau gravels' were developed at one time over the entire seaboard of the Island and covered much of the lowlands. Since then they have suffered denudation and are now represented by detached and often widely scattered outcrops as, for example, around Tangalla, Hambantota, Ranna and Minihagalkande. Patches of ferruginous angular gravel containing a few rounded pebbles are said to be present on the east coast too, at small elevations above lagoon levels a short distance from the coast. Many of these gravels are said, by Wayland, to contain stone implements, and those at Ranna, now 50 feet above sea level, contain mollusc shells similar to those which inhabit the very shallow inlets of the sea that run into the coast.

The relationship of the ferruginous gravel to the formations above and below it can be seen in exposures north of Puttalam, in the Kalpitiya, Kudremalai, and Marichchukkadi areas. Here the gravel is exposed in a number of *vembus,* more or less elliptical depressions about a quarter of a mile in extent and generally bounded by steep faces (Pl. 19B), or in innumerable stream channels which dissect the so-called Plateau Deposits[29]. The gravel rests on soft, powdery limestones and marls of Miocene age and is overlain by the later Red Earth deposit ; it consists mainly of chert fragments, small pellet-like concretions of iron, and quartz grains of varying sizes from a fraction of an inch to nearly two inches in length, cemented together by oxides of iron and clayey matter. The gravels are mottled and show various shades of red and reddish brown patches in a grey matrix. Further south, in the Battulu Oya and Chilaw areas, the ferruginous gravel rests on a basement of peneplained and kaolinised crystalline gneisses.

The origin of the ferruginous gravel is not known with any certainty. It may, on the one hand, be a marine beach deposit formed when the Pleistocene sea swept over much of the present coastal tracts of the Island. This may explain its relatively wide distribution and at the same time its restriction to this belt. On the other hand, the gravel may be a river deposit, laid down on the alluvial plains of an ancient river system by extensive sheet floods.

Red Earth

The Red Earth formation of north-west Ceylon is one of the most distinctive members of the Quaternary System, not only in appearance but also in its topographic expression. It is essentially a clayey sand or loam with a characteristic venetian red or brick-red colour, and forms a number of low, narrow, elongate ridges or domes.[30a] These ridges are generally less than 100 feet high (but sometimes more), about 2 to 3 miles long, and 1 to 1½ miles wide ; they are consistently aligned in a north-south direction. The natural vegetation cover is dense jungle, but owing to the highly pervious nature of the Red Earth formation it has been extensively cleared for coconut plantations.

Good deposits of Red Earth are seen from the Maha Oya bridge (north of Negombo) to Puttalam, and beyond that to Kudremalai. The road from the Maha Oya to Chilaw runs along one of these Red Earth ridges and a conspicuous ridge of the same formation runs along the east side of the road from Kiriyankali to Mundel. Other well known ridges are crossed on the road between Palavi and Kalladi (the old airport at Puttalam is built on Red Earth) and on the Puttalam-Anuradhapura road. Several elongate ridges of Red Earth are also found between Puttalam and Kudremalai, as for example those near Karativu and Aruakalu hill. Wherever the Red Earth occurs the fence-posts, tree trunks and telegraph poles are covered with a fine red dust, and this made a very striking feature of the landscape, especially during the dry season. Another feature that reveals the presence of this deposit is the dark red colour of the walls of the mud huts made with it.

The thickness of the Red Earth formation varies from place to place, but is usually about 50 to 75 feet. It may, however, attain thicknesses of over 100 feet, the maximum recorded being 121 feet, at Aruakalu.

The Red Earth deposit is made up mainly of small, rounded quartz grains in earthy material composed of clay and iron oxide ; small amounts of ilmenite, magnetite, spinel, zircon, garnet, and monazite are also present. The quartz grains are very well rounded and have smooth, polished surfaces which, under the microscope, are seen to be finely pitted. The majority of the sand grains are less than 1/16 inch in diameter. The colour of the Red Earth is due to the oxidation of the clayey matrix and the presence of finely divided hematite ; the surfaces of the quartz grains are also heavily stained red, as can be seen if a handful of the material is washed to get rid of the clay. The Red Earth, which is quite free from pebbles, is extremely uniform, there being no signs of stratification or bedding. The particles which make up the Red Earth are derived from minerals found in the surrounding crystalline rocks, and the decomposition of the unstable minerals like feldspar and mica has resulted in the finely-divided kaolin and hydrated iron oxide which make up the clayey portions of the deposit.

Wayland, who first described the deposit, thought that the Red Earth was a wind-blown deposit, largely on the evidence of the small, well-rounded-quartz grains. He did, however, recognize that there were certain features which argued against such an origin. The elongate ridges of Red Earth resemble in many respect the barrier bars and beaches now forming at the northern end of the Kalpitiya Peninsula or north of Chilaw. At Kiriyankali, for example, a definite terrace is clearly visible near the Maternity Hospital; it is undoubtedly a raised beach. Further, the elongate nature of the ridges, their shape in cross-section, and the fact that stretches of marsh and diversions of drainage occur on the east of them, are all points of resemblance with the existing barrier beaches. Finally, and perhaps most important of all, the Red Earth ridges immediately east of Puttalam and

Palavi are on the eastern margins of wide stretches of salt flats and tidal flats which are clearly the silted up portions of an older, much more extensive lagoon than the present one. Similarly, the ridge at Mundel overlooks the tidal flats of the present Mundel Lake, itself a remnant of an older lagoon, and a well marked terrace of Red Earth runs southwards from the village of Karaitivu, overloking a wide expanse of barrier flats and lagoon on the west (see Pl. 27A.). It is most probable, therefore, that the Red Earth ridges formed the old shoreline of this north-western portion of the island, and that the formation originated partly as a beach deposit and partly as dunes.

Deposits of Red Earth are generally flanked on the sides of the ridges and mounds by yellowish and whitish sands and sandy loams ; the light-coloured sands occupy the lower slopes near the *villus* (water holes or small lakes) and streams in the intervening low-lying areas. These whitish sands and loams are now recognized as the bleached portions of the Red Earth formation. The bleaching has been caused by the acidic nature of the water in the villus which, in the wet season, seeps into this part of the formation. The bleached portions of the Red Earth also have a higher clay content than the unbleached portions, and for this reason do not retain water for so long ; consequently, wells in the light-coloured sands dry up sooner than those in the Red Earth during periods of drought.

Terrace Gravels

The third member of the older Quaternary group is a coarse quartz gravel, distinct from the ferruginous angular gravel, which occupies the edges of small river terraces in several scattered localities in the Chilaw and Battulu Oya areas (Fig. 53) and also elsewhere in the island. One of the best outcrops of this gravel can be seen at Erunwala, a village north-east of Chilaw, near the 5th mile on the road from Bangadeniya to Anamaduwa[31]. The gravel is being quarried here, and good sections are exposed in the quarry faces, but owing to its restricted outcrop the gravel may be completely worked out in time to come.

Erunwala Gravel

The Erunwala gravel is a mixture of quartz pebbles set in a matrix of greyish or whitish clayey sand which is mottled in shades of yellow, orange and brown (Pl. 22A). The pebbles are very well rounded and occur in a mixture of sizes ranging from less than a quarter of an inch to 2 or 3 inches in length. Although no bedding is present, some layers are more pebbly than others, and in certain other layers the pebbles are uniformly large ; this gives the deposit a slight appearance of stratification. The maximum thickness of the gravel is about 17 feet but it thins away rapidly from the edge of the terrace ; the bottom of the gravel deposit rests on a basement of decomposed gneiss. The gravel deposit at Erunwala forms a terrace overlooking a valley in which a small, undersized stream flows, the top of the gravel bed being about 15 feet above this valley. About half a mile along the village road, on the opposite side of the valley, is another terrace with an identical gravel formation. Elsewhere, as at Muttibendiwila, 5 miles south-east of Madampe (N.W.P.) the gravel rests on steeply dipping quartzites and forms a terrace which is as much as 30 feet above the floor of a valley; a small stream flows in this valley and is a fair distance away from the terrace. The typical form of these terrace gravels is shown in Fig. 53.

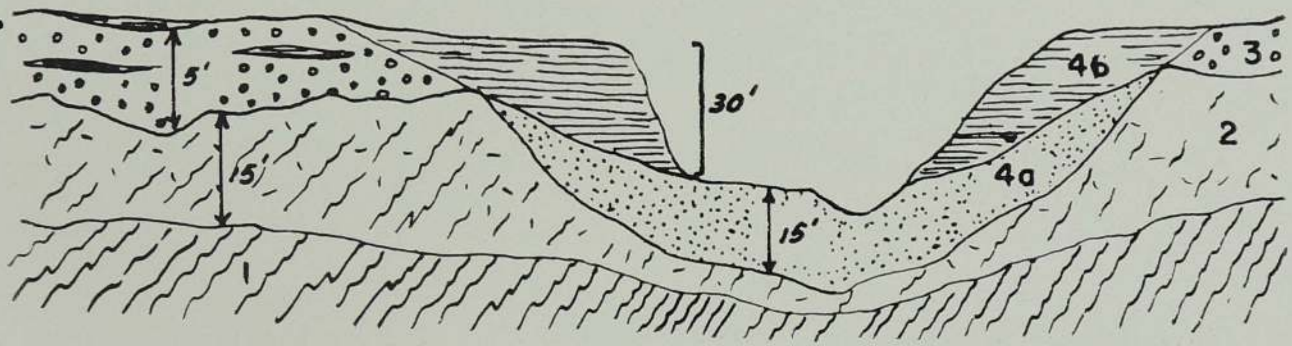


Fig. 53. Section across the Maha Oya at Bambakuliya. (*D. N. Wadia*, field notebook) (1) gneiss, (2) laterite, (3) terrace gravel, (4*a*) alluvial sand, (4*b*) alluvial silt.

At the top of the gravel at Erunwala, and forming a part of it, is a layer of nodular ironstone (see p. 147) which varies from six inches to about 2 feet in thickness. In this layer the pebbles of quartz are cemented together by iron oxide into pellets and nodules up to two inches across ; the nodules are closely packed together and in places they may form a solid crust (or cap) of *ferricrete* on top of the gravel.

Several other occurrences of terrace gravel are found north and north-east of Erunwala, as at Addipola, Attangane, and Pallama, all of which show similar features. The occurrence north of Andanankatuwa, on the track to Attangane (in the Battulu Oya sheet) is particularly interesting. Here, very large pebbles, cobbles, and even small boulders of granite up to 2 or 3 feet across are present in the gravel which forms a steep terrace overlooking the valley about 20 feet below ; a small, sluggish stream now flows along this valley.

Kalladi Gravel

A very good exposure of this type of quartz gravel that we have been decribing is seen in the large 'gravel' quarry near milestone 2½ on the road from Palavi to Kalladi, immediately east of the site of the new cement factory at Puttalam. The soft, mottled gravel forms the floor of the quarry, being made up of smooth, rounded to disc-shaped pebbles of quartz set in a matrix of creamy coloured clayey sand. The material actually being quarried for use as road metal is, however, the nodular ironstone horizon above this soft, mottled gravel ; it is from 2 to 4 feet thick (Fig. 54). Within this ironstone horizon the eye can easily pick out lenses and streak of large quartz pebbles similar to those in the gravel below. It is clear therefore, that the nodular ironstone belongs to the gravel formation and is not a separate bed. The gravel at Kalladi does not form a terrace but it may be an old river channel deposit.

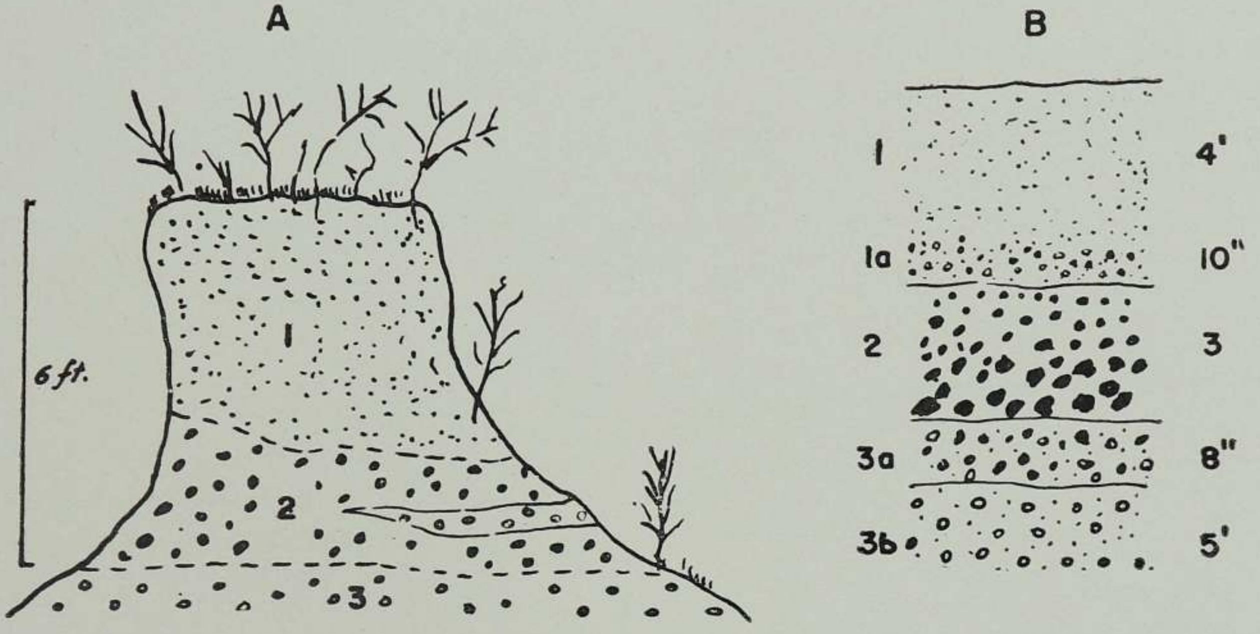


Fig. 54. Generalised sections at gravel quarry, Kalladi.
A. Section of earth pillar shng lens of quartz pebbles in ironstone layer (2).
B. Detailed succession of layers.
(1) reddish brown earth (4 ft.), (1*a*) zone of much quartz, (2) nodular ironstone with small quartz grains, nodules increasing in size downwards (3 ft.), (3*a*) partly indurated grave, (3*b*) soft, mottled gravel with rounded quartz pebbles.

Kelani Ganga Gravels

A number of gravel deposits, similar in appearance to the Erunwala Gravel and possibly of the same age, occur in several river valleys inland from the coast. Between Kaduwela and Hanwella on the Kelani Ganga, for example, a high-level gravel known as the *Malwana* formation is present at 50 feet above the present river level (Fig. 55) ; a lower gravel, the *Ranale* formation, is found at 20 feet above the present river level[32]. The Malwana formation contains beds of coarse, well rounded quartz pebbles embedded in a matrix of laterite separated from each other by

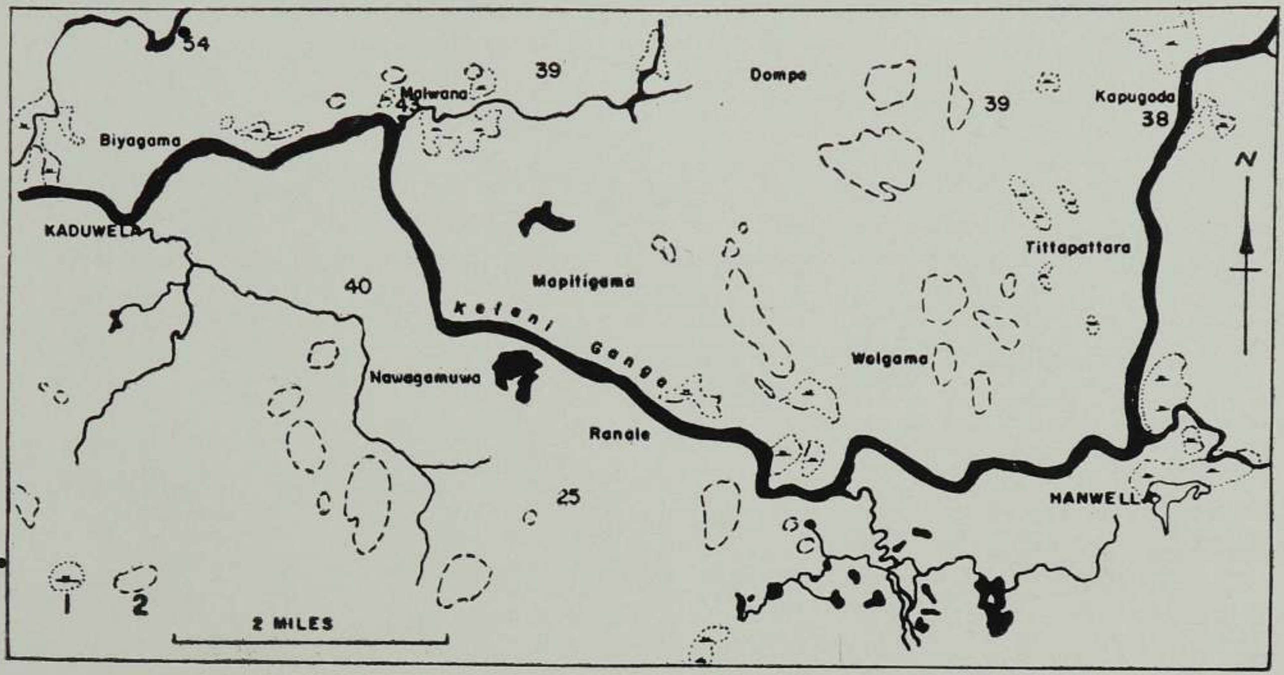


Fig. 55. Sketch map of the Kelani Ganga valley between Hanwella and Kaduwela showing localities where high-level gravel terraces have been noted.
(1) marsh, (2) 100 ft. contuour ; figures are spot heights.

pebble-free layers of laterite. Remnants of this formation are seen capping the ridge that runs parallel with the river in Ranale and Nawagamuwa villages on the south side, and at Mapitigama, Weelgama, Chittipatire, and Wiyalananda on the north (Fig. 55). Outlying patches of gravel are seen downstream at Hiyagama, Waragoda, and Talangama.

The Ranale gravel forms a terrace about a mile wide and at a uniform height of 32 feet above mean sea level. It is at least 12 feet thick and was probably formed by the erosion, re-sorting, and deposition of the higher gravel formation during the progressive lowering of the river valley at a later stage. Outcrops of these gravels can be seen at several scattered points on either side of the Kelani Ganga valley, some of them being away from the present course of the river. We can deduce from these facts that not only has the river changed its course but also that the bed of the Kelani Ganga must once have had a much steeper gradient than it has at present.

Chipped and worked pebbles of chert and quartz (Fig. 56) which are considered to be the implements of Palaeolithic and Neolithic (or Stone Age) man have been found in many of these gravel deposits, and it is on this evidence that E. J. Wayland (and P. E. P. Deraniyagala) considered them to be Pleistocene in age. It is an interesting fact that similar gravel terraces in other parts of the world, such as those in the Thames River valley in England, have been found to contain evidence of habitation by Stone Age man.

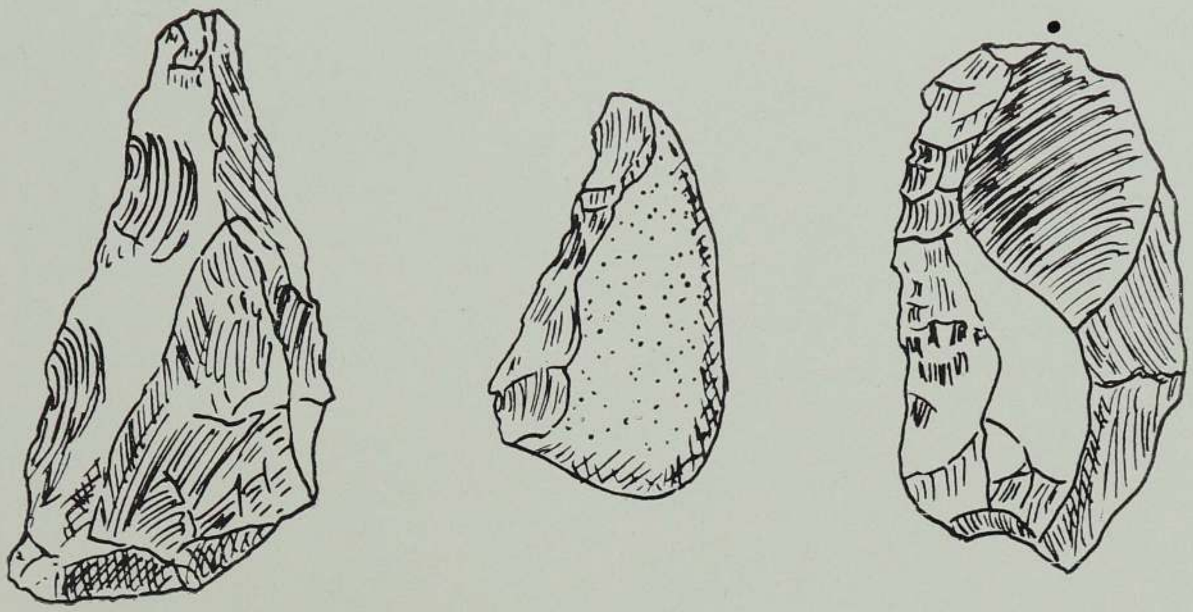
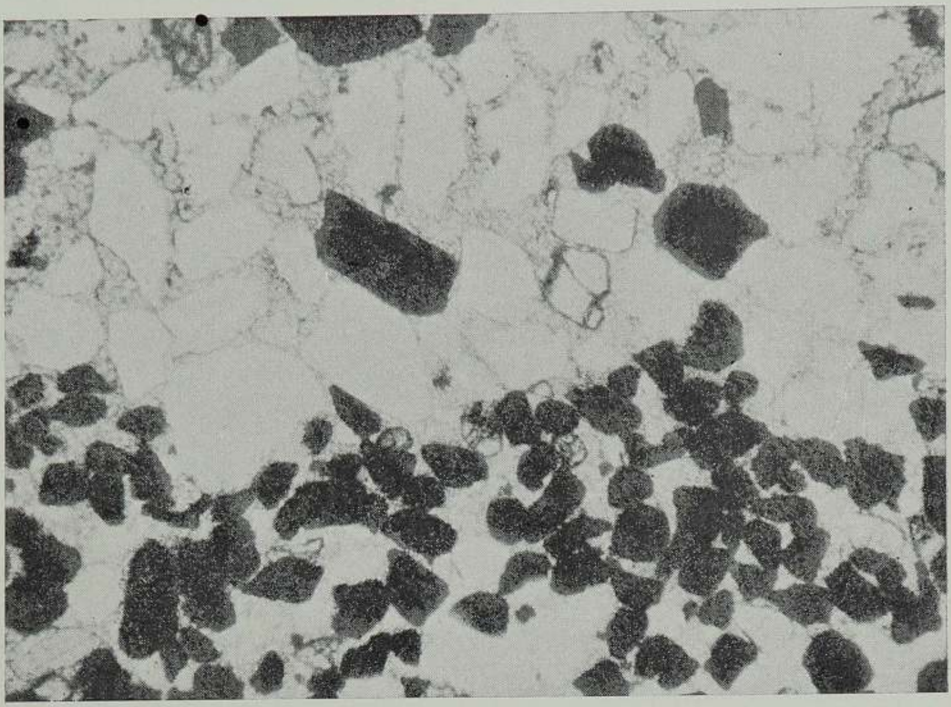


Fig. 56. Typical Palaeolithic stone implements from Ceylon. (*E. J. Wayland*, 1919)

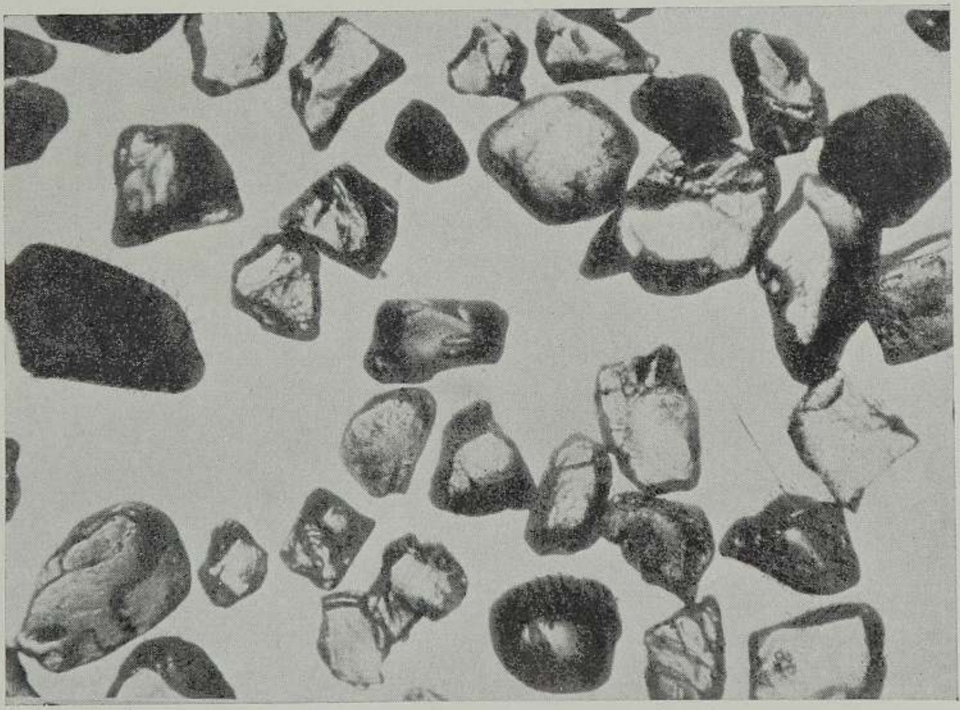
Other quartz gravel beds at about 50 feet above present river levels are found at Avissawella (above the Sitawaka Ganga), Peradeniya, Madampe Estate (on the Madampe Oya), near the Hulanduwa Oya in the Southern Province, in the Pattipola-Horton Plains region, and above the Badulla Oya on the Spring Valley Estate road[33]. The last of these was observed by J. Parsons in a road-cutting in which the gravel covered the eroded surface of decomposed gneiss; the road cut shows a good section of an old pot-hole. The base of the gravel is 51 feet above present river level, the gravel itself being 12 feet thick.

Origin of Terrace Gravels

The Erunwala Gravel and others like it are river deposits laid down on the edges of the flood plains of rivers when the latter overflowed their banks during periods of flood. Some of these gravels obviously belong to the existing rivers which must have flowed at higher levels than at present, but in many instances they were formed by earlier river systems (or tributaries and former channels of the present rivers), only traces of which are left. These remnants are generally too scanty and too widely scattered to trace the former river courses, but the large sizes of the pebbles and boulders as well as their well-rounded nature leads us to the conclusion that they must have been powerful, swiftly flowing streams, with steep gradients and a greater carrying capacity than the present streams. The climate too was probably wetter, perhaps the Ratnapura climatic phase, with frequent torrential rains leading to floods. After the gravels were laid down, uplift of the land or lowering of the sea level resulted in active denudation. As a result, well-rounded quartz pebbles are sometimes seen at present river levels, in thin beds and



A. Photomicrograph of littoral sandstone from the reef at Pamunugama, with angular grains of quartz (top) and layer of ilmenite (bottom) set in a calcareous cement. X 35



B. Photomicrograph of heavy minerals, mostly garnet and ilmenite, from dune sand, Hambantota. Contrast rounded and polished form of wind-blown sand grains with angular water-borne sand grains above.

layers, but without an ironstone cap. Similarly, the gem-bearing gravels of the Ratnapura Beds may have resulted from the resorting of older river terrace gravels within the Ratnapura valleys.

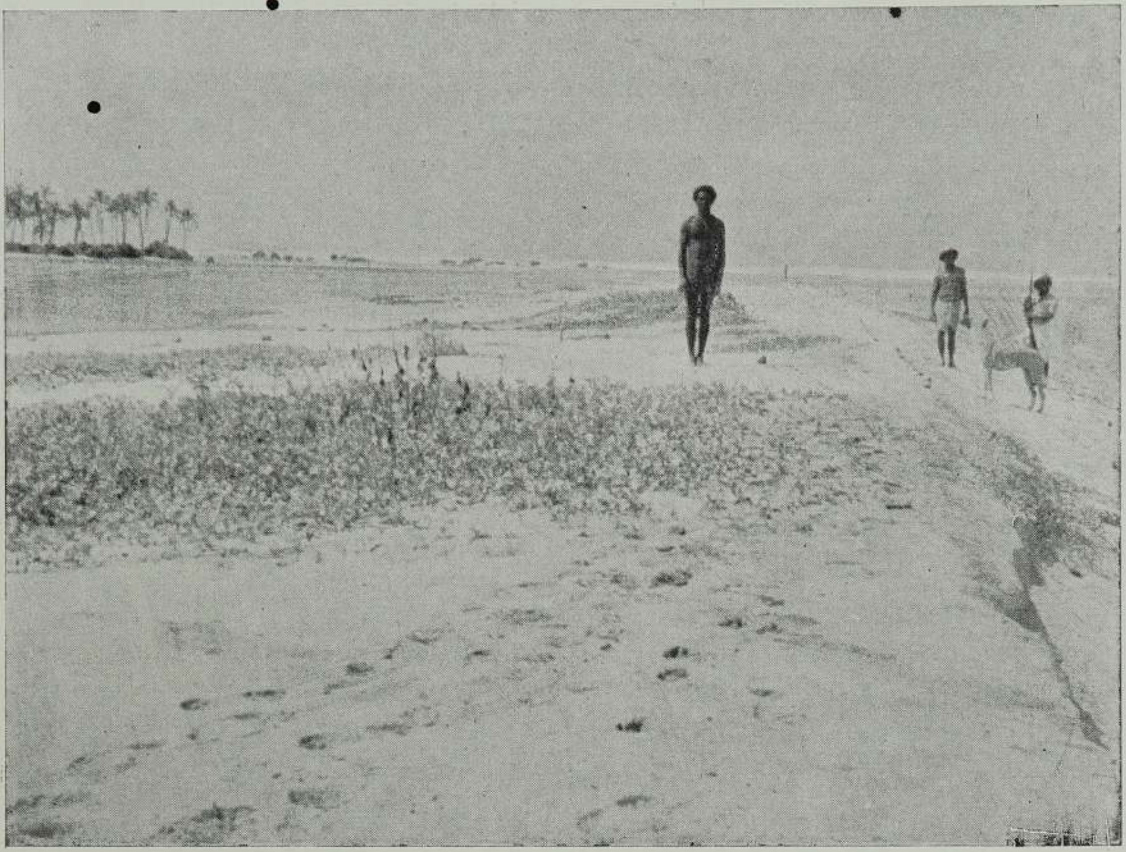
YOUNGER GROUP

Littoral Sandstone

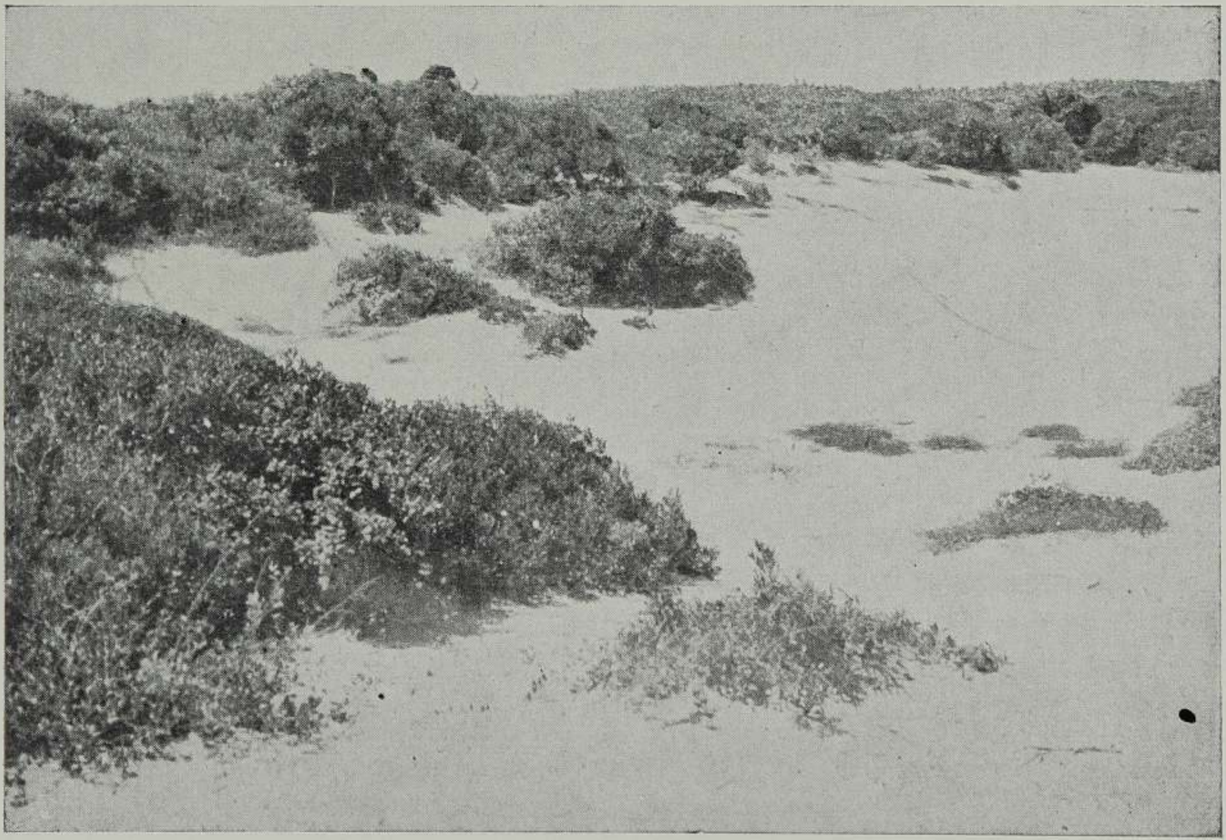
This sandstone, probably the oldest of the 'Younger' group of Quaternary deposits, forms discontinuous reefs fringing the shores of the Island at many places, generally exposed between high and low-water marks but sometimes below sea level. On the west coast it can be seen as far south as Galle and Matara, and at Beruwala the reef forms a wide platform between Barberyn Island and the mainland. The presence of this reef at Beruwela has probably preserved the headland from the rapid erosion that is attacking the rest of the coast. The reef can again be seen on the Kollupitiya and Galle Face beaches in Colombo, and northwards from Colombo it becomes more prominent, running almost continuously between the mouth of the Kelani Ganga and Negombo. It is found again along the seaward side of the Chilaw sand spit (Pl. 22B) and runs out into the sea as a wide platform at the end of the spit. In all these places the sandstone lies below the sand bars and spits of the coast, emerging on their western margins but almost never seen on the eastern (landward) side. Further north, around Karativu, the sandstone reef is exposed along the coast, a few feet above sea level, whereas at Negombo a submerged offshore reef runs parallel to the one near the shore.

The coastal sandstone is also exposed on the east coast between Kalmunai and Batticaloa, and again at Mullaitivu, but here it may be a short distance inland or exposed on the landward side of a spit but still lying under it. The sandstone appears either on the shore or at the mouths of lagoons between Batticaloa and Okanda, and patches of sandstone are sometimes found overlying the gneiss on headlands. These sandstones are generally coarse-grained, and in one spot the sandstone includes corals which probably grew on the surface of the bed until they were covered by more accumulations of sand. Another sandstone reef extends for several miles along the coast near Tirukkovil ; at first it is about half a mile out to sea but it gradually approaches the shoreline until at Tirukkovil it is found at low water mark.

The sandstone of the west coast is composed mainly of grains of quartz (Pl. 23A) and is either fine-grained, as in the Chilaw reef, or coarse-grained and of mixed sizes, as at Beruwela. The sizes of the grains vary,



A. Barrier bar at the mouth of the Deduru Oya (see Fig. 57) with 'Water's Meet', Chilaw, in the background.



B. Beach jungle vegetation on the sand dunes of Narakkali, Kalpitiya Peninsula.

however, from place to place. Shell fragments are present in some sandstones and others have grains of garnet and ilmenite ; the Beruwela sandstone even contains some small pebbles. The sand grains are cemented together with calcium carbonate but the degree of cementation is variable ; in some reefs the sandstone is extremely hard and is used for building stone, but in others the sandstone is very friable and can be broken by hand. The lower beds are more conglomeratic than the higher ones, being made up mostly of corals, shells and fragments of both.

One interesting feature in some sandstones is the presence of bands of ilmenite and garnet, but especially the former ; other heavy minerals that occur are magnetite, zircon, sillimanite and spinel. Cross-bedding similar to that seen in the existing small sand cliffs on the beaches is present in the sandstone and is brought out by the layers of black ilmenite. When the heavy mineral bands increase in thickness the sandstone may become an ilmenite-rich rock, as at Pamunugama (Pl. 23A), and when the black bands are thick the sandstone looks almost like a banded metamorphic rock.

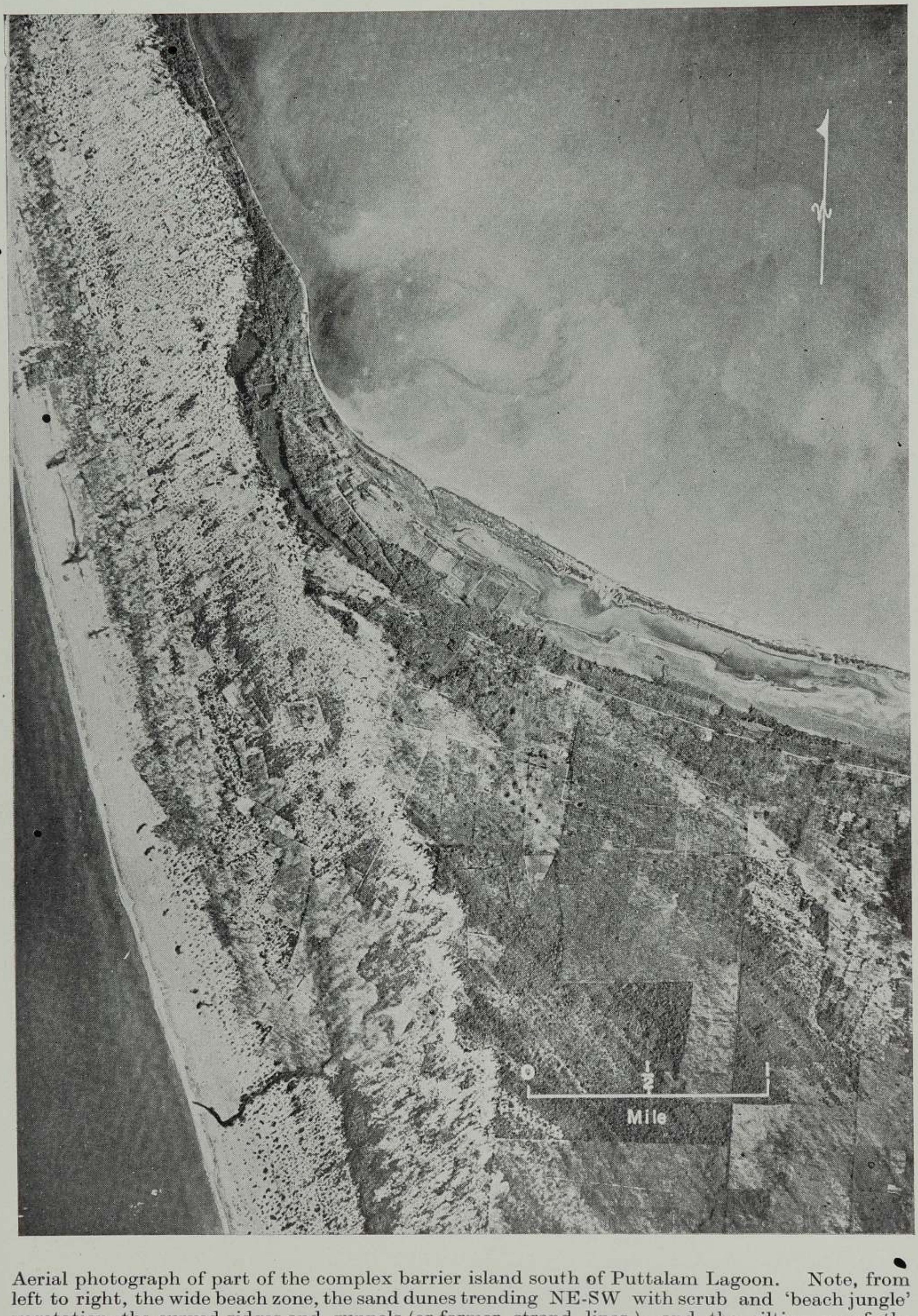
The littoral sandstones are the cemented portions of former beaches which have formed by the precipitation of calcium carbonate between the sand grains. This cementation has been brought about by the seepage of calcium-rich water, either from above or from the adjacent lagoons, and its contact with sea water. The sandstones are thus related to the groundwater table and to the level of the sea at any one time. Where there are parallel sandstone reefs at different levels, therefore, they are an important pointer to the changing level of the sea during Quaternary times.

Unconsolidated Sands

Perhaps the most extensive of the Quaternary deposits of Ceylon are the large stretches of unconsolidated sands that cover the coastal tracts of the island, and which have originated in a variety of ways. Apart from the present beach sands, many of these are old beach deposits now raised above sea level, others are dune sands which have been transported and deposited by wind from the beaches, and still others are river sands belonging to the existing and to previous systems of drainage. These unconsolidated sands are economically important as carriers of fresh water and as placer deposits of economically valuable mineral sands along the coast.

Beach Sands

The present coastline is, as we have seen (in Chapter 4), built up of



Aerial photograph of part of the complex barrier island south of Puttalam Lagoon. Note, from left to right, the wide beach zone, the sand dunes trending NE-SW with scrub and 'beach jungle' vegetation, the curved ridges and runnels (or former strand lines), and the silting up of the southern margin of the lagoon.

(*Hunting Survey (now Lockwood Survey) Corporation, Canada. Crown Copyright Reserved*)

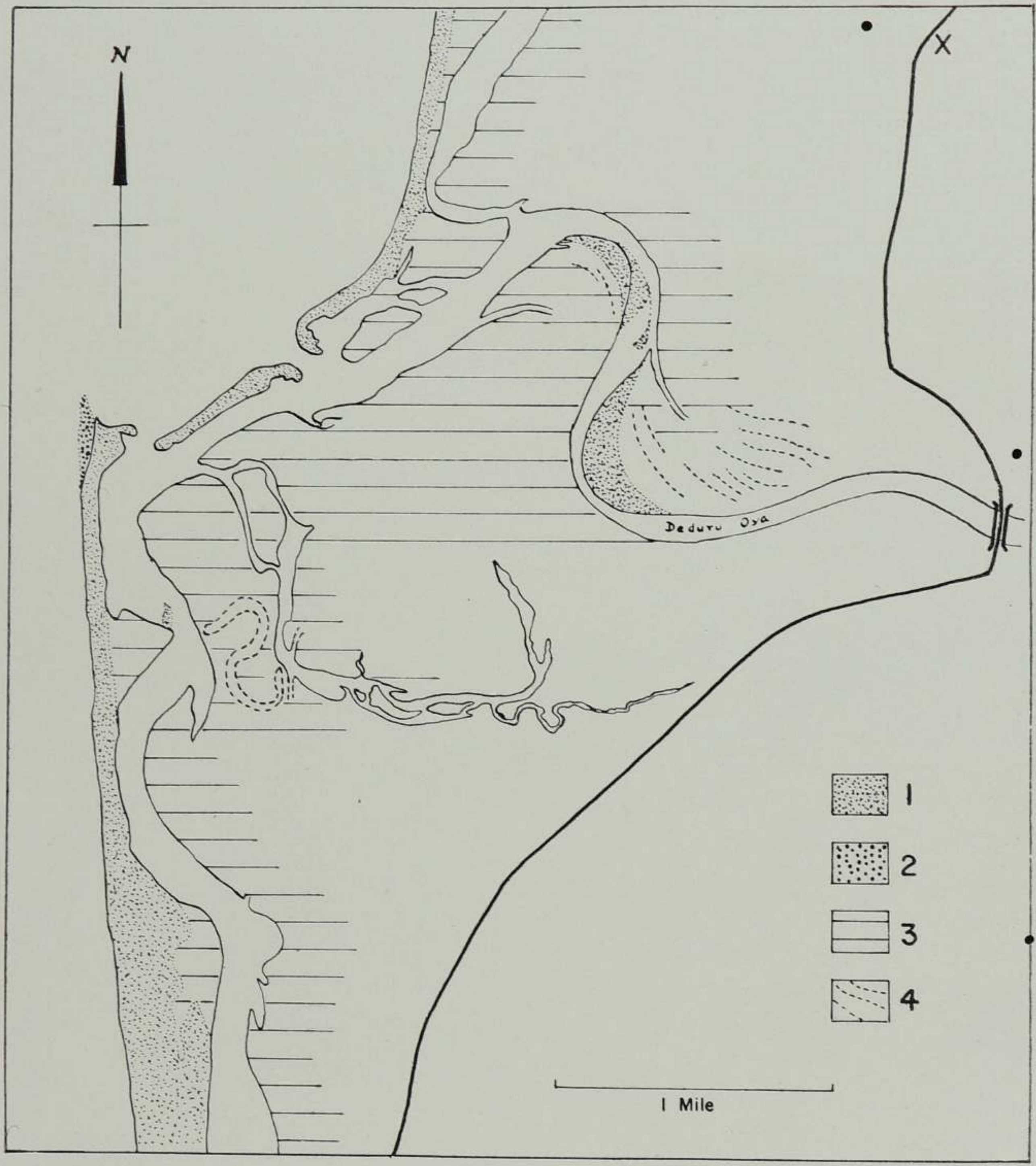
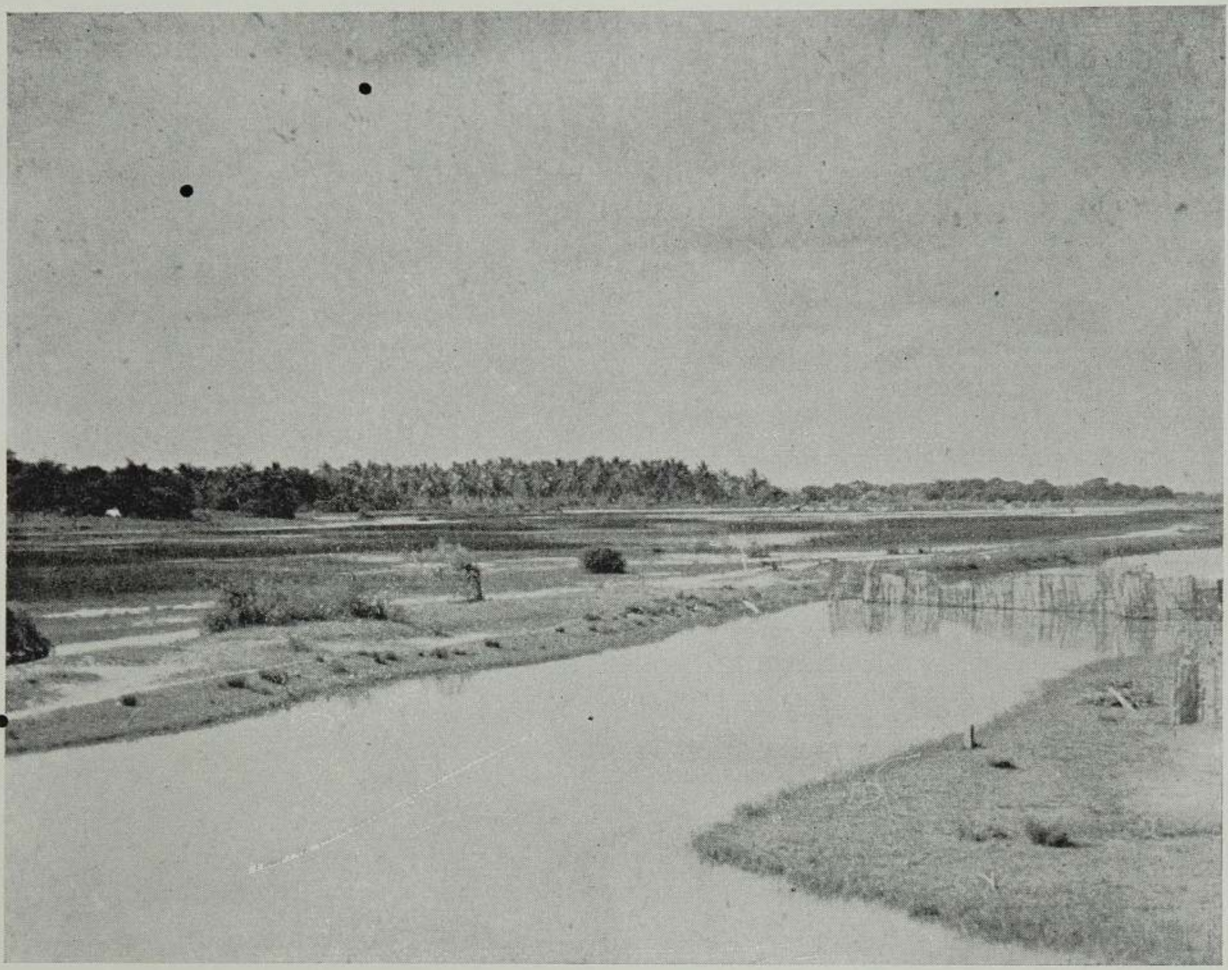


Fig. 57. Sketch map of the mouth of the Deduru Oya showing changes in the course of the river, growth of barrier beaches and bars (see Pl. 24A), the littoral sandstone reef, and old lagolona beds. (*Drawn from an aerial photograph*)

(1) unconsolidated sand, (2) sandstone, (3) clays and silts, (4) former drainage channels, (X) position of new bridge where oyster shells in bluish-grey mud were found at depth.

a succession of beaches (see Pl. 26B), barrier bars (Pl. 24A), and sand spits (Pl. 11) which have grown in several directions and have extended themselves during the most recent geological times.



A. Barrier flats with creek, near Madurankuli.

B. Barrier beach separating barrier flats and Mutupantiya Lake (on left) from the sea (on right), south of Udappu.

Examples of these existing beach deposits can be found in almost any part of the coast (Fig. 57) and are best examined with the aid of the excellent topographical maps and aerial photographs of the Island.

Behind many of the present beaches are extensive stretches of sand, often made up of a remarkable series of low, parallel, curved ridges and runnels which run for several miles. These ridges and runnels show up well on aerial photographs (Pl. 25), but are hardly noticeable on the ground. They can sometimes be recognised, however, by the alternation of stretches of dry sand (the ridges) with stretches of water-logged ground (the runnels) when driving across them. Such 'ridge-and-runnel' zones are very prominent in the coastal belt south of Puttalam Lagoon, on the west side of Kalpitiya Peninsula, in the coastal stretch between Batticaloa and Kalkudah, and around Point Pedro. These wide stretches of unconsolidated sand are in fact old beaches formed by the ebb and flow of the tide over a shallow sea floor.

Other raised beaches are marked by the presence of terraces about five to fifteen feet above sea level and which are quite conspicuous features of the topography (Pl. 27A). One such raised beach occurs at Mundel, on the side of the Red Earth ridge there, as we have seen (p. 151), and others are found on the south and east coasts. Raised beaches are found, for example, on the inner edges of the lagoons around Hambantota, and near Trincomalee and Kalkudah where beaches of shelly sand and coral debris are found on headlands a few feet above sea level. A wide, level sand platform, about five feet above high water mark, is also seen between Batticaloa and Tirukovil ; this too appears to be a raised beach.

Sand Dunes

Sand dunes, which we have noticed briefly in Chapter 4, are a striking feature of the north-west, north-east, and southern coastlines, and are particularly well displayed along the north-west coast, especially between Chilaw and Kalpitiya.

Beginning from Chilaw, it is easy to make out that the road along the Chilaw sand spit (Beach Road) runs on the edge of a zone of low, shifting sand dunes, while about a hundred yards to the east is a narrow zone of high sand dunes whose leeward slopes fall steeply to the lagoon. This same division into low dunes and high dunes can be seen better north of Chilaw, between Battulu Oya and Palavi, and it becomes really marked in the Kalpitiya Peninsula. Here, the high dunes form an older, well-defined prominent zone on the east with tree species of the 'beach jungle'[34] growing to 8 or 10 feet in height, between which are clumps of shrubs and carpets of grass (see Pl. 24B). The eastern margin of this zone generally marks the western limit of cultivation in the Peninsula, though attempts are now being made to grow betel and coconut within the dune zone. The high dunes, rising to 15 or 20 feet, sometimes more, can be seen almost by the side of the road near milestone 8¼, at Narakkali village. These high dues extend for the length of the Peninsula and the zone varies from ½ to 3 miles in width.

On the west of this high dune zone is the zone of low dunes, up to half a mile wide, in which the dunes seldom rise to over 5 feet and are generally about 2 or 3 feet high. These form a low, hummocky surface on which only grass and ground creepers like *Spinifex littoreus* and *Zoysia matrella*[35] grow, shrubs and trees being completely absent.

The source of the sand in the dunes is the wide sandy beach that lies west of the low dune zone. It is interesting to note that there are two zones of high dunes separated by low-lying swampy, clayey ground in the middle of the Kalpitiya Peninsula ; the low ground is probably a former arm of the present lagoon. Owing to the lack of cultivation on the dunes, the areas in which they occur are marked 'sandy scrub' on the topographical maps. Further north from Kalpitiya, in the Dutch Bay Peninsula, sand dunes, sand bars, and ridge-and-runnel beaches of comparatively recent formation can all be seen.

Well marked zones of sand dunes are also found in the extreme north-east of Ceylon, between Point Pedro and Elephant Pass. These form the eastern coastline of the Jaffna Peninsula and are in fact part of a very long tombolo joining the Jaffna Limestone platform to the mainland. Very pure sands suitable for glass-making are found in these dunes. In the south, around Hambantota, the dunes separate a line of lagoons or *lewayas* from the sea and here the sands are reddish in colour due to the presence of garnet grains (Pl. 23B).

The marked NE-SW trend of the sand dunes in all parts of the Island is very marked, a feature brought out in aerial photographs by the pattern of the vegetation growing chiefly along the crests of the dunes (see Pl. 25). This constant orientation is the result of the dominating influence of the south-west and north-east monsoonal winds on the coasts, the dunes being elongated parallel to these directions.

Lagoonal and Estuarine Deposits

North-west Coast

Most lagoons have slow, sluggish rivers flowing into them, and these rivers are continually depositing fine silt and clay on the lagoon floors and gradually filling them up. Slight changes in sea level lead to portions of the lagoon floors being lifted up above the sea level and subsequently being covered by water only from time to time. Such 'lagoon flats' or 'barrier flats' can be seen within and around most lagoons today (see Fig. 58A). In course of time they become covered with a layer of sand and then only very rarely are they submerged. These barrier flats, with water channels (or creeks) running between, ultimately acquire a vegetation cover of a very special type and are now found away from the immediate vicinity of the lagoons. Such flats are found extensively in the area south of Mundel lake and east and south of Puttalam Lagoon (Pl. 26A) ; they can also be seen immediately around Puttalam town on the north, east and south.

The clays which form the floors of the lagoons and the surrounding flats are generally dark bluish grey in colour and are highly plastic when wet but extremely hard when dry. They may be present below several feet of sand and sandy clay and often contain the shells of living brackish-water forms such as oysters. This was the case when excavations were being made for the foundations of the new bridge at the 53rd mile on the Chilaw-Puttalam road ; large quantities of the flat shell of the window-pane oyster *Placenta* were dug up with the dark clay. As this locality is about a mile from the mouth of the Deduru Oya (Fig. 57) it must be presumed that the Deduru Oya formerly flowed into a lagoon that extended much further east than at present. This is only part of a process taking place at the estuaries of rivers, where sea water flows in and out of the many distributaries, creeks and backwaters so common in these estuaries. Here, clayey deposits with marine or brackish-water forms of life alternate with sands and clays with fresh-water forms.

Another excellent example is seen at Ilavankulam, at the bridge near milestone 18 on the road from Puttalam to Marichchukkaddi. At this point is an outcrop of indurated sandstone rich in lamelllibranchs (Pl. 27B) and oyster shells (*Placenta* sp.) A few yards along the road going westwards from this point is another bridge and here can be seen an oyster bed about 6 inches thick resting on a pebble bed with rounded quartz pebbles up to 4 inches in diameter. The upper part of the succession suggests that this is an estuarine deposit, now elevated to about 10 feet above sea level.

West Coast

Such conditions are very common around the coasts of Ceylon and they have existed for much of the Quaternary era. One of the best documented examples is the Beira Lake where a series of bore holes drilled across the lake showed that this irregular expanse of water once formed part of the estuary of the Kelani Ganga (Fig. 59) and was submerged under the sea

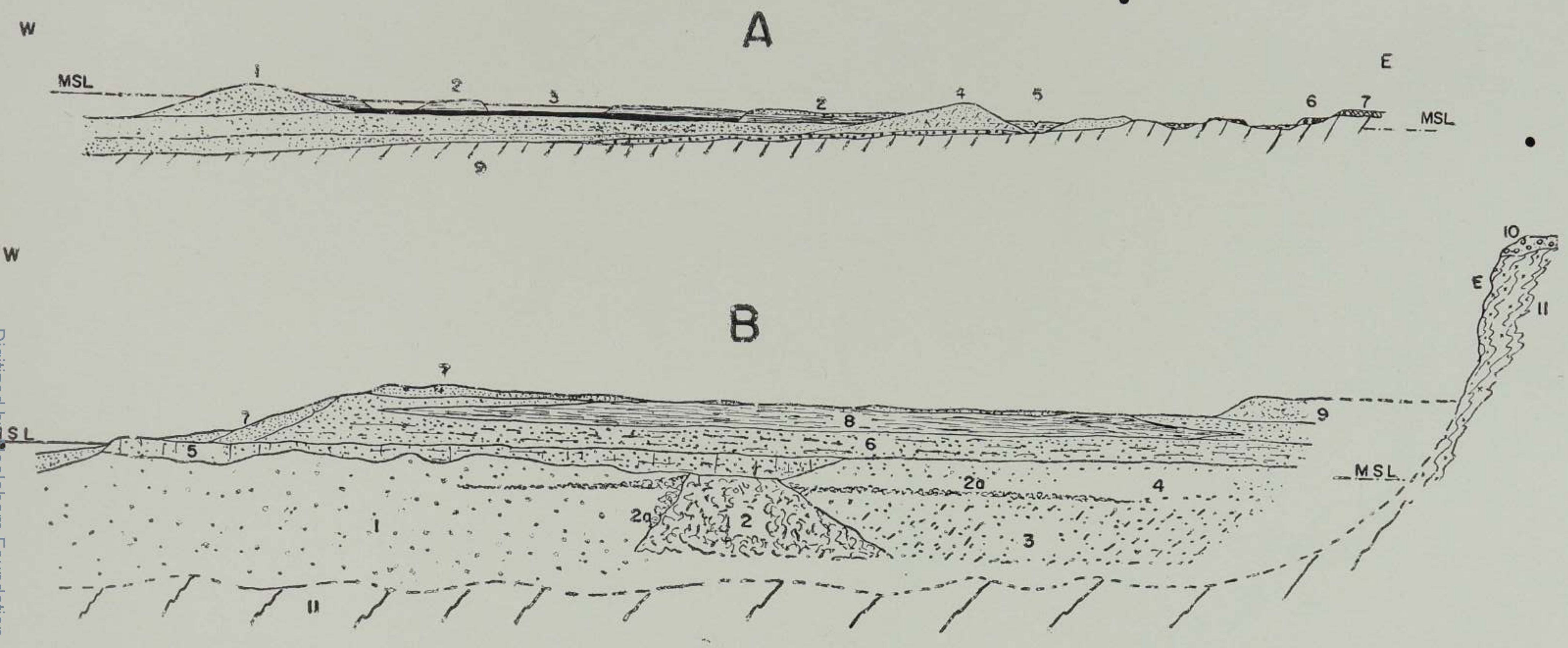


Fig. 58. Generalised cross sections showing successions of beds in coastal areas.

A. Across the north-west coast near Mundel.

(1) sand dunes, (2) barrier flats, (3) lagoon, (4) Red Earth ridge, (5) alluvial valley, (6) terrace gravel, (7) laterite, (8) basal ferruginized gravel, (9) crystalline basement.

B. Across the south-west coast near Wellawatte. (*E. J. Wayland*, 1916)

(1) fine sand, (2) coral reef, (2a) fragments and masses of coral,
(3) grey sandy clay, (4) unconsolidated sand, (5) sandstone,
(6) vegetable earth and sea sand, (7) recent beach and blown sand,
(8) vegetable earth, (9) ancient beach and blown sand,
(10) implementiferous plateau gravels, (11) ancient crystalline rocks.

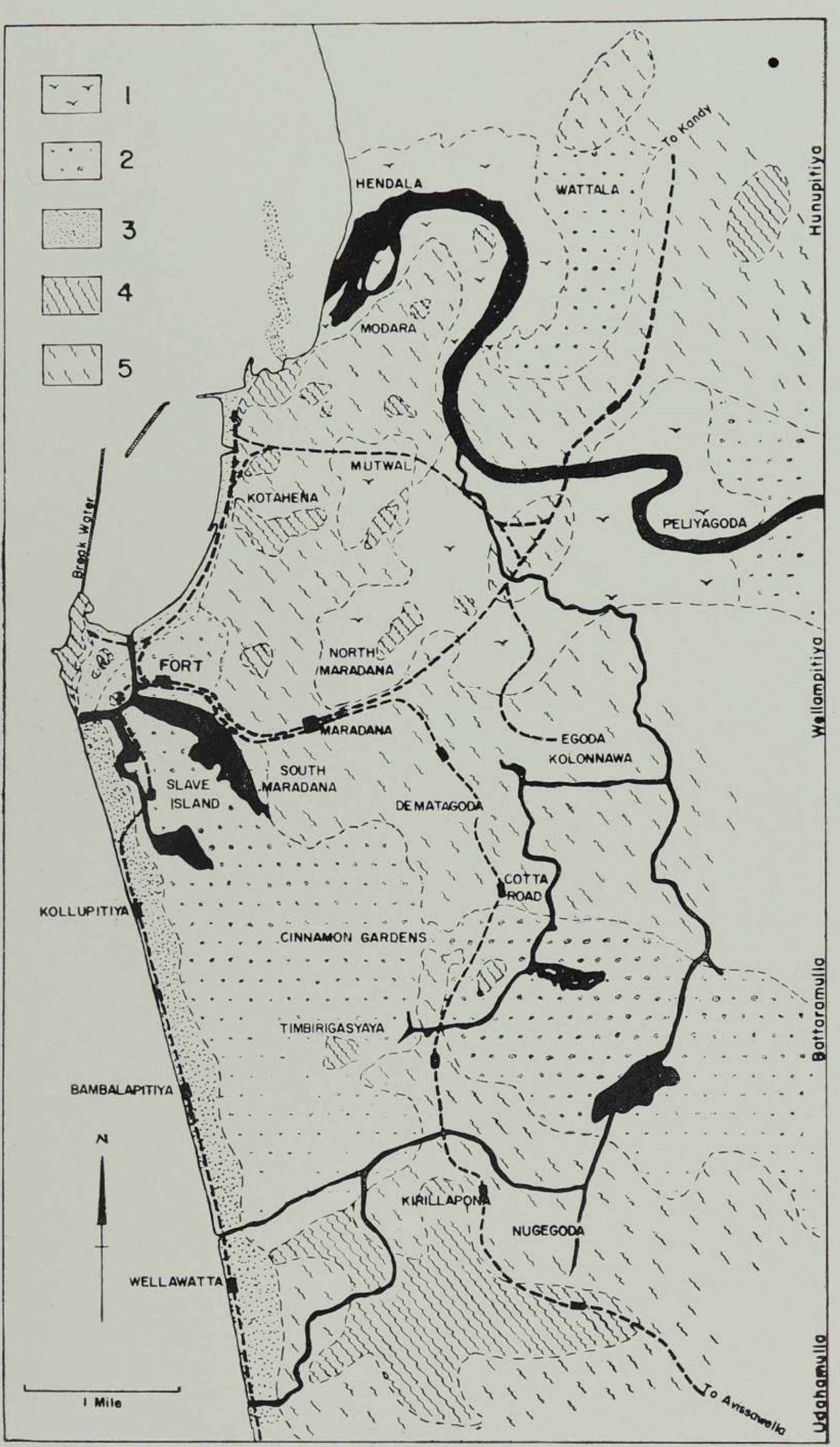


Fig. 59. Sketch map of the geology of the Colombo area.
(*After D. N. Wadia*, 1941)

(1) alluvium, (2) sand and semi-compact sandstone, (3) littoral shelly sandstone, (4) crystalline rock outcrop, (5) laterite; Solid black—rivers, canals and lakes

at least twice in its recent history. This is shown by the sequence of stratified deposits, 30 feet thick, reaching down to the actual bed of the Beira Lake[36]. These deposits are (see Fig. 60A.), reading from bottom to top:

(5) Coarse, white river sand, resting on lateritic cap of gneissic bedrock, 1-3 feet ;

(4) Dark coloured clay with decayed wood of living tree species, representing slightly submerged marshland ;

(3) Grey and black silty clay with plentiful marine shells, at places a shelly marl, representing a marine submergence, 8 feet ;

(2) Peaty silt, with much vegetable matter but no marine shells, represents uplift above the sea, 2-3 feet ;

(1) Lacustrine silt with marine shells of living species, represents a second submergence, 2-3 feet.

Another recorded example of this type of succession of beds is known from near the coast at Wellawatte (Fig. 58B). Underneath a layer of blown sand on the surface is a deposit of vegetable earth indicating a land surface ; below this is a layer of vegetable earth and sea sand, probably caused by swamp conditions ; below that is a stratum of sea sand with marine shells overlying a reef or stratum of coral fragments. The coral reef rests on coarse grey sandy clay which is identical with the mud-flat deposits near Puttalam[37].

South Coast

Several examples of similar conditions are known from the south coast. At Hatagala, for example, 6 miles west of Ambalantota, shell beds are found at 15 feet above sea level, more than one mile from the coast[38]. These beds thin out towards the sea and several mounds between Hatagala and the coast are capped by remains of shell beds, sometimes only a few inches thick. The section at Hatagala (Fig. 60B), through nearly 17 feet of deposits, shows a succession of blue and black shell-bearing muds, with intercalations of sand and sandstone. The shells belong to a mixture of recent marine and fresh-water forms such as *Carium, Cerythium Planorbis,* and *Cyprea*, indicating a brackish-water marginal environment of deposition.

Patches of shell-bearing clayey beds are also found at intervals along the rims of the Hambantota lagoons. These shells belong to existing species and the beds are 12 to 20 feet above present sea level. On the other hand, shells of the window-pane oyster *Placenta placenta* and of gastropods have been dug up from pits 6 to 10 feet below sea level, in a wide stretch of alluvium north of Matara, at Attaduwa and Nadugala[15]. Both localities are some distance north of the present sea coast * and at the former the bed is of fine greenish-grey lagoonal mud.

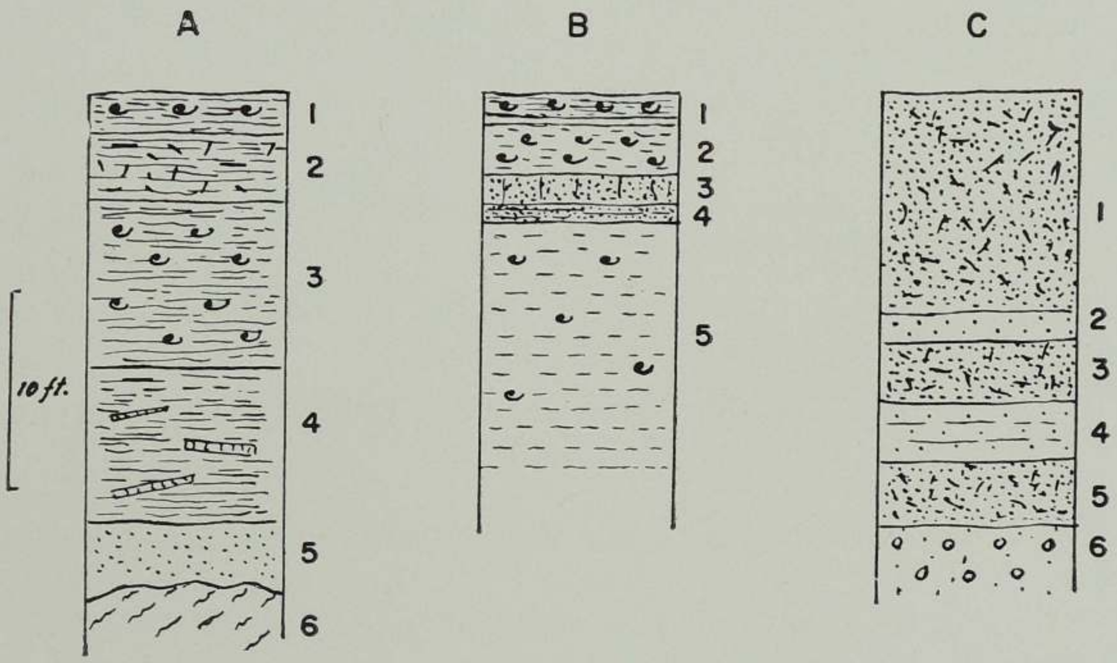


Fig. 60. Generalised sections showing sequences in typical estuarine (A and B) and lacustrine (C) beds.

A. Beira Lake. (*After D. N. Wadia*, 1941)

(1) silt with marine shells, (2) silt with vegetable matter, (3) silty clay with marine shells, (4) dark clay with tree remains, (5) white sand, (6) lateritic cap.

B. Hatagala. (*Drawn from data by J. A. Daniel*, 1908)

(1) abundant shells in black mud, (2) shells with blue-black mud, (3) gritty yellow sandstone with few shells, (4) thin alternating beds of yellow sand and black mud, (5) blue clay with some shells.

C. Culvert 14/2 on the Galagedera-Kurunegala road. (*Drawn from data in P. E. P. Deraniyagala*, 1958)

(1), (3), (5) black sand with vegetable matter, (2) white sand, (4) laminated white sand, (6) gravel (white sand and pebbles).

North-east Coast

Another good example is the Salape Aar estuary, about 22 miles north of Trincomalee and just south of Kuchchaveli, first described by Coomaraswamy in 1905[39]. (A map of the estuary with the fossil-bearing localities marked is found in Deraniyagala[15].) Here a bed of fossiliferous clay with coral occurs about 2½ miles inland from the present coast and at a depth of 10 feet below the surface. The fossils are mainly crab shells of estuarine species (*Callianassa, Schylla serrata* and *Macropthalmus latreilli*) but

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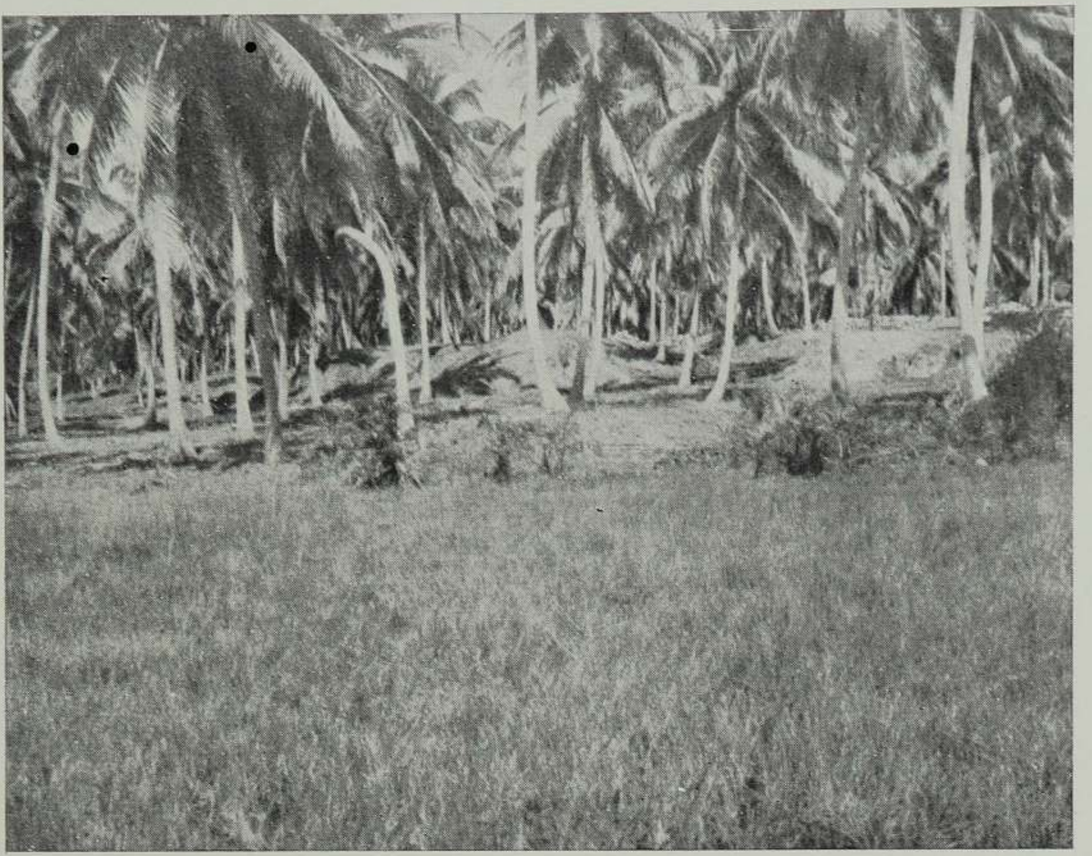
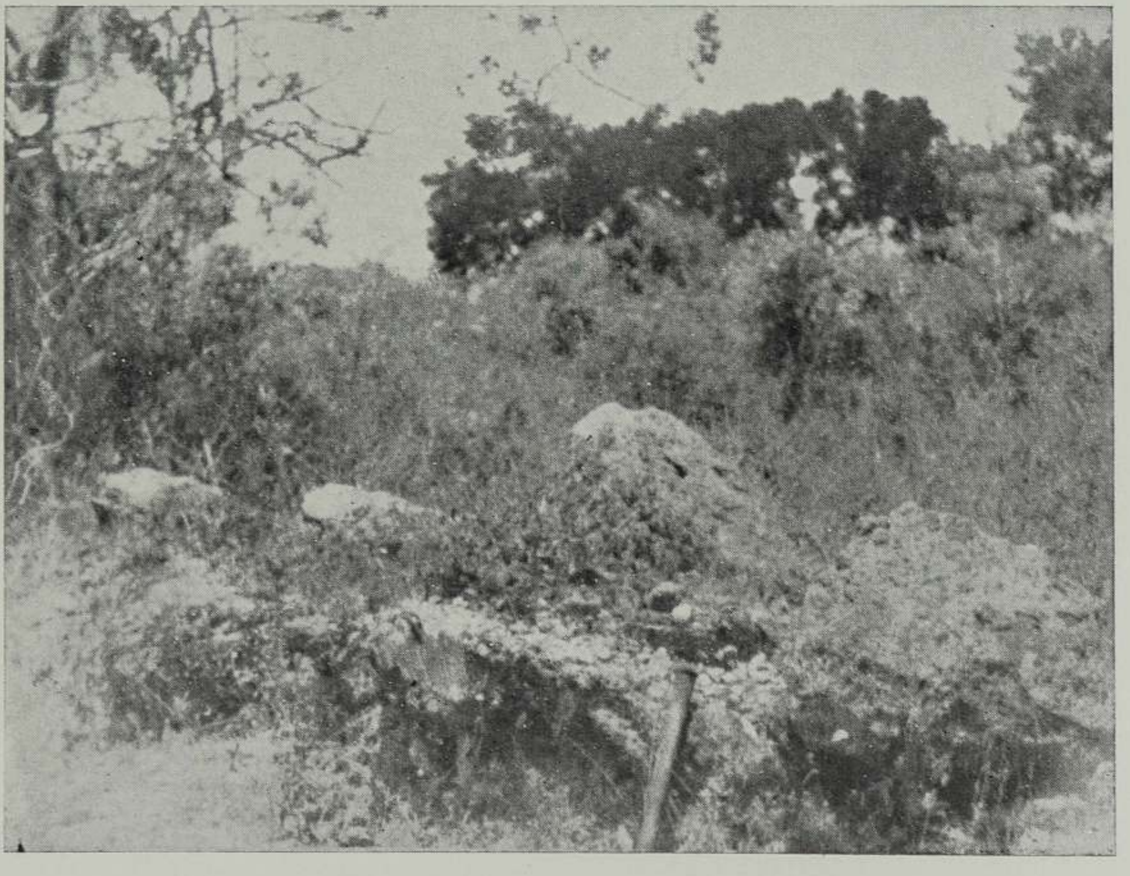
* Attaduwa is four miles from the sea and ¾ mile from the Nilwala Ganga ; Nadugala is one mile from the sea and 1¼ miles from the Nilwala Ganga.



A. Raised beach, Kalladichena. (*K. S. O. Perera*)



B. Shelly sandstone, Ilavankulam.

together with them are oyster shells of the window-pane oyster and other littoral species. Coprolites (mineralized excreta) of what is probably an estuarine crocodile (*Crocdylus porosus minikanna*) occur with the crab shells[15].

Muthurajawela Swamp

A special type of lagoonal deposit is the peat swamp at Muthurajawela, a few miles north of Colombo, which is bounded on the east by a belt of laterite and on the west and south by recent alluvium and sands. The swamp represents the southern extension of the Negombo lagoon which has been silted up during Quaternary times (see p. 79).

The peat, which is about 20 feet thick in places, represents the debris of several generations of forest and swamp growth that have been swept into the marshes, together with the remains of brackish-water vegetation which grew in the lagoon itself. The presence of abundant molluscan shells of living species at certain levels within the peat shows that several temporary depressions of the land must have occurred when sea water inundated the lagoon and swamps. It is also clear, from the presence of lenses of sandy clay and clayey sand, that conditions of deposition within the swamp must have changed from time to time. The peat deposits rest on a basement of decomposed gneisses.

Three main types of peat have been recognised at Muthurajawela, classified largely according to the type of organic matter found in each[40].

(*a*) *Shrub-and-tree group*. The peat of this group is composed mainly of the remains of trunks, branches, bark, roots, and twigs of trees and shrubs. The remains of the vegetable matter are clearly recognizable and form a tangled mass in a matrix of finely divided material. The texture is compact and hard objects such as tree trunks are occasionally found.

(*b*) *Reed-and-sedge group*. Peat of this type consists largely of the remains of sedges, reeds, grasses and other swamp vegetation. This type is light and spongy and has a fibrous, strongly matted appearance; it may have formed near the borders of the swamp.

(c) *Humus peat group*. This peat is very different from the others and is so decomposed that the identity of the vegetation cannot be recognized. It is dark brown in colour and is in the form of a thick slurry with finely comminuted plant remains. Its occurrence is very local.

Aerial photograph of the Mi Oya delta, north of Puttalam. Note the meandering forms of the distributaries, the submerged deposits off their mouths, and the outward growth of the delta.

Hunting Survey (*now Lockwood Survey*) *Corporation, Canada. Crown Copyright Reserved*)

It will be seen from the many examples of lagoonal and estuarine deposits quoted above that the fossil-bearing horizons in these deposits are above sea level in some instances and below it in others. This fact, as well as the frequent alternation of sands and clays, shows very clearly that there have been many fluctuations of sea level around the coasts of Ceylon during the Quaternary period ; we shall read more about such fluctuations when we trace the geological history of the island in a later chapter.

Alluvium

Alluvium, in its broadest sense, is applied to the detrital clay, silt, and sand brought down by streams and rivers and deposited in their flood plains and deltas. Alluvial deposits thus cover relatively large areas in Ceylon, particularly in the lowest peneplain, where the rivers flow sluggishy or even dry up in the Dry Season but overflow their banks during periods of flood. The stretches of alluvium are particularly extensive near the coast, as in the case of the Bentota Ganga, Mi Oya (Pl. 28), the Mahaweli Ganga, and Kelani Ganga (Fig. 59) to quote only a few ; many rivers have several distributaries flowing into the sea and spread their alluvium over several square miles.

In many river valleys, too, gravel beds can be seen on the banks of the rivers. These gravels are loose and unconsolidated, with little clay material. In the north-west, the sizes of the pebbles are comparable to those in the Terrace Gravel, and it is probable that the present rivers have eroded this formation and re-distributed the pebbles in later and lower terraces. An example of a modern terrace gravel is seen at Nuwara Eliya at the confluence of the Talagala Oya with the Nanu Oya.

The clays, sands, and mixtures of clay and sand of the major river valleys are economically important for several reasons. They are rich agricultural soils ; they carry large quantities of groundwater ; they provide raw material for the brick and tile industry, as along the Kelani Ganga valley ; and they provide vast quantities of sand for the building industry.

These alluvial deposits may be quite thick, as much as 80 feet in places, as at Manampitiya. Alluvium in the Kelani Ganga valley near Malwana is nearly 50 feet thick, and goes down to about 18 feet below sea level ; it is made up of alternating layers of sandy and clayey sediments[32].

This great thickness of the alluvium is the result of the gradual subsidence which has taken place in the coastal belt during Quaternary times. The subsidence has been general along the west coast as can be seen in the instance of the Kelani Ganga quoted above and in the case of the Kalu Ganga. The bed of the Kalu Ganga is 60 feet below sea level a few miles from its mouth, where the water can only be a foot or two above sea level.

At times, peaty layers are found within alluvium deposits as in the Ratnapura Beds, and these show that swamps and lakes have occupied part of the river courses during their history. One of the best described examples of such a deposit is found between Galagedera and Weuda on the Kurunegala road, in the valley of the Dik Oya, a tributary of the Deduru Oya[15]. In a section by the road (Fig. 60C) can be seen alternating layers of white sand and fine black silt with decaying vegetable matter, to a depth of about 20 feet. According to tradition, a lake existed here in the time of King Buddhadasa, about 300 A.D., and this is supported by such names as Weuda (above the lake), Wewa Devale (temple on the lake), Weralagama (beach village), and Mattibokka (clay bay) close to each other in the locality.

Coral Reefs

Coral reefs, too, are found at several points off the coast of the island, the best known being those at Colombo, Mt. Lavinia, and Hikkaduwa. Others, not so well known, are found on the west side of the Kalpitiya Peninsula, between Puttalam and Mannar, fringing the north coast of the Jaffna Peninsula, and on the east coast between Vakarai and Kalkudah (see Fig. 28). Coral reefs are still being formed along parts of the coast.

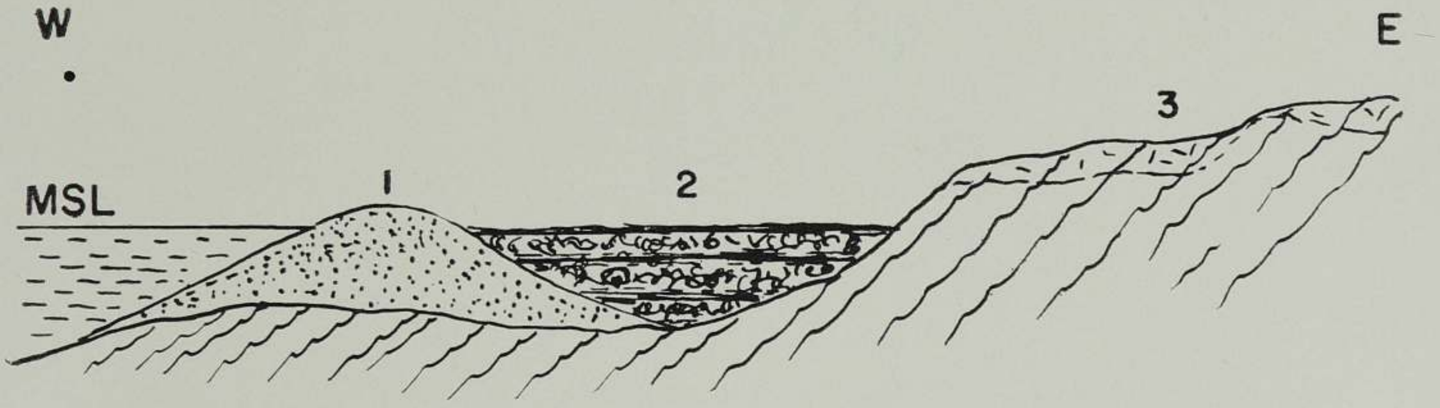


Fig. 61. Generalised section across the coral swamp at Akurala. (*After D. N. Wadia, field notebook*)
(1) Sand barrier, (2) coral, (3) laterite.

Elsewhere, however, large deposits of coral debris are found inland from the coast, as between Ambalangoda and Matara. The best known of these are the Akurala deposits which are about 1,000 yards wide and bounded on the west by a sand bar and on the east by a low plateau of decomposed crystalline rock (Fig. 61). The debris here is a mixture of pieces of coral, shell fragments, and fine sand as well as complete shells of various forms, most prominent of which is the giant clam *Tridacna squamosa*[15]. The deposit is about 20 feet thick and appears to be an accumulation of debris washed off the outlaying reefs by storm waves and covered by later sand. This debris is being excavated on a large scale for lime-burning, and piles of it can be seen on both sides of the main road for a distance of about 2 miles. Where the coral debris has been excavated, large swamps and pools of water now exist. Similar accumulations of coral debris are found on some present day beaches, as at Foul Point, Tricomalee, where they have been washed ashore by storm waves which break up the off-shore coral reefs.

SECONDARY FORMATIONS

Laterite

Laterite, locally known as *cabook,* is the most extensive of the secondary formations, and is a product of the weathering of the rocks underlying it. Further, true laterite is found only within a well marked coastal belt in the Wet Zone of Ceylon, and is restricted to the south-western part of the island.

The most important physical property of laterite is that the freshly dug material is soft enough to be cut into blocks but upon exposure to air it rapidly becomes as hard as brick and highly resistant to the action of air and water. In fact, the indigenous local name for laterite in many languages in S. India is 'brickstone' and it was this that led Buchanan, in a book called 'A Journey from Madras' written in 1907, to coin the word laterite from the Latin word *later* meaning brick[41].

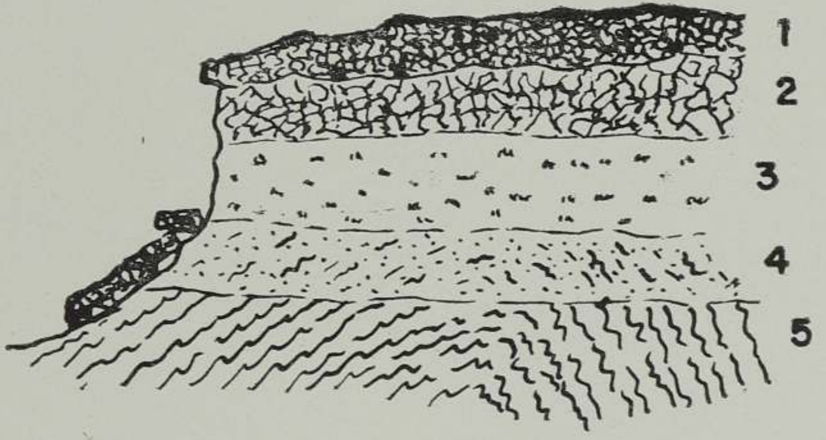


Fig. 62. Diagram of a typical laterite profile.
(*After D. B. Pattiaratchi and J. W. Herath*, 1963)

(1) ironstone cap, (2) hard, vesicular to concretionary laterite, (3) soft, mottled kaolinitic zone, orange yellow to yellow in colour, (4) decomposed bedrock, (5) fresh bedrock.

Very detailed and vivid descriptions of laterite are found in the writings of Newbold and it is worth quoting the following passage in full. According to Newbold,[49]

> 'The laterite of Beder, generally speaking, is a purplish or brick-red, porous rock, passing into liver brown, perforated by numerous sinuous and tortuous tubular cavities either empty, filled, or partially-filled with a greyish-white clay passing into an ochreous, reddish and yellowish-brown dust; or with lilac-tinted lithomargic earth. The sides of the cavities are usually ferruginous and often of a deep brown or chololate colour; though generally not more than a line or two in thickness, their laminar sructure may frequently be distinguished by the naked eye ...... The interior of the cavities has usually a smooth polished superficie (surface), but sometimes mamillary and stalactiform on a minute scale... The hardest varieties of the rock are the darkest coloured and most ferruginous. The surface masses of the softer kinds present a variegated appearance. The clay and lithomarge exhibit lively coloured patches of yellow, lilac and white, intersected by a network of red, purple or brown.'

Laterite can thus be defined as a highly weathered, clayey, rock material rich in secondary iron or aluminium oxides but poor in silica, and either massive or vesicular (full of cavities) in structure; it is usually reddish, purplish, brownish, or yellowish in colour, and very few recognisable minerals are present in it. Although the exact chemical processes by which laterite is formed are not fully known, the broad principles underlying the process of lateritisation can be stated. It is known, for example, that an alternation of a wet and a dry period in the climatic conditions of the area where it forms is necessary. During the wet season, when the water-table is high, slica and the alkali metals like sodium, pottassium, and calcium, are leached out of the rocks and carried away. During the dry season, when the water table is low, iron and aluminium oxides in their hydrated forms are deposited in the laterite-forming zone.

Various forms of laterite are present throughout the tropical regions of Asia, Africa, S. America and Australia, and it is also known to occur as 'fossil laterite' in temperate regions that have experienced a tropical climate in past geological ages. A good example of such fossil laterite is the laterite horizons found within the Tertiary volcanic lava flows which make up the plateau of Antrim in north-west Ireland.

Laterite is best developed in the south-west of Ceylon within a belt extending six or seven miles inland from the coast and up to about 100 feet above sea level. Good examples can be seen at Ragama, Hunupitiya, Colombo, Homagama, Beruwala and Ambalangoda, where the laterite is exposed in quarry faces and in road and railway cuttings. In nearly all these localities laterite can be seen to have developed by the weathering of many types of crystalline rocks such as charnockites, garnet-biotite gneisses, and amphibolites ; this is shown by the presence of unweathered or partly weathered blocks of these rocks within the laterite horizons, and by the continuation of the foliation of the underlying gneisses through the laterite above.

The presence of laterite boulders in streams above the 100-foot level suggests that laterite was once more extensive than at present, and layers of nodules and small pellets of lateritic ironstone in valleys, streams, and low ground indicate that the more massive laterites have been or are being broken down.

A typical cross-section through laterite from Hendala (Fig. 62) shows the following zones from top to bottom[48] :

A—ironstone cap (ferricrete) forming a hard crust, which, where exposed, is breaking down to nodules and pellets ;

B—laterite, hard and cellular, with a skeleton of iron oxides and clay-filled cavities ;

C—soft, clayey laterite in various colours ;

D—weathered bedrock showing traces of the structure of the parent rock and in which the feldspars are kaolinised ;

E—parent rock of garnetiferous gneiss.

The total thickness of the laterite here is about 75 feet but elsewhere in the south-west it ranges from 20 to 100 feet in thickness.

The laterite now seen in the south-west region was formed during the Quaternary period, and the process is still continuing. Laterite is an important building stone in this part of the country.

Nodular Ironstone

In many parts of the island, but particularly in the Dry Zone, it is common to find an iron-rich layer or 'hardpan' either at the surface or just below it. This formation has been called by such varried names as 'nodular gravel', 'pisolitic gravel', or 'lateritic gravel' but a more convenient group name for it is *nodular ironstone, or ferricrete* when it forms a continuous crust.

Such a layer of nodular ironstone is, as we have seen (p. 153), present at the top of the terrace gravel at Erunwala. In it, small pebbles of quartz and grains of sand are cemented together into pellets and nodules by iron oxides, the size of these concretionary bodies increasing from the top of the layer to the bottom (Pl. 29A). The nodular ironstone layers at Erunwala and Kalladi are 6 inches to two or three feet thick (see Fig. 54) and are overlain by several inches of reddish-brown sandy soil; the same features can be seen wherever the terrace gravels are exposed.

We have also noticed that the upper layer of most laterites is in the form of a ferricrete cap or crust, formed by the aggregation of small pellets and nodules of iron and lying above the layer of vesicular laterite. The ferricrete is brownish black in colour, contrasting with the softer laterite below, has a smooth, almost polished, surface, and is botryoidal (= 'cluster of grapes') in form. The pellet-like concretions pass downwards into larger nodules exactly as they do in the terrace gravel, but these nodules only contain angular fragments of quartz.

The most extensive type of nodular ironstone is found on top of the crystalline rocks of the Dry Zone, where it has formed from the disintegrated rock material lying above these rocks. It can be seen in many places in the northern half of the island and especially in the area between Puttalam, Kurunegala, and Galgamuwa. The nodular ironstone in this part of the country forms caps to the small hillocks and undulations which are typical of the topography here and is made up of nodules of angular to sub-rounded grains of quartz and other minerals as well as small pellets of ironstone cemented together by iron oxides. The nodules are dark brown in colour and are often mixed with yellowish to brownish clay. Where not exposed at the surface, the presence of the ironstone is revealed by the brownish, rusty colour of the water in the wells sunk in it.

This type of nodular ironstone, unlike the ironstone of the gravels, passes downwards into disintegrated rock material and finally into a crystalline floor on which it rests, sometimes filling cracks and fissures in the granites and gneisses which form this floor.

All these nodular ironstones have certain common features. In places they may form a continuous flattish crust on the surface but elsewhere they may be broken up into blocks, boulders, and pellets of ironstone. They are all formed in place from the underlying material and have not been transported from elsewhere. Finally, nodular ironstone is used extensively as 'gravel' for road surfacing, the number of roadside pits on the Puttalam-Kurunegala road bearing witness to this.

The stages in the formation of nodular ironstone can be seen in many sections in gravel pits, and can be described as the upward migration of hydrated iron oxide and its deposition in layers and concretions in the upper horizons. The formation of nodular ironstone thus appears to be a response to climatic conditions, namely, heavy rainfall during which iron oxide is leached from the rocks, and a hot dry season during which evaporation results in the capillary movement of the iron oxide to the surface. The process is thus similar to lateritisation in some respects.

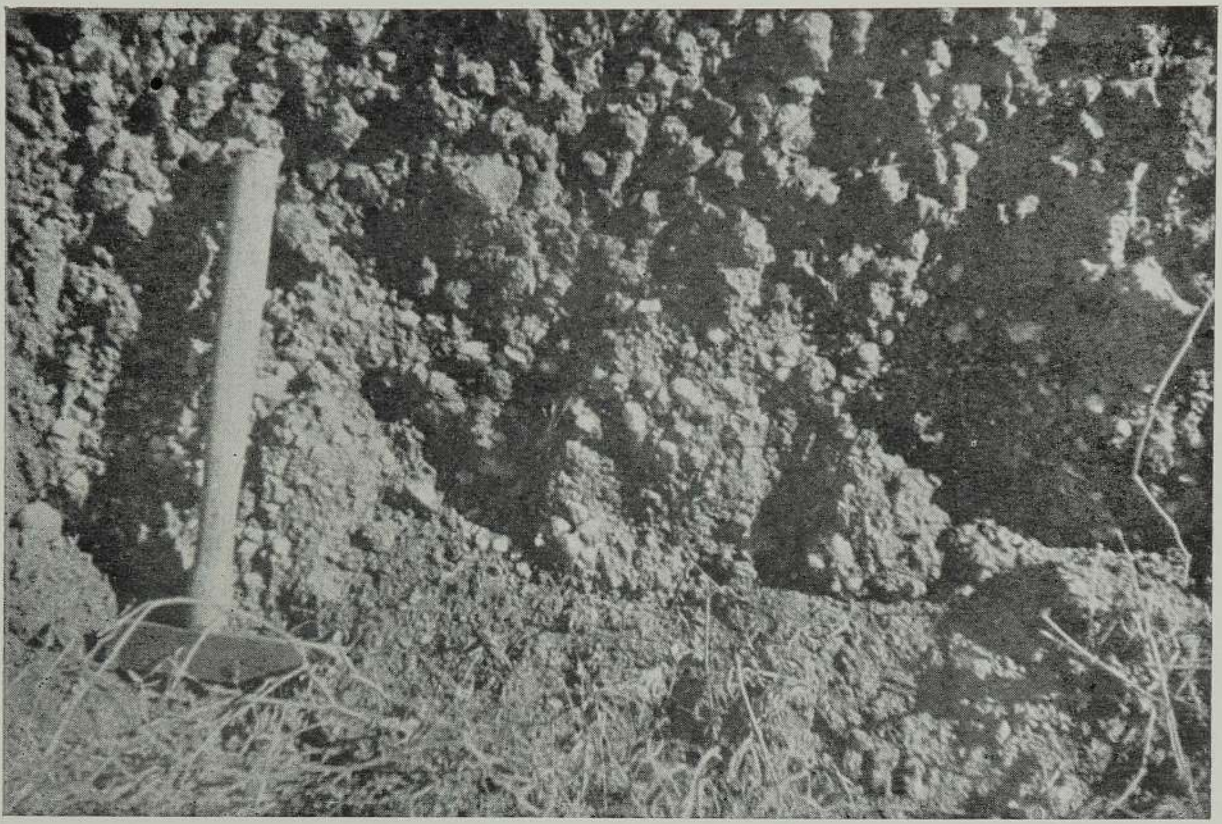
Chert

Chert is an amorphous or non-crystalline form of silica and it is generally found within other rocks (such as granulites, gneisses, and crystalline limestone), as bands, layers, veins, and cavity infillings. It is a secondary deposit formed by silica-bearing solutions which traverse these host rocks, and it sometimes even replaces pre-existing minerals. Chert varies in quality from an opaque, splintery substance to a type that is translucent in thin flakes. Cherts are seldom homogeneous, some being mottled, others brecciated or conglomeratic, and still others containing strings or rosettes of fibrous silica ; white, laminated (finely layered) chert is also seen in places, as in the lower part of the Moderagam Aru basin[30].

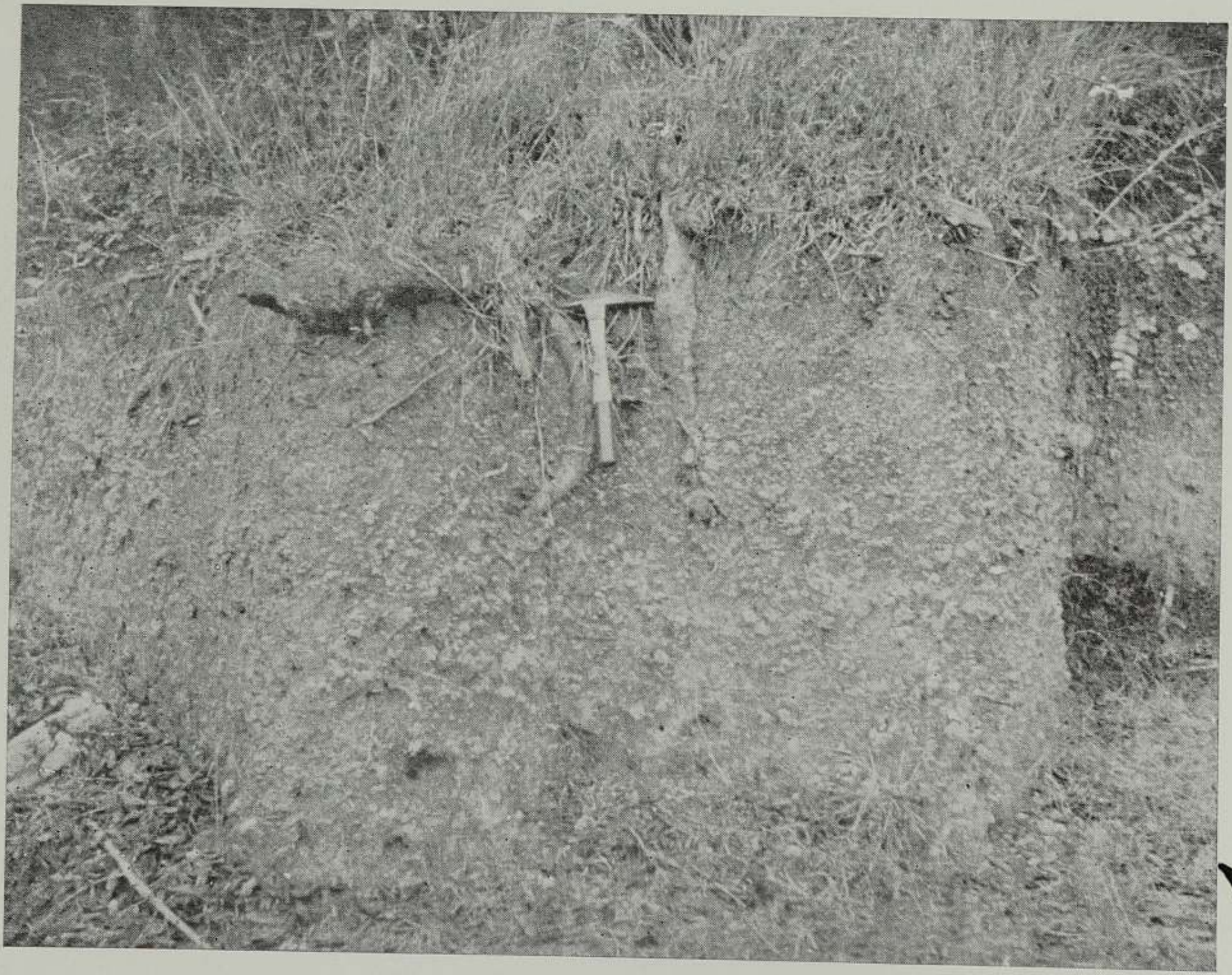
Large boulders of massive chert are often met with in the Dry Zone, particularly in the north-west of Ceylon. In the Wilpattu area, for example, large blocks of chert in variegated colours ranging from black to red can sometimes be seen ; elsewhere they may be white, brown (Sinh. *ginigala*), greenish brown, buff, grey, bluish, or greenish in colour. At Aparekka, near Galle, chert boulders mark the outcrop of a corundum-bearing pegmatite ; several bands of chert are also found in the eastern part of the Ambalangoda area.

Chert is extremely difficult to break, and when it does it does so with a conchoidal or curved fracture. For the latter reason Stone Age man used it extensively for making stone tools, specimens of which can be picked up in many of the gravel deposits of the island. Brown chert, which is the commonest variety, was used by the Sinhalese in former days, and also probably by the Portuguese, Dutch, and British, for making gun-flints.

Other forms of secondary silica found in Ceylon are pure *chalcedony*, common *opal* (in the Kal Aru basin), and red and yellow *jasper* (near Pomparippu), but these are relatively rare.



A. Nodular ironstone, Kottukachchiya.



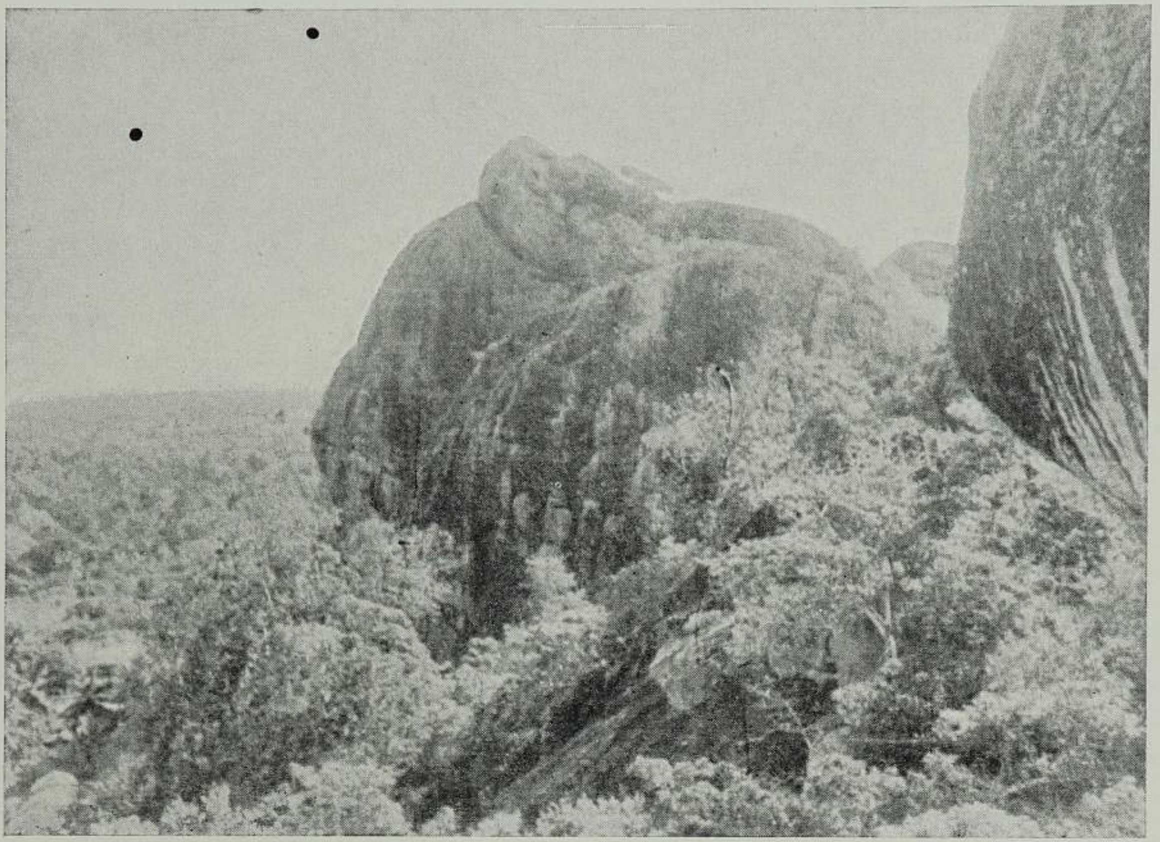
B. Nodules of *kankar* (Calcium carbonate) in soil, Karodipooval.

Travertine and Kankar

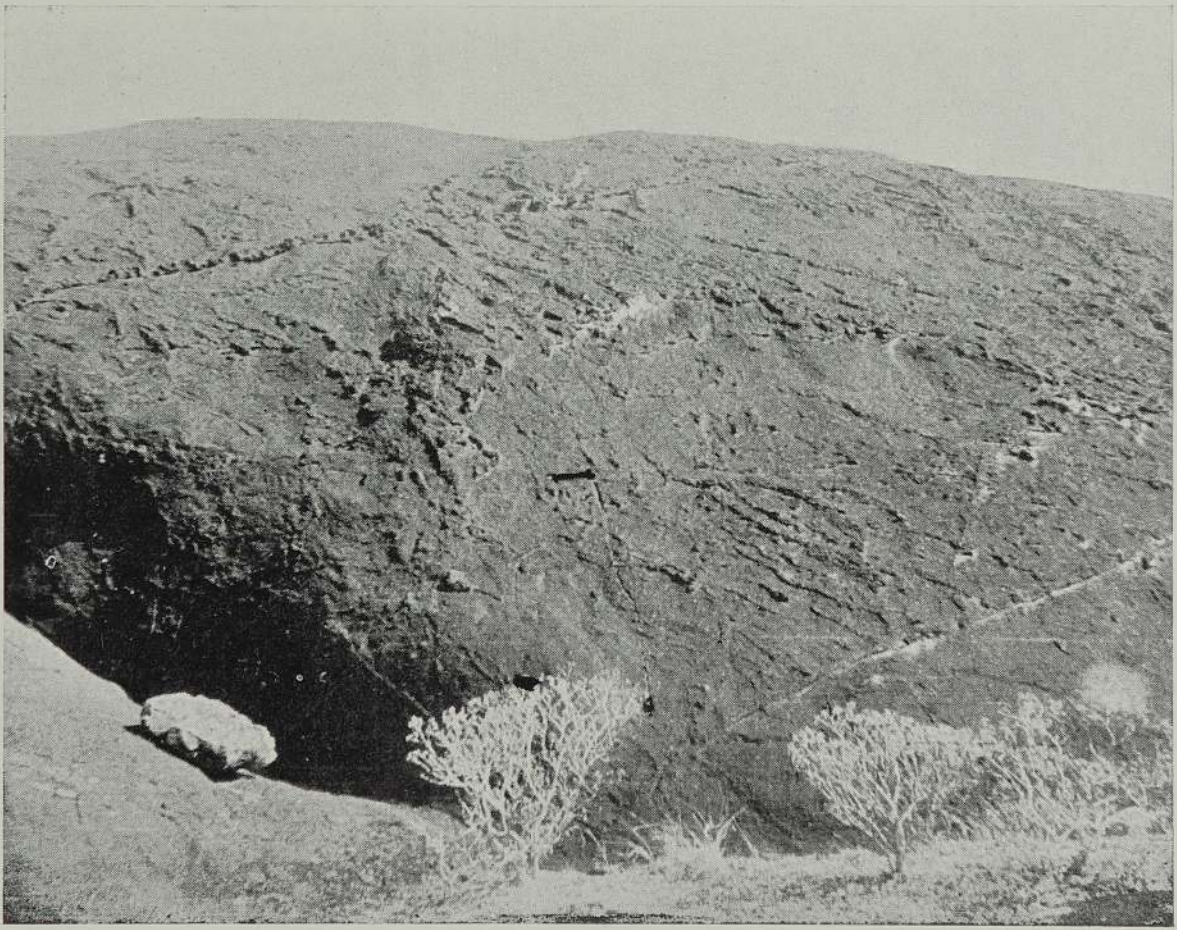
Travertine and kankar are two forms of calcium carbonate, both secondary in origin. Travertine is light-coloured, cream, compact calcium carbonate very often met with near crystalline limestone bands. It has been reported from such widely-separated localities as Agratenne (near Passara), Bibile, Mankulam, Talawa, Dombakota (near Habarana), Tellula and Pelawatte (near Weragantota). In all these instances, calcium carbonate is dissolved from crystalline limestone by running water and carried in solution until it is precipitated elsewhere.

Travertine is often deposited on the leaves, branches, trunks, and roots of the trees, sometimes forming a step-like series pools of clear water in the midst of the forest.

Kankar is a nodular form of calcium carbonate and is generally in white or yellowish white nodules. It occurs mainly in the Dry Zone within a few inches of the surface (Pl. 29B). Kankar is commonly believed to have formed by the leaching out of calcium from the silicate minerals of the underlying gneisses and by precipitation from solution during the dry periods.



A. Erosion remnant of Tonigala Granite, Paramakande.



B. Bare weathered surface of Tonigala Granite showing presence of numerous cross-cutting dykes and veins, Tonigala, behind P.W.D. Lines.

CHAPTER 9

INTRUSIVE AND EXTRUSIVE ROCKS

THIS chapter has been headed 'Intrusive and Extrusive Rocks' rather than 'Igneous Rocks' because, within recent decades, geologists have found that some granites and allied rocks, though apparently intrusive, have not crystallised from molten magma and therefore cannot strictly be called 'igneous'. Very few true igneous rocks are found in Ceylon, the commonest being dolerite. Other basic and acid igneous rocks like gabbro, basalt, and rhyolite are completely absent.

Dolerite

Dolerite dykes are present both on the eastern and western sides of the Island, but they are comparatively restricted in their occurrence. The largest and best known of these dykes is found at Gallodai, where it crosses the Badulla-Batticaloa road near the 57th milestone. The outcrop of the dyke is marked by a line of large boulders of dark, heavy, medium-grained rock on either side of the road. On account of the resemblance of the weathered surface of the dyke to a rough road it used to be called the Gallodai 'causeway' (Sinh. *Kalubamma*) and thought to be an ancient road.

The Gallodai dyke has been traced for a distance of about 40 miles in a NW-SE direction, but it probably continues for a much greater length. For example, a similar dyke has been found in the bed of the Herati Oya in the Elahera area, in the same line of strike[44], the Gallodai Dyke may therefore be about 100 miles long. Other smaller dykes are found in the Elahera area where they appear to form a small parallel dyke swarm. Dolerite dykes have also been noted near Trincomalee, Kantalai, Kalkudah, and the Uda Potana lagoon on the east side of the Island[13].

A number of fine-grained dolerite dykes are also found on the west side, near Induruwa, Matugama and Badureliya, but these are all extremely narrow, often a few inches wide. The dyke rocks are dark greenish-black to black in colour, and pebbles of dolerite are common in some of the streams in this area.

Dolerite, because of the manner in which it is jointed, often undergoes a type of weathering known as spheroidal weathering. In this, the squarish, jointed blocks weather first around the corners until large spheroids of dolerite are surrounded by layers of yellowish-brown decomposed rock material and clay.

The actual age of the dolerites of Ceylon is not known, but they can be seen to cut across the Pre-Cambrian rocks, both the Highland Series and the Vijayan Series ; they must therefore have been intruded after the formation of the gneisses and other rocks of these Series.

Granites

The commonest intrusive rocks in Ceylon are granites, pegmatites, and granitoid rocks of various types. They occur as small plutons, as sheets parallel to the foliation of the surrounding gneisses, as cross-cutting dykes and veins, or as large irregular bodies intimately mixed with the gneisses.

Tonigala Granite

The best known of the granites is the Tonigala Granite, a pinkish, medium-grained granite with few dark minerals, though parts of it are gneissic in texture owing to the presence of streaks of biotite and hornblende. The granite occurs mainly as two sheets (Fig. 63), each of which is half a mile to a mile wide[45]. The more southerly of the two crosses the road from Puttalam to Kurunegala at Tonigala, near

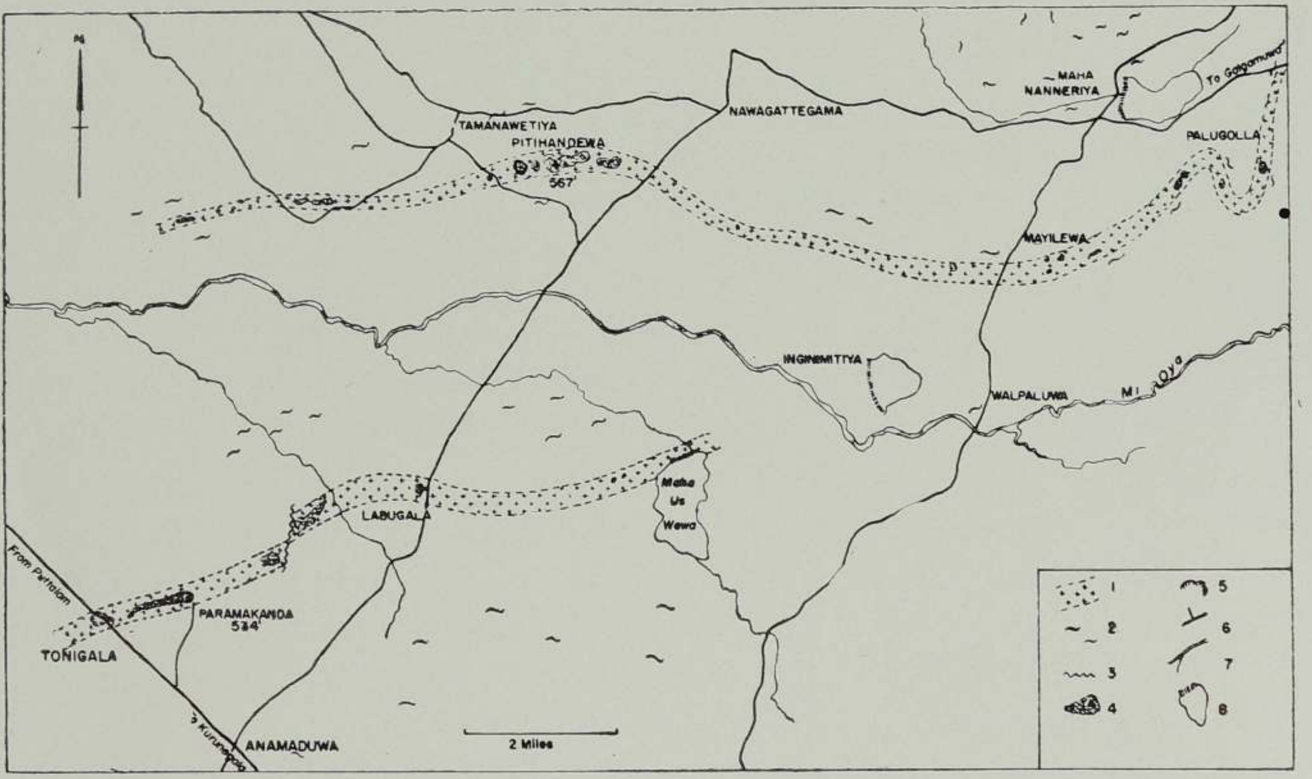


Fig. 63. Sketch map of the Tonigala Granite.

(1) Pink, microcline granite, (2) foliation of gneissic country rocks, (3) probable fault, 4) rocky outcrops, generally with rock caves and shrines, (5) quarry, (6) motorable road, (7) river, (8) irrigation tank.

Anamaduwa, as a number of low, turtle-backed outcrops (Pl. 30B), one of which bears the famous 'Tonigala inscription.'* It can be traced for about 9 miles in a WSW-ENE direction but is not seen beyond the bund of Maha Us Wewa (Fig. 63). The more northerly sheet can be followed for over 15 miles, most of it running in a E-W direction but changing sharply to a N-S direction near Maha Nanneriya.

The main outcrop of the granite is marked by a line of prominent rocky outcrops or erosion remnants, such as Paramakande (534′), Labugala, and Pitihandewa (567′), most of which are the sites of rock caves, ancient Buddhist shrines, and ruins (Pl. 30A).

The granite is composed mainly of quartz, feldspar (microcline), and a little biotite, its reddish colour being due to the presence of minute specks of hematite in the feldspar. Within the granite are coarse pegmatitic patches as well as streaks of biotite and hornblende schist. Parts of the granite have a foliated texture caused by elongate hornblende crystals parallel to the strike. The granite sheets are either vertical or dip steeply to the south, and their margins are parallel to the foliation of the gneisses that surround them.

Sheets, dykes, and veins of pink granite and pegmatite, similar in every respect to the Tonigala Granite but smaller in size, are found throughout the Tonigala Complex (see p. 118).

Ambagaspitiya Granite

Another pink microcline granite occurs at Ambagaspitiya, about 4 miles south of Veyangoda (Fig. 64). The outcrop of the granite is roughly circular in shape and it covers an area of about 15 square miles, rising prominently above the surrounding plain. This granite is less uniform than the Tonigala Granite, patches of gneissic rock being common within it[46].

Several small granite outcrops occur around the main granite body, in an area occupied chiefly by migmatitic granite gneiss, and this suggests that the Ambagaspitiya Granite is really much larger than its present outcrop, lying a little below the surface in much of the surrounding area.

The very famous Warana Temple is built in several caves beneath the large boulders of granite lying on top of the outcrop at Warana, and the granite is extensively quarried for building purposes at a number of localities.

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* The Tonigala Inscription is a semi-circular inscription in letters of the ancient Brahmi scrip a foot high ; it is on the bare rock face of one of the turtle-backs of granite.

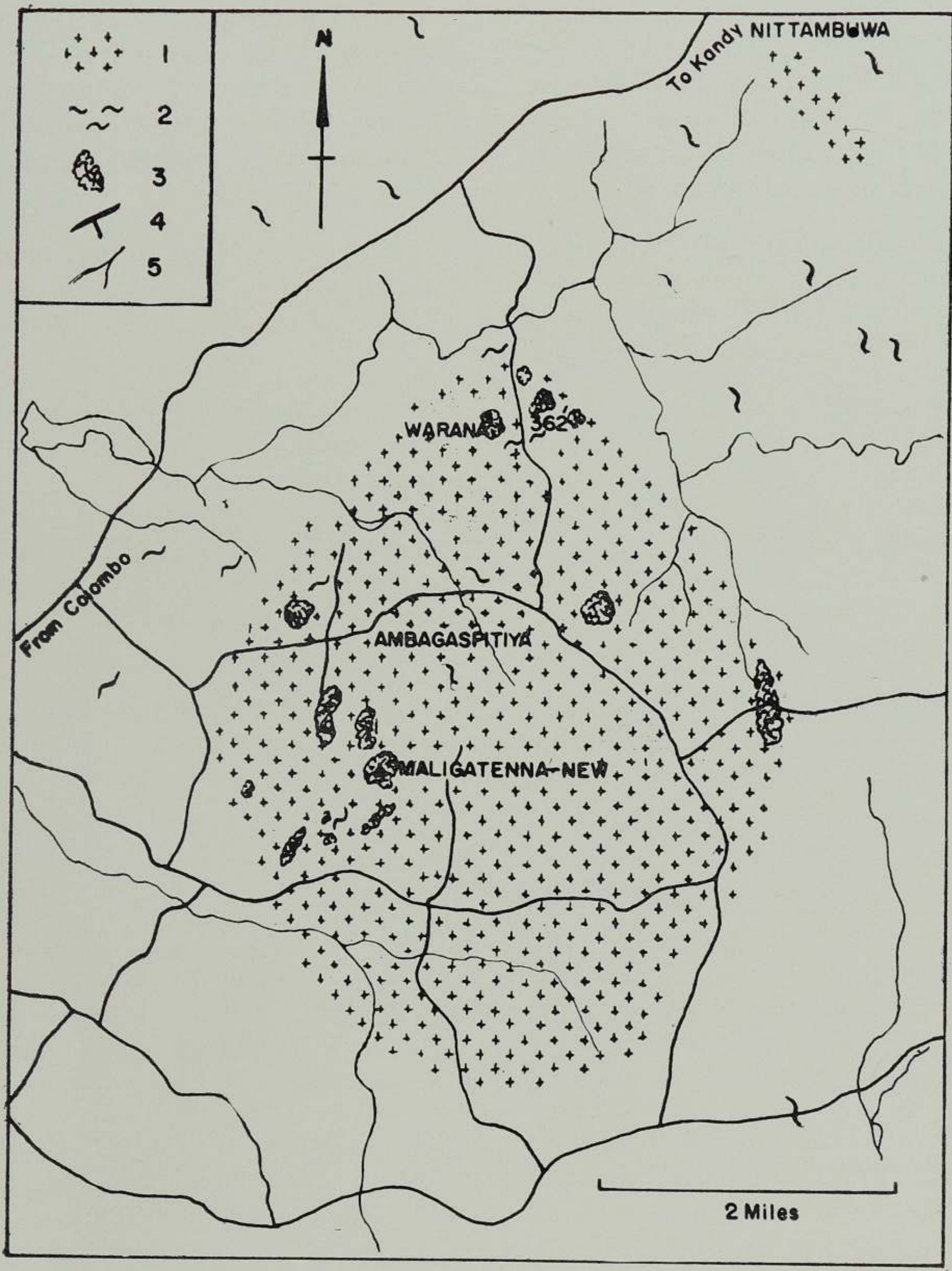


Fig. 64. Sketch map of the Ambagaspitiya Granite. (*After J. W. Herath*)
(1) granite, (2) foliation of gneisses and granitic gneiss, (3) rock outcrop,
(4) motorable road, (5) river.

Arangala Granite

A smaller but not less interesting rock is the Arangala Granite which forms a prominent headland near milestone 44 on the Colombo-Galle road and is in the form of a circular pluton intruding the surrounding rocks (Fig. 65)[47]. This granite can be recognized wherever it occurs by its typically fluted surface where weathering has taken place along parallel lines. The appearance of the granite is striking. It is a coarse-grained, porphyritic rock with large crystals of hornblende, some over 4 inches long (Pl. 31A) ; in places the hornblende crystals have an orientation due to flow. Slender purplish-brown crystals of zircon are also present. Blocks of an earlier formed, even-grained variety of the same granite which were disrupted and moved about by the later

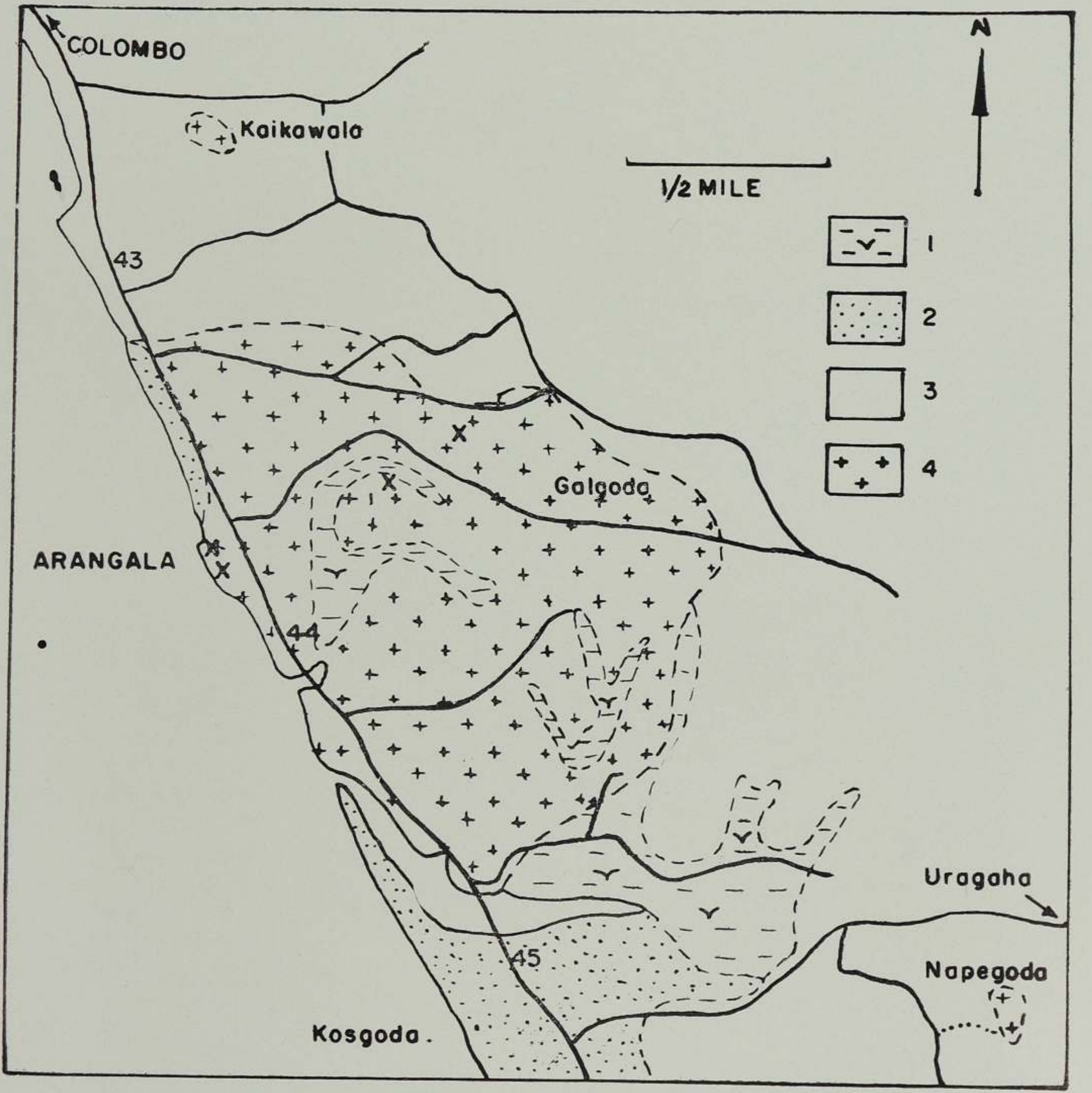
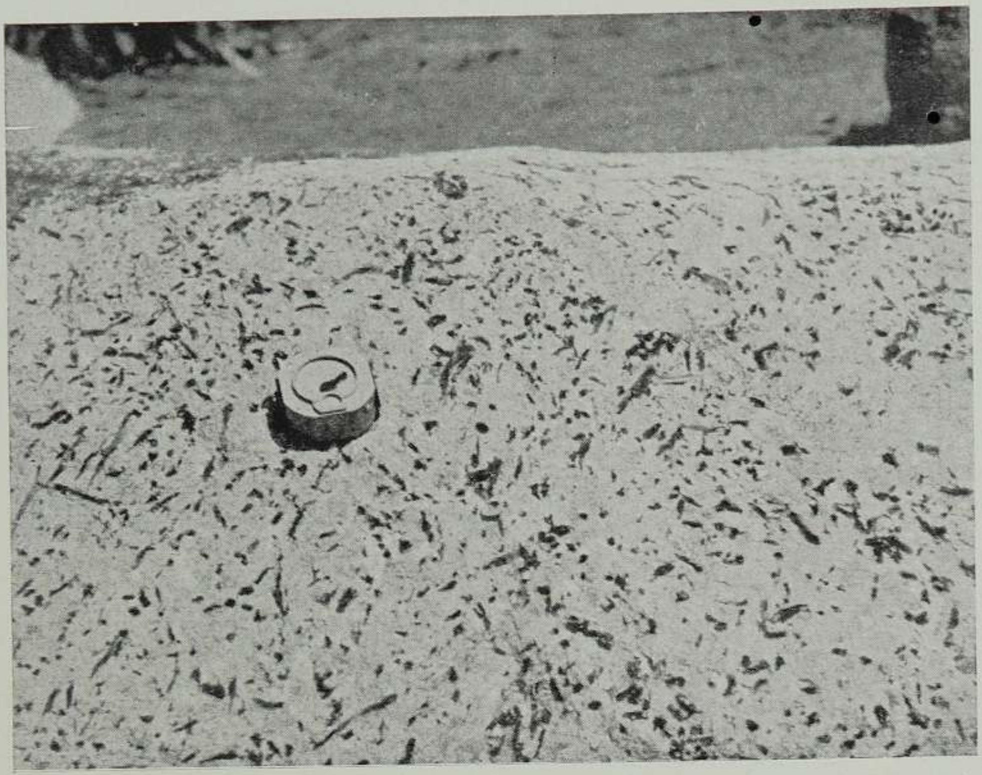
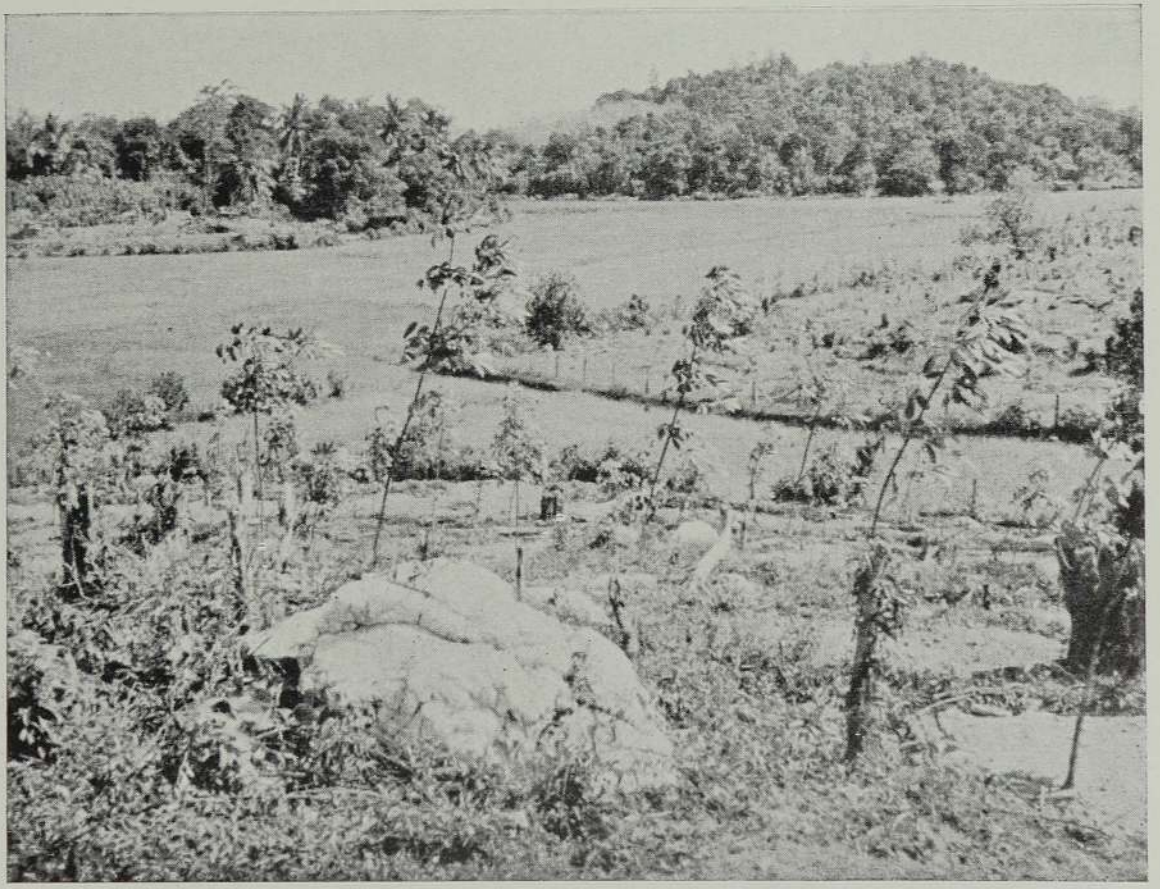


Fig. 65. Sketch map of the Arangala Granite.
(1) alluvium, (2) unconsolidated sand, (3) charnockite with laterite cover, (4) hornblende granite.



A. Porphyritic granite at Arangala with large, black, hornblende crystals.



B. Boulders of vein quartz marking the occurrence of a vein.

coarse-grained variety can be seen here. The granite forms several high, rocky prominences east of the road, and occurrences of similar granite can be seen at Napegoda, Ahungalla, Kekiriskanda, and other localities in the vicinity.

Balangoda Granite

A common type of granite in the south-west of the Island is a zircon-granite in which honey-brown, well formed crystals of zircons can be seen with the naked eye. The best-known occurrence is the Balangoda Granite, so called because it occurs on Massena Estate near Balangoda, where it outcrops as a line of enormous boulders lying in a paddy field[49]. The granite here is very coarse-grained and almost pegmatitic; its surface is strikingly fluted, like the Arangala Granite. Large zircons, some over 2 cm. long, can be seen with the naked eye. One interesting feature of the Balangoda Granite is that the zircons in it have lost their internal atomic structure as a result of bombardment by radioactive particles from within; such zircons are said to be *metamict*[49].

Other occurrences of zircon-bearing granites have in recent years been located in various parts of the Island, as for example at Beruwela and Loluwa.

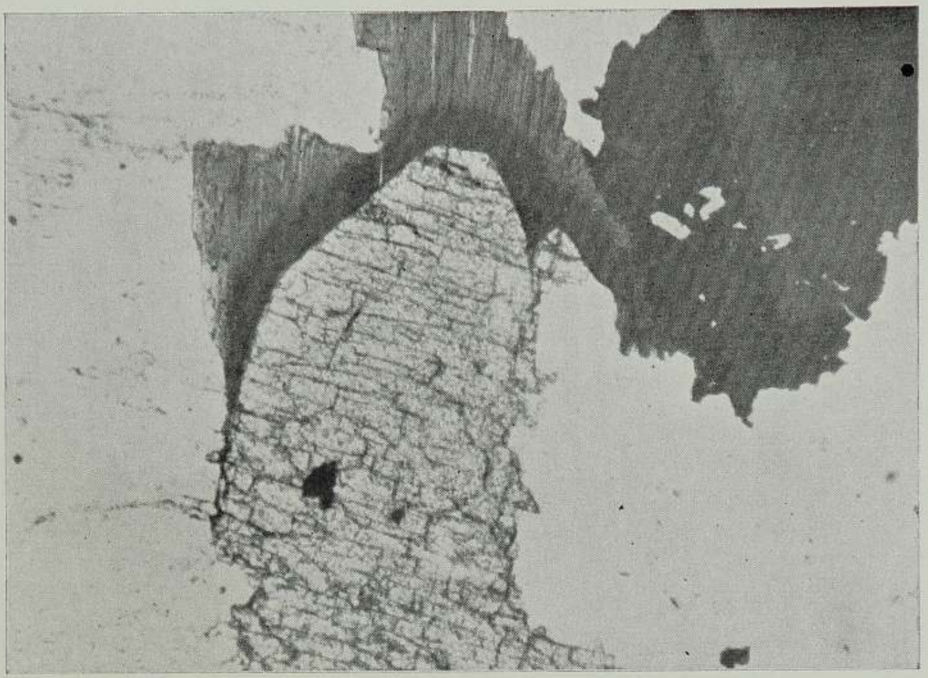
Pegmatites

There are, throughout Ceylon, a very great number of ordinary pegmatites composed of quartz, feldspar, and mica. These occur in all sizes and cut across all the Pre-Cambrian crystalline rocks. The mica books in some of these pegmatites attain sizes of over a foot across and these are mined for commercial mica. Other pegmatites (as at Elahera) contain very large crystals of feldspar which is used in the ceramic industry.

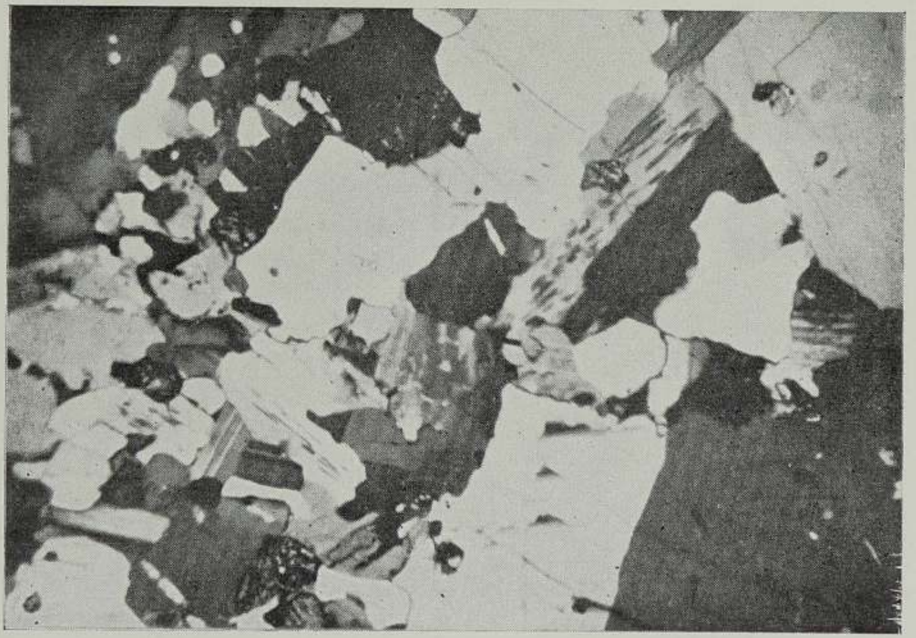
A restricted but more interesting group (or groups) of pegmatites, occurring chiefly in the south-west of the Island, carry a variety of interesting, and sometimes valuable, minerals. These are the rare-earth minerals like thorianite, thorite, monazite (Pl. 32A), zircon, and allanite, which contain varying amounts of uranium, thorium, zirconium, cerium, lanthanum and yttrium (see p. 224). Many gem minerals also occur in pegmatites.

Quartz veins

Veins of pure quartz are seen in many parts of the Island, for example in the Ratnapura area, and they often occur as large white boulders, 8 or 10 feet high, strung out on the surface in a line (Pl. 31B). Such quartz



A. Photomicrograph of a monazite crystal in biotite, surrounded by a dark halo where the crystal structure of the biotite has been destroyed by radioactive bombardment from the monazite. X 35



B. Photomicrograph of hornblende granite showing the interlocking nature of the crystal boundaries. X 35 veins generally are intrusive into the surrounding rocks and they are known to occupy fractures in the crust. Although the majority of them are barren, containing nothing but massive quartz, some have well formed crystals of black tourmaline, and others bear masses and pockets of graphite. Quartz from a large vein at Pussella is being mined for use in the ceramic industry.

Pumice

Pumice is a spongy, vesicular, glassy lava (*obsidian*) of highly acid composition, occurring as blocks and fragments on the cost of Ceylon. It is locally known as *kuddal murree* (' rock foam ' or ' petrified foam '), a particularly apt description.

Pumice fragments occur on the margins of the present beach between Trincomalee and Kalkudah as well on the raised beaches between Chundikulam and Kokkilai. The latter are frequently encrusted with coral and are associated with dune sand and recent coral. The pumice on the present beach may have originated in the Krakatao explosion in 1883 ; those on the raised beach are probably from an earlier submarine volcanic eruption through a fissure in the crust running parallel to the north-east coast[50]. According to divers, a bund of this material runs between Matadam and Mullaitivu, a mile and a half out to sea and under 5 or 6 fathoms of water.

This fissure eruption is the only known volcanic event in the post Pre-Cambrian history of Ceylon, and it must have taken place during Quaternary times.

CHAPTER 10

MINERAL RESOURCES *

> *The products of S Lan include cat's eye, red transparent glass, camphor, blue and red precious stones.*
>
> Chua Ju Kua,
> Inspector of Foreign Trades in Fukien, China.
> End of 10th Century.

THE chief economic minerals of Ceylon that are at present being exploited are *gemstones, graphite, mineral sands* (ilmenite, monazite, quartz), *kaolin* and *other clays, limestone, feldspar,* and *quartz,* all of which may be classed as 'industrial rocks and minerals'. Of these minerals, the first three are

TABLE 8—Mineral Production in Ceylon, 1964 and 1965

MINERAL	1964		1965	
	Quantity (Long Tons)	*Value* Rs.	*Quantity* (Long Tons)	*Value* Rs.
Graphite*	10,676	6,722,352	8,740	5,427,390
Gemstones*	n.a.	1,312,127	71,254 (carats)	4,080,241
Ilmenite	45,429	908,580	50,608*	1,373,000*
Monazite	23	10,994	125*	66,119*
Baddelyite*	nil	—	40	1,992
Limestone†	123,056	892,156	114,141	707,674
Dolomite	n.a.	—	5,004	225,765
Clay†	45,122	642,086	27,294	395,763
Kaolin	1,502	270,315	803	120,450
Silica sand (quartz)‡	3,079	30,790	6,425	64,250
Feldspar**	4	276	613	121,224
Quartz (vein)**	632	43,924	560	27,720
TOTAL ..		10,833,600		12,611,588

* Export figures only, from Ceylon Customs Returns.
† For cement manufacture only.
‡ For glass manufacture only.
** For ceramic manufacture only.

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* For fuller account see papers read at a Symposium on *Ceylon's Mineral Resources and their Development,* held during the 20th Annual Sessions of the Ceylon Association for the Advancement of Science, Sept. 1964, and published in the *Ceylon Geographer,* v. 18, 1964. The most recent information in this chapter is taken from these papers. For a year by year account of mineral production, see *Ceylon Year Book.*

mainly for export and the rest are being used in local industry for internal consumption. Ceylon also possesses deposits of *iron ore, zircon, rutile,* and *garnet sands, mica, peat,* and *radioactive minerals* (thorianite) which are either to be exploited in the near future (iron ore, zircon, rutile), or which cannot at present be mined owing to poor quality or difficulty of extraction. No fuels such as coal, lignite, or oil, or metals like lead, zinc or copper have so far been found. A map of the known mineral deposits of Ceylon is given in Plate 37.

Owing to defects in the law, *accurate* statistics relating to the production, value, and consumption of minerals in Ceylon are sadly lacking and almost impossible to obtain. Some idea of mineral production and export can, however, be given from the Customs Returns and from figures provided by individual industrial concerns. As far as the available figures show, the total value of the annual mineral production in Ceylon is comparatively small, being only Rs. 10.8 million in 1964 and Rs. 12.6 million in 1965 (see Table 8). These figures, which do not include the value of solar salt produced, work out to about Re. 1.00 per head of population, a very low value when compared with those of other countries of comparable size. This figure is bound to be higher when the value of production of clay for bricks and tiles, gemstones not exported, sand and laterite for building, stone for road making, etc. is taken into account, but it will not be very much higher.

It will also be seen from the Table that over four-fifths of the annual value is accounted for by the exportable minerals graphite, gemstones, and ilmenite.

Gemstones [51]

Ceylon has been justly famous all over the world and for many centuries for its gemstones, for almost nowhere else, in an area of comparable size, are so many varieties of gemstones to be found. Most of the gem fields are situated in the south-west of the island, and within an area of about 800 square miles are to be found the delicately coloured varieties of the minerals corrundum (*ruby and saphire*), *beryl, chrysoberyl* (*alexandrite* and *cat's eye*), *spinel, topaz, tourmaline, garnet, zircon and quartz* (*citrine* and *amethyst*). A full list of the varieties of precious and semi-precious stones found in Ceylon is given in Table 9 and from this it can be seen that many gem varieties have acquired incorrect mineral species names largely because of colour similarities. For example, the gemstone topaz in its charasteristic yellow colour is seldom found in Ceylon, and what passes as Ceylon topaz is generally a yellow variety of quartz named *citrine*.

MINERAL RESOURCES

Table 9—Gemstones of Ceylon

MINERAL Gem Variety	COLOUR	*APPROXIMATE PRICE PER CARAT *Rs.*
Corundum		
Sapphire	Blue	50–700; 750–2000
Star sapphire	Blue	50–250; 250–750
White sapphire	Colourless	50–200
Yellow sapphire	Yellow	5–90
†*Oriental topaz*	Yellow	5–90
King topaz	Yellow	5–90
Ruby	Red	400; 1000
Star ruby	Red	100–400; 500–900
Oriental amethyst	Purple	5–90
Oriental emerald	Green	5–90
Chrysoberyl		
Alexandrite	Green to red	100–400; 500–1000
Cat's eye	Greenish	100–400
Beryl		
Yellow beryl	Yellow	3–25
Topaz		
Topaz	‡Colourless	1–3
Zircon		
Zircon	Blue	20–40; 40–90
Hyacinth		3–25; 5–45
Jargon		5–45
Matara diamond	Colourless	5–45
Spinel		
Ruby spinel	Deep red	5–25; 25–80
Balas ruby	Rose red	
Rubicelle	Yellow, orange, red	
Amethyst	Violet	
Garnet		
Pyrope	Deep red	1–30; 30–60
Almandine	Crimson red to violet	
Grossularite	Gooseberry tint	
Hessonite	Yellow	
Cinnamon stone	Cinnamon brown	
Spessartite		
Feldspar		
Moonstone	Bluish white, milky	1–5; 10–60
Orthoclase	Yellowish	2–5
Tourmaline		
Tourmaline	Black to brown	3–25
Rubellite	Pink	3–25
Indicolite	Blue	
Brazilian emerald	Green	
Brazilian sapphire	Blue	
Peridot of Ceylon	Yellow green	
Quartz		
Rock crystal	Water clear	1–3; 6–15
Amethyst	Purple	15–20
Citrine	Yellow	1–5; 5–10
Ceylon topaz	Brownish yellow or yellowish pink	6–15
Rose quartz	Pink	15
Smoky quartz or Cairngorm	Brown	1–2
Cat's eye quartz		50–100
Cordierite		
Water sapphire	Blue	25

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* Prices vary mostly according to colour, but also according to weight.

† A trade name containing an incorrect mineral species name is shown in italics.

‡ The pure yellow topaz does not occur in Ceylon and the yellow stone generally called 'topaz' is citrine, a variety of quartz. Most yellow stones are, however, called topaz in Ceylon.

Ratnapura, the 'City of Gems', is the centre of the gemming industry. Mining is carried on all round it, for example in Pelmadulla, Rakwana, Balangoda, Eheliyagoda and Kuruwita (Fig. 66), but most of the cutting and polishing of the gems is done in Ratnapura by age-old methods.

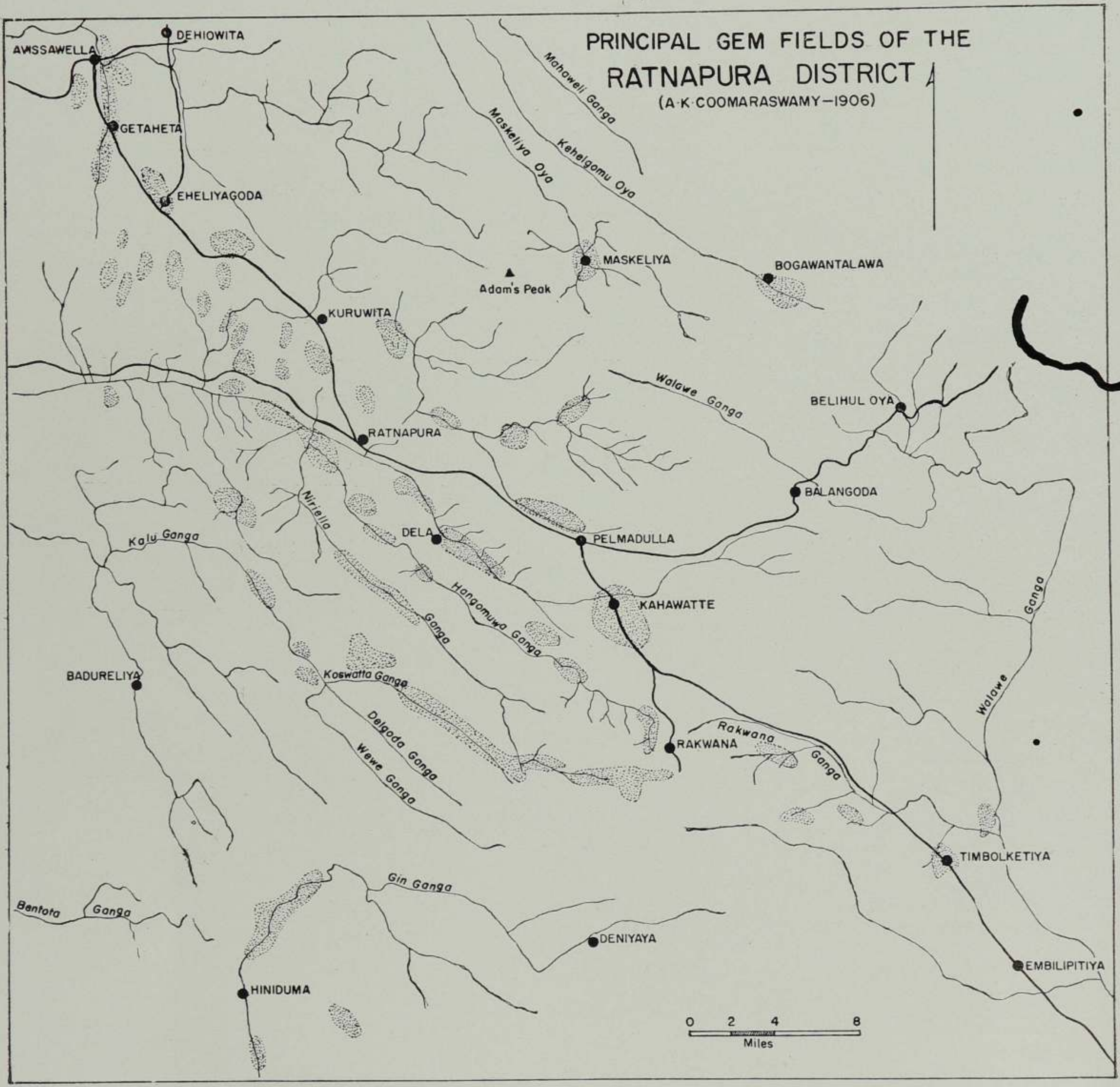


Fig. 66. Map of the gem fields in the Ratnapura area.

The majority of gemstones, in their uncut state, occur as rounded pebbles and worn fragments embedded in layers of gravel and sand known as *illam* in the river beds, marshes, alluvial flood plains, terraces, banks, and talus slopes of the gem-bearing area. Typical *illam* or gem-bearing gravel is lens-shaped and is never a constant horizon throughout a gem field. It is generally a few inches to 2 feet in thickness and it may appear anywhere from 5 to 50 feet below the surface (Fig. 67). More than one *illam* may be present in a gempit but such *illama* always lie above the *malawa* or surface of the decomposed underlying bedrock.

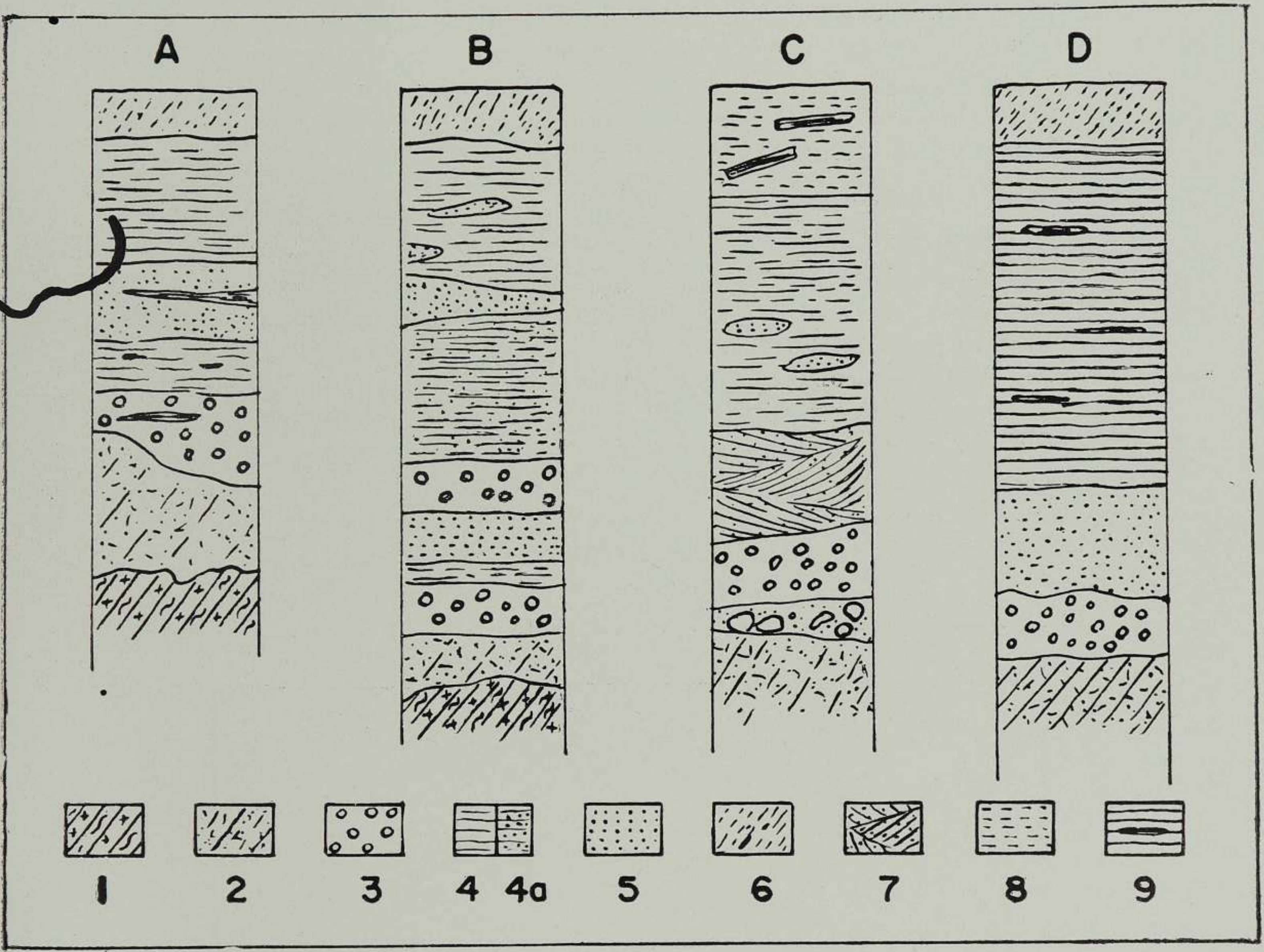


Fig. 67. Cross-sections of gem pits. (*After D. N. Wadia and L. J. D. Fernando*, 1945)

A. On edge of swamp. B. On high ground in lateritic cap (*duwa*). C. In swampy land (*deniya*). D. In rice field in broad, alluvial valley.

(1) bedrock, (2) decomposed bedrock (*malawa*), (3) gem gravel (*illam*), (4) clay, (4*a*) sandy clay, (5) sand, (6) soil cover, (7) false-bedded ferruginous sand, (8) black, peaty earth with carbonised wood, (9) rudely bedded alluvium with plant remains.

The most abundant constituent of the gem-bearing gravels is quartz, in smooth, rounded pebbles from less than an inch to several inches in diameter. and it is often accompanied by detrital grains and crystals of rare-earth minerals like thorianite, thorite, allanite, and baddelyite; tourmaline pebbles are also very common in the illam. With the exception of some tourmalines and garnets (found in the parent rocks), and of moonstone (which is mined from decomposed pegmatites at Meetiyagoda), all the other gemstones are therefore secondary in origin. In other words, they occur as original constituents of the crystalline rocks, most probably pegmatites (Fig. 68), but are released from their parent material by the weathering and decomposition of the latter. They are then rolled along their beds by rivers and streams, in the course of which process the crystals become broken up and rounded. The pebbles are finally deposited in the valleys and flood plains of the same streams and subsequently buried by later deposits of alluvium, sand, and clay.

The methods of mining, though simple and unchanged for centuries, are well-adapted to local conditions, involving little capital outlay and only seasonal activity. The commonest method of mining is by sinking a pit, 10 to 15 feet square, in a likely spot, and excavating the *illam* which is brought to the surface (Pl. 33A). When a large enough quantity of illam has thus been collected, it is washed in large wicker baskets either in a stream, pond, or even in the pit itself (where the water has not been pumped out). The washing is done by swirling the basket round and at the same time dipping it into the water (Pl. 33B); by this means the lighter material is washed away and the minerals of high density—gemstones and rare-earth minerals—are left behind. These are then sold in lots and the buyer takes a chance on whether or not he gets a valuable gem. The profits from the sale are shared among the owner and the miners in

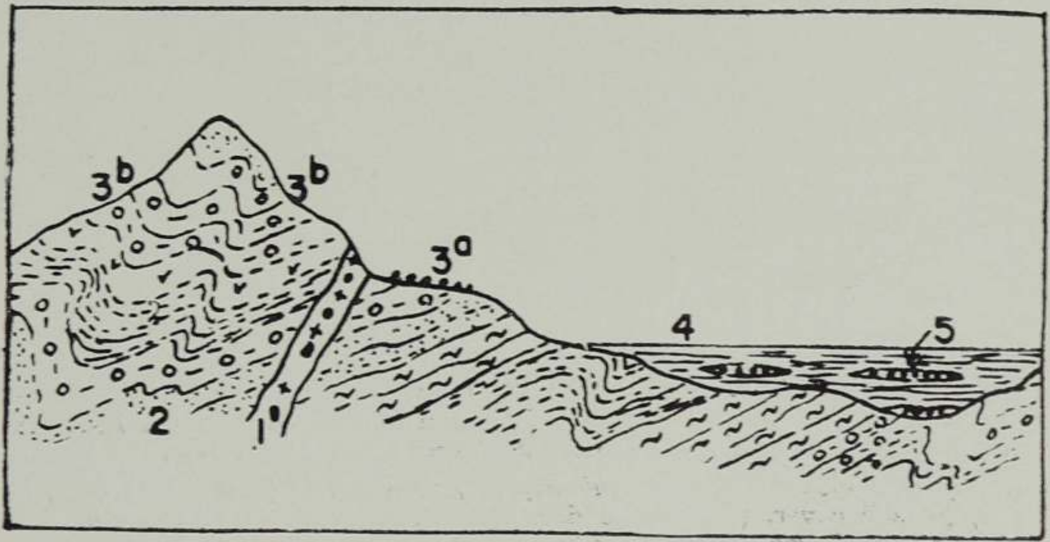
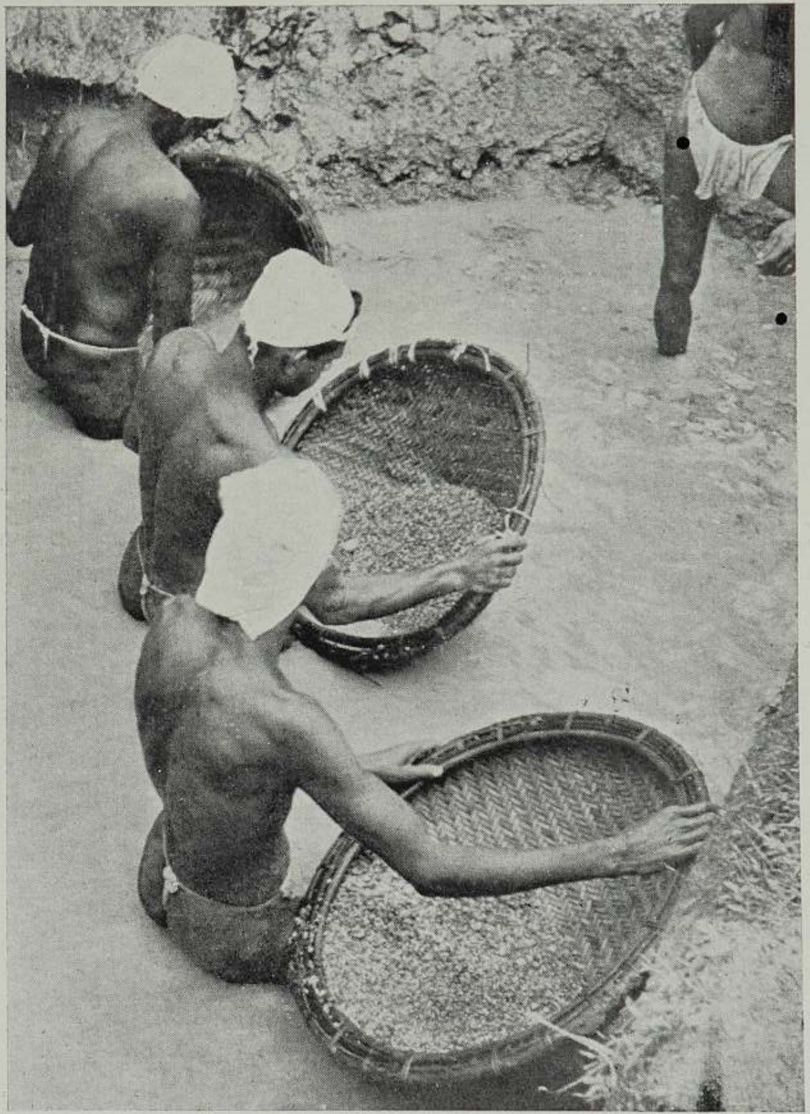


Fig. 68. Generalised section showing the origin and mode of occurrence of gem deposits. (*After D. N. Wadia and L. J. D. Fernando*, 1945)

(1) gem-bearing pegmatite, (2) country rock, (3*a*) gems in detritus on hill slope below pegmatite, (3*b*) barren hill slope, (4) rice field, (5) gem-bearing gravel layer.

A. A typical gem pit in the Ratnapura District, showing timbered walls. (*E. Gubelin*)



B. Panning the gem gravel in wicker baskets. (*E. Gubelin*) traditional proportions. When the gem gravels occur in the beds of streams, the stream is first dammed and the miners, using long-handled shovels, drag the river upstream of the dam until the gravel is excavated. This is collected in a ridge from which the lighter material is washed away by the running water, the balance material being sorted in the manner described above.

After a gemstone has been selected it is first dressed in such a way that the existing flaws are eliminated, and then cut by means of a lead disc, about 12 inches in diameter, the cutting edge of which has been reinforced with abrasive powder. The wheel is rotated by hand with a bow string and the stones are held against the cutting edge of the disc and cut to various shapes such as *cabochon* (with a rounded surface) and *table* (with facets). These various cuts bring out the natural beauty of each stone and the stones are then polished on copper plates. In spite of these simple and rather primitive methods of cutting and polishing, and of an ignorance of the optical properties of each stone (which should really govern the way it is cut), many fine stones have been turned out by local gem cutters (or *lapidarists*), largely owing to their inherent skill and ingenuity. Gemstones are sold by weight (the unit of weight being a carat*) and many fiine stones are unfortunately spoilt owing to the tendency to cut them for weight rather than for perfect appearance.

TABLE 10—Exports of cut Gemstones from Ceylon, 1958–65

Year	*Amount* (carats)	*Value* (Rs.)	*Avg. price per carat* (Rs.)
1958	285,846	1,535,952	5.38
1959	566,733	2,964,254	5.23
1960	489,863	3,016,698	6.16
1961	321,871	2,359,576	7.33
1962	227,803	3,563,586	15.64
1963	157,538	3,646,891	23.15
1964	n. a.	1,312,127	n.a.
1965	71,254	4,080,241	57.26

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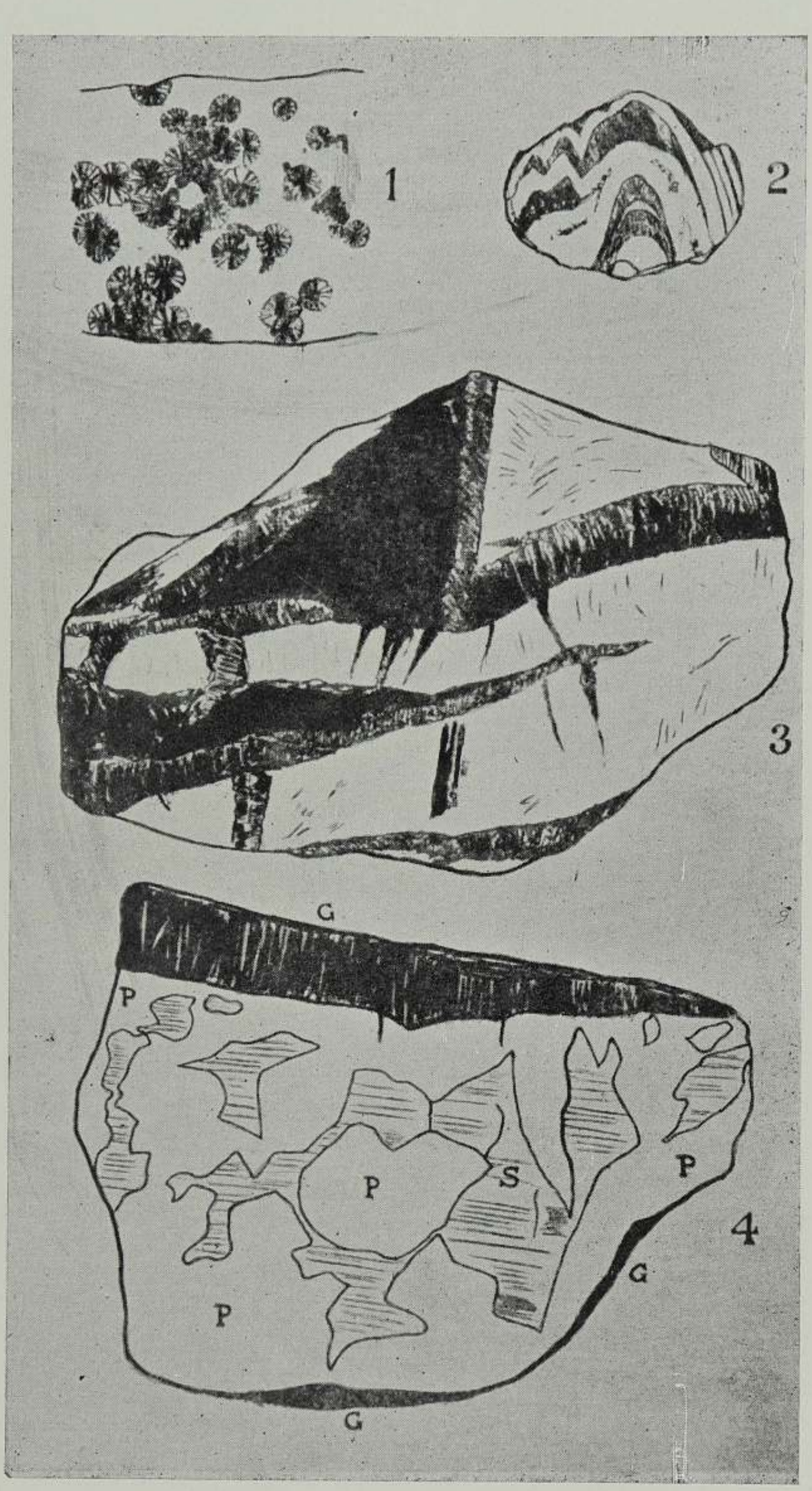
* 5 carats = 1 gram ; 141.5 carats = 1 ounce



Modes of occurrence of graphite (about half natural size). 1—rosettes, 2—folded veins, 3—veins in joints and fissures, 4—'Needle' graphite (G) with associated pyrite (P) and selenite (S). (*A. K. Coomaraswamy*)

TABLE 11—Chief Importers of Ceylon Gemstones, 1962–63

Country		*Amount* (carats)	*Value* (Rs.)	*Avg. price per carat* (Rs.)
Japan	1962	6,907	967,036	140·01
	1963	2,509	462,722	184·42
Hong Kong	1962	118,170	693,781	5·87
	1963	111,275	1,661,734	14·93
U. S. A.	1962	7,671	686,253	89·46
	1963	9,912	381,488	38·49
U. K.	1962	10,231	418,401	40·90
	1963	5,758	635,139	110·31
Federal German Republic	1962	45,686	284,454	6·23
	1963	12,837	211,452	16·47
Others	1962	39,138	513,661	13·[illegible]2
	1963	15,247	294,356	19·31
Total	1962	227,803	3,563,586	15·6[illegible]
	1963	157,538	3,646,891	23·15

Although gem mining is the second largest mineral industry in Ceylon it is essentially a small-scale industry, scattered and seasonal in nature. For this reason it is almost impossible to obtain figures of the total production of gemstones each year. Export figures are, however, available (see Table 10) and from this it can be seen that the annual exports between 1958 and 1965 have varied between Rs. 1.3 million and Rs. 4.1 million. The value of the total production of gemstones each year is probably of the order of Rs. 0.5 to Rs. 1.0 million more than these figures. The chief importing countries vary from year to year, but the chief importers over the last six years have been Hong Kong, Switzerland, Japan the U.S.A., Great Britain, and the Federal German Republic. It is interesting also to note that whereas Japan, the U.S.A., Gt. Britain, and Switzerland import the higher priced gemstones, Hong Kong and the Federal German Republic take only the semi-precious, cheaper varieties of stones (see Table 11).

Graphite

The mining of graphite is still the most important mineral industry in Ceylon, being over a hundred years old. Only the largest and most mechanised mines which go down to a thousand feet or more are in operation today, but in times of boom, as during the last two World Wars, thousands of pits of all sizes and depths are opened up all over the graphite-producing areas of the island.

Graphite (or *plumbago* as it is commonly known) is pure crystalline carbon, and the economically workable deposits occur in the form of plates and needles of almost pure graphite occupying veins and fissures in the

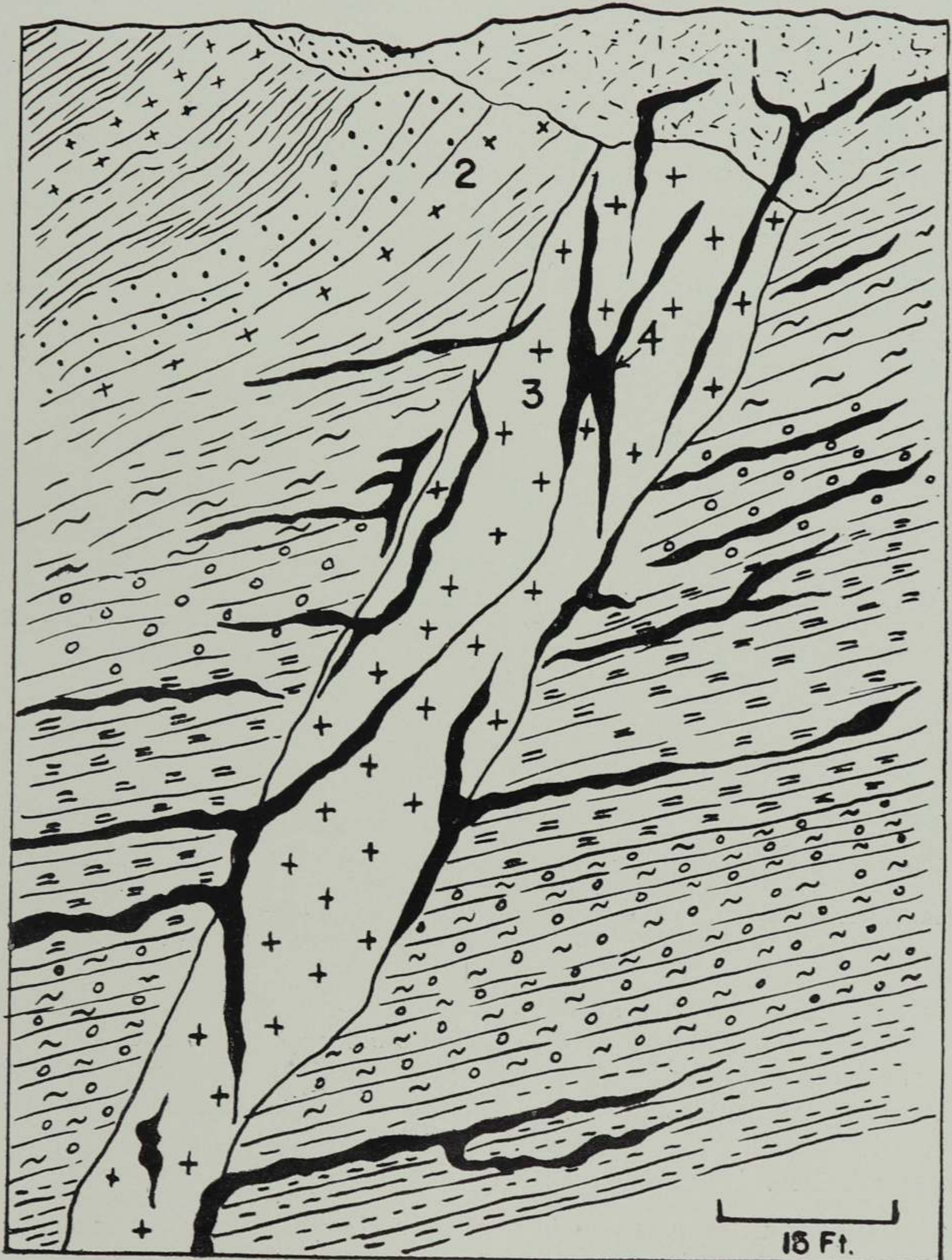


Fig. 69. Sketch section showing common types of graphite veins in Ceylon. (*D. N. Wadia,* 1945)

(1) laterite, (2) country rock, (3) pegmatite dyke, (4) graphite veins

crystalline rocks (Pl. 34 and Fig. 69). Graphite veins vary from a few inches to 3 or 4 feet in width, though they sometimes reach up to about 12 feet; they generally occur in groups of veins within narrow zones (Fig. 70). Such zones may continue in the same direction, generally NW-SE or NNW-SSE, for several miles, and sometimes for as much as 50 miles. These mineralised belts appear to be restricted to the cores of anticlines or to areas where earth movements have produced intensive fracturing and fissuring of the rocks, so enabling the graphite to enter the resulting spaces. Very few other minerals are associated with graphite, and where such gangue minerals (for example, quartz, pyrite, calcite) are present they occur in very small amounts[52].

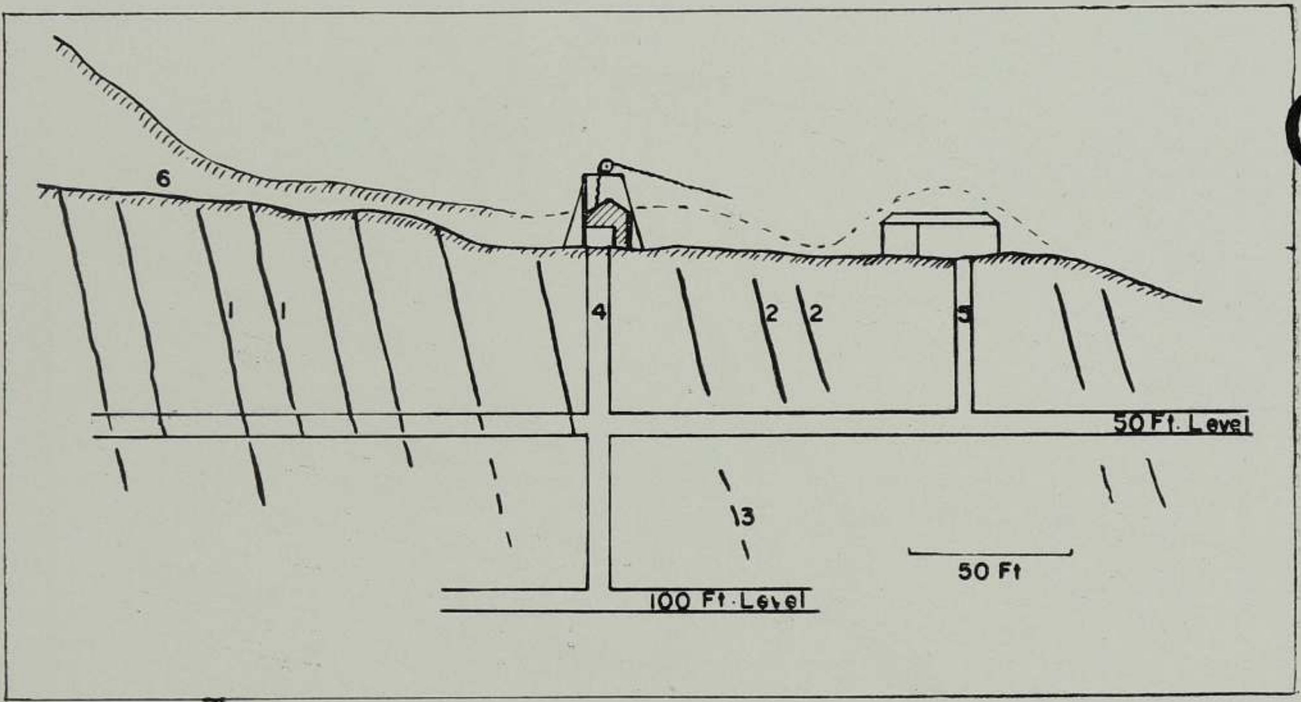


Fig. 70. Diagrammatic section showing working of old graphite mine at Laxapana. (*A. Coomaraswamy*, 1906)

(1) rich veins of graphite, (2) good veins only to 50 feet, (3) only stringers from veins above (4) main shaft, (5) main pumping shaft, (6) old drive.

The major deposits of graphite in Ceylon are confined to the south-western sector of the island (Pl. 37), the most important mines being the Bogala Mines (near Ruwanwella) and the Kolongaha and Kahatagaha Mines (near Kurunegala). The Kahatagaha Mines go down to over 1,500 feet below the surface and the main shaft of the Bogala Mine is nearly 1,000 feet deep.

The extraction of graphite is relatively simple. The veins are mined underground along horizontal adits (Fig. 70) by blasting, pneumatic drilling, or by hand picks, the lumps of more or less pure graphite being brought to the surface by trolley and electrically operated lifts (in the mechanised mines). Here the graphite lumps (Pl. 35) are sorted and dressed by hand and then crushed and graded into sizes, either by hand or by mechanical sieves. Until recently, most of the graphite exported from Ceylon was in the form of lumps of crude graphite, but increasing amounts of ground graphite are now being exported.

TABLE 12—Exports of Graphite, 1956–64

Year	*Amount* (*Long Tons*)	*Value* (Rs.)	*Avg. Price per ton* (Rs.)	*Destination*		
1956	9,207	6,210,510	675			
1957	8,190	5,945,700	726			
1958	5,637	3,822,147	678			
1959	7,872	5,193,816	660	U.K. (23%),	U.S.A.((31%),	Japan(28%)
1960	9,024	5,754,912	638	,, (28%),	,, (23%)	,, (31%)
1961	8,942	5,723,401	640	,, (32%),	,, (22%)	,, (29%)
1962	8,630	5,610,138	650	,, (28%)	,, (27%)	,, (21%)
1963	8,286	5,105,959	610	,, (28%),	,, (29%),	,, (22%)
1964	10,676	6,722,352	630	,, (21%),	,, (27%),	,, (22%)

The entire production of graphite is exported, more than 75 per cent of the exports going to the United Kingdom, Japan, and the United States (Table 12). It is used chiefly for lead pencils, crucible and foundry linings, wet and dry lubricants, paints, electrodes, and dry batteries. The reserves of graphite in Ceylon appear to be very large, but there is no estimate of the amount. Export figures for the year 1956 to 1964 (Table 12) show that the industry is recovering slowly after a depression in 1958. In 1961, for example, 8,942 tons of graphite valued at Rs. 5.7 million were exported whereas the corresponding figures for 1958 were 5,637 tons valued at Rs. 3.8 million. Exports of graphite from Ceylon have been highest during the two World Wars, with a peak of 27,000 tons in 1942. The average amount exported before 1939 was about 15,000 tons per annum.

Mica

Small workable deposits of amber mica or phlogopite occur as pockets and small veins in pegmatites (Fig. 71) or they are associated with crystalline limestones, particularly in the Kandy, Matale, and Badulla districts (Fig. 72). Talatu Oya and Madumana were two well known mica-mining localities. The mica occurs as books, some over a foot wide, but the deposits are sporadic and inconstant and the marketable mica which can be recovered from these deposits is small. One reason for this is that the

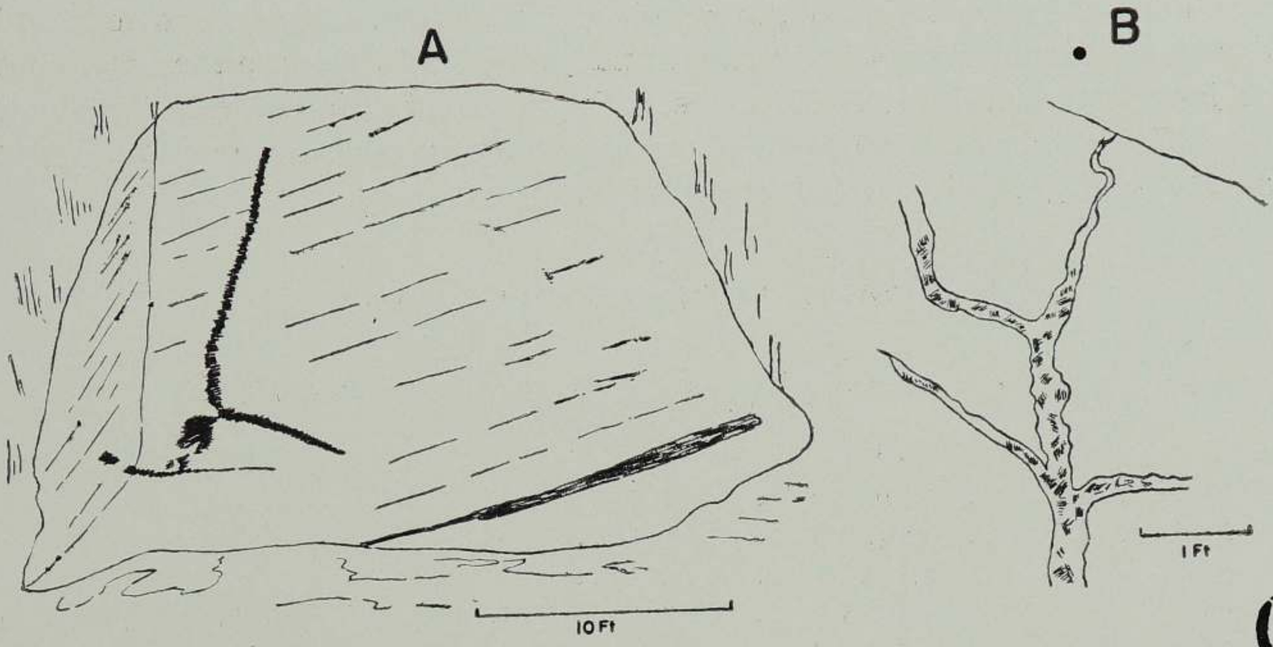


Fig. 71. Occurrence of mica in veins, near Badulla. (*A. Coomaraswamy*, 1902)

A. Face of mica pit.

B. Branching vein of mica in crystalline limestone.

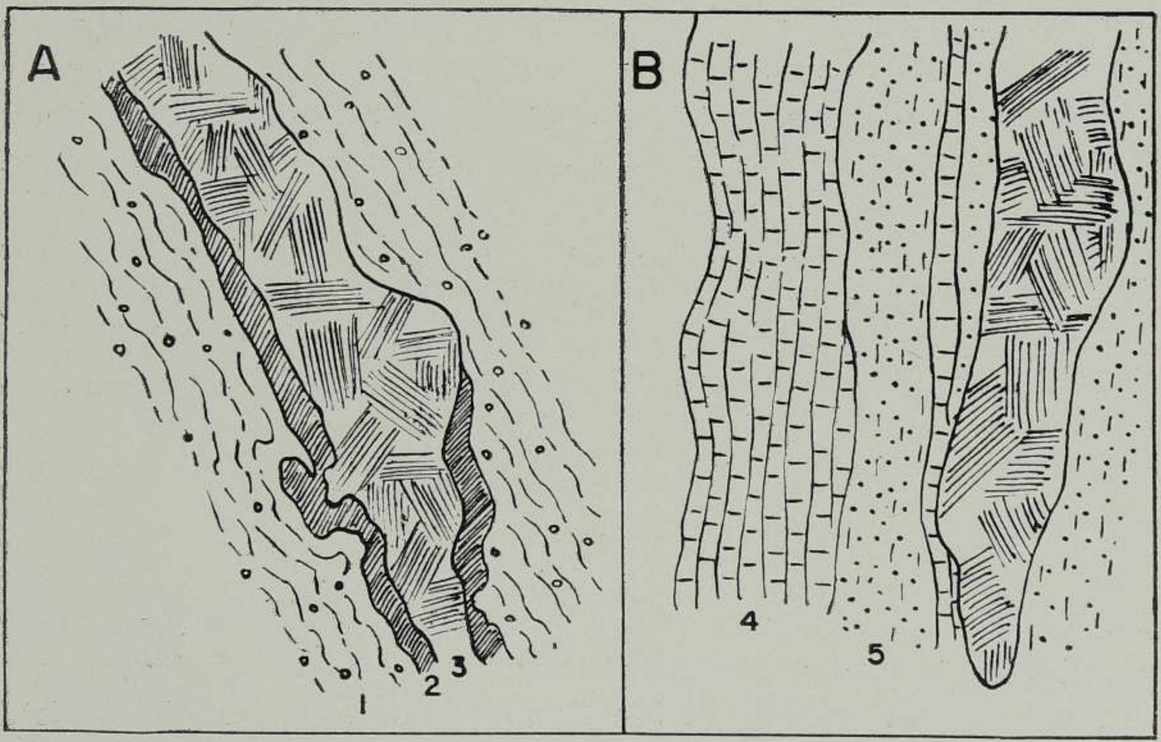


Fig. 72. Occurrence of mica in pockets. (*D. N. Wadia*, field notebook)

A. Polgolla, B. Mailapitiya

(1) garnetiferous gneiss, (2) pyroxenite dyke, (3) mica-bearing pegmatite (4) crystalline limestone, (5) quartzite.

mica crystals are usually so cracked and shattered that only relatively small pieces of unblemished mica can be obtained from the books by trimming. Phlogopite mica has in the past been exported from Ceylon when the demand was high, for example during the last war, but at present there is very little mining or export (see Table 8).

Some pegmatites, for example at Pinnawala near Balangoda, carry white mica or muscovite.

Mineral sands

Scattered round the coasts of Ceylon near the mouths of rivers, in isolated bays, and in raised beaches, are large placer deposits of mineral sands totalling several millions of tons and containing a high proportion of ilmenite, monazite, garnet, zircon and rutile[53]. These heavy minerals (with densities over 4.0 and a high degree of hardness) are constituents of the crystalline rocks of the island; they have been released by weathering and carried down to the sea by rivers and streams where they were probably deposited in old lagoons and beaches that existed when the shoreline was further inland than at present (and possibly in existing off-shore regions). When uplift took place these deposits were subject to strong wave action during the monsoonal periods, and the lighter quartz grains were removed leaving the present concentrations on the beaches. Such appears to be the process of concentration of the monazite deposits along the west coast. At Pulmoddai, on the east coast, the heavy minerals are scoured out from Koddilai lagoon during heavy rains and subsequently concentrated on the beach by wave action.

Ilmenite

Ilmenite, an oxide of iron and titanium ($2FeTiO_3$) which is black in colour, is the predominant mineral in the 'black sands' around the coast. It can be seen almost anywhere, as for example on the beach at Galle Face, Colombo, where it occurs in streaks and small pockets, and on many footpaths and gravel roads in the interior of the country, where it is concentrated by rain water.

The most important deposit of ilmenite is at Pulmoddai on the north-east coast, 34 miles from Trincomalee, where it forms the present beach down to low water mark for a stretch of 4 miles, between Arisimalai headland and the mouth of the Kokkilai lagoon (Fig. 73). Until recently, the amount of black sand present at Pulmoddai was estimated at four million tons, but the total reserves are now known to be several times this amount.*

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* See footnote, p. 136.

The beach sand is made up of 75-80 per cent ilmenite, 8-12 per cent rutile, 8-10 per cent zircon, 2-3 per cent magnetite, and significant amounts of monazite, together with a small proportion of garnet, hypersthene, and quartz. The extensive deposits of black sand in the scrub-covered sand dunes lying behind the present beach contain from 10 to 60 per cent ilmenite. The TiO_2 contents of the ilmenite at Pulmoddai is about 52 or 53 per cent, and this makes it one of the best deposits in the world (see Appendix IV, Table 22).

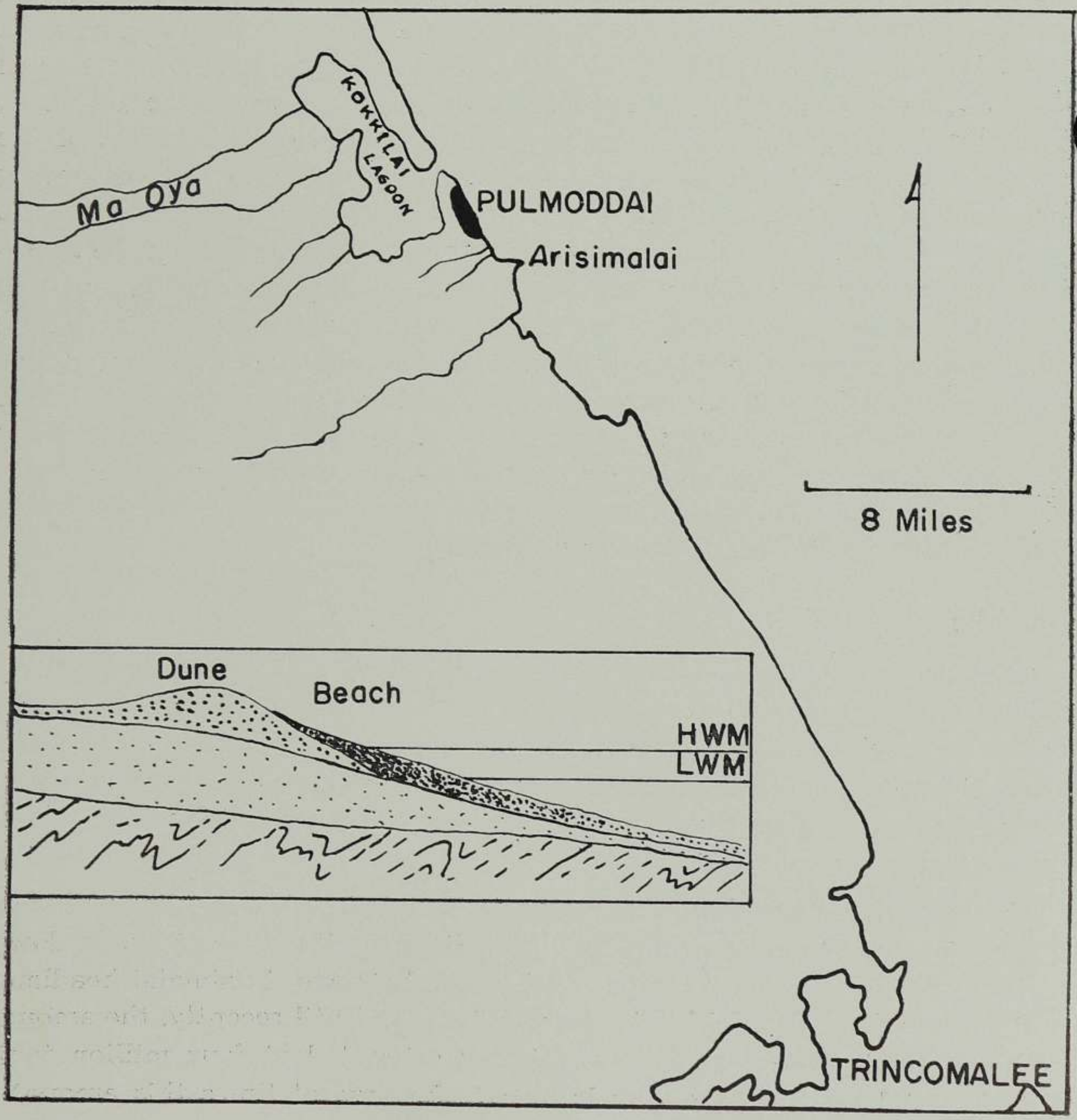


Fig. 73. Sketch map of ilmenite deposits at Pulmoddai. *Inset :* Diagrammatic section showing occurrence of ilmenite in beach and dune sands.

The mineral sand deposit at Pulmoddai is worked by the Ceylon Mineral Sands Corporation, a State-sponsored body set up in 1957. The sand, after collection by hand from the beach, is passed through magnetic separators where first magnetite and then ilmenite are separated from the other less-magnetic or non-magnetic minerals. The concentrated ilmenite is taken by conveyor belts to the end of a pier, 300 feet long, where it is loaded into barges and conveyed to ships which anchor about a mile away. The ilmenite is loaded into the ships from the barges by means of mechanical grabbers.

The plant, when working at full capacity, is capable of producing 60,000 tons of ilmenite a year from 100,000 tons of raw sand, with rutile and zircon as by-products. The present production of ilmenite is small, however, and no by-products are being produced. The production of ilmenite has risen from 14,880 tons in 1963 to 45,429 tons in 1964; exports in 1965 amounted to 50,608 tons valued at nearly 1.4 million (see Table 8).

A smaller deposit of about 250,000 tons of beach sand containing 50 to 60 per cent ilmenite is present at Tirukkovil (about 40 miles south of Batticaloa), on either side of the old Resthouse. Beach sand concentrations containing 60 to 75 per cent ilmenite also occur at several points along the west coast during the period May to July each year. Such places are Chilaw, Negombo, the mouths of the Kelani Ganga and Kalu Ganga, Beruwela, Kaikawela, Kaluwella near Galle, Weligama, and Dondra.

Ilmenite is the main source of titanium dioxide (TiO_2) which is used in the manufacture of high-grade white paint, but in recent years the metal titanium has increased in importance, particularly in the aircraft industry, owing to its lightness.

Monazite

Golden yellow monazite is a phosphate of the rare earths cerium, yttrium, and lanthanum (about 60 per cent) and it also contains a fair proportion of radioactive thorium oxide (see Table 22). For this reason it is now a potential nuclear raw material and has strategic importance ; its main use earlier was for the manufacture of incandescent gas mantles.

The main concentrates of monazite are located at Beruwela, Kaikawala and Kudremalai on the west coast and it has also been proved to be a recoverable constituent of the Pulmoddai ilmenite deposit. The monazite content of these sands varies considerably from one point to another and from day to day, rich localized patches with about 15 per cent or more monazite lying next to patches with only 3 per cent of the mineral. Like ilmenite on the west coast, monazite is concentrated in lenses, streaks, and pockets (Fig. 74), during the months of the south-west monsoon and during this period it is collected by hand and treated in magnetic separators at the pilot plant maintained by the Geological Survey Department at

Katukurunda, near Kalutara. Ceylon monazite has an average thoria (ThO_2) content of about 10 per cent, which makes it, with monazite from Travancore in South India, the richest in the world; a small amount (0·2 to 0.4 per cent) of uranium oxide is also present. (The monazite concentrate offered for export it guaranteed to contain 66 per cent rare earth oxides, including about 9 per cent thoria.) The monazite-rich deposits of the south-west also contain ilmenite, zircon (4 to 5 per cent), rutile, garnet, tourmaline, and thorianite.

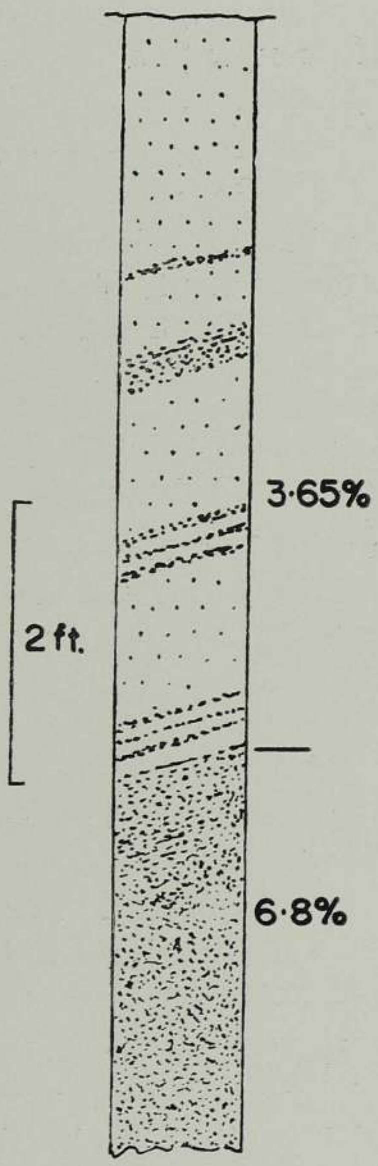
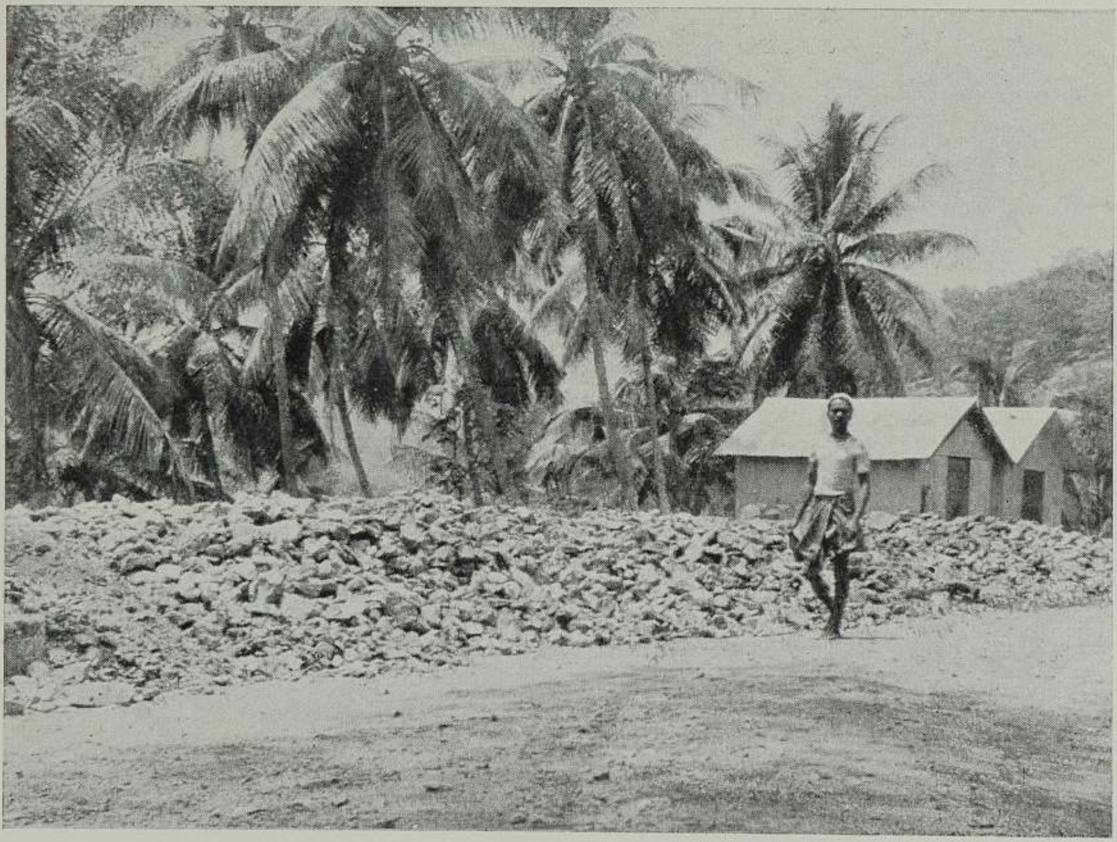


Fig. 74. Section through beach at Beruwela showing concentration of heavy minerals in streaks; monazite content on right.

Garnet, Rutile and Zircon

Garnet is a pink to red mineral used largely as an abrasive, zircon is generally brown and is the source of an important new metal zirconium, and reddish-brown rutile is being used today as a source of titanium dioxide.

A. Crushing and grading mill, Bogala Graphite mine.



B. Stockpile of lumps of graphite, Bogala Mine.

These three minerals are found in varying proportions in the beach sands and sand dunes around the coast of the island. Garnet increases in proportion towards the south until it reaches its greatest concentration in the rich, garnet-bearing dune sands around Hambantota (see Pl. 23B). Rutile and zircon are generally found in the ilmenite-rich sands, as at Pulmoddai, and can be recovered as a by-product of the separation of ilmenite. Steps are now being taken to make this recovery at Pulmoddai.

Quartz

Ceylon is rich in this mineral, several millions of tons of almost pure quartz sand occurring as surface deposits within the Marawila-Nattandiya-Madampe area north of Negombo. The quartz sand here averages about 98 per cent silica, but it unfortunately has a relatively high iron content. Only a few thousand tons of the quartz sand around Nattandiya have so far been utilised, mainly for the manufacture of low-grade glassware like coloured bottles and tumblers, but colourless glass bottles are now being manufactured from the purified sands.

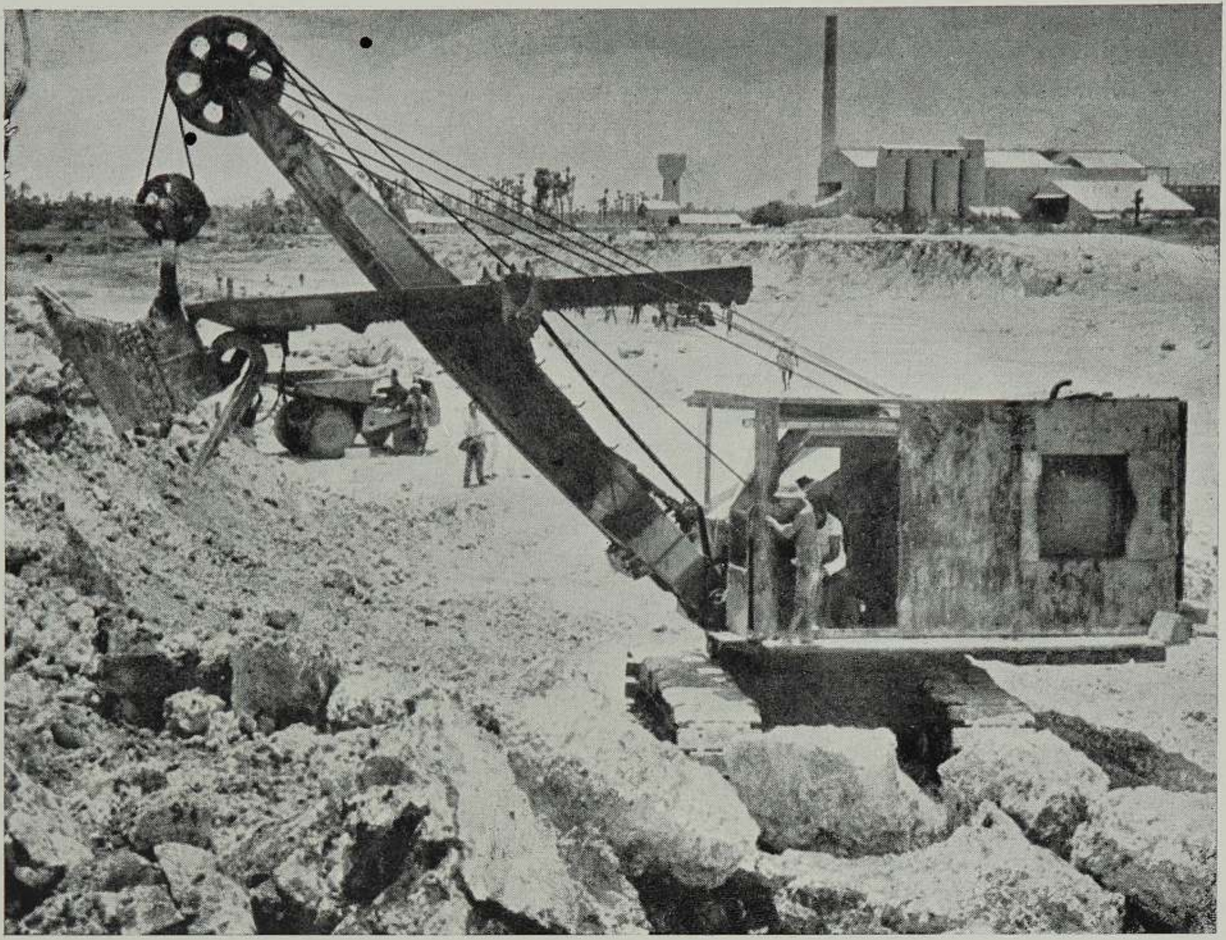
Limestone

The limestone resources of Ceylon are of three main types, each of which is used in different ways.

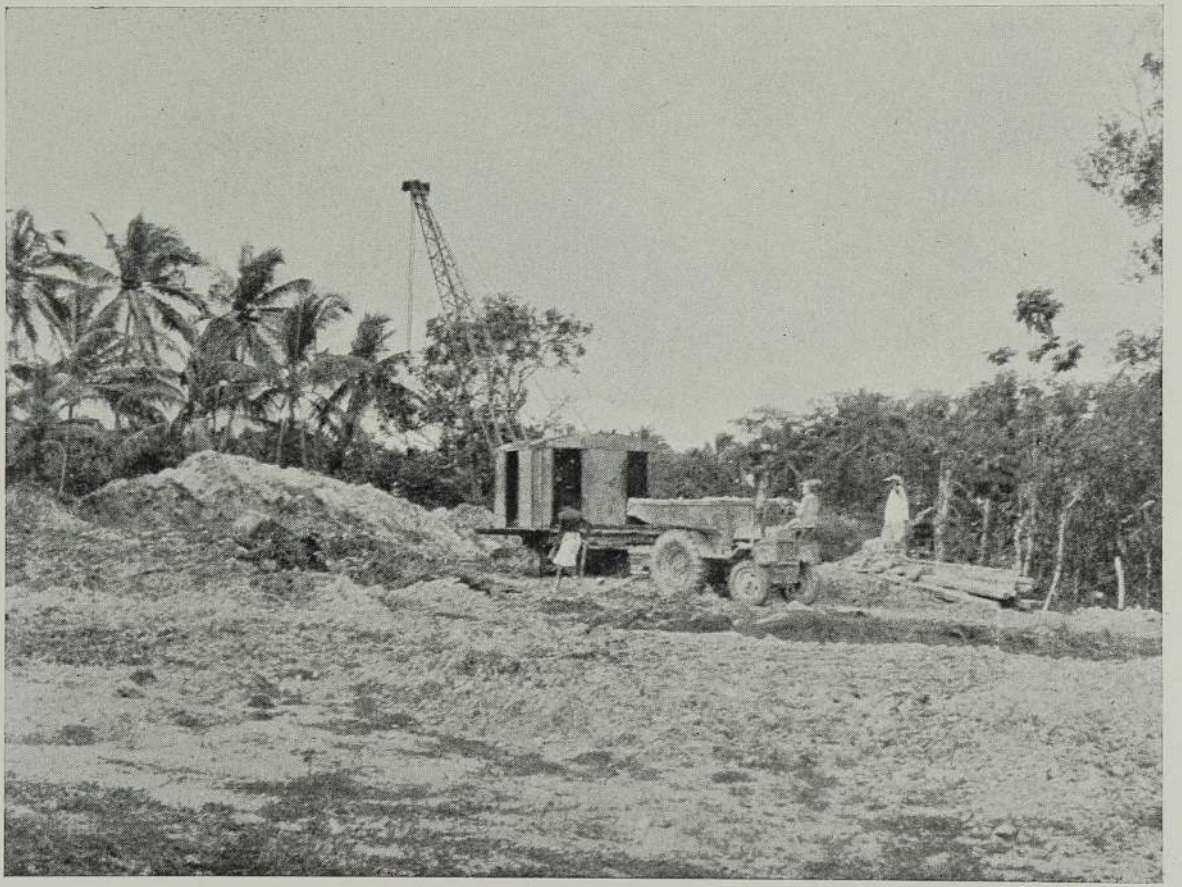
The *sedimentary limestone* of the Jaffna Peninsula and the north-west coast, owing to its accessibility, great extent, and purity (CaO=52 per cent) is eminently suitable for the manufacture of cement, and this is its major use at present (Pl. 36A). In the 5-year period 1959-64, for example, nearly 700,000 tons of limestone valued at almost Rs. 3.3 million were used in the Ceylon Cement Corporation's factory at Kankesanturai. The reserves in the Jaffna Peninsula alone run to tens of millions of tons of usable limestone which can be drawn on for many years to come.

A further deposit of nearly 18 million tons of limestone has recently been proved at Aruakalu, 18 miles north of Puttalam, and it is this deposit that will be used by the second cement factory being built at Puttalam. The reserves at Aruakalu will be sufficient for a plant producing 200,000 tons of cement per year for 60 years.

In the manufacture of cement, proper proportions of limestone and clay are burnt to produce a 'clinker' which is then cooled and stored; the finished cement is made by grinding clinker with a small amount of gypsum. The factory at Kankesanthurai uses clay from Murunkan, and the Puttalam factory will obtain its clay from the large clay field at Ralmadu which is close to the source of the limestone.



A. Quarrying limestone at the Cement Factory site, Kankesanthurai. (*Joe Perera*)



B. Mining kaolin at Boralesgamuwa.

Coral limestone, though of relatively pure calcium carbonate and easily obtainable, does not occur in large enough quantities for the manufacture of cement. It is, however, extensively burnt for chemical lime, namely, *quicklime* and *slaked lime,* especially along the south-west coast near Hikkaduwa, and is transported to lime kilns many miles inland where no other source of limestone is available.

The Pre-Cambrian *crystalline limestones* are not suitable for the manufacture of cement owing to their impure nature, many being dolomitic or magnesia-rich in composition. When pure, however, the crystalline limestones are used for the manufacture of chemical lime. The large numbers of lime kilns in the Kandy and Badulla areas are based on the large bands of pure crystalline limestone found in those areas.

The dolomitic limestone or those containing both calcite ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$) have been recorded in the Ratnapura, Matale, Kandy, and Badulla areas (see Table 21). This variety is mined on a moderate scale (5,000 tons in 1965), the rock being reduced to small aggregates for mixing with fertilisers to correct magnesia deficiency in soils. The more dolomitic varieties will be used for foundry bricks in the Iron and Steel Factory, and a suitable deposit of 150,000 tons has so far been located at Uda Niriella in the Ratnapura District.

A small deposit of crystalline *magnesite* (magnesium carbonate, $MgCO_3$) is associated with dolomitic limestone at Randeniya, 4 miles north of Wellawaya. About 4,000 tons are known to occur here and this deposit is a potential source of raw material for the production of refractory bricks, cements, and flooring.

Feldspar and Quartz

Small amounts of pure feldspar and quartz are utilised as refractory materials * in the ceramic and glass industries of the island.

Pure feldspar is obtained from large pegmatites, and during 1965 nearly 613 tons valued at Rs. 121,224 were mined from a pegmatite at Talagoda, near Elahera, for use by the Ceramic Factory at Negombo.

Quartz is mined from quartz veins at Pussela, near Ratnapura, where almost inexhaustible reserves of this mineral are found. The same source has supplied quartz to the ceremic industry for the last 25 years. In 1964, 632 tons of quartz valued at Rs. 43,924 were mined at Pussela (see Table 8).

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* A *refractory* mineral is one that can be used at high temperatures.

Industrial Clays

The clay deposits of Ceylon are extensive, and they occur in the flood plains of the major rivers, in old river channels (*owitas*), in tank beds, and in the deep weathered zones of the crystalline rocks. Some of these deposits have been utilised in a small way for centuries, but their large-scale exploitation has only recently begun. As far as their industrial use is concerned, the clays can be divided into two main types, namely, *kaolin* or white clay, and coloured, *alluvial clays*.

Kaolin

Kaolin is the name given to the pure white clays composed chiefly of the mineral kaolinite. It is the final product in the weathering (or *kaolinisation*) of feldspars in rocks like granite, pegmatite and fedspar-rich gneisses. Kaolin has a high refractoriness and also the important

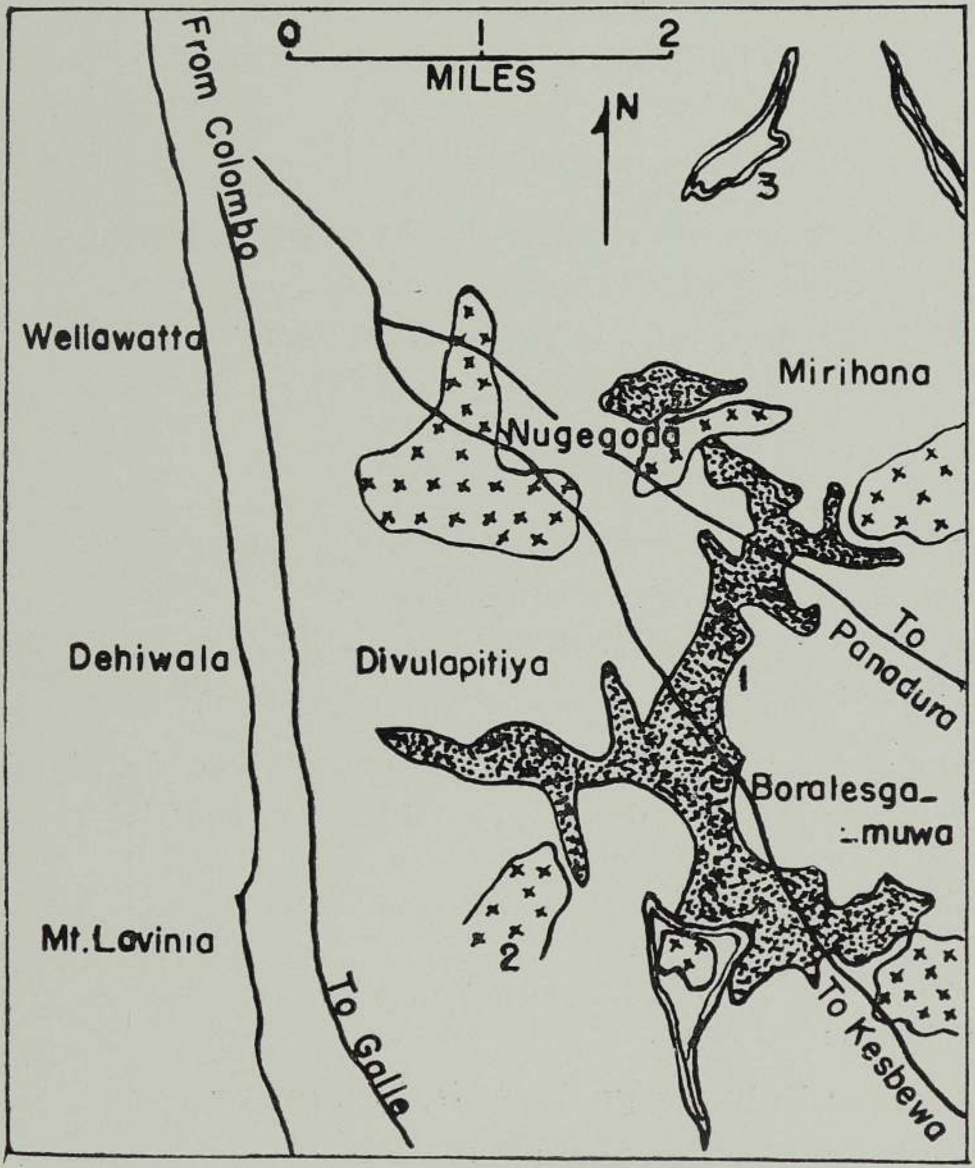

Fig. 75. Sketch map of the kaolin deposit at Boralesgamuwa.
(*After J. W. Herath,* 1963)

property of turning pure white in colour when fired. The uses of kaolin are numerous, among them being for the manufacture of pottery, electrical insulators, sanitary ware, refractory bricks and as a filler in textiles, paper, paints and powder.

The largest known deposit of kaolin in Ceylon is found in the swampy ground between the laterite hillocks around Boralesgamuwa, 9 miles south-east of Colombo (Fig. 75). It occurs here in lenses, beds, and pockets within 10 to 30 feet of the surface and overlying the decomposed gneisses of the area ; these deposits are generally covered by a few feet of sandy clay[54]. The kaolin can therefore be scooped out easily without any difficulty or expensive mining operations (Pl. 36B). It has been estimated that there are at least 8 million tons of kaolin in the Boralesgamuwa deposit. The kaolin is mixed with a certain proportion of sand, silt, and mica, and is refined in the newly built Kaolin Refinery at Boralesgamuwa. The refinery produced 595 tons in 1963, its first year of working, but when working at full capacity is capable of producing 5,000 tons of pure kaolin per year.

There are other deposits of kaolin in the island, notably the one at Meetiyagoda, near Ambalangoda, but they are of comparatively minor importance when compared to the Boralesgamuwa deposit.

Alluvial Clays

These are mostly coloured clays with a high proportion of ferromagnesian minerals and a low refractoriness, used for the manufacture of structural clay products (like bricks, tiles, stoneware, and pipes) and for cement. The clays are soft, highly plastic, and easily worked.

Alluvial clays occur in all the major river valleys of the island and their distribution, according to Districts, is as follows[55] (Fig. 76) :—

1. *Colombo :* Kelani Ganga, Dandugam Oya.
2. *Chilaw :* Maha Oya, Deduru Oya.
3. *Puttalam :* Ralmadu.
4. *Kalutara :* Kalu Ganga, Bolgoda, Dediyawela.
5. *Galle :* between the Bentota Ganga and Gin Ganga.
6. *Matara :* Weligama, Kirinda, Nilwala Ganga.

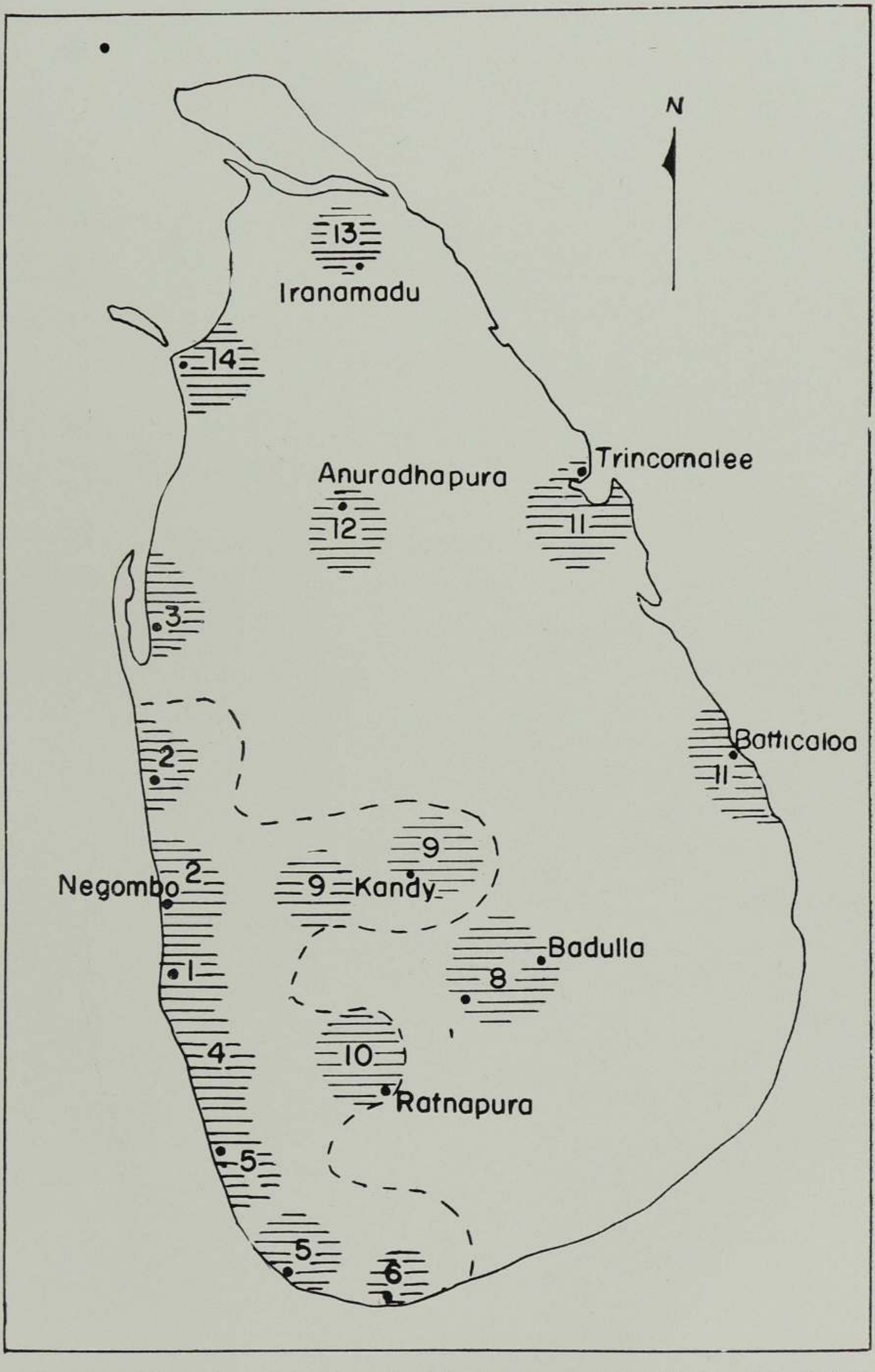

Fig. 76. Map of the principal clay deposits of Ceylon according to Districts; dashed line marks eastern limit of concentration of cottage brick-and-tile industy. (*After J. W. Herath*, 1964)

(1) Colombo, (2) Chilaw, (3) Puttalam, (4) Kalutara, (5) Galle, (6) Matara, (7) Kandy and Matale, (8) Nuwara Eliya and Badulla, (9) Kurunegala and Kegalle, (10) Ratnapura, (11) Batticaloa and Trincomalee, (12) Anuradhapura, (13) Jaffna, (14) Mannar.

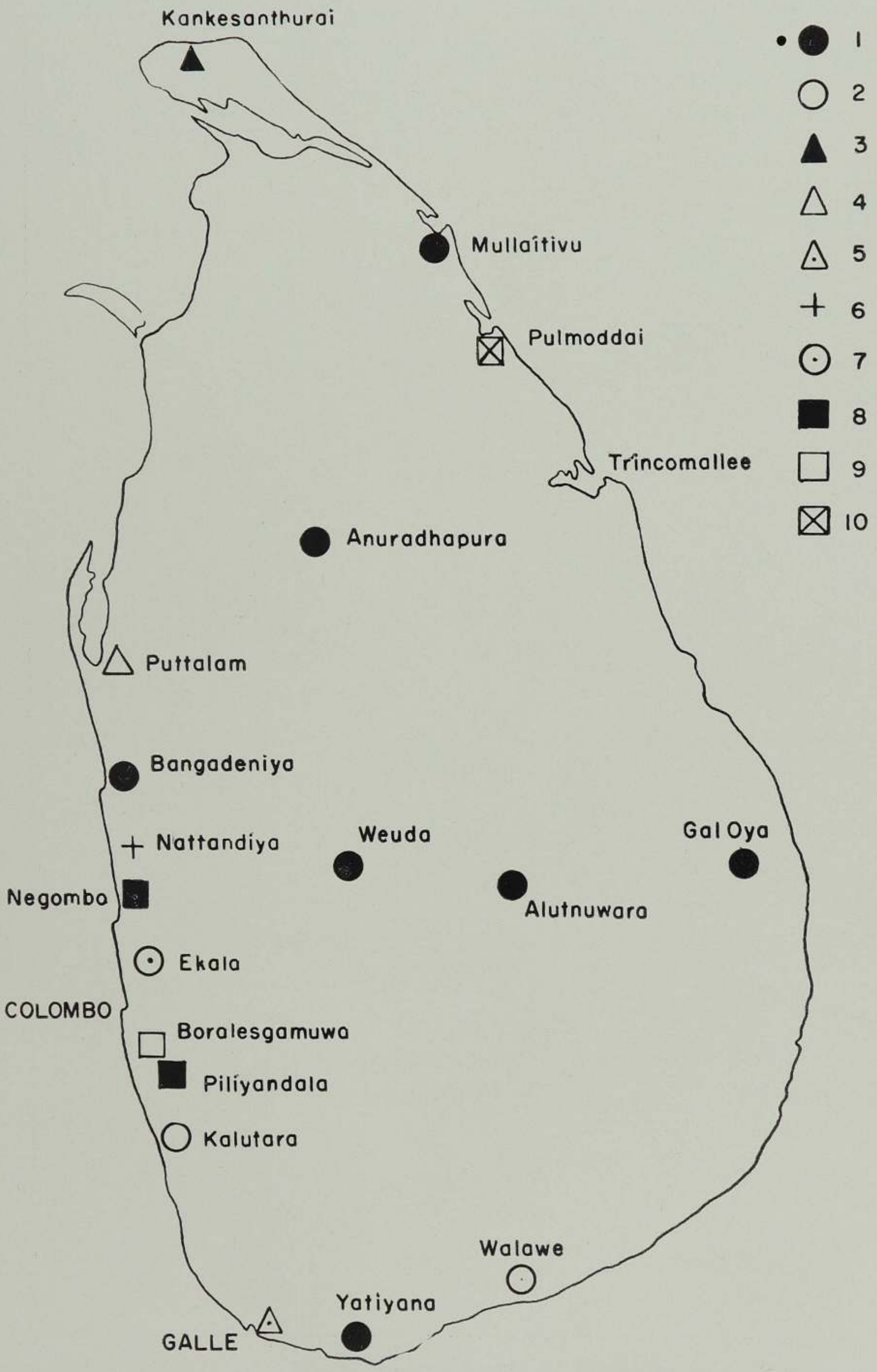

Fig. 77. Map showing locations of main factories using local mineral raw materials. (*After J. W. Herath*, 1964)

(1) tile, established, (2) tile, planned, (3) cement, established, (4) cement (proposed), (5) clinker grinding plant (established), (6) glass, (7) sand-lime brick (proposed), (8) ceramic, (9) kaolin refinery, (10) mineral sands refinery.

7. *Kandy* and *Matale :* south of Peradeniya, Kandy-Matale area, Gampola, Wattegama, Galagedera.
8. *Nuwara Eliya* and *Badulla :* few deposits.
9. *Kurunegala* and *Kegalle :* upper Maha Oya.
10. *Ratnapura :* upper Kalu Ganga.
11. *Trincomalee* and *Batticaloa :* Mahaweli Ganga.
12. *Anuradhapura :* few deposits.
13. *Jaffna :* Iranaimadu.
14. *Mannar :* Murunkan.

The manufacture of bricks and tiles was, until recently, predominantly a widespread, small-scale, seasonal, cottage industry, concentrated in the valleys of the Kalu Ganga, Kelani Ganga, and Maha Oya. A few large-scale factories for the manufacture of the better type 'Mangalore' tiles were also found, mainly between Colombo and Negombo. These factories have, within the last few years, been considerably modernised, and in addition, the State has established modern tile factories at places like Bangadeniya, Gal Oya, and Alutnuwara, with plans for several more (Fig. 77).

Among the alluvial clays are two special types that need to be mentioned. *Ball clays* are dark in colour but burn to a white or cream body, and are used for ceramics ; good deposits are found in the Dandugam Oya and Kelani Ganga valleys as well as near Dediyawela. Clays suitable for *cement manufacture* are found at Murunkan and at Ralmadu, north of Puttalam. The former deposit is used in the Cement Factory at Kankesanthurai, production of this clay in 1963 being about 25,000 tons, valued at Rs. 361,000 (see also Table 8).

Iron Ore

The presence of slag heaps in many scattered parts of the island such as the Kandyan districts, Balangoda, Rakwana, and Bingiriya, shows that a small-scale iron-smelting and steel-making industry existed almost all over Ceylon in the time of the ancient Sinhalese kings ; it died out completely only at the beginning of the present century. The ore was smelted in furnaces with bellows blown by foot, and the iron so produced was used largely for the manufacture of spear heads, swords, and other implements[56]. Examples of these implements can be seen in the Colombo Museum and some recently found clay tubes or moulds (*kova*), still with their casts (*wane karal*), are on view in the Museum of the Geological Survey Department. The ancient iron-smelting industry was based on locally available ore which is now known to occur on the surface in several million tons.

Surface deposits consist of either a massive ore of *hematite* or a spongy aggregate of hydrated ores such as *limonite* and *goethite* ; the latter, which resemble laterite in appearance, are porous, non-crystalline, and comparatively soft. These iron ores occur as surface cappings or as lenses, pockets and irregular masses extending a few feet below the surface (Fig. 78), and can be seen as large blocks and boulders on the crests of hills or on hill slopes. They appear to be the residual products of the weathering of the underlying rocks, particularly those with an abundance of iron-rich minerals like garnet. The higher grade, massive, hematitic ores have an average metallic content of 50 per cent Fe and the lower grade lateritic ores have from 30 to 40 per cent Fe[57]. Both types of ore suffer from a relatively high content of phosphorous (about 0.5 per cent).

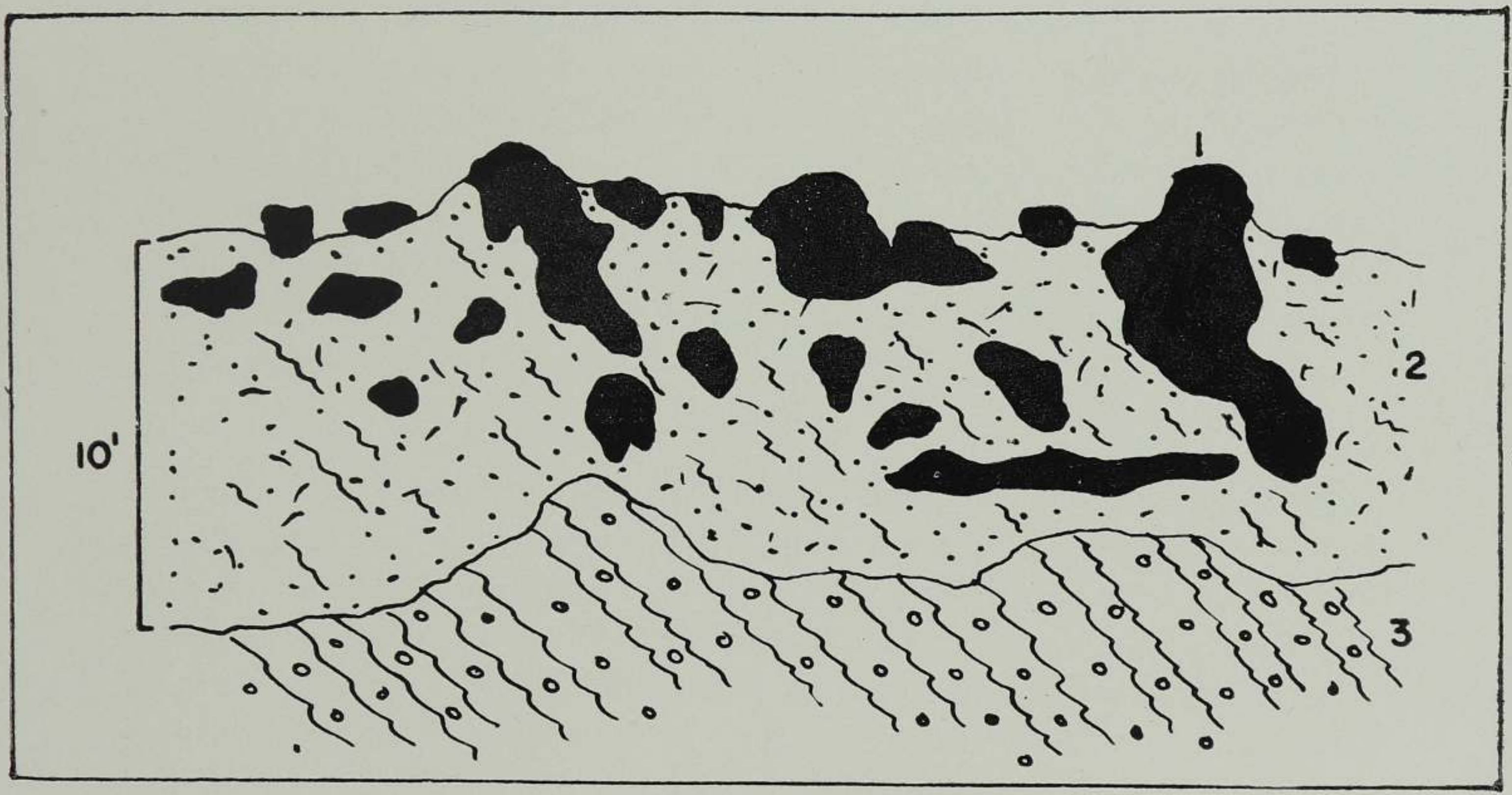

Fig. 78. Nodular masses of limonitic iron (1) occurring as boulders of float ore in decomposed overburden (2) of garnetiferous gneiss (3) ; Fairfield Estate. (*D. N. Wadia*, field notebook)

The most important areas in which the hydrated iron ores are found are mainly in the south-west portion of the island, in belts running practically parallel with the regional strike of the rocks. These areas are—

(*a*) the Ratnapura-Balangoda area (mainly Dela and Noragalla) ;

(*b*) the Kalutara-Baddegama area ; and

(*c*) the Chilaw, Ruwanwella and Kandy-Matale areas.

A total of 2 to 3 million tons of surface ore are easily accessible both by road and railway in these localities, and they can be mined with ease by open-cast methods not involving underground working.

Within the last few years, a different and perhaps more important type of iron ore has been located in the North-Western Province, at Wilagedera and Panirendawa, near Bingiriya. The ore here consists chiefly of *magnetite* (magnetic iron) and is found in bands 5 to 20 feet thick at depths of 70 to 500 feet below the surface, where it is interbedded with calc granulites, quartzites, and basic rocks[58]. This banded iron formation (which appears to be a sedimentary deposit) is very similar to the 'banded hematite quartzites' found only in Pre-Cambrian successions elsewhere in the world, as in the Lake Superior region of Canada, in Mysore in S. India, in Brazil, Liberia, and Mauretania. These rocks contain some of the world's largest reserves of high-grade iron ore.

The magnetite at Wilagedera and Bingiriya is associated with sulphide minerals (pyrite, pyrrhotite and chalcopyrite) and sometimes with barytes (barium sulphate). The average metallic content of this ore is about 65 per cent Fe, which makes it much richer in iron content than the hydrated ores of the south-west ; the phosphorous content is negligible (about 0.05 per cent). The investigation of these banded iron ore deposits is proceeding, using modern geophysical and geochemical methods, and already 3 to 4 million tons of utilisable ore have been found to be present. The exploitation of the deposits will present more difficulties than those of the south-west and may involve underground mining methods.

The proposed iron and steel factory at Kelaniya which is to be operated by the Ceylon Steel Corporation will, in the early stages, use imported pig iron for the manufacture of iron and steel products, but will later mine and smelt the local ores. In the absence of coal, the factory will probably use charcoal made from rubber wood which has been found suitable for iron ore smelting. Ample supplies of limestone and dolomite are available for the iron and steel industry.

Peat

Nearly 50 million tons of peat are known to exist at Muthurajawela in an area of about 13 square miles, just north of Colombo. The peat occurs as a bed with an average thickness of 12 to 15 feet and a maximum thickness of 20 feet[59]. The deposit is badly drained, the normal water level in the greater part of the swamp being about six inches to one foot above the surface, except during the dry season, when it is about surface level.

The exploitation of these peat deposits as a source of fuel and as a basis for a nitrogenous fertilizer industry will first require a scheme of mining, de-watering, and drying.

Gold

Extremely minute quantities of gold are widely distributed in the rocks of Ceylon but nowhere does it occur in sufficient concentration to be worked profitably. Small amounts of gold dust have been found in the alluvium and gravels of several rivers, for example the Maha Oya near Ambepussa, the Kelani Ganga at Malwana, the Katugasella near Ratnapura, the We Ganga, and the Weralupe Dola[60]. Gold is also sometimes found in decomposed bed rock below the alluvium but is here even less concentrated than in the alluvium. In spite of systematic surveys for gold from time to time, such as those in 1902-03, 1909, 1943-46, no workable placer deposits of gold have yet been found in the island.

Radioactive and Rare Earth Minerals

The raw materials for nuclear energy are the radioactive minerals contraining uranium and thorium, of which the chief are *uraninite* (U_3O_8) and *thorianite* (ThO_2), and a series of minerals containing mixtures of these two ; the mineral *uranothorianite*, with about 50 per cent of each, is midway in the series. The hydrated oxides of uraninite and thorianite, namely, *gummite* and *thorogummite*, are also radioactive.

Uraninite has not been found in Ceylon, but thorianite was first discovered here in 1904-5. Several tons of thorianite were exported between 1905 and 1906, when the saleable value was £ 1,700 per ton, but at that time the thoria content of the mineral was used only for the manufacture of incandescent gas mantles[61]. No other use was then known for thoria, as radioactivity had not been discovered or was in its infancy.

Thorianite occurs as heavy, black, cubic crystals with a density of 9 ; it is thus the heaviest known mineral in the island. Owing to this high density and hardness the crystals remain close to their source after being released from their parent rocks by weathering, and they also largely retain their cubic shape. Thorianite occurs widely as a heavy mineral in the stream beds of the Bambarabotuwa and Mitipola areas and decomposed thorianite-bearing pegmatites have been found in the Bambarabotuwa and Maddegama areas. Thorianite from Ceylon generally has 70-80 per cent ThO_2 and from 12-30 per cent $U_3 O_8$ (see Appendix V).

Thorite ($ThSio_4$), the silicate of thorium, is a brown, flattish mineral quite unlike thorianite; it has about 50-70 per cent ThO_2. This mineral is also present in river and gem gravels in the south-west of the island, and has recently been located in some pegmatites in the Balangoda, Welimada, and Matale areas[62]. Thorite in these pegmatites is often associated with smoky quartz. *Uranothorianite,* with 48-54 per cent ThO_2 and 35-40 per cent U_3O_8 has recently been found in the stream gravels of Mitipola[62].

Monazite, with 9-10 per cent ThO_2, is the other major radiactive mineral in Ceylon besides thorianite. Apart from occurring as a beach concentrate (see p. 211) it occurs widely as an accessory mineral in many of the gneisses and granites of the south-west, north-west, and central parts of the country.

Other feebly radioactive minerals found in Ceylon are *zircon* and *allanite.* Zircon ($ZrSiO_4$) with about 65 per cent zirconium oxide occurs an an accessory mineral in most of the crystalline rocks of the island, as a major mineral in some granites and pegmatites (for example the Balangoda Granite), in many river gravels and gem gravels, and as a constituent of beach sands on both sides of the island. Its chief use is as a source of metal zirconium.

Allanite, with about 2 per cent ThO_2 is a brownish liver-coloured mineral with a submetallic lustre, which occurs in large charnockitic pegmatites (at Alutepola near Negombo, and Godagala near Beruwala), in the Balangoda Granite, in some graphite-bearing veins, and in many gneisses. It is frequently surrounded by redish reaction rims due to radioactive bombardment.

Several of the minerals mentioned above contain the elements thorium, cerium, lanthanum and yttrium, which together with niobium, tantalum and others, constitute the group of rare-earth elements. Minerals containing these elements are often called 'rare-earth' minerals and Ceylon has a large variety of these. The majority of them are more in the nature of mineralogical curiosities, being difficult to identify and seldom met with. The list is too long to be detailed here but among the minerals may be mentioned *geikielite, fergusonite, gadolinite, xenotime, samarskite, columbite,* and *aeschynite*[61]. Most specimens of these minerals were found in the early years of the present century in the gem gravels of the south-west, generally in the *nambuwas* or discarded material from the gem pits. Most of these minerals have little economic importance at present.

Other Metallic Minerals

A few metallic minerals, belonging mostly to the sulphide group, are known to occur in Ceylon, but only as minor, accessory minerals in the crystalline rocks. The chief of these are the iron and copper sulphides *pyrite* (FeS_2), *pyrrohotite* (Fe_5S_6) and *chalcopyrite* ($CuFeS_2$) which are found in calc gneisses, graphite-bearing veins, and banded ironstones. *Molybdenite* (MoS_2 or molybdenum sulphide) occurs in some pegmatites, granites, and graphite-bearing veins, and *galena* (PbS or lead sulphide) is present as small, cubic crystals in the Wanni gneisses at a few localities. So far none of these minerals has been found in sufficient concentration to be regarded as economically valuable.

Building Stones

Any rock, to be suitable for use as a building stone, must be both strong and durable, or in other words, must be able to endure the stresses placed upon it not only at the time of construction but for many years to come. In these respects most of the crystalline rocks of Ceylon and some of the sedimentary types are eminently suitable as building stones. Some rock types have been used extensively in the past, and many local stones are once again being increasingly used for building purposes.

The crystalline limestones, owing to their attractive appearance and easy working, were popular with the early builders and sculptors in Ceylon, especially in the ancient capital of Anuradhapura *. Although subject to some degree of weathering, these crystalline limestones, particularly the dolomitic varieties, have stood the test of several centuries of exposure to the elements extremely well, and inscriptions made in these limestones still bear the traces of the original chisel marks.

One of the most beautiful stones in Ceylon is a green serpentinous marble, at present known to occur in small quantities at Rupaha, near Nuwara Eliya, and near Hatton. The Rupaha marble, used by the local villagers for making small ornaments, is in a very inaccessible spot. These green marbles, when polished, make excellent ornamental stones such as monuments and wall facings, but they are too soft to be used for flooring.

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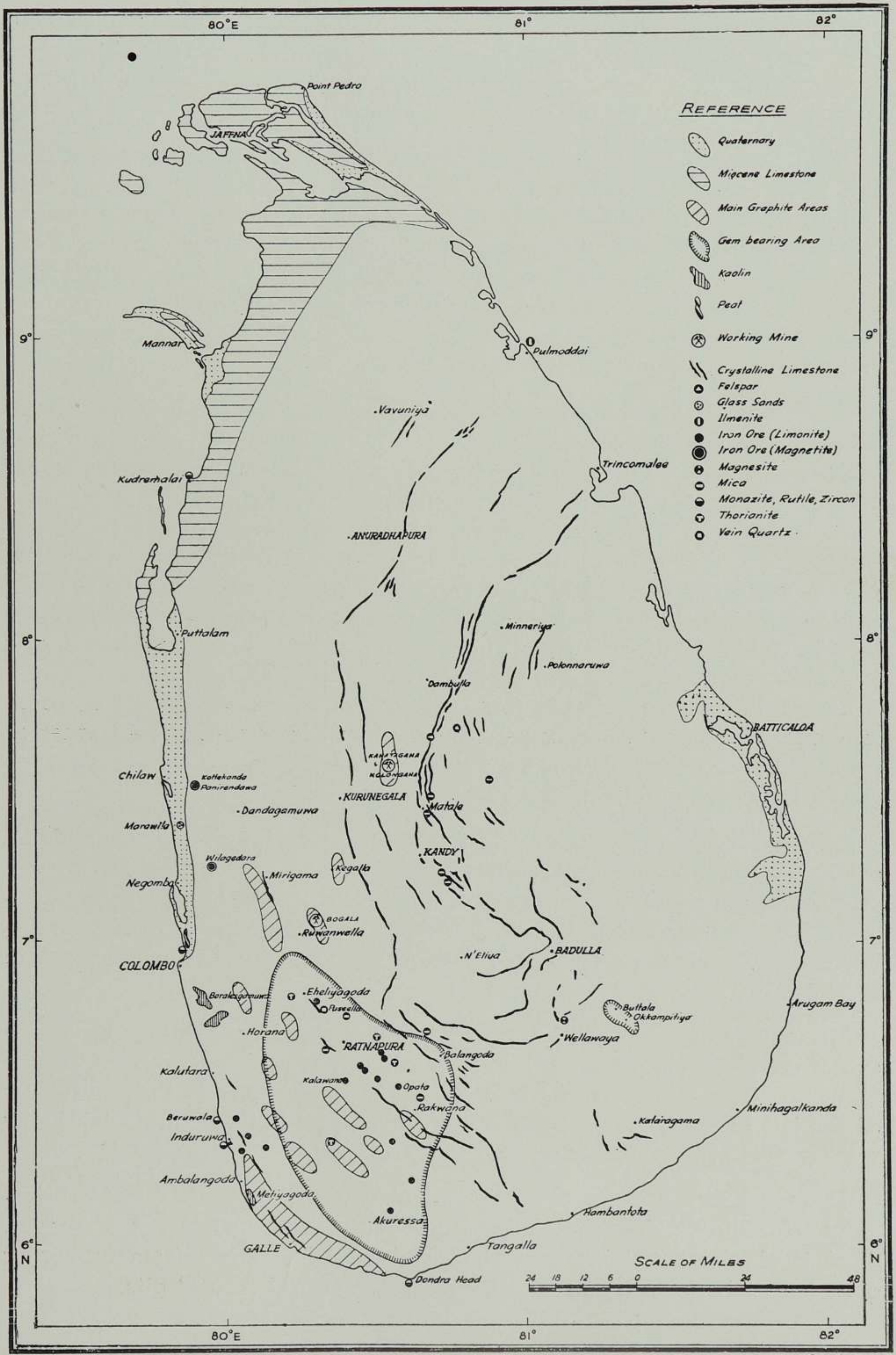
* A fine example of sculptured crystalline limestone is the beautiful statue of the seated Buddha from Toluwila which now adorns the entrance hall of the Colombo Museum.

MINERAL MAP OF CEYLON



Printed by Survey Dept. Ceylon May, 1966.

Drawn by G. de Mel

Dark grey charnockite is a favourite building stone in the central Hill Country where great quantities of it occur, and several of the small churches in this part of the country, for example those at Lindula, Norwood, and Madulkele, are built of this rock.

Quartzites and garnetiferous gneisses too have been used, the former near Kandy and the latter in the Balangoda and Pelmadulla areas, but they are less suitable than other types for several reasons. Quartzites are generally well jointed and fractured and the garnetferous gneisses have regular foliation planes in them, as well as being highly weathered. Sometimes, however, the former defect makes for easy splitting and trimming of the rock into suitably sized blocks, as in the case of the attractive Khondalite Group gneisses with the large garnets.

By far the commonest crystalline rocks used for building purposes are the granites and gneisses of the Vijayan Series and those found in the south-west region. These rocks, with their high proportion of the resistant mineral quartz, the lack of regular joints and fractures, and their medium grain size, are extremely durable and strong, and have been much used in the past. In most of the ancient ruined cities of Ceylon, large monolithic pillars, blocks, and slabs of gneisses lie about in great abundance as a testimony to their popularity as building material. One good example is seen in the hundreds of steps going to Mihintale, but many more examples will be known to the reader. These pillars and slabs have been expertly trimmed and worked by the stone masons of Ancient Ceylon and some magnificent sculptural works have been hewn out of them. The statues of the Buddha at Dambulla and the Gal Vihare at Polonnaruwa are a few of those that come readily to the mind.

A very striking variety is the Tonigala Granite, whose pinkish to reddish surface, when polished, makes a particularly fine ornamental stone. Nearly all varieties of the crystalline gneisses and granitic rocks take a good polish and all types have been used as ornamental or monumental stones. Excellent examples can be seen in most cemetries, especially the one at Kanatte in Colombo.

Apart from the crystalline rocks, only laterite and sedimentary limestone are of any importance as building stones. In the Jaffna Peninsula, nearly 15 per cent of the houses are built of Jaffna Limestone ; in the south-west of the island *kabook or laterite* is the commonest building material, being readily available and cheaper than clay bricks.

Also used for a variety of constructional purposes are sand and crushed stone (for building) and nodular ironstone (for the surfacing of roads). Sand is obtained mainly from river beds, crushed stone from numerous quarries in the island, and nodular ironstone from ‘ gravel ’ pits.

CHAPTER 11

THE GEOLOGICAL HISTORY OF CEYLON

The same regions do not remain always sea or land, but all change their conditions in course of time.

Aristotle (384-322 B.C.)

ATTENTION was drawn in the first part of this book (see p. 42) to William Smith's careful studies in England and Wales, as a result of which he showed that south-eastern England was made up of sedimentary formations deposited in the sea during every period from the middle of the Palaeozoic to the end of the Teriary era. The picture is strikingly different in Ceylon, however, for the geological record is completely blank during large stretches of geological time. Wadia has put this rather well in the following words[63].

> " The geological history of Ceylon may be summarised in a sentence as the history of the first chapter, rather fully recorded, and a fragmentary record of the last chapter of the geological history of the earth. The rest of the chapters forming the bulk of that history being a total blank, except for a few obliterated lines belonging to a page or two relating to events of an enthrallingly interesting period during the Mesozoic when Ceylon formed part of a large Indo-Afro-Australian Continent of the southern hemisphere, when the Himalayas were yet in the making and lying under the waters of the Mediterranean ocean. "

Although our knowledge of the rocks of the island, their ages, and the conditions of their formation has increased considerably since the time when Wadia wrote, this knowledge is still far from complete. Consequently, we can still only outline the main events in the geological evolution of Ceylon, basing the story partly on the available evidence, partly on the geological history of Peninsular India, and partly on conjecture. We can best do this by describing the geological history of the island under five ' chapter ' headings, namely,

(i) *The Taprobanian Geological Cycle—a Pre-Cambrian event*
(ii) *A Cambrian Orogeny*
(iii) *A Fragment of Gondwanaland*
(iv) *The Miocene Marine Transgression*
(v) *Quaternary Fluctuations*

TABLE 13.—Ages of Chief Isotopically Dated Orogenic Belts and Igneous Events in Africa, India, Ceylon, Australia, and Antarctica

(After A. Holmes, 1965)

EAST AFRICA	Millions of Years	INDIA and CEYLON	AUSTRALIA and ANTARCTICA
	0		
ALPINE (Atlas)		ALPINE (Himalayas)	
		Deccan Plateau Basalts	
Karoo lavas & intrusions		Rajmahal lavas & intrusions	Basic lavas & intrusions
	200		
CAPE FOLDS			
	400		
MOZAMBIQUIAN		Travancore Late Metamorphism, E. Ghats *Late Metamorphism, Vijayan*	S. and W. Australia E. Antarctica ADELAIDE OROGENY
DAMARAN LATE KATANGAN	600		
		DELHI	
	800		
		SATPURA--ARAVALLI	Broken Hill Metamorphism MUSGRAVE OROGENY
	1,000		
		Cuddapah Dolerites	E. Antarctica Dolerites
	1,200		
KARAGWE-ANKOLEAN (Uganda) KIBARAN (Congo)		Charnockite Met., E. Ghats	
	1,400	*Charnockite Met., Highland Series*	
Madagascar			
MAYUMBIAN (Congo) UBENDIAN (Tanganyika) TARKWAIAN (Ghana)	1,600	EASTERN GHATS, Khondalite Met. TAPROBANIAN, Highland Series,	Adelie Land Met., (Antarctica) BROKEN HILL WILLYAMA PROVINCE
	1,800		
KIBALEAN (Congo) TORO (Uganda)			
	2,000		
	2,200	'IRON ORE' OROGENY UPPER DHARWAR	
	2,400	MIDDLE DHARWAR	
		BUNDELKHAND	
	2,600		

THE GEOLOGY OF CEYLON

Chapter One—The Taprobanian Geological Cycle—a Pre-Cambrian Event

In any account of the history of Ceylon during Pre-Cambrian times, we must keep clearly in mind the fact that what is now an island formed a very small portion of an enormous landmass in the southern hemisphere, and that the geological events in any one region of this landmass were reflected in the adjacent regions. Thus, if we are to recognise the main episodes in the island's history, we have to know the main events in those parts of Africa, S. India, Australia, and Antarctica that were likely to have been in close proximity to Ceylon. These events can best be shown in the form of a table (Table 13) and we shall refer frequently to it in the following pages.

The beginnings of Ceylon's geological history are obscure and unrecognizable at present. What are thought to be the oldest rocks of the Island, namely, the metasediments of the Khondalite Group, must themselves have originally been deposited on a geosynclinal floor, but no traces of this floor have so far been found. Such a floor would be difficult to recognise, however, except by radioactive dating, for the reason that it would have been caught up and considerably altered in the intense metamorphism and folding that the overlying sediments were later subjected to.

To seek a beginning we have to look to the Eastern Ghats of India, where a belt of khondalites and charnockites strikingly similar to those of the Highland Series of Ceylon stretches from Orissa in the north to the Nilgiri Hills and beyond in the south (Fig. 79). In fact, so striking is the similarity of the rock types, that the garnet-sillimanite schists of the Central Highlands of Ceylon were named 'khondalites' after their Indian counterparts. One branch of this Eastern Ghats belt of rocks strikes out to the sea in the vicinity of the mouth of the Kistna River north of Madras and can be made to continue into Ceylon in the neighbourhood of Trincomalee (Fig. 80). The other part of the Eastern Ghats belt continues into the extreme south of the Indian continent in the region of Travancore, and it could possibly extend into the south-western region of Ceylon. Isotopic ages of minerals from the Eastern Ghats belt indicate that clayey sediments were laid down in a long geosyncline along the margins of an old mountain chain known as the Dharwars, and that these sediments were turned into khondalites by metamorphism and folding about 1600 m.y. ago.[63a] Major metamorphisms of the same age are also known to have occurred in East Africa, Australia and Antarctica (Table 13). There are, unfortunately, still no isotopic ages either of rocks or minerals of the Highland Series

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that can be compared with these ages but we will continue to assume, on indirect evidence, that they are of approximately the same age, until the contrary is proved by radioactive dating.*

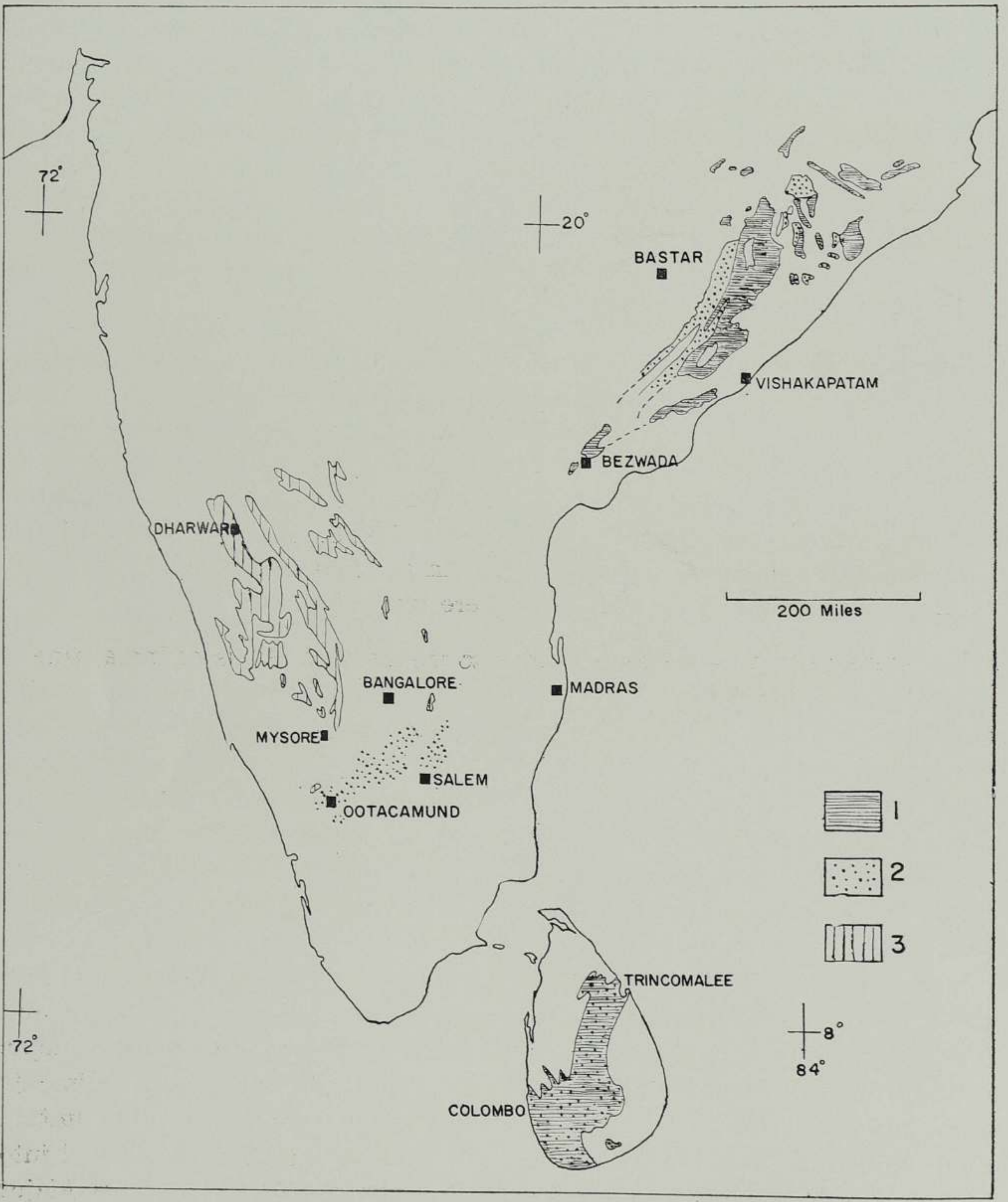

Fig. 79. Distribution of Pre-Cambrian metasediments and charnockites in Peninsular India and Ceylon. (*From the Geological Map of India*, 1957)

(1) metasediments, (2) charnockites, (3) Dharwars.

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* See Appendix II, 'Isotopic Ages of Minerals from Ceylon.'

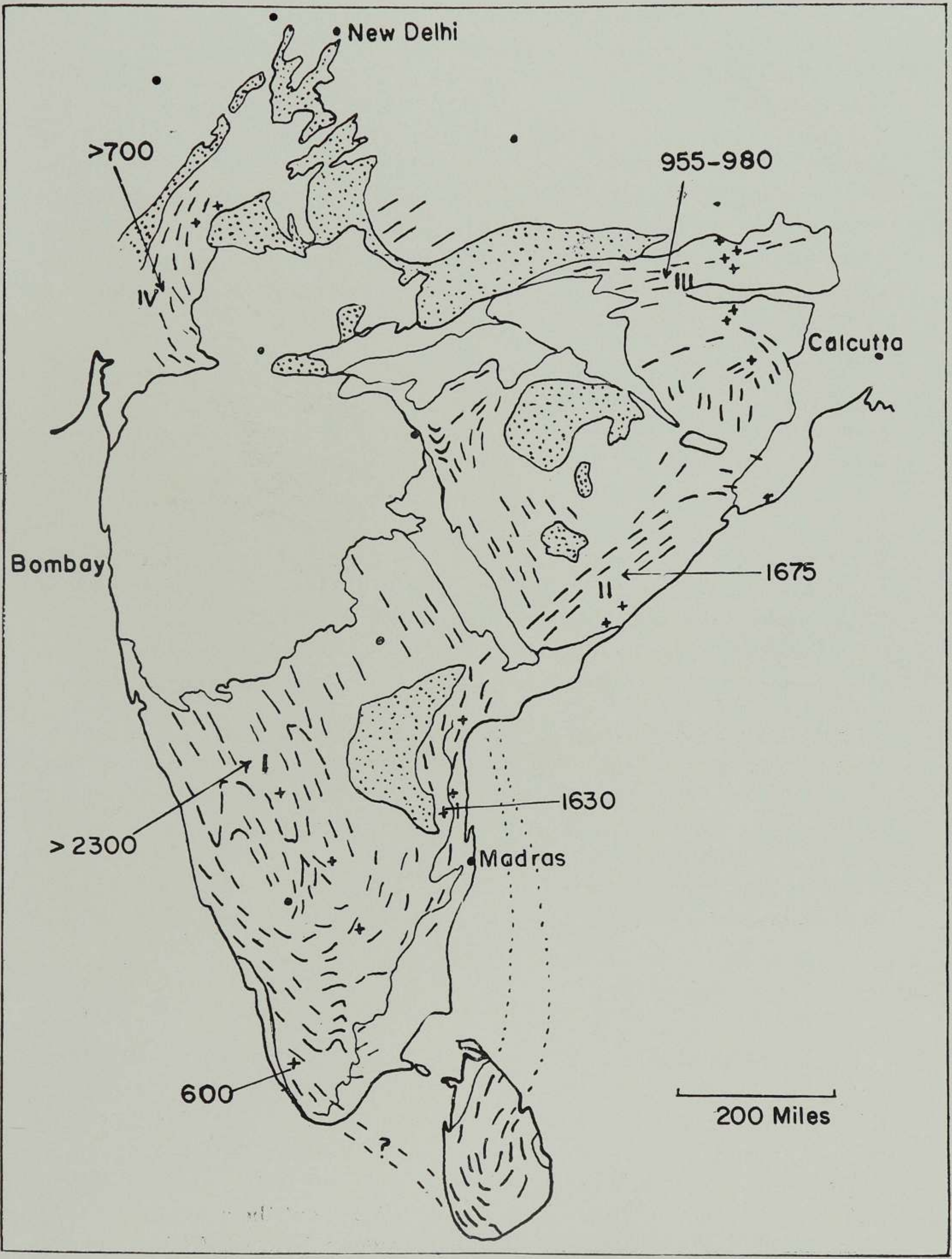

Fig. 80. Map of the orogenic belts of Peninsular India and Ceylon with isotopic ages of rocks and minerals. (*After U. Aswathanarayana*, 1956 and *C. S. Pichamuthu*, 1962)

(i) Dharwar Belt (2300 ± 100 m.y.)	(iii) Satpura Belt (955 ± 40 m. y.)
(ii) Eastern Ghats Belt (1625 ± 75 m. y.)	(iv) Delhi-Aravalli Belt (735 ± 50 m. y.)

The earliest recognisable episode in the geological history of Ceylon is thus thought to be the existence, perhaps about 1700 m.y. ago, of a geosyncline stretching for several hundreds of miles along the margin of an early Pre-Cambrian landmass. It was in this elongate basin of deposition that the waste matter from the Dharwarian mountains accumulated as a thick succession of marine sediments such as shales, limestones, marls, sandy clays, and sandstones. Volcanic lava flows and intrusions of basic igneous rock must also have formed part of the succession, but they cannot be identified as such now.

The floor of the geosyncline sank, in course of time, and the geosynclinal rocks were eventually buried at great depth where they came under the influence of enormous heat and high pressures, the former possibly of the order of 700° to 800° centigrade. The total effect of these conditions was to convert the sedimentary and other formations into the highly crystalline quartzites, crystalline limestones, garnet-sillimanite gneisses, charnockites, and basic rocks that we see today and know as the Highland Series. Lateral pressures, acting at the same time or later, folded these rocks into the Taprobanian system of parallel folds of great magnitude and considerable length ; some of the folds were symmetrical, others were overturned, and a few lay on their sides as recumbent folds.

Recent age determination on charnockites in the Eastern Ghats belt of India suggest that some of them were formed after the main metamorphism, about 1300 to 1500 m.y. ago[63]. On indirect evidence this was also thought to be so for some of the more gneissic varieties of charnockites in the Highland Series, though no actual ages had been determined. We can now presume that remelting and recrystallisation of some charnockites in the Highland Series took place between 1300 and 1500 m.y. ago (Table 13).

Chapter Two—A Cambrian Orogeny

We do not know when the Taprobanian geological cycle came to an end, but we do know now that the rocks in the Eastern Ghats belt, especially those in the south, suffered renewed metamorphism, possibly accompanied by folding and uplift, about 500 m.y. ago[63]. We also know that major orogenies or mountain-building episodes took place in the adjacent regions of Africa, S. America, Australia, and Antarctica about the same time[64] (Fig. 81 and Table 13). The Mozambiquian orogeny in East Africa and the Adelaide Orogeny in South Australia are two such examples (see Table 13)

In our own portion of the crust we have new evidence that similar events must have taken place between 450 and 550 m.y. ago, that is, during Lower Palaeozoic times (see Appendix II).

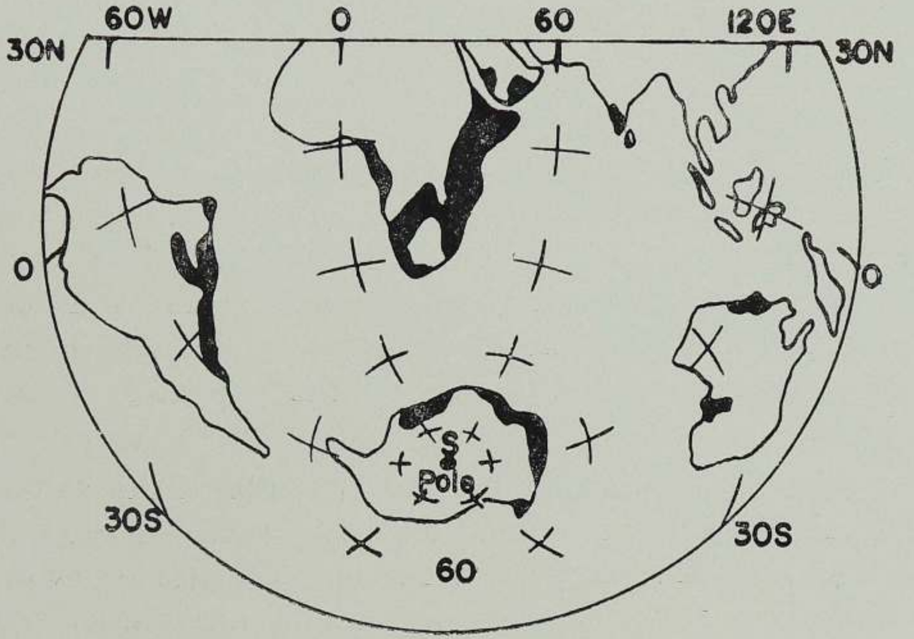

Fig. 81. Map showing the distribution of metamorphic rocks, granites, and pegmatites formerly thought to be Pre-Cambrian but now known by their isotopic ages to have been formed during the Cambrian and Ordovician periods, when the shaded areas were probably, in part, geosynclinal seas. (*After A. Holmes,* 1965)

It is uncertain whether sedimentation preceded the Cambrian orogeny in Ceylon. During the orogeny, however, renewed heat as well as waves of fluids carrying sodium, potassium, fluorine, chlorine and water, seeped into and soaked the earlier formed crystalline rocks, altering their mineral compositions and imposing new textures on them. Large areas previously occupied by metasediments and charnockites were turned into gneisses, migmatites, and granitic rocks of various types which we know collectively as the Vijayan Series. This soaking, or *permeation,* was accompanied by internal pressures that distorted the somewhat plastic rocks into an irregular pattern of folds. In certain parts, the rocks were so altered as to become granitic in composition, and so mobile as to behave in an intrusive fashion, pushing aside the gneisses into which they moved. Certain individual bands of metasediments and at least one large area, around Kataragama, were either unaffected or only slightly affected by the action of these later fluids ; these remained as the metasedimentary relics that we now see surrounded by later formed Vijayan rocks. The present belt of Highland Series rocks remained more or less unaffected by these events, except that micas were recrystallised in some and that mica-bearing pegmatites were intruded into the belt.

Nearly all the crystalline rocks of Ceylon had already been formed by the end of the Cambrian orogeny, and they finally evolved into a mountain chain rising above the sea. These mountains were immediately attacked by weathering and erosional processes, and the products carried away to form the beginning of a new geological cycle elsewhere. What we now see are only the 'roots' of this mountain chain, after thousands of feet of material have been eroded away.

The cooling and solidification of the crystalline rocks, together with the release of overlying pressure following uplift and erosion, led to the development of tensional planes of weakness such as joints and fissures in the rocks. Dykes and veins of pegmatite and quartz were intruded into some of these planes of weakness, while movement along others resulted in faults, now sometimes recognised by the presence of mylonites and augen gneisses.

Granitic pegmatites generally occur in groups of the same age and of similar composition, and we have at least two such groups in Ceylon. The ages of both groups are fairly well defined. The older group of zircon-bearing pegmatites, found at Balangoda and elsewhere, were intruded about 570 m.y. ago, just after the end of the Pre-Cambrian and at the beginning of the Palaeozoic era. The younger group of thorium-bearing pegmatites (with thorianite, and possibly also thorite, allanite, and monazite) were formed about 485 m.y. ago during Lower Palaeozoic times ; they probably mark the closing stages of the Cambrian orogeny. The important fact about these younger pegmatites is that they are similar in age to thorium-bearing pegmatites found in East Africa, Madagascar, and South India, and must have formed part of a vast dyke swarm in this part of the pre-Gondwana landmass[64a] Once more we see that the geological history of Ceylon cannot be studied in isolation but must be related to the major geological events in the adjoining areas.

Finally, some of the granitic gneisses of the Vijayan and of the south-western region have micas that were formed, either newly or by recrystallization, between 450 and 350 m.y. ago. In other words, changes were going on in the crystalline rocks of Ceylon even in Devonian times, and we must recognise and accept the fact that rocks that were once thought to be Pre-Cambrian in age were really formed during the Lower Palaeozoic era.

Chapter Three—**A Fragment of Gondwanaland**

It is important to note, at this point in our story, that the present outline of Ceylon was not even hinted at during the Palaeozoic and Mesozoic Eras, that is, for about 450 million years after the end of the Pre-Cambrian. The 'island' as we know it today, formed only a very small portion of a vast landmass, which, by Mesozoic times, included the present continents of South America, Africa, Madagascar, India, Australia, and Antartica. This landmass is known as *Gondwanaland* (after the Kingdom of the Gonds, an aboriginal tribe of India). The palaeogeography of Gondwanaland during the Upper Palaeozonic and Mesozoic Eras makes fascinating reading [65,66] but is outside the scope of this book. Ceylon was a portion of this continent, however, and therefore the geological history of Ceylon is, in part, the history of Gondwanaland.

During Lower Palaeozoic times, that is during the Cambrian, Ordovician and Silurian periods, the pre-Gondwanaland landmass of India was being eroded away ; to the north of it, stretching from present day Kashmir to Assam, was a long geosynclinal basin in which continuous deposition was taking place. The climate changed considerably towards the end of the Palaeozoic and an enormous ice cap covered this pre-Gondwana continent during the Permian and Carboniferous periods (Fig. 82). As the ice melted and the ice cap shrank, thick deposite of glacial till were laid down over most of the land surface and areas released by the ice were covered by vast fresh-water lakes and marshes, or were transgressed by the sea. Evidence of this glacial period is widespread. The Talchir Boulder Bed, for example, which is recognized in many parts of Peninsular India

Fig. 82. Suggested reassembly of Gondwanaland showing distribution of Permo-Carboniferous glaciation. (*A. Holmes*, 1965)

at the base of the Gondwana System*, is correlated with the Dwyka Conglomerate of South Africa and similar glacial beds in Australia, Tasmania, and South America.

No evidence has so far been found that suggests that Ceylon was also covered by the ice cap. If it was, then all signs of glaciation have since been removed by weathering and erosion. Alternatively, Ceylon may have been outside the main glaciated region.

The melting of the ice cap at the end of the Palaeozoic era was followed by uplift of the land and a general regression of the sea. This regression continued throughout the beginning of the Mesozoic era (the Triassic Period) and deposition of sediments took place only in more or less isolated basins. Ceylon and the east coast of India continued to remain a comparatively high area, still subject to denudation which removed great thicknesses of the Pre-Cambrian crystalline rocks until even such deep-seated granites and gneisses as the Tonigala Complex were exposed.

The regression of the sea in the Triassic period was followed during the Jurassic (about 150 million years ago) by a general encroachment of the sea on the land, and it was only now that Ceylon formed low land where sediments were being deposited (Fig. 83). Even then Ceylon lay on the borders of the sea, as did South India, and experienced many fluctuations of sea level. In Madras, for example, marine Jurassic deposits alternate with continental deposits, and the same is likely in Ceylon, the only difference being that marine beds which might have been above the present Tabbowa Beds have since been eroded away, and marine beds which might lie below the Tabbowa Beds cannot at present be seen.

Several large rivers drained the surface of Gondwanaland during this time, bringing down to the sea vast quantities of detrital matter such as clay, silt, sand, and organic matter. Some of these rivers deposited this material in deltas and inland basins along the present coasts of south-east India and north-west Ceylon. Most of these deposits were eroded away subsequently but small patches of them were preserved in basins faulted into the underlying crystalline basement either during the sedimentation or after it. It is possible that fault movements were widespread at this time and caused the block uplift of the mountain masses of Central Ceylon and South India to form the existing peneplains[67].

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* The glacial beds, together with the overlying doposits, are known as the *Gondwana System* in India, the *Karco System* in South Africa, and the *Santa Catherina System* in South America. Though widely scattered, these Gondwana formations are, perhaps, unique for the similarity of their sediments and fossil contents.

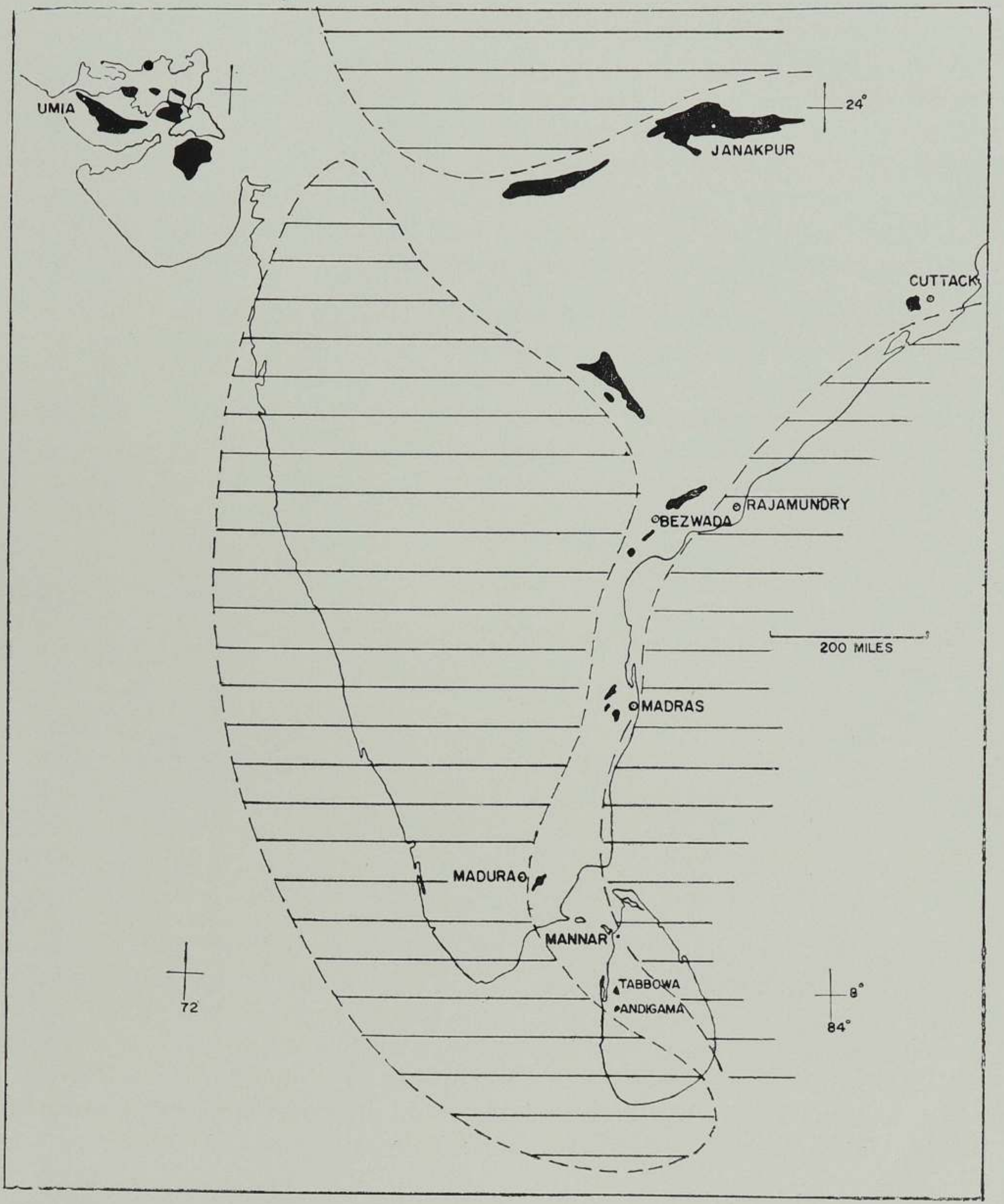


Fig. 83. Distribution of Jurassic rocks of Peninsular India and Ceylon. (*From the Geological Map of India*, 1957)

Approximate extent of landmass shown by horizontal ruling.

These preserved basins of Jurassic rocks are found at Tabbowa and Andigama in Ceylon and near Madras, Ongole, and Rajamundry on the east coast of India (Fig. 83). They are seen to be roughly aligned in a N-S direction, and other basins may be hidden below later deposits. In fact, drillings carried out in the Mannar area in 1963 and 1964 showed that sandstones and shales very similar to those at Tabbowa lie below the Miocene limestone at depths of about 250 feet[25]. The nature of the sediments shows that climatic and other conditions varied rapidly in the deltas and basins of Gondwanaland (see p. 134). Igneous activity was pronounced during the Jurassic and Cretaceous Periods, as seen in the vast Rajmahal Traps of South India and the Karoo Dolerites of South Africa, but the Tabbowa Beds do not contain any such igneous rocks.

It was only at the end of the Mesozoic era (that is, during the Cretaceous Period) that the coastline of Africa was defined for the first time, and India (with Ceylon) and Australia became separate entities. An arm of the Cretaceous sea lay close to Ceylon, once again a landmass, and it was possibly from this landmass that garnets and other detrital materials were provided to the sediments that now form part of Australia[65].

Chapter Four—The Miocene Marine Transgression

The break-up of Gondwanaland began towards the end of the Mesozoic era, and its parts drifted apart to become the southern continents as we now know them. Ceylon remained above the sea until Miocene times and no deposits are recorded within its boundaries during this long interval of about 120 millon years. On the contrary, many thousands of feet of waste material were removed during the peneplanation of this landmass.

One of the most important palaeogeographic features of the Mesozoic and Tertiary Eras was the existence of a great sea, the *Tethys Sea,* between Gondwanaland on the south and a northern landmass called Laurasia. In this geosynclinal sea were deposited several thousands of feet of marine sediments like sandstones, shales, and limestones, which were, in Tertiary times, to be raised into the great fold mountain systems of Asia, Europe, North Africa, and South America (see below).

About 20 million years ago, during the Miocene, an arm of the Tethys Sea stretched down the west coast of India, a long narrow gulf of which gradually encroached on the peneplaned land surface between India and Ceylon (Fig. 84). This gulf severed the extreme portion of the Indian mainland and turned Ceylon, for the first time, into an island. The sea here was comparatively shallow. In its warm waters grew extensive coral reefs which harboured a rich fauna, and several hundreds of feet of limestone, calcareous clay, and sand accumulated on the floor of the sea. This

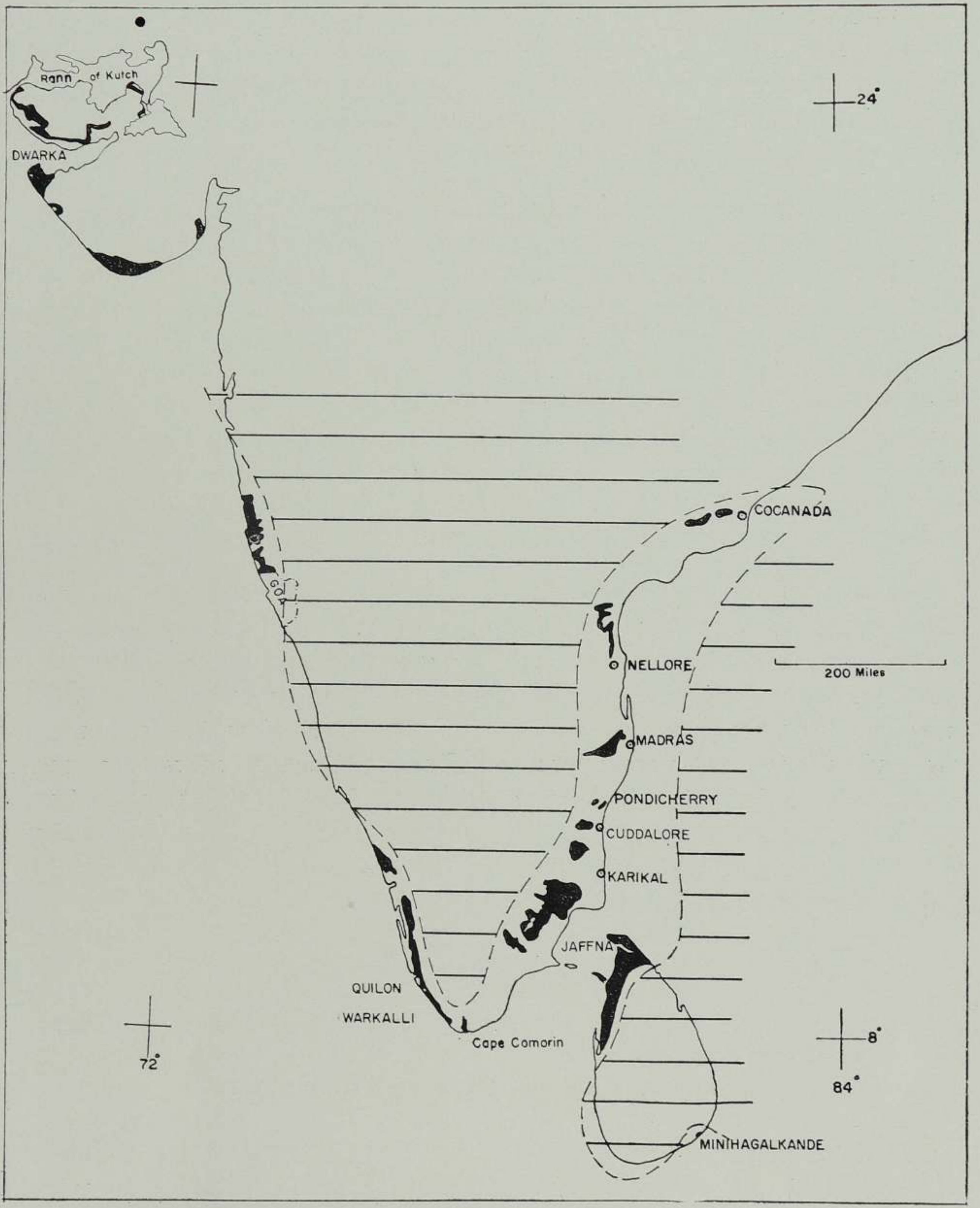


Fig. 84. Distribution of Miocene rocks of Peninsular India and Ceylon. (*From the Geological Map of India*, 1957)

Approximate limit of marine transgression shown by dashed line.

submarine depression, during which the north-western margins of Ceylon were under the sea, is recorded in the thick limestone beds of Jaffna and in the Karikal and Warkalli beds of South India.

A much smaller gulf of the sea encroached on the southern margin of Ceylon, and here sandy and clayey deposits, with intercalations of limestone, were laid down at Minihagalkande. Conditions of deposition at Minihagalkande were generally much less quiet than in the north-west, more detrital material being carried into the sea.

The Tertiary period throughout the earth was marked by a great mountain-building episode, when the geosynclinal sediments of the Tethys Sea were folded and pushed up to form the mountain belts of the East Indies, Himalayas, Carpathians, Alps, Atlas mountains, and Andes, which stretch from East Asia through Western Europe to South America. In the Himalayan mountains, for example, marine sediments formed below the sea, are now found more than 20,000 feet above sea level. This Alpine orogeny, is still not over. It is one of the major events in the history of the earth's crust, when tremendous internal forces were at work, disrupting the Gondwana continent and folding and thrusting the sedimentary rocks to the north into the gigantic nappes we see today.

Ceylon was far from these areas of intense earth movements and its Miocene rocks were hardly affected by them. All that happened was a slight warping of the surface and a slow but continuous uplift of the sea floor whereby the nearly horizontal Miocene limestones, once at the bottom of the sea, are now exposed in cliffs from 50 to 75 feet high in the Jaffna and north-west coasts. These Miocene rocks dip gently westwards to form the bed of the shallow Palk Strait between Ceylon and India, the sea being only about 5 fathoms deep in places. By contrast, the sea floor off Trincomalee on the east coast deepens within a comparatively short distance to 2,000 fathoms and more.

Chapter Five—**Quaternary Fluctuations**

The detailed history of Ceylon during the Quaternary period has still to be worked out, but it is clear that the island has retained its present outline and has remained more or less above the sea for the 10 million years or so since the end of the Miocene. The deposits formed during this time are mostly continental in character, being mainly wind-blown sands, river and flood plain deposits, and lacustrine and lagoonal sediments. The varied characters of these deposits show that post-Miocene times have been marked by changing climatic conditions varying from pluvial

TABLE 14.—Major Events in the Geological History of Ceylon

PERIOD		Millions of years ago	GEOLOGICAL EVENT	FORMATION	EQUIVALENT IN INDIA
QUATERNARY		2	*Fluctuations of sea level*, climatic changes, and changes in drainage systems. **Sedimentation**, continental type deposits inland, mixed continental and marine deposits around margins of island.	YOUNGER GROUP Laterite, nodular ironstone OLDER GROUP RATNAPURA BEDS	Alluvium, sands Laterite Terrace deposits, Madras
TERTIARY	Pliocene	12	*Uplift and erosion*	*Unconformity*	
	Miocene	25	**Sedimentation**—marine deposits *Submergence*—encroachment of Tethys Sea making Ceylon an island for first time	JAFFNA LIMESTONE MINIHAGALKANDE BEDS	Kutch Beds ; Quilon Beds
	Oligocene	40			
	Eocene	60			
	Palaeocene	70			
CRETACEOUS		135	Break-up of Gondwanaland ? *Intrusion* of dolerite dykes *Peneplanation, faulting, uplift*	?DOLERITE DYKES (Gallodai and others) *Unconformity*	Rajmahal lavas
JURASSIC		180	**Sedimentation**—mixed continental and marine deposits in deltas on margins of landmasses *Submergence*—encroachment of Jurassic sea on Gondwanaland	TABBOWA BEDS, ANDIGAMA BEDS	Upper Gondwana deposits of Madras Coast
TRIASSIC		225			
PERMIAN		270			
CARBONIFEROUS		350	*Uplift and erosion* *Intrusion* of granites and pegmatites Continued *granitisation* and migmatisation	*Unconformity* ARANGALA GRANITE, AMBAGASPITIYA GRANITE GNEISSES OF SOUTH-WESTERN REGION	
DEVONIAN		400			
SILURIAN		440			
ORDOVICIAN		500	Continued *granitisation and migmatisation* *Intrusion* of pegmatites **Metamorphism and folding** involving migmatisation, granitisation etc. and profuse intrusion of pegmatites	TONIGALA COMPLEX PEGMATITES—with thorianite, thorite, allanite, monazite VIJAYAN SERIES—granitic and migmatitic gneisses, granites.	?Closepet Granite Travancore pegmatites, with thorium ?Peninsular Gneisses Granitic gneisses and pegmatites in E. Ghats belt
CAMBRIAN		600	*Intrusion* of pegmatites	PEGMATITES in Highland Series, recrystallisation in H.S. PEGMATITES – with zircon (Balangoda granite etc.)	
PRE-CAMBRIAN		1300 1500 1600 1700	*Metamorphism* involving melting and recrystallisation **Regional metamorphism** at high temperatures and pressures (granulite facies). **Folding** *Burial* of sediments at depth *Sedimentation in geosyncline* on edge of Dharwarian landmass ; volcanic flows and basic igneous intrusions *Erosion*	Gneissic charnockites in Highland Series HIGHLAND SERIES—Khondalite Group, charnockites, basic rocks ; KATARAGAMA COMPLEX *Unconformity* (not seen) BASEMENT ROCKS (not seen)	Gneissic charnockites in E. Ghats belt EASTERN GHATS BELT—khondalites and charnockites Dharwar System

periods when torrential rains fell on the island to comparatively dry periods when desiccation of the land was predominant. Some of these periods may be correlated with the glacial and inter-glacial periods of the Quaternary Glaciation of Western Europe and N. America. Minor oscillations of the relative levels of land and sea, of the order of 50 to 100 feet, have also taken place, as seen in the high-level gravel terraces, raised beaches, buried river channels, lagoonal deposits, and sandstone reefs now below sea level. These changes of sea level have led to more than one depression of the coastal areas of the island below the sea and to subsequent uplift, resulting in a succession of alternating beds of marine sands and lagoonal clays.

The evidence from boreholes in the Colombo area (Fig. 60A) has led to the suggestion that the following episodes can be recognised in the Quaternary history of this part of the coast of Ceylon [67a] :—

(i) Deposition of sands along the coast by the action of waves and currents ;

(ii) Slow depression of these sands and the accumulation of sandy clays in lagoons ;

(iii) Further depression and the covering of these deposits by marine sands ;

(iv) A slow upheaval which led to the uplift of the sands and the formation of sandstones by lime-charged waters ;

(v) A subsidence of the land leading to the formation of swamps (now represented by vegetable beds), and later to the deposition of lagoonal clays and sands (with shells) in parts of the low plains invaded by the sea ;

(vi) A slow, discontinuous upheaval which is still in progress and which has led to the emergence of the littoral sandstone reefs.

That sea level has remained practically constant for the last few thousand years is demonstrated by the fact that the coral reef now below Hikkaduwa Rest House and about one foot above sea level has been dated at 3,000 years [67b].

The main events in the geological history of Ceylon are shown in Table 14.

PART THREE

GEOLOGY AND THE COMMUNITY

CHAPTER 12

GEOLOGY AND WATER SUPPLY

Rivers do not rise with the first rainfall, the thirsty ground absorbs it all.

Seneca (A.D. 3-65)

General Conditions

THE water resources of any country are of two kinds, namely, *surface water* and underground water or *groundwater*. The surface waters are found in rivers, streams, lakes, and artificial tanks, and the problems involved in their use are primarily engineering problems concerned with conservation and proper storage. Groundwater, on the other hand, which is an important source of water for human consumption in many parts of the world, is water occurring in large quantities in the rock formations of the earth's crust. The conditions governing its occurrence and extraction (by means of wells of one kind and another) are therefore mainly geological, and it is these conditions with which this Chapter is concerned.

Nature's Water Cycle

The source of all water is precipitation, in the form of rain, snow, and dew. One part of this precipitation evaporates from the earth's surface and from seas or is lost through transpiration by plants; another part runs along the surface into rivers and ultimately flows into the sea; the

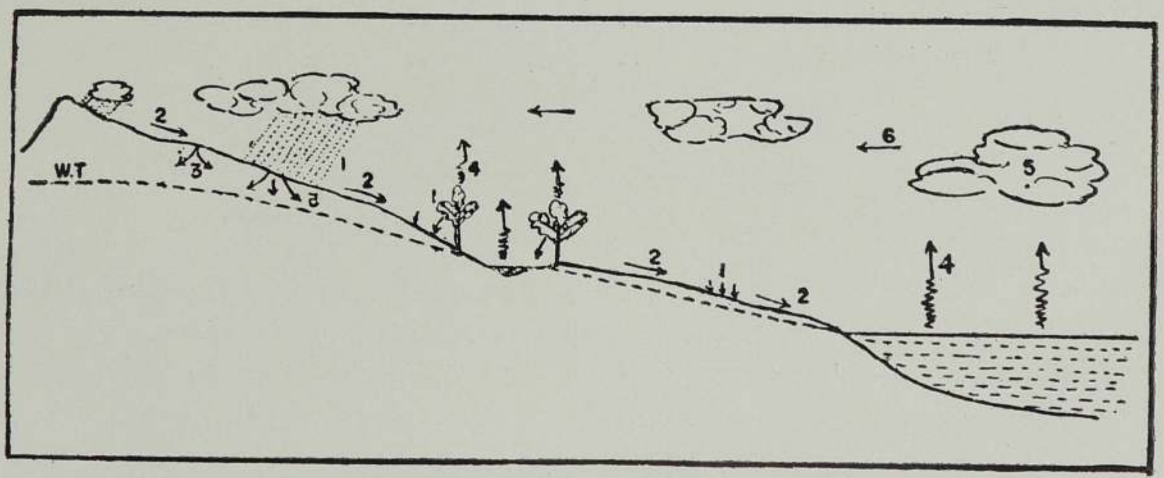


Fig. 85. Diagrammatic representation of Nature's Water Cycle. (*After P. H. Keunan*, 1955)
(1) precipitation by rain, snow, dew, (2) run-off in rivers and streams, (3) percolation, (4) evaporation and transpiration, (5) condensation into clouds, (6) wind currents, (WT) water table, upper surface of zone of saturation.

GEOLOGY AND THE COMMUNITY

third part seeps through the surface and is stored within the earth as groundwater. Thus we see that Nature's Water Cycle consists of a continuous process of precipitation, evaporation, condensation, and precipitation, as shown in Fig. 85. The relative amounts of water which evaporate into the air, run off the surface, or percolate into the earth, depend on several factors, chief of which are topography, temperature, surface geology, soil, and vegetation cover. The influence of geology, for example, is seen in the fact that 50 per cent or more of the rain falling on an area of loose, unconsolidated sand will percolate into the ground, whereas in regions of unweathered crystalline rock practically the entire rainfall will run off the surface.

Water-bearing properties of rocks

The amount of percolation that takes place, on which ultimately groundwater depends for its supply, is governed by two major textural properties of the surface rocks, namely, porosity and permeability. *Porosity* is the amount of pore space present in a rock and on it depends the rock's capacity to store water. *Permeability* is the capacity of the rock to transmit water and it depends on the presence of fissures, fractures, and other passages in the rock. Crystalline rocks, for example, with their interlocking mineral grains, have low porosities (0.2 to 0.8 per cent as shown in Table 15) but some permeability owing to the presence of joints in them ; the same is true of cemented sediments like sandstones.

TABLE 15—Porosities of some Ceylon Formations

Crystalline rocks	
Basic charnockite	0·2 per cent
Intermediate charnockite	0·5 per cent
Pink granite gneiss	0·6 per cent
Grey biotite gneiss	0·8 per cent
Sedimentary rocks	
Jaffna Limestone	4·7 per cent
Gravel	12·0 per cent
Beach sand	25 to 30 per cent

On the other hand, unconsolidated sands and gravels have both high porosity (about 30 per cent) and high permeability. The Jaffna Limestone has a low porosity (4.7 per cent) but high permeability, as we shall see, owing to the numerous cavities and solution channels in it.

The best measure of the capacity of a formation to yield water is its *specific yield*, but in this country, owing to the absence of precise data, the measure used is the *specific yield capacity*[68]. This is determined by pumping tests on wells in a particular formation and is expressed as the

GEOLOGY AND WATER SUPPLY

amount of water (in gallons per hour) percolating in a formation from a square foot of percolating area under a head of one foot. The specific yield capacities of some water-bearing formations in Ceylon are given in Table 16. From this table it can be seen that unconsolidated sands have the best specific yield capacities, namely 15 to 20 gallons per hour; alluvial clays and sandy clays have between 2.6 and 4.5 g.p.h.; specific yield capacities in the Jaffna Limestone are extremely variable, being from 0.8 to 8.0 g.p.h.

TABLE 16—Specific Yield Capacities of some Ceylon Formations

Jaffna Limestone (fissured) ..	8·0	*gall. per hour/sq. ft./ unit head*
Jaffna Limestone (unfissured) ..	0·8	,,
Alluvium	2·6 to 4·5	,,
Sand and sandy clay	3·0	,,
Unconsolidated sand	15 to 20	,,

Besides its texture, however, the thickness and extent of a formation, its structure, and the area over which it outcrops (and therefore permits percolation into it), are all important factors in determining the value of a geological formation as an *aquifer* or water-bearing formation.

The Water-table

When water percolates into the ground it saturates the rocks up to a certain level, forming a *zone of saturation*. The base of this zone is generally unweathered crystalline rock or a layer of impermeable material like clay. The upper surface of the zone of saturation is known as the *water-table* (Fig. 85) and it undulates rather like the surface topography but to a lesser extent (see Fig. 88). Within the zone of saturation water is always on the move from higher to lower levels. The water-table rises or falls according to the amount of water that percolates through to the saturation zone and so recharges it. Surface wells draw their water from this zone and the oscillations of the water-table explains why many wells are full after periods of continuous heavy rains (when recharge exceeds extraction) but run dry during long drought periods (when extraction exceeds recharge). Where the configuration of the surface topography crosses the water-table, springs may issue, or there may be ponds, lakes and streams (Fig. 85).

In other words, groundwater is continually being discharged to the surface at many points and a part of it is being extracted from underground storage for use by man; at the same time recharge is going on by percolation and by seepage from such large bodies as tanks, rivers, and irrigation channels. It is for this reason that many wells in rural Ceylon are sited by the sides of small village tanks, below the tank bunds in the paddy tracts (*yaya*), or by the side of large irrigation channels.

When water is stored underground at great depth and is confined by an impermeable layer, it possesses a certain amount of pressure. A well penetrating such a formation is know as an *artesian well,* up which the water rises of its own accord, and at great pressure.

Physical and chemical properties of water

The physical and chemical properties of groundwater depend on the formations traversed by it and on the dissolving capacity of water. The physical properties are colour, turbidity, taste, odour, reaction, and deposit ; the chemical properties include hardness, the amount of solids, and the quantity of dissolved salts present. Some organic matter is also present in all groundwater.

Brackishness is the measure of the chloride content of groundwater. Water containing up to 150 parts per million is considered good drinking water, and that containing between 150 and 500 p.p.m. is fair quality. Water with over 500 p.p.m. is considered brackish (see Table 17). Sea water has about 20,000 p.p.m. of chlorides. The chloride content of groundwater in the centre of the Jaffna Peninsula is about 50 p.p.m. but this may rise to as much as 1,500 p.p.m. in the overdeveloped areas along the coastal belt[69].

Hardness is a measure of the dissolved calcium and magnesium in water. Water with over 300 p.p.m. is considered 'hard' and below 100 p.p.m. is 'soft'. Groundwater in the Batticaloa area has about 200 to 300 p.p.m. and is generally hard, and springs in crystalline limestone in the Polonnaruwa area have a total hardness of 350 to 500 p.p.m. (Table 17).

TABLE 17—Chemical Analyses of Groundwater in Ceylon
(in parts per million)

Locality	*Formation*	*Electrical Conductivity*	*pH*	*Total Solids* (p.p.m.)	*Total Hardness* (p.p.m.)	*Chlorides* (p.p.m.)
Avissawella	Alluvium	70	6·6	58	30	12
Batticaloa	Beach sand	500	7·6	364	250	44
Hambantota	Dune sand	470	7·4	392	175	95
Tinnevelly	Jaffna Limestone	530	7·4	408	293	42
Jaffna	do.	2,500	7·3	1,480	504	584
Keerimalai(spring)	do.	3,000	n.d.	2,220	680	940
Minneriya	Quartzite	300	7·6	348	125	29
Naula (spring)	Crystalline limestone	500	7·5	392	350	18
Tissamaharama	Weathered cryst. rocks	1,000	8·0	670	550	36
Maho	do.	550	7·8	446	205	12
Ragama	Laterite	73	6·2	680	20	12

Figures for Maho and Ragama from P. W. Vitanage(1959) [14]; all others from W. R. Chanmugam (1952) [72].

Where water passes through alluvium and loose sand, these formations serve as natural filters and purify the water to almost the same extent as filtration plants.

Groundwater in Crystalline Rocks

Nearly nine-tenths of Ceylon is underlain by crystalline rocks, and nearly half of that is in the Dry Zone with low rainfall and a long period of drought ; the problems of water supply are therefore of major and vital importance in this part of the country.

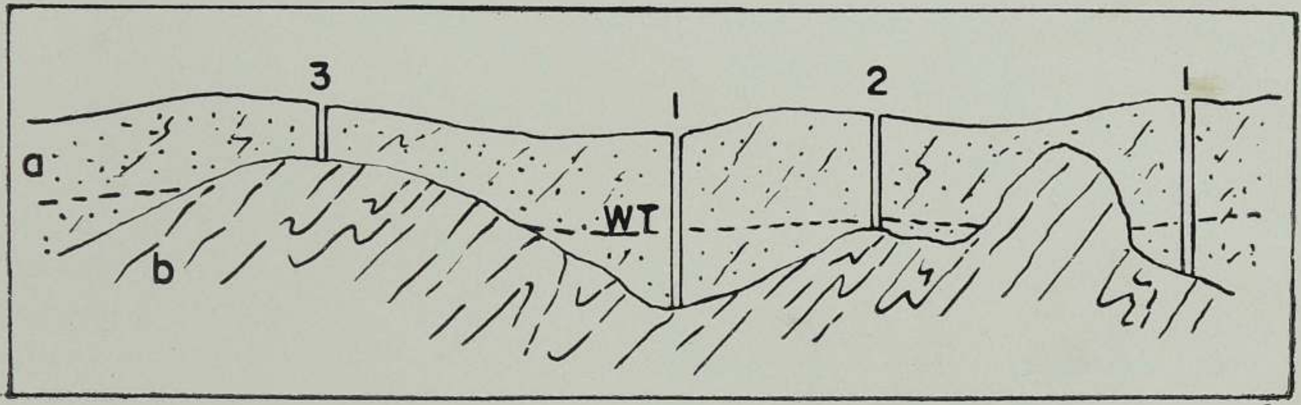


Fig. 86. Sketch section showing occurrence of groundwater in pockets in crystalline rocks (*a*) weathered overburden, (*b*) bedrock, (WT) water table, (1) good well in pocket of ground water, (2) poor well on margin of pocket, (3) dry well on bedrock.

The unweathered crystalline rocks, by their very nature, are relatively impervious and non-porous. What circulation does take place is mainly along joints and fissures, but also along planes of foliation, schistosity, and cleavage. Where joints and fissures are concentrated in zones, as in fault zones, or in particular rock types like quartzites, then permeability is increased to important proportions. There is, therefore, no continuous body of groundwater with a single water-table in crystalline rocks, but rather separate pockets of groundwater, each with a distinct water-table (Fig. 86). The utilisation of such water pockets depends on their exact location and this is often indicated by heavy fissuring and jointing. Haphazard well-sinking in areas of crystalline rocks often leads to failure.

Springs

Fortunately, however, Nature has compensated for this deficit in two ways. Firstly, where the surface has been eroded down to the local water-table in a fissured zone, water issues at the surface in the form of springs. Such springs are most prolific in the highly jointed and fissured rocks like quartzites, as in the Polonnaruwa area and at Bandarapola in the Matale valley (Fig. 87). In the Polonnaruwa area, for example, the quartzites are the principal water-bearing strata, being continuous for long distances, of wide lateral extent, and highly permeable. They abound in perennial wells and springs, lines of springs marking the contact between quartzite and impermeable granulite below them[18]. The water in such quartzites is generally of good quality and the approximate yields from springs in quartzites ranges from 7,000 to nearly 30,000 gallons per day. The yields of the Bandarapola springs varies from about 50,000 g.p.d. in the dry season, to over 100,000 g.p.d. in the wet season[68].

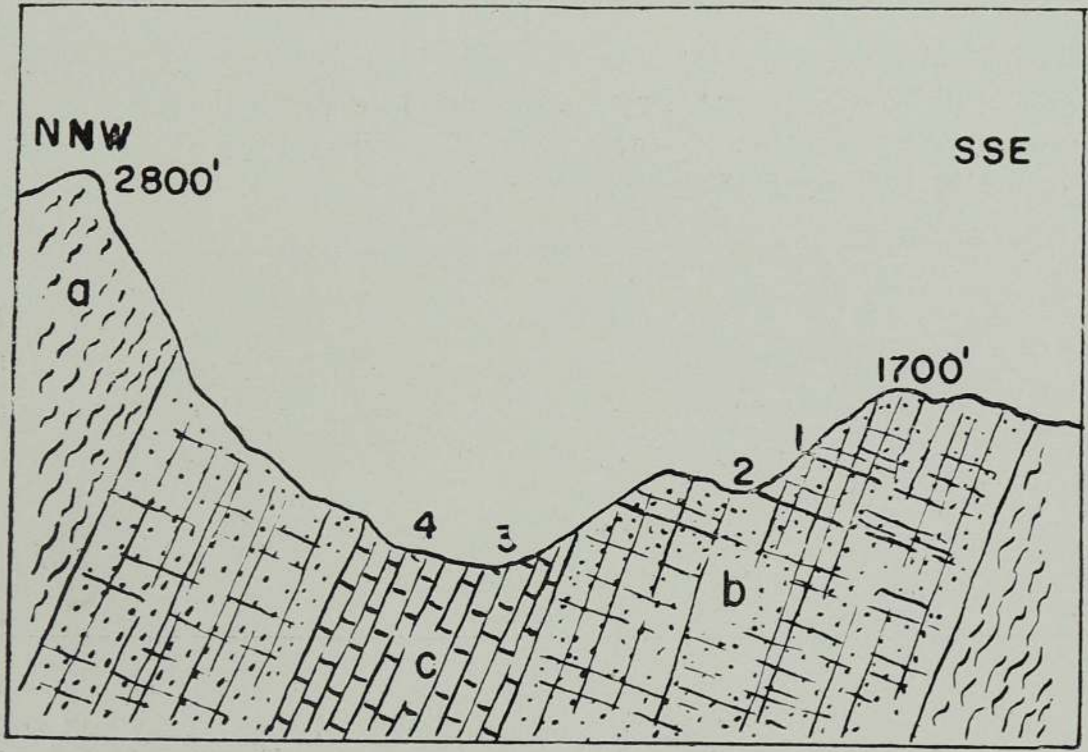


Fig. 87. Section across the Matale Valley between Wiltshire Estate (2800′) and Bandarapola Estate (1700′) showing positions of springs in bands of quartzites (*b*) and crystalline limestone (*c*). Note absence of springs in gneiss (*a*). Yields of springs : (1) 50,000 gallons per day, (2) and (3) 100,000 g.p.d., (4) 30,000 p.g.d. (*After D. B. Pattiaratchi*, 1956)

Some limestone bands, owing to joints and fissures which have been enlarged by solution, contain large perennial springs (*bubula* or *ulpotha*) which are important sources of water. There even appears to be an underground movement of water northwards in the thick marble band which runs through Matale and Habarana as the amount of calcium and magnesium in solution increases in this direction. Water from springs and wells in crystalline limestones possess this characteristic hardness, indicated by such a village name as Kiwulwadiya (*kivul* or *kiwul* = *hard*).

Springs (or *pila*) are, in fact, common in the Hill Country, where planes of bedding and foliation as well as joint planes in the Highland Series rocks intersect the surface topography. Individual springs in the quartzites crystalline limestones, and fissured schists and gneisses are capable of yielding 15,000 to 300,000 gallons daily in the wet zone and between 5,000 and 30,000 gallons per day in the dry zone, where the recharge from rainfall is much less.

Weathered overburden

The second way in which Nature has compensated for the low porosity of the crystalline rocks is by the considerable depths to which these rocks have been weathered in many parts of the Island. The weathered overburden on crystalline rocks generally ranges from 5 to 50 feet in thickness and sometimes reaches to 100 feet below surface level, but it often occurs in patches and pockets which are separated from each other by areas where impermeable bedrock is near the surface (see Fig. 86). The decomposition products, when relatively sandy as in quartzites, gneisses, and granites, are moderately porous and permeable and are able to retain water.

A good example of these conditions is the Polonnaruwa area where the occurrence of water in wells and springs has recently been described[14]. The depth of weathering in this area is about 25 to 30 feet generally, and layers of 'ferruginous laterite nodules and gravel' (or nodular ironstone) are often present, varying in thickness from a few feet to about 30 feet thick. The depth of the water-table ranges from 10 to 25 feet below the surface during the Dry Season (from July to September) and wells in the overburden are of two kinds. The shallow wells, generally less than 15 feet deep, often dry up in the Dry Season, except when located by the sides of tanks and irrigation channels where the water level is maintained by seepage. The deep wells, generally 20 to 30 feet and located in the nodular ironstone layers, are perennial; these have fair yields of water in the Dry Season.

Generally speaking, the water in these wells is suitable for drinking, with less than 500 p.p.m. chlorides, but it is hard and contains considerable amounts of dissolved calcium and magnesium. Although, therefore, the crystalline rocks and their weathered overburden are not likely to carry vast unlimited reserves of groundwater, they can in most instances be exploited for local purposes. Where, as in Ceylon, the greater part of the population lives in small villages and hamlets, such a source of water for human consumption becomes more important than large underground resources; rather than ignore them, every effort and means should be used to locate them.

Laterite

Laterite is also a product of the decomposition of crystalline rocks but occurs only in the special climatic conditions of the south-western region. The behaviour of groundwater in laterite is thus of special importance in view of the fact that the south-west sector is the most densely populated part of the island.

The cellular or vesicular nature of typical laterite (see p. 176) gives it a high porosity and permeability, and this accounts for the absence of permanent streams on it. Wherever laterite outcrops a large number of wells are developed on it ; owing to its variable thickness, the wells are generally deep, often going down to between 50 and 100 feet below surface level.

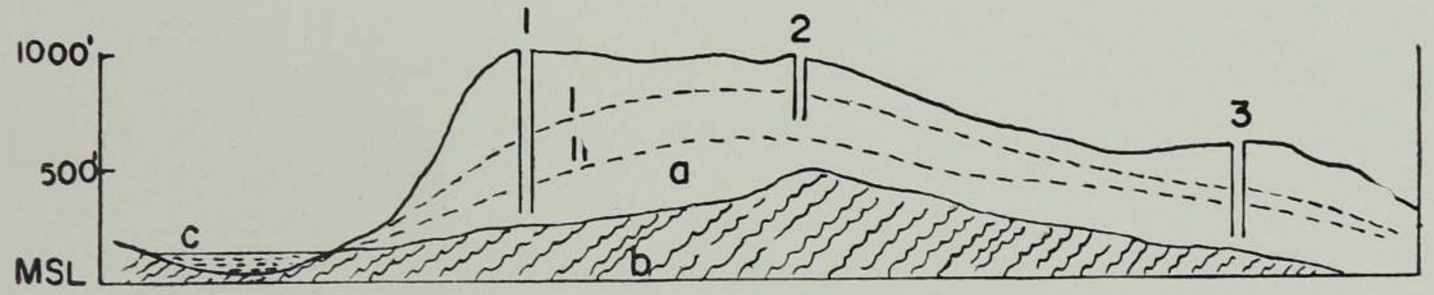


Fig. 88. Groundwater conditions in typical laterite at Ragama. (*C. H. L. Sirimanne*, 1952)
(*a*) laterite, (*b*) gneiss, (*c*) alluvium, (I) wet-weather water table, (II) dry-weather water table ; (1) and (3) permanent wells, (2) seasonal well, runs dry in dry weather. Length of section about 2 miles.

Groundwater conditions in a typical laterite area like Ragama are shown in Fig. 88. Part of the rain water (100 inches per year) falling on the surface drains away rapidly along short-lived surface streams, gullies, footpaths, and roads, but most of it percolates downwards, eventually seeping into the marshes and streams between the laterite hills. Owing to the high permeability of laterite, the water-tables oscillates over a wide range, namely, about 20 feet at the top of the hill and 10 feet on the slopes[68]. The best sites for wells are, therefore, those points towards which extensive groundwater flow takes place, that is, at the valley edges. Another feature of the water-table in laterite is that it rises very rapidly, and, in the case of a small hill, the upper limit may be reached only a few hours after a heavy shower. Even in laterite, yields vary from area to area, depending on the permeability of the formation in each area. In Ragama, for example, where the interspaces in the laterite are partly filled with kaolin, eleven wells yield 60,000 gallons per day, whereas at Gongitota, where the vesicles are free of clay, a single well yields 80,000 gallons per day.

Groundwater in Sedimentary Rocks

Of the sedimentary rocks, the unconsolidated formations are more important as aquifers than the consolidated rocks and the Jaffna limestone presents a special set of conditions.

Alluvium

One of the largest carriers of groundwater among the sedimentary formations is alluvium, which, in the major river valleys, may vary from 30 or 40 feet to 100 feet in thickness and may extend laterally for several hundreds of feet on either side of the river bed. A good example is the alluvial flood plain of the Mahaweli Ganga at Manampitiya where the river channel is about 900 feet wide and the alluvium is 60 to 80 feet thick and over a mile wide. Considerable underflow of groundwater must take place in such extensive alluvial tracks.

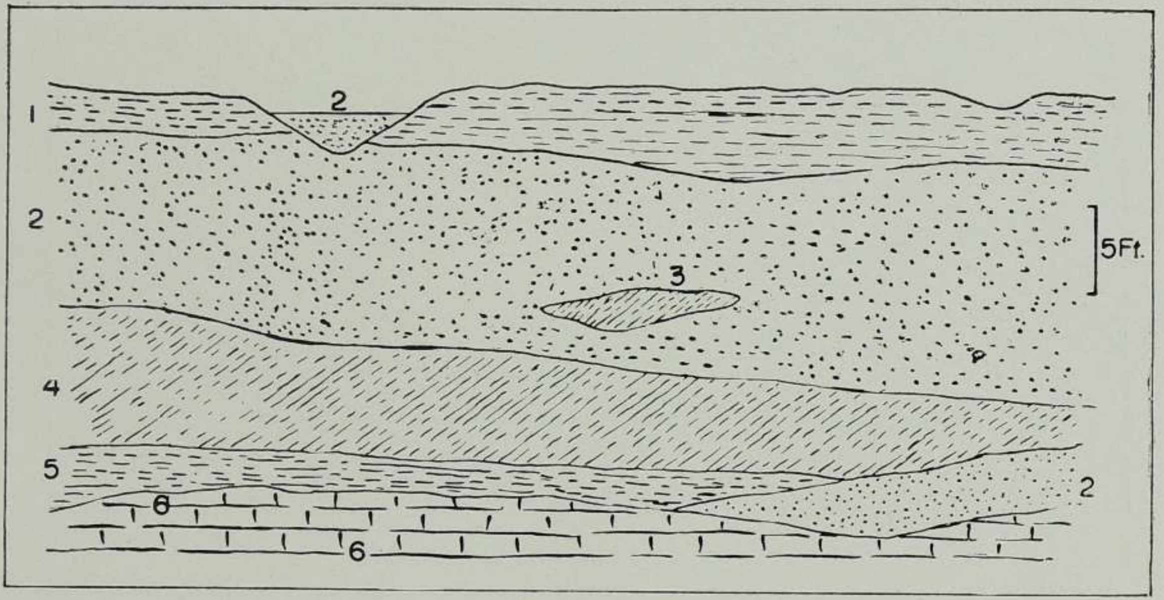


Fig. 89. Section showing alluvium of the Mi Oya from which the Puttalam water supply is drawn. (*After C. H. L. Sirimanne,* 1957)

(1) clay, (2) sand, (3) black, peaty clay, (4) black, impermeable clay, (5) grey, plastic clay, (6) bedrock, probably Miocene limestone.

Some idea of this underflow can be obtained from the results of investigations carried out for the water-supply scheme of Puttalam town. The pipe-borne town supply comes from a battery of wells and lateral adits which draw the water from a buried layer of sand on the south side of the Mi Oya (Fig. 89). The aquifer, which is sealed at the top and bottom by layers of impermeable clay, has an average thickness of 20 feet, is 30 acres in extent, and lies at a depth of about 8 feet[70]. The porosity of the sand is 25 per cent. The total storage capacity of this sandy layer is 30 million gallons, and it provides 300,000 gallons of water per day, or

30 gallons per head to a population of 10,000 people. What is important is that the groundwater in this aquifer is recharged each year by seepage of water from the river during the 150 days in the year in which it normally flows. In other words, the annual recharge of about 90 million gallons is sufficient for the total annual consumption, with a certain amount of restricted pumping during the Dry Season. It is only during an exceptionally dry year that the ground storage of 30 million gallons, which is in effect a reserve, need be drawn upon.

Besides the major flood plains, however, are numerous wide valleys and depressions, a few hundred feet wide, in which well defined river beds are rare but which sometimes contain small rivulets and streams which meander across the valley floor. Such valleys are generally the flood plains of former rivers that have either changed their courses or have ceased to flow. They are usually filled with sandy clay or sand, with a basal gravel layer resting on bedrock ; the gravels mark the buried channels of the former rivers. The topmost layers of such valleys may sometimes be impervious clay. The bottom gravels are important water-bearing horizons and recharge of groundwater may be by permeation from above, or, where an impervious layer exists, by recharge from the upper reaches of the stream. An excellent example of this type of groundwater storage is seen in the Kiraam Oya (Fig. 90) [72].

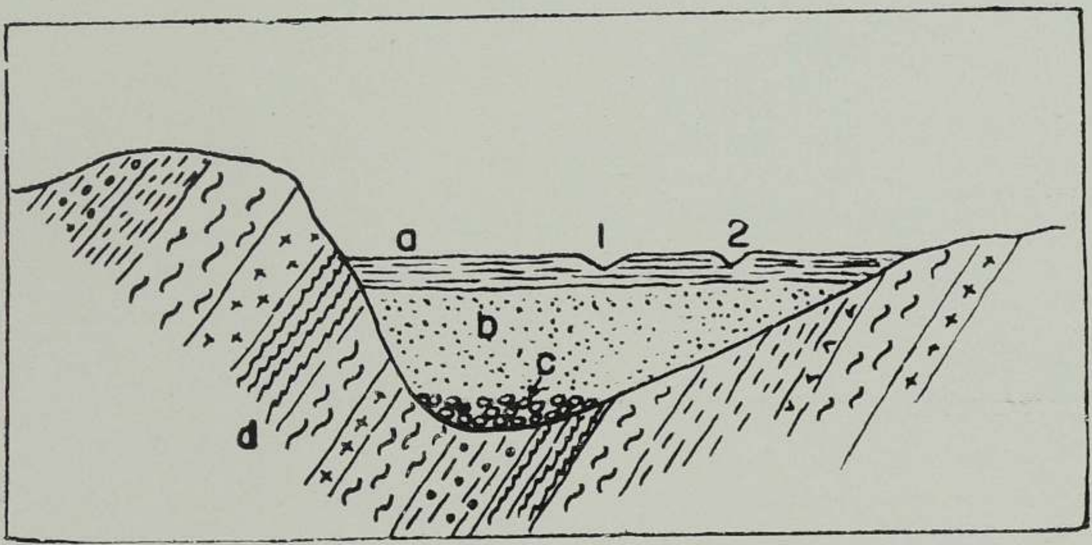


Fig. 90. Section across the Kiraama Oya showing groundwater storage in buried river channel. (*After J. S. Coates*)

(*a*) alluvial clay, 6 ft. thick, (*b*) sands and sandy clays, 30 ft. thick, (*c*) bed of quartz gravel at bottom of old channel, (*d*) gneissic bedrock, (1) and (2) surface streams.

Many of the streams and rivers of the Dry Zone have pools of water along their sandy beds and it is at these that the animals of the forest quench their thirst during the dry season of the year ; most of such pools dry up only during the longest droughts. These pools have been formed by water flowing underground being obstructed by sub-surface bands of crystalline rock.

Gravels

The ferruginous gravels of the Older Quaternary formation in the north-west and the more recent gravels of other areas vary in thickness from 8 to 50 feet, and, when developed extensively, are capable of yielding large supplies of water if they are favourably situated for recharge. At Madampe town in the North Western Province, a bed of gravel, 5 to 18 feet thick, is overlain by 10 to 30 feet of Red Earth with fine sand; the gravel appears to be the principal aquifer in the area and most of the wells derive their water from it. The gravel here contains angular quartz sand and rounded pebbles cemented together with ferruginous matter, as well as nodules of iron oxide containing fine sand.

Sands

The unconsolidated sands of spits, bars, raised beaches, and dunes which are so common along most of the coastline of Ceylon (see pp. 68-69) are also important carriers of groundwater. Apart from several large towns like Mannar, Batticaloa, and Hambantota, all of which obtain their water

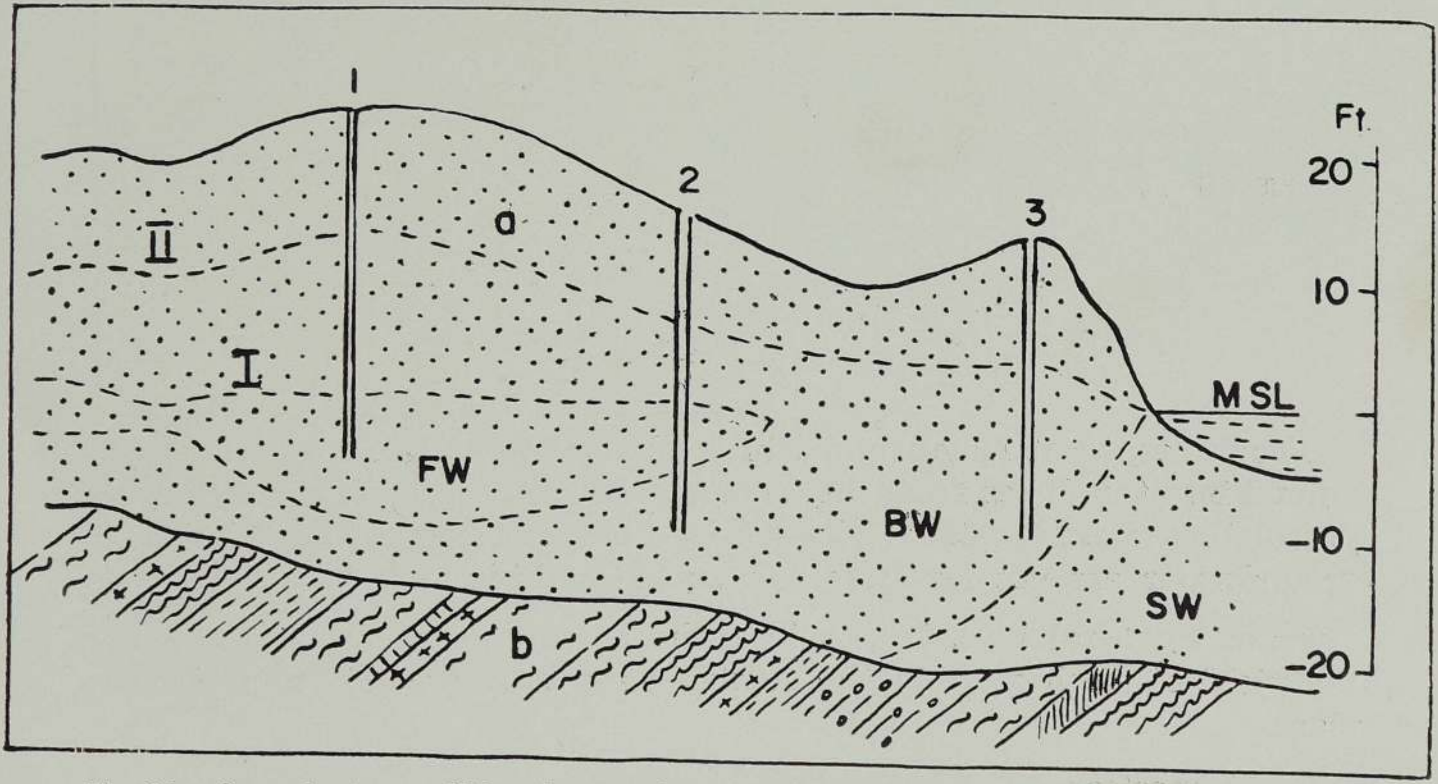


Fig. 91. Groundwater conditions in coastal sands at Pulmoddai. (*C. H. L. Sirimanne*, 1952)

(*a*) sands and sandy clays, (*b*) granitic gneiss bedrock; I–water table in November, before rains, II–water table in December, after rains, FW–fresh-water lens, BW–brackish waterzone, SW—salt water; (1) fresh-water well, (2) and (3) brackish water wells.

from this source, small supplies of fresh water are obtained from thousands of individual wells dug by the fishing population around the coast. A good example is the Chilaw sand spit.

The freshwater in these permeable coastal sands is generally in the form of a lens-like body resting on salty sea water, with a wide transitional zone of brackish water between the two, as at Pulmoddai (see Fig. 91). Wells situated outside the fresh-water lens, or those which penerate the lens, will encounter the brackish-water zone and will be unsuitable for domestic consumption. The extraction of water even from wells within the fresh-water lens has to be carefully controlled, however, as excessive pumping may cause the intrusion of salt water from below into the fresh water, so contaminating it (Fig. 92).

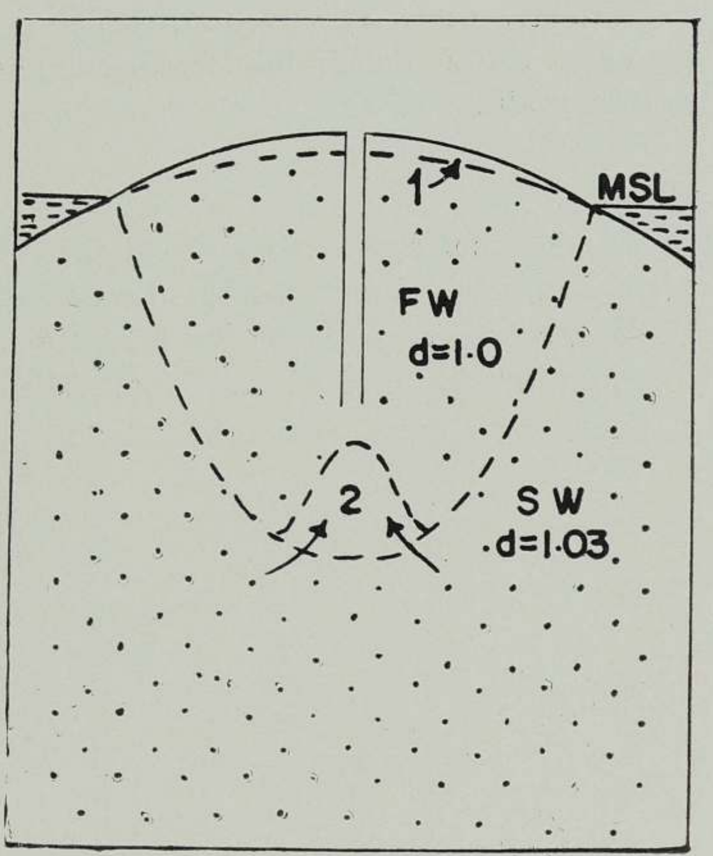


Fig. 92. Development of the *cone of salt-water intrusion* (2) by overpumping of the fresh-water lens (FW) resting on salt water (SW) in permeable sandy formation. (*After C. F. Tolman,* 1937)

Sometimes, as at Hambantota, intercalations of tough, impervious clay extend into the dunes from the lagoons, and these obstruct the downward percolation of freshwater[71]. Conditions for the storage of large bodies of groundwater are not favourable in such localities.

Though generally good, therefore, the occurrence of groundwater and the yield of freshwater in the coastal areas vary greatly from place to place.

Jaffna Limestone

The special conditions governing the occurrence of groundwater in the Jaffna Peninsula are due to the joint planes, fissures, cavities, solution chambers, and channels, some of considerable size, which are present in the limestone. Most of these openings are being constantly enlarged by solution, the slightly acid waters which circulate in them as an underground drainage system using the fissures and joints as river courses and the chambers as reservoirs of fresh water (Fig. 93).

The level of permanent saturation of groundwater in the Jaffna Peninsula is about 1 to 2 feet above mean sea level, and the depth of the fresh-water zone varies from a few feet to about 100 feet below mean sea level. Below the freshwater is a zone of brackish water which itself passes downwards into salt water. As in the coastal tracts, therefore, the freshwater in the limestone rests on a body of sea water.

Intensive pumping tests carried out on wells in the Peninsula have shown two important characteristics of groundwater behaviour in the Jaffna Limestone. One is that yields are very high (up to 100,000 gallons per day) with hardly any appreciable lowering of the water-table ; the second is that the water-table recovers its former level very quickly after such depression[68]. At the same time, excessive pumping has to be avoided because this will ultimately result in contamination of the fresh water by salt water, as in the case of the coastal sands (see Fig. 92).

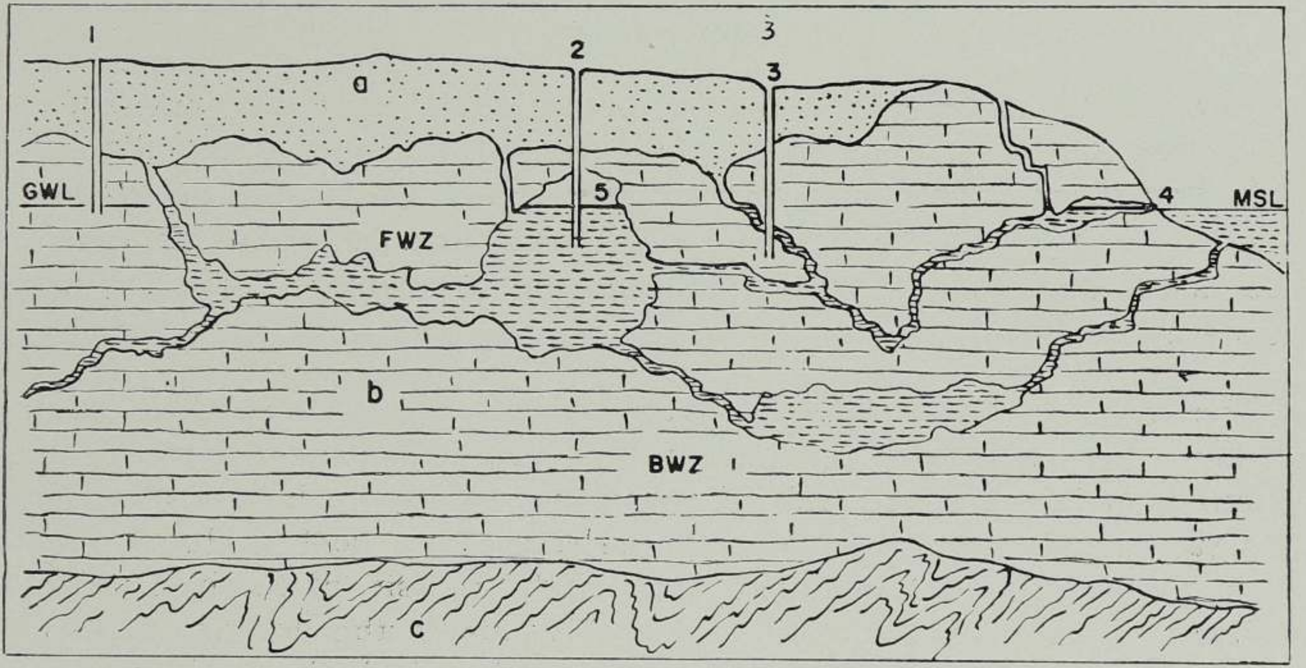


Fig. 93. Groundwater conditions in the Jaffna Peninsula. (*After C. H. L. Sirimanne,* 1952) (*a*) Red Earth, (*b*) Jaffna Limestone, (*c*) granitic gneiss, (MSL,) mean sea level, (GWL,) ground water level, (FWZ), zone of fresh-water saturation, (BWZ), probable zone of brackish water; (1) dry well, (2) well of Puttur type, (3) ordinary successful well, (4) spring of Keerimalai type, (5) solution cavern.

Several interesting phenomena in the Peninsula are expressions of the special hydrological conditions in the Limestone. The 'bottomless' well at Puttur, for example, is the mouth of a very large underground cavern in the limestone, with a total depth of 145 feet (Fig. 93). The thickness of the fresh-water zone here is about 80 feet, and this rests on a brackish water zone nearly 50 feet thick; salt water is present below 130 feet. Test pumping in 1946 yielded 150,000 gallons of water per day for one week. The level of the water surface remained the same after the test as before it but the relative thicknesses of the fresh and brackish water had changed to 50 feet and 60 feet respectively, and the salt water level had risen 200 feet above its normal level[69].

Many fresh-water springs are also present, mainly along the coast of the Peninsula, and of these the spring at Keerimalai is the best known. The outlet of the spring, which is at sea-level, is the terminus of a solution channel (Fig. 93).

Hot Springs

Several hot springs are known to occur in the crystalline gneisses of the eastern coastal plain of Ceylon, the best known being those at Kinniyai (near Trincomalee), Maha Oya, Mahapalessa (east of the Walawe Ganga), and Pallan Oya; others have been recorded from Marangala, Kapurala, Wahawe Oya, and Patipalaar (on the border of the Uva and Eastern Provinces).

The water at Maha Oya rises with considerable force by three vents in the sandy bottom of a pond about 30 feet in diameter and 2 feet deep; it bursts at irregular intervals of about one minute, bubbles of odourless gas rising with the water. Mud at the side of the pool smells strongly of hydrogen sulphide and there is a slight deposit of sulphur on the surface of the mud. This gas is probably due to the decomposition of organic matter. The people of the area occasionally bathe in the pool as a cure for itch and other diseases, but fresh elephant tracks by the side of the pool shows that the water is not obnoxious to animals[33]

Most of the other hot springs of the Island have this characteristic smell of hydrogen sulphide. Temperatures of the waters range from 100°F to 130°F, though there is very little variation in temperature at any particular spring. Only the spring at Kapurala, a remote and inaccessible spot, has a temperature much more than 130°F.

TABLE 18—Chemical Analyses of Thermal Spring Waters

(in parts per million)

Locality	*Temp.* °F	*Electrical Conductivity*	*pH*	*Total solids* (p.p.m.)	*Chlorides* (p.p.m.)	*Principal salt*
Kinniyai, Well No. 3	105°	275	6·2	221	19	Calcium bicarbonate
Maha Oya	131°	1,200	7·5	1,032	90	Sodium sulphate
Wahawe Oya	n.d.	900	7·6	662	44	Sodium sulphate
Mahapelessa	111°	6,000	8·1	4,540	2,574	Sodium chloride
Pallang Oya	96·8°	800	7·5	658	38	Sodium sulphate

Detailed chemical analyses of the waters from these springs are given in Table 18. They do not show sufficient salts in solution to be called 'spas' or waters having a therapeutic value; calcium bicarbonate ($Ca(HCO_3)_2$), sodium sulphate (Na_2SO_4) and sodium chloride ($NaCl$) are the chief salts in solution; none of the waters shows any radioactivity[72].

Although several modes of origin have been suggested for these thermal springs, it is likely that they are normal ground waters that have probably come from great depths along joints and fissure planes and so derived their thermal energy.

CHAPTER 13

GEOLOGY AND ENGINEERING

BUILDING sites and the materials of construction are some of the fundamental aspects of engineering, but being closely related to the nature and structure of the earth's crust they are also aspects of geology. It is therefore not surprising that the application of geological knowledge and principles is essential to the successful solution of most civil engineering problems. That this is clearly recognized in the 'advanced' countries is seen in the fact that (1) geology forms an essential subject in the curriculum of training for civil engineers, and (2) geological advice is almost always sought in the preliminary stages of civil engineering construction projects.

Among the many problems that confront the civil engineer, the geologist's advice can be most useful in determining—

(*a*) the suitability of sites for dams, reservoirs, bridges, docks, harbours, airfields, tunnels, railways, and factories ;

(*b*) the suitability of foundation conditions for all types of construction ;

(*c*) the selection of constructional and ornamental materials and the siting of stone quarries ;

(*d*) the location of tunnels ; and

(*e*) the treatment of landslides and unstable slopes.

The aim of this chapter is to show how knowledge of geological conditions has assisted the solution of some of these problems as found in Ceylon from time to time.

Suitability of Dam Sites

The ideal site for the building of a dam is along the geological strike, for only then will the same rock type be continuous along the length of the proposed dam. The beds should also dip upstream of the dam so that the force resulting from the pressure of the water and the weight of the dam will be perpendicular or nearly so to the bedding or foliation planes of the rock (Fig. 94).

GEOLOGY AND THE COMMUNITY

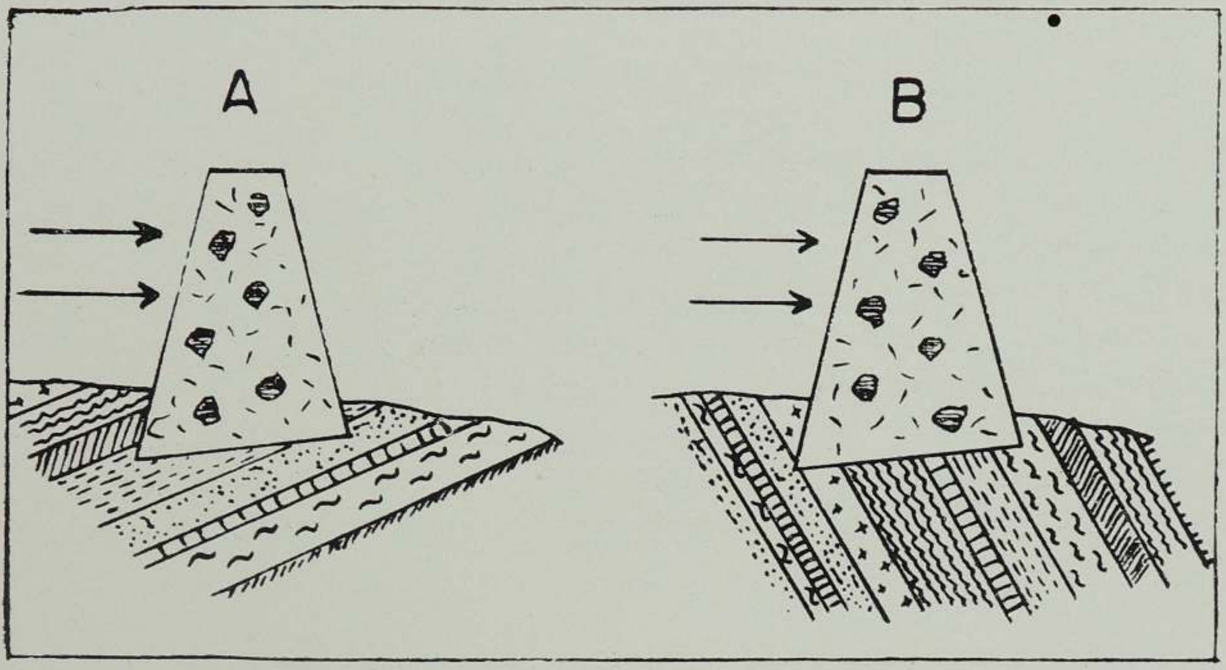


Fig. 94. Diagrams showing possible relations of dams to dip of bedrock. (*After C.S. Fox*, 1935)

A. Beds dipping upstream, ideal. B. Beds dipping downstream, unsatisfactory except in hard, crystalline rocks.

That these ideal conditions were known instinctively by the ancient engineers of Ceylon is seen in countless instances where the dams or bunds of irrigation tanks have been sited along the strike of rock outcrops. The bunds of Galgamuwa Wewa, Sorabora Wewa, Minneriya Wewa (Fig. 95), and Kala Wewa are only a few of the very many that come to mind at once. These ideal conditions, especially the first, have also been found in siting many modern dams such as the Nalanda Oya dam and the bund of the Senanayake Samudra.

In many such instance the rocks at the dam sites are massive crystalline rocks with very few planes of weakness. But dams have sometimes to be located on highly jointed rocks like quartzites or on readily soluble ones such as crystalline limestones and action must be taken to prevent seepage of water through such fissures, joints, and solution channels as may exist in the rocks. This is done by a process known as 'grouting' in which liquid cement is pumped into the rocks under high pressures so that it enters all the crevices and cracks and seals them.

This was the problem in the construction of the Nalanda Oya dam[73]. Geologically, the area consisted of granulites, quartzites, crystalline limestones, gneisses, and basic rocks, with plentiful granitic veins, all striking north to south and dipping steeply to the west. The proposed dam was along the geological strike and it was therefore ideally sited.

GEOLOGY AND ENGINEERING

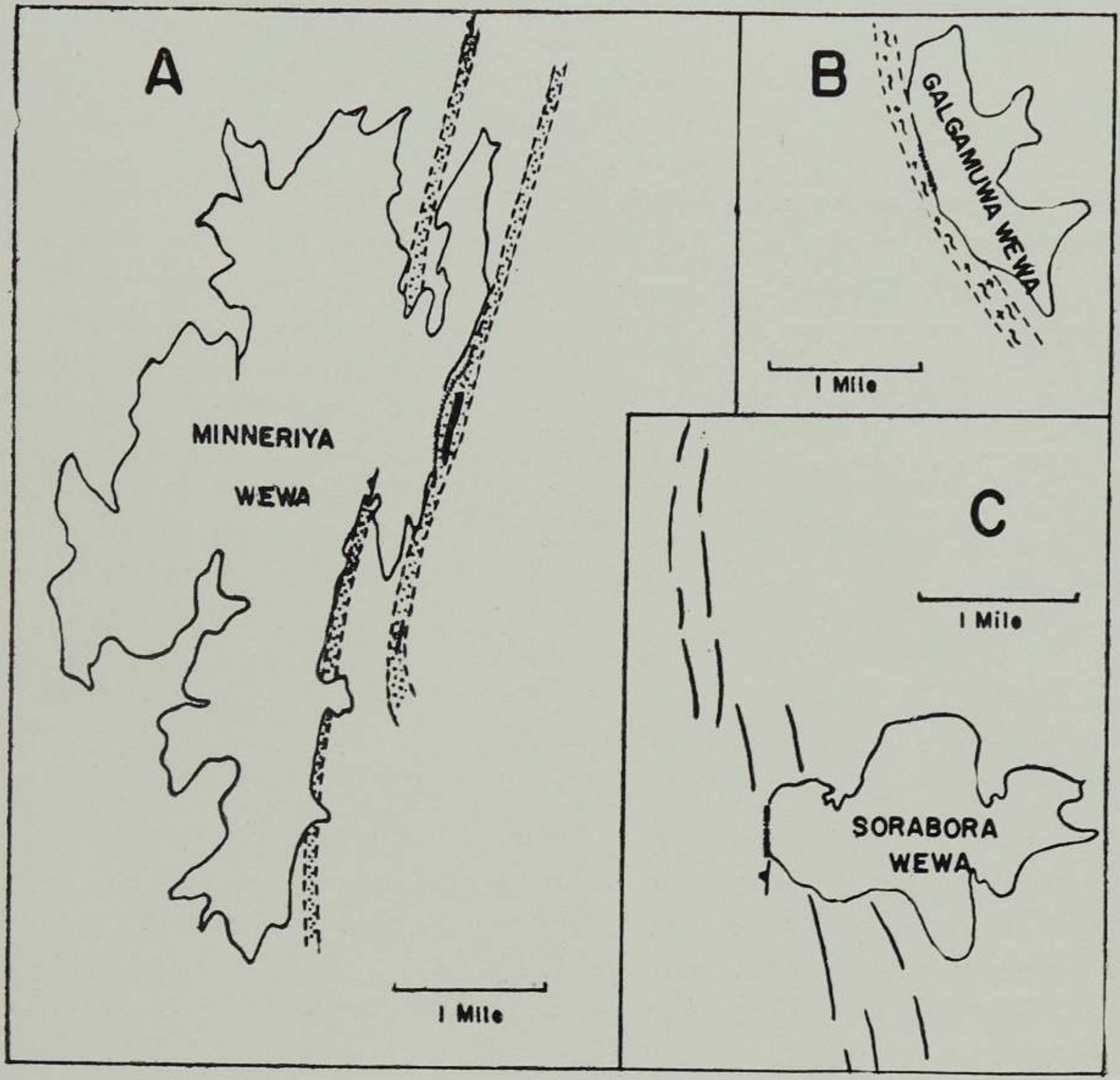


Fig. 95. Typical dam sites of ancient irrigation tanks.

A. Minneriya Wewa, dam along quartzite ridge.

B. Galgamuwa Wewa, dam along near-vertical granite gneiss.

C. Sorabora Wewa, dam along westerly dipping biotite-hornblende gneiss.

Drill cores showed, however, that the rocks were jointed and fissured and that zones of weathering existed at depths below what appeared to be solid rock ; as the direction of the fissures was roughly west to east, seepage of water was likely to take place below the dam. Grouting of all fissures and weathered zones provided a water-tight foundation for the dam.

It is the geologist's task, when a dam site is proposed, to identify the rock types and their structure at the proposed site and to determine the nature, extent, and directions of any planes of weakness that may exist. The geologist is then, on the basis of the known surface geology, in a position to advise the engineers on the location of drill holes which will give the maximum information on the sub-surface geology and foundation conditions. The value of such preliminary geological consultation and advice is seen when, as sometimes happens, a site proposed by engineers may be found to be geologically unsound and a new site has to be found.

The dam at Castlereagh which forms Stage IIA of the Norton Bridge Hydro-Electric Scheme had to be built across the strike of the rocks owing to the fact that the Kehelgomu Oya flows *along* a strike valley. (This is in contrast to the Nalanda Oya dam which is located where the river cuts *across* a large strike ridge.) There was thus an initial disadvantage as the dam had to be built on rocks of differing strengths and resistances to weathering. The site originally selected had the additional disadvantages of not possessing suitable side abutments and being overlain by a great thickness of weathered material. After a study of the geology of the site, a new site was selected where these disadvantages were minimised and the dam was constructed on this new site.

Foundation Conditions

In considering the foundation conditions of any structure, the depth at which solid bedrock occurs, the nature of such bedrock, and the type of earth material overlying it are fundamental problems for the engineer. The depth at which fresh, solid rock appears is governed partly by the geological structure and partly by the amount of weathered overburden at the site.

Weathering is generally uniform over a small area and the depth of bedrock can often be estimated from the surface geology. Sometimes, however, rocks which appear unweathered at first sight may be found to be weathered at depth along joints and other fissures through which atmospheric water has been able to penetrate into the solid rock (Fig. 96). This is generally revealed by drilling and it is the task of the geologist to examine the drill cores, foot by foot, and to recognize such zones of weakness, however insignificant they appear to be.

Foundations cannot always be laid on solid rock and often have to be located on unconsolidated material like sands, sandy clays, and lateritic soils, particularly in the coastal belt around the island. In such instances the geologist's advice is essential not only for the strength of the formations but also on the groundwater conditions at the site.

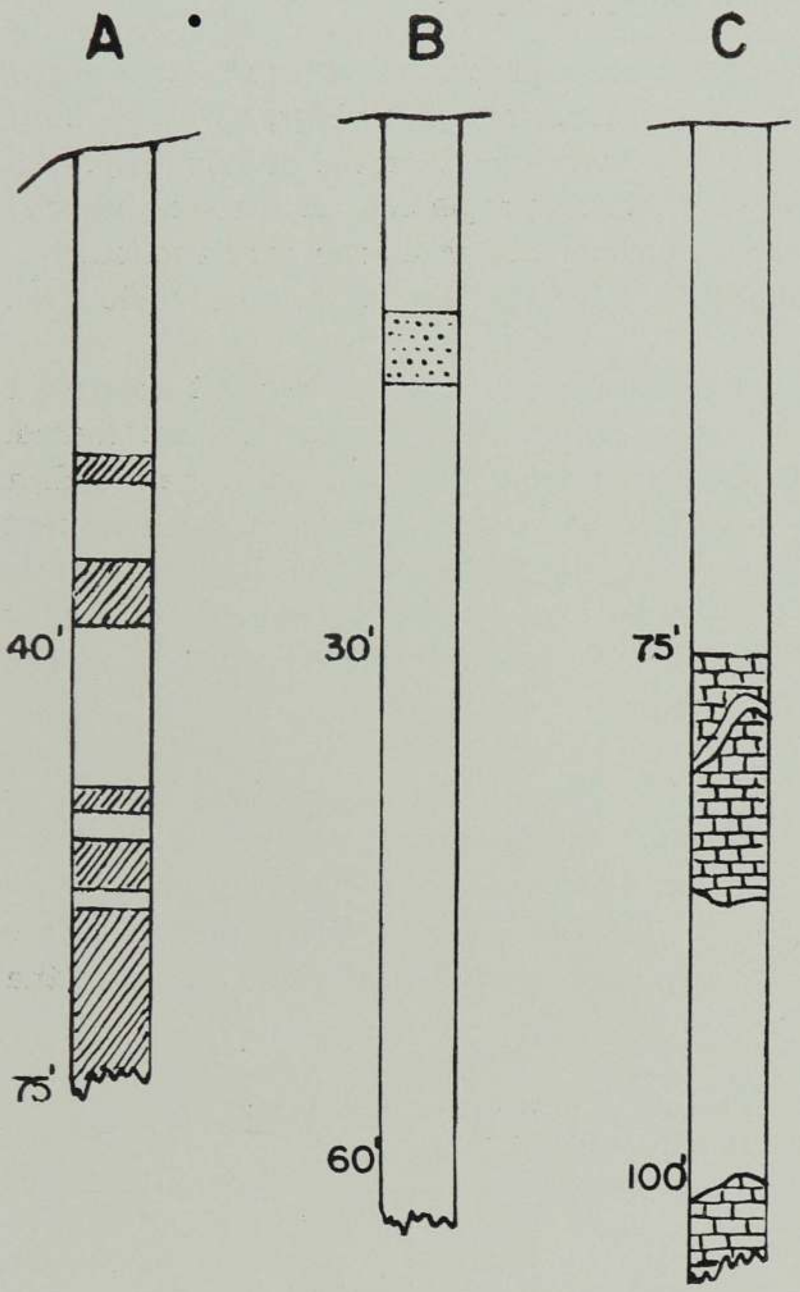


Fig. 96. Borehole sections showing weathering of rocks at depth. (*Modified from D. B. Pattiaratchi*, 1956)

A, Charnockite.
B, Quartzite.
C, Crystalline limestone.

Blank spaces represent weathered rock and absence of core.

Within recent years, geological advice has been given in a number of foundation investigations, among which may be mentioned the Ekala Industrial Estate (in sands and clayey sands), the Veyangoda and Pugoda Textile Mills, the Flour Mill and Grain Elevator at Galle (in beach sand, coral debris and clay, overlying charnockite), the Iron and Steel Factory at Oruwela (in deep lateritic soils), and the Rubber Tyre Factory at Kelaniya (on variable material like sandy clays, swamp, and lateritic soil).

These investigations show that there is an increasing awareness in Ceylon of the necessity of geological investigation and advice before embarking on major construction works.

Constructional Materials

Rock types differ considerably in such properties as *texture, porosity, specific gravity, crushing strength* (resistance to crushing), *abrasion index* (resistance to abrasion), *weathering quality,* and degree of *solubility.* All these are together called the 'engineering properties' of a rock and they are of utmost importance when choosing materials for construction, but certain properties are more important than others for some specific uses.

The degree and nature of the weathering of a rock are most important when it is to be used for building. Where the feldspars are weathered, for example, they will affect the strength of the rock, and when such a rock is used in concrete this may lead to contraction and the subsequent development of cracks and fissures. Again, if the feldspars in a feldspathic quartzite are kaolinised or weathered to a clayey substance, this may lead to the disintegration of the rock into a sandy mass. Such rocks can often be crushed between the fingers.

Equigranular or massive rocks are generally stronger than banded or foliated rocks. In the latter, certain foliae may be weaker than others or may be slightly weathered in an otherwise fresh rock. Slippage may then take place along such foliae. On the other hand, banded rocks are very resistant to pressure if the pressure is applied at right angles to the banding (see Table 19).

TABLE 19—Crushing Strengths of some Ceylon Rock Types

(After D. B. Pattiaratchi, 1956)

Rock type	*Number of Specimens*	*Specific Gravity*	*Average Crushing Strength (in tons/ sq. ft.)*	*Range*
Biotite gneiss and granite gneiss	6	2·6	1660	1240*–2120†
Charnockite	11	2·7	1650	950–2800
Garnetiferous granulite	7	2·7	1600	800–1900
Pink granite	3	2·6	1580	1440–1800
Quartzite	4	2·5	1420	960–2200
Khondalite	2	2·9	760	—
Jaffna Limestone	4	2·6	1300	560–1800

* Parallel to foliation. † Perpendicular to foliation.

Road metal should be hard and tough, and have a high abrasion index. Granite, diorite, basalt, and charnockite are good for this purpose as these rocks have an interlocking texture of their constituent minerals. Quartzites, on the other hand, are too brittle for road metal as they grind easily to sand and dust. But because of the ease with which they can be quarried, quartzites and quartz schists are frequently used as surface dressing for earth roads on tea estates in the Hill Country. Impure marbles are better than quartzites, but they generally have to be covered with tar. Slates and phyllites are too soft.

Where solubility is an important factor in the material of construction, limestones are generally unsuitable, except when they contain a high proportion of dolomite or magnesian carbonate. Thus, dolomitic marbles have been used extensively in the buildings of ancient Polonnaruwa and have survived after several centuries.

Although not much work has been done yet on the engineering properties of Ceylon rocks, some useful, if general, information is available ; this is given in Table 19.

Tunnels

Where a tunnel is to be constructed, the most important fact to be known beforehand is the nature of the rocks to be met with along the proposed trace of the tunnel. For example, if highly jointed and fractured rocks like quartzites are to be met with, then there will be much seepage of water into the tunnel, and this will provide many more problems for the engineer. Or again, if the tunnel runs across the strike of the rocks, several different rock types will be met with, each with different physical properties ; these will have to be treated separately in the problems of construction. Ideally, of course, a tunnel should go through the same rock type throughout its length, or at least through as few different rock types as possible. On the other hand, when a tunnel goes across the strike, the amount of overbreak (or material removed beyond the actual limits of the tunnel) is less than when it goes along the strike. Finally, massive, crystalline rocks are generally better than softer rocks in which to drill a tunnel. It should be remembered that tunnel lines, once proposed, cannot often be changed and therefore geological advice is of primary importance both before and during the construction of the tunnel.

One of the most recent examples of a tunnel in Ceylon is the one carrying the water of the Kehelgomu Oya from above Castlereagh Dam to near the head of the Norton Bridge reservoir ; this is commonly known as Stage IIB of the Norton Bridge Hydro-Electric Scheme. The rocks here are mainly interbanded charnockites and quartzites which strike in a NW-SE direction and dip to the south-west. The tunnel runs roughly NNW-SSE, or slightly oblique to the strike of the rocks. The line of the tunnel was kept as far as possible to the compact charnockites, so as to avoid the highly jointed quartzites[73].

All this preliminary information was obtained by large-scale geological mapping of the area (at 1 inch = 240 feet), on which was based the location of sixteen exploratory drill holes to confirm the rock types and geological structure present at the level of the tunnel. A flexible programme of drilling was maintained throughout the investigation so that the locations of drill holes could be altered on the basis of information acquired. The close co-operation between engineers and geologists during the tunnel project thus resulted in a successful tunnel line being proposed.

The value of continued liaison between the two sciences, even during the construction of the tunnel, was seen recently when a zone of decomposed and weathered rock was met with near the end of the tunnel. The depth and thickness of this zone was soon determined by geological interpretation of the cores of two deep drill holes, as well as by examination of the tunnel, and the construction work was continued without undue delay.

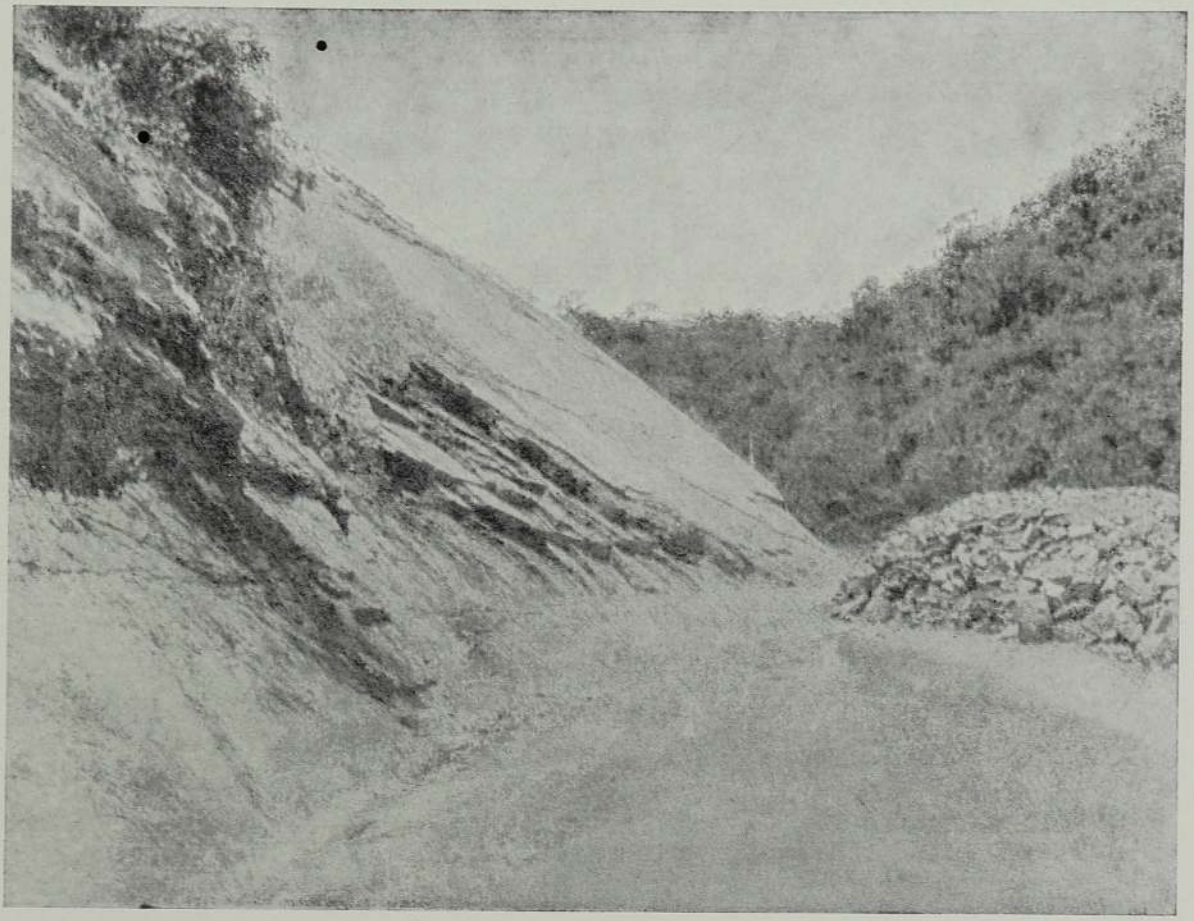
Earthslips

Several parts of the Central Highlands of Ceylon frequently suffer from landslides, earthslips, and other types of mass movement of earth and rock. Although the areas so affected are relatively small, these earthslips cause a great deal of damage and inconvenience, and the problems arising from them have to be solved by geologists and engineers, working in conjunction, in a relatively short space of time.

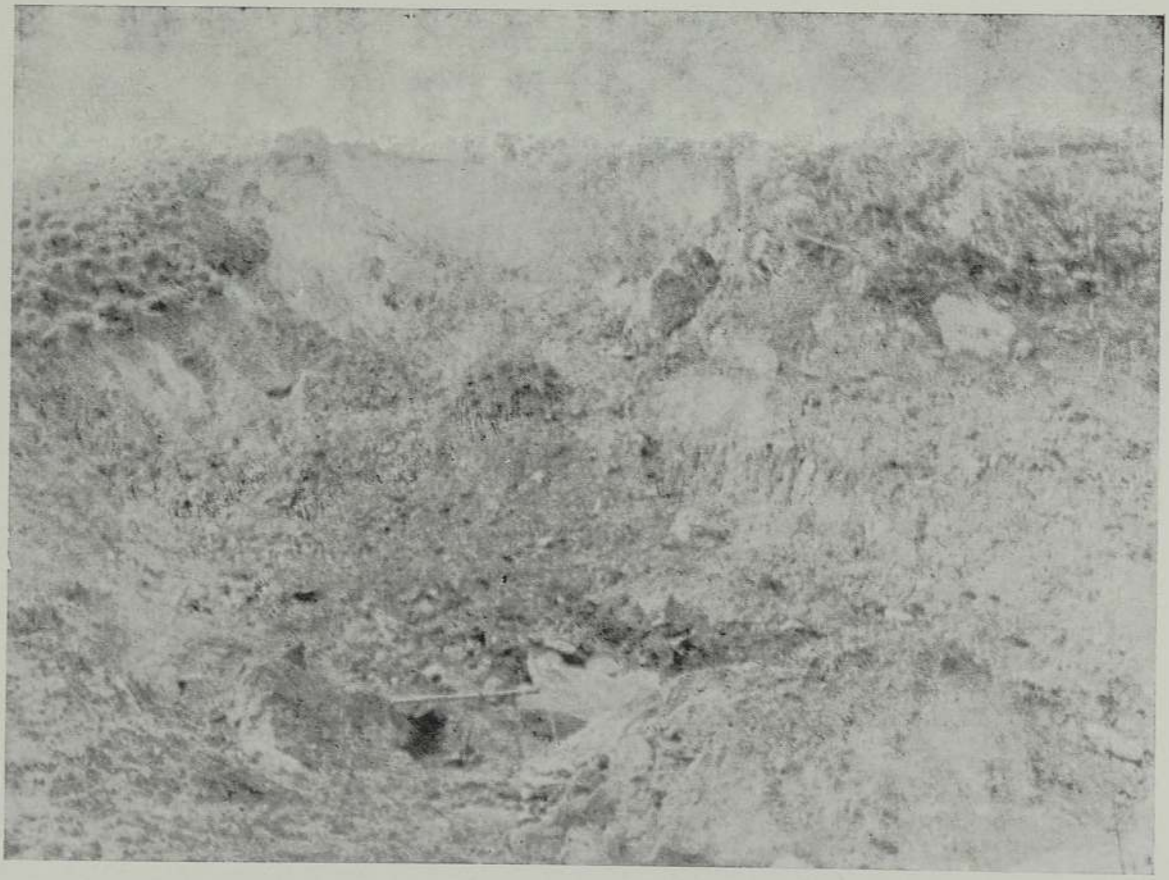
Causes of Earthslips

The occurrence of landslides is due to such factors as topography, rock type, geological structure, rainfall, and agricultural practice. In most instances the major factors are geological, although the immediate cause which triggers off a landslide is generally heavy and continuous rainfall. Some of the areas worst affected by landslides in recent years have been Kadugannawa, Ginigathhena, Kurunegala, Kotmale, Hunasgiriya, and Teldeniya.

It has been found in all these areas that mass movement of earth occurs most commonly (*a*) on dip slopes in poorly consolidated weathered material lying as a thick cover above solid, unweathered bed rock, or (*b*) in steep talus or scree slopes lying at the feet of escarpments and cliffs. The Central Highlands, as we have seen, are made up of well bedded



A. Site of earthslip in bedded and jointed quartz schist, near Teldeniya. Note earthslip material by side of road



B. View of the 1957 earthslip at Waradawila, Rangala, looking upwards to head of slip. Note large boulders of rock on sides and piped spring in foreground.

metasedimentary rocks of the Khondalite Group which often contain a high proportion of feldspar and are sometimes well jointed (Pl. 38A). These rocks weather into a reddish brown clayey material known as lithomarge in which are embedded boulders of varying size. When this weathered material is saturated with water, the clayey material acts as a kind of lubricant, causing the mass of earth and rock to more rapidly down the slope under the force of gravity, especially if there is no natural vegetation cover to bind and hold this material together. The lubricative action of wet clay may act within the mass of the loose material itself, or at the junction of overburden and solid rock, the latter acting as a surface along which slip may take place. Where the land is steeply sloping the mass movement is rapid and takes the form of *debris avalanches, earth flows* and *debris slides*. For example the debris avalanche at Waradawila, just south of Rangala, in 1957, was over in 7 minutes, and that at Kadugannawa in the same year which took away part of the road and the cars on it, lasted only a few minutes.

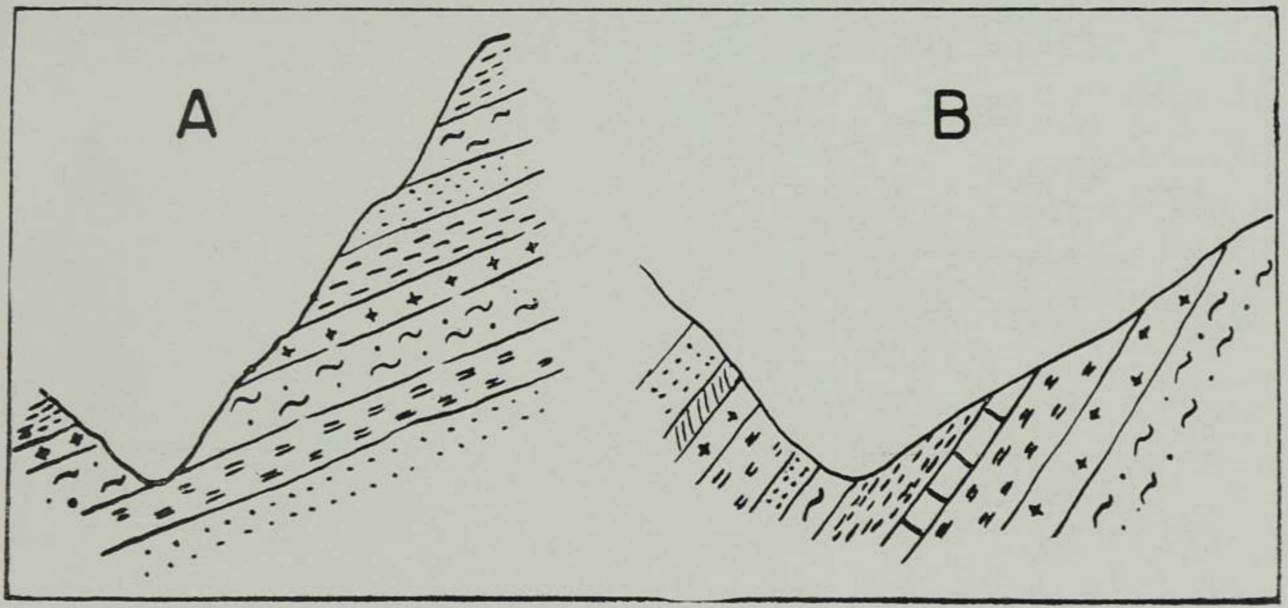
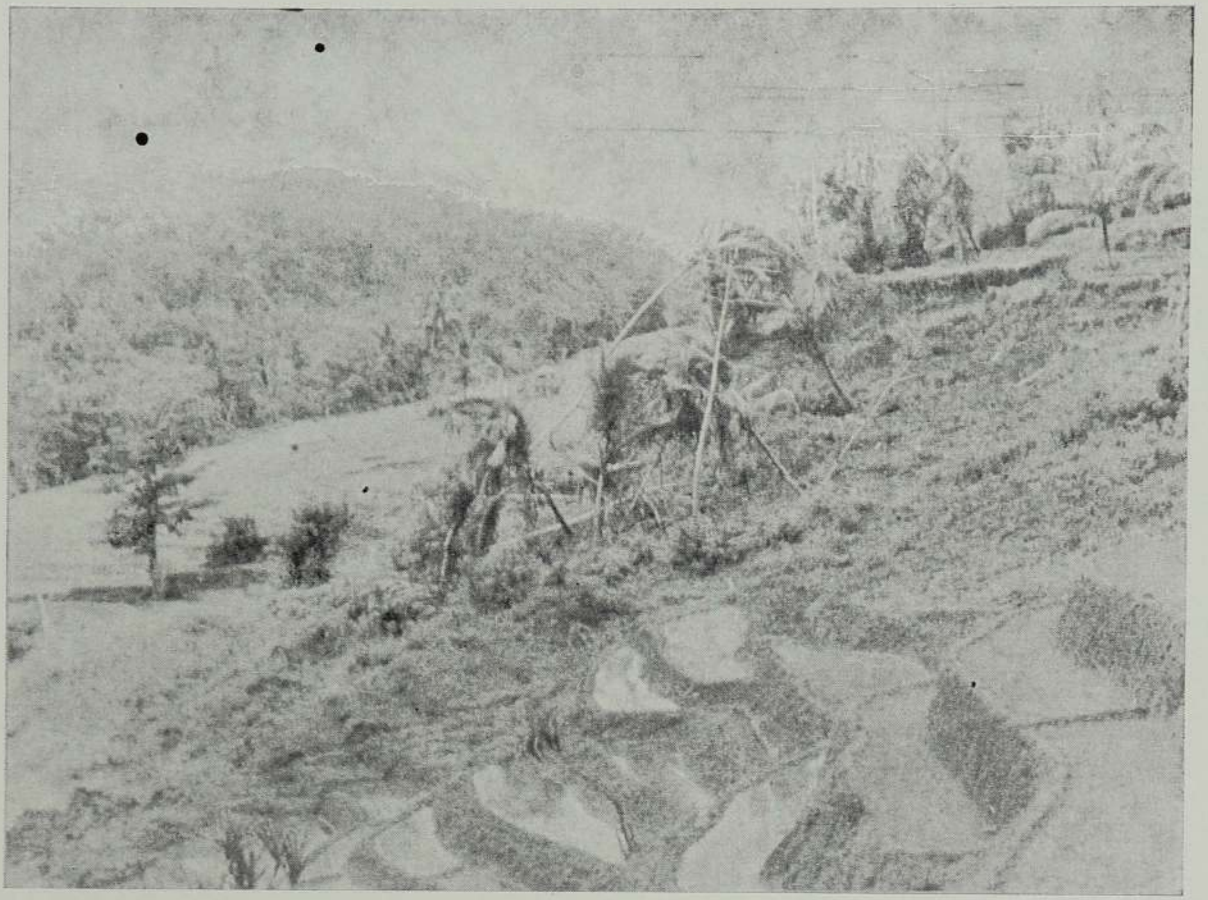


Fig. 97. Sketches showing the stability of slopes.

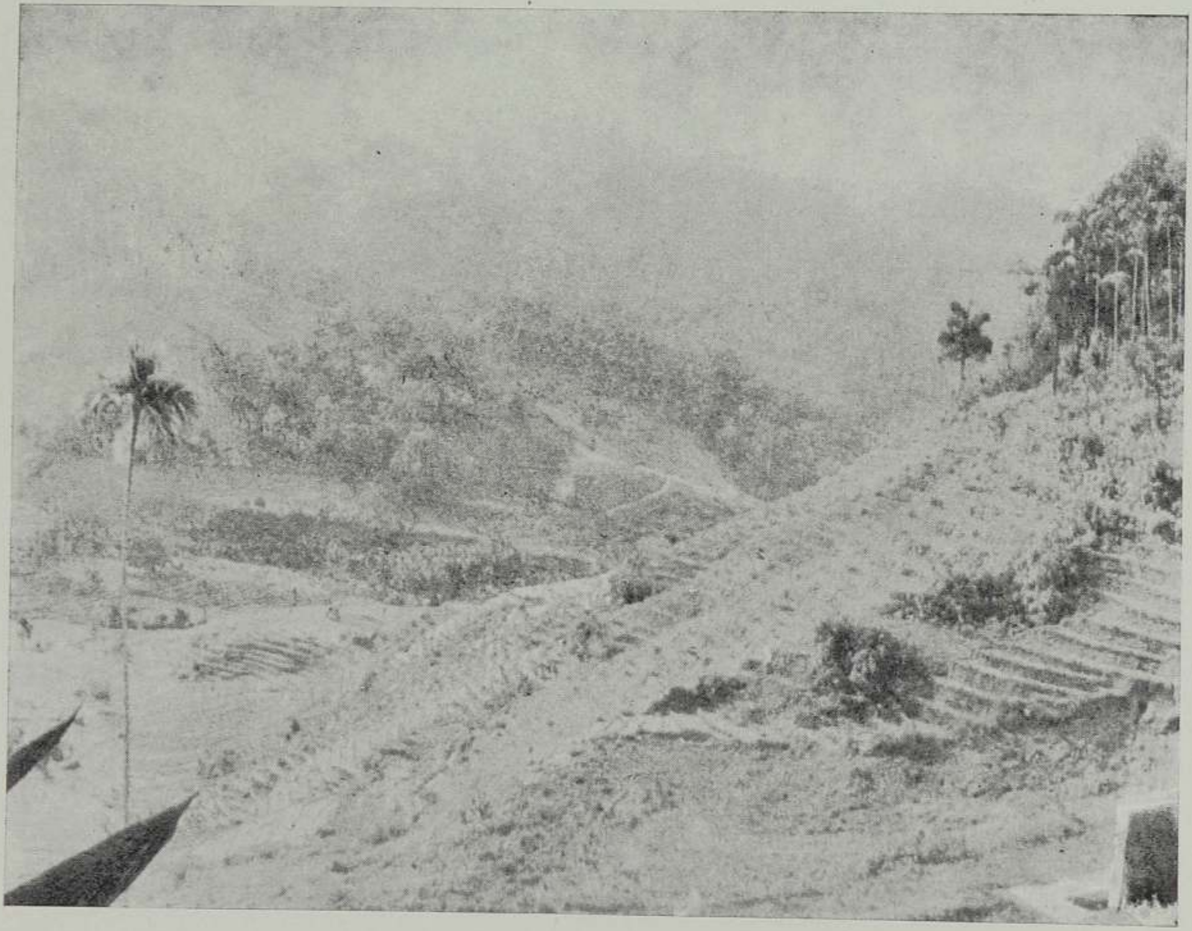
A. *Unstable*, ground slope greater than or equal to dip of rocks.

B. *Stable*, ground slope less than dip of rocks or opposite to it.

Of fundamental importance in areas of bedded and banded rocks like those of the Highland Series is the relation between the slope of the ground and the dip of the strata. Unstable conditions are especially present where the ground slope is greater than or equal to the dip (Fig. 97). Conditions are relatively stable when the slope of the ground is less than the dip or where the strata dip in the opposite direction to the ground slope ; in the latter instance, however, jointing in the rocks may cause instability.



A. Subsidence in terraced rice fields, Giddawa village.



B. Earthslip on steep, terraced slope. Dehigashinne.

Mass movement on gentle slopes, on the other hand, is slow, and though the effects are not as spectacular as the rapid movements, they can be widespread. These slow movements generally result in *subsidence of* various kinds which can go on for many years. The village of Nugatenne, for example, situated on the long scree-and-talus slope of Medamahanuwara, Hunasgiriya, has had a long history of instability, the first subsidences being reported over 50 years ago. Here, linear or curved cracks in the ground have been continuously growing in size with each period of heavy rain, as was experienced in 1911, 1919, 1929, 1938, 1947, 1953 and 1957.

Descriptions of Typical Earthslips

One of the worst affected areas in the almost unprecedented rainfall in 1957 was the Hunasgiriya-Teldeniya area where more than 15 major earthslips took place within twenty square miles. Several types of slips were experienced here, and a good idea of mass movements of earth can be had by looking at some of them in detail[74].

The immediate cause of the earthslips was the unusual combination of climatic factors towards the end of 1957. After a period of long drought, the entire north-eastern part of the Central Highlands suffered from practically continuous monsoonal rainfall from the middle of October to the end of December ; during November, for example, St. Martin's Upper had a rainfall of 46 inches, an excess of 23 inches over its normal November rainfall. Then from December 17 to 25, exceptionally heavy rain was caused by a trough of low pressure in the Bay of Bengal and this was accentuated on the last two days by a depression off the east coast. Many stations received over 20 inches on December 25 and 26, and several stations had December totals of over 60 inches, this being three times the monthly average for some of them. Such heavy, intense rainfall, falling on ground that was already over-saturated, led to a large number of mass movements, classified as debris avalanches, earth flows, debris slides and rock slides (rapid movement), and subsidence (slow movement).

The *debris avalanche* at Lunugalawatte, Waradawila, at milepost 19¼ on the Teldeniya-Rangala road, was the largest of the 1957 landslides (Fig. 98 and Pl. 38B). About six hundred feet of a steep north-west facing slope suddenly gave way with a terrific sound of crashing and rumbling, and the debris of boulders, sand, and mud was carried down for a total of about 2 miles, destroying many acres of paddy land far below the actual slip. Four persons were killed, much tea land was destroyed, and a 40-foot section of the road was carried away, isolating the Rangala community for about a month.

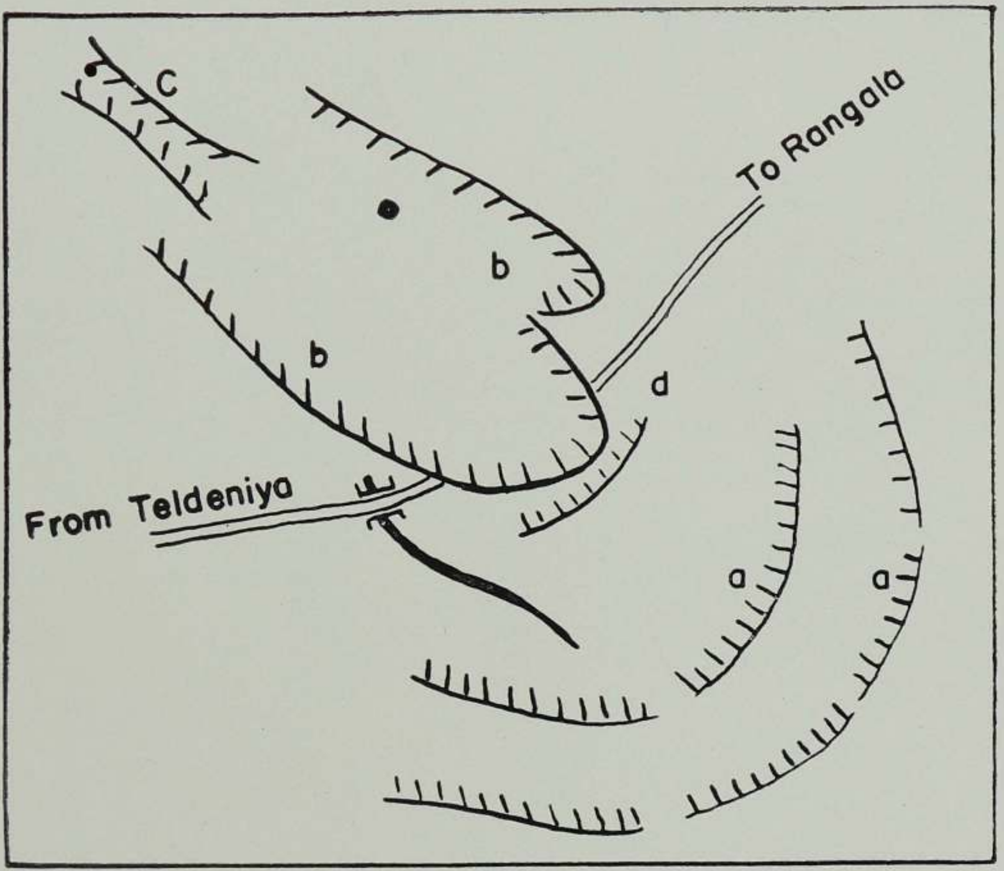


Fig. 98. Sketch plan of earthslip at Lunugalawatte, Waradawila, near milestone 19½ on Teldeniya-Rangala road.

(*a*) early subsidence, (*b*) area of debris avalanche, (*c*) earth-flow gully, (*d*) new road cut ; circle-spring.

The head of this major landside occurred immediately within a semi-circular area which had subsided some years earlier, and the main cause of the slip was the lack of proper drainage within this area, a small, totally inadequate culvert being expected to carry away the large outflow of water from it (Fig. 98). Owing to this absence of adequate drainage, over-saturation of the thick weathered overburden took place, leading to the lubrication of the highly clayey material. Once movement occurs on such material on a moderate or steep slope, it quickly gathers momentum and the entire unstable slope will eventually give way, as it did in this instance.

Earthflows were common at Godamunne, Kandekumbura, and Naranpanawa (Fig. 99A), most often on terraced paddy lands on steep slopes. These begin as *slumps* (where a mass moves along a definite, steep, slip plane separating it from the stable ground), and are most often found immediately below irrigation channels. Excessive saturation soon converts slumps into earthflows where a mixture of water, clay and sand moves downwards as a slushy mass.

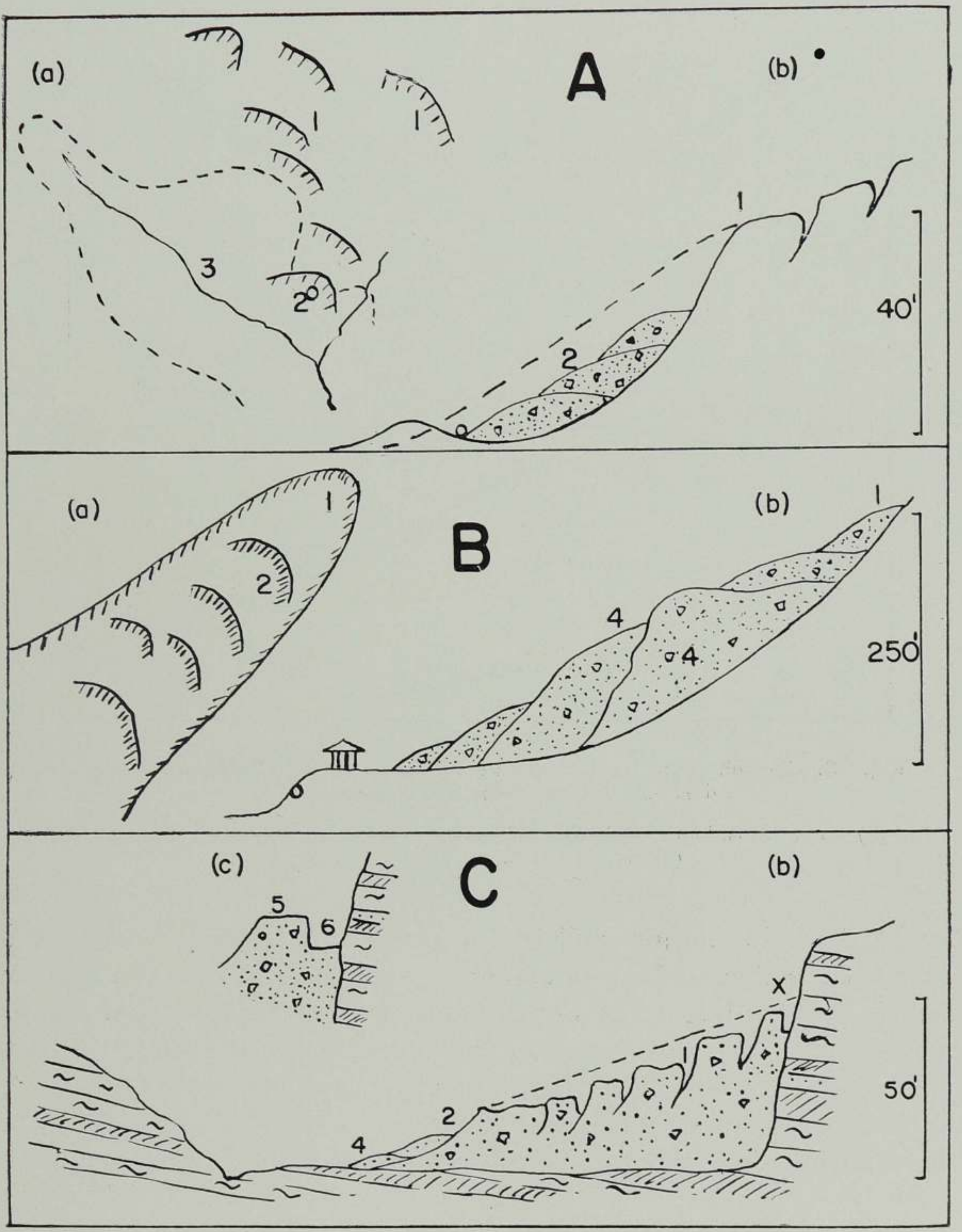


Fig. 99. Diagrammatic sketches of earthslips in the Kandy District.

A. Subsidence at Kandekumbura, near Naranpanawa.

B. Debris slide at Giddawa, south side.

C. Subsidence at Giddawa Colony.

(*a*) in plan, (*b*) in section, (*c*) detail at X; (1) subsidence, (2) debris slide, (3) stream, (4) earthslip material, (5) footpath, (6) drain, circle-spring.

One of the largest *debris sliders* was at Giddawa (Fig. 99B), on the south side of the village. Here, a series of slumps and debris slides had taken place along a scree slope for about 250 to 300 feet. The slope of the ground was about 45 degrees and the scree material was a highly micaceous clay. The main part of the slide had formed a terrace half way down the slope and the sides of the slip were vertical, with a displacement of from 5 to 15 feet.

Heavy *rock slides* and *rockfalls* occurred between milestones 15 and 16 on the Teldeniya-Weragantota road, completely blocking it and making it impassable for several weeks. At the 15th mile the road runs through heavily jointed quartzites which strike at right angles to the road, and the intense rain caused a rockfall of joint blocks and rocks.

The rocks at milestone 15½ on the other hand are thinly-bedded, flaggy, quartz-feldspar gneisses and schists ; they are also jointed (Pl. 38A). The road at this point runs on the dip slope of the rocks which here coincides with the slope of the ground. Lubrication of the feldspathic material along the bedding and joint planes caused a large amount of loose rock debris to slide down the slope on to the road for a distance of 150 to 200 feet.

Two examples of *subsidence* can be mentioned. A series of parallel subsidences occurred on a scree slope in Giddawa Colony, the earth sinking in a succession of near-parallel steps with displacements of 2 to 6 feet (Pl. 39A). The largest subsidence was along a drain by the side of a vertical rock face at the top of the scree slope (Fig. 98C). At the time of the slip the water is reported to have come over this drain from the upper slope as a massive sheet of water ; oversaturation of the scree material naturally occurred. Small slips in the paddy fields on the lower part of the slope probably triggered off a series of subsidences on the higher coconut-cultivated slope.

At Hunasgiriya, between milestones 22 and 23 on the Teldeniya-Weragantota road, the road itself and the paddy fields are located on a slope of unconsolidated weathered material which fills a strike valley. At the time of the damage about 20 feet of road had been washed away and the surface of the road was buckled for about 100 feet. Extensive damage to houses had also taken place. There is a long history of instability here and the road has been undergoing continuous repair for many years owing to the fact that it sinks and buckles after each period of heavy rain.

It can thus be seen that although earthslips and other mass movements take place on naturally occurring unstable slopes of weathered clayey material, where conditions are favourable for such movements they are often accelerated by man-made conditions. These include deforestation and the removal of a vegetation cover which naturally binds the soil, inefficient and inadequate systems of drainage, the cultivation of paddy on steep slopes (Pl. 99B), and the pressure of population which settles and cultivates unstable slopes. Such man-made conditions suggest their own remedies, as for example, adequate and efficient drainage systems to carry away surface water as quickly as possible from unstable ground, the planting of quick-growing trees and grasses on slipped and unstable areas, the building of retaining walls and terraces on slopes that have suffered movement, and the prohibition of the cutting of vertical embankments without sufficient safeguards. Unless these and other measures are taken, landslides and similar types of movement will continue to take place in areas that already have suffered from them, and fresh landslides may occur on unstable slopes, hitherto unaffected.

CHAPTER 14

GEOLOGY AND SOILS

> *The soil considered as a rock, links common stones with the atmosphere, and the dead dust of the earth with the continuing of life.*
>
> Grenville A. J. Cole, 1913.

Composition of the Soil

ALTHOUGH the earth's crust is many miles thick it is the uppermost few inches known as the soil that ultimately supports all terrestrial life, animal and vegetable, in its variety of forms. A close look at the soil in one's garden will show that it is made up of four simple constituents, namely, *mineral grains, organic matter, air,* and *moisture*, but the proportions of these constituents vary not only between different soils but even at different depths within the same soil. On the average, however, the top soil is made up in the following manner:—

Mineral grains	45 per cent
Organic matter	5 ,, ,,
Moisture	25 ,, ,,
Air	25 ,, ,,

The most important constituent of the soil is its mineral matter. Part of this mineral matter consists of fragments of original minerals like quartz that have persisted, more or less unchanged, from the original rock. The rest is made up of secondary minerals such as the clay minerals (kaolinite, montmorillonite), limonite, gypsum and secondary mica, all of which have been formed by the weathering and alteration of less-resistant minerals like feldspar and mica. Organic matter consists of the remains of dead plants that have been changed into *humus* and mixed with the mineral matter by the action of small insects and animals (such as earthworms) which turn the soil over. It is this organic matter that gives the soil its dark colour. Moisture and air in a soil are extremely variable and their proportions are largely responsible for the suitability of a soil for plant growth.

The soil is thus mainly a product of rock weathering, the ease of which depends both on the climate and on the nature of the parent material at any particular locality. Weathering is rapid, for example, in warm, wet, tropical regions, and relatively slow in cool, temperate regions. Intermediate or slightly basic rocks weather more easily than very basic rocks, and acid rocks weather least easily. Other factors besides climate and

GEOLOGY AND THE COMMUNITY

parent material that govern the formation of soil are the presence or absence of vegetation, the age or duration of weathering, and situation of the soil with respect to topography. Some of these factors act in a complex manner and their influence on soil formation is not fully understood except in a general way.

The modern study of soils has shown that a soil is best characterised by the nature and arrangement of the different layers or *horizons* present in the *soil profile* (the vertical section through a soil). These layers, which result from soil-forming processes, are grouped under three heads, namely,

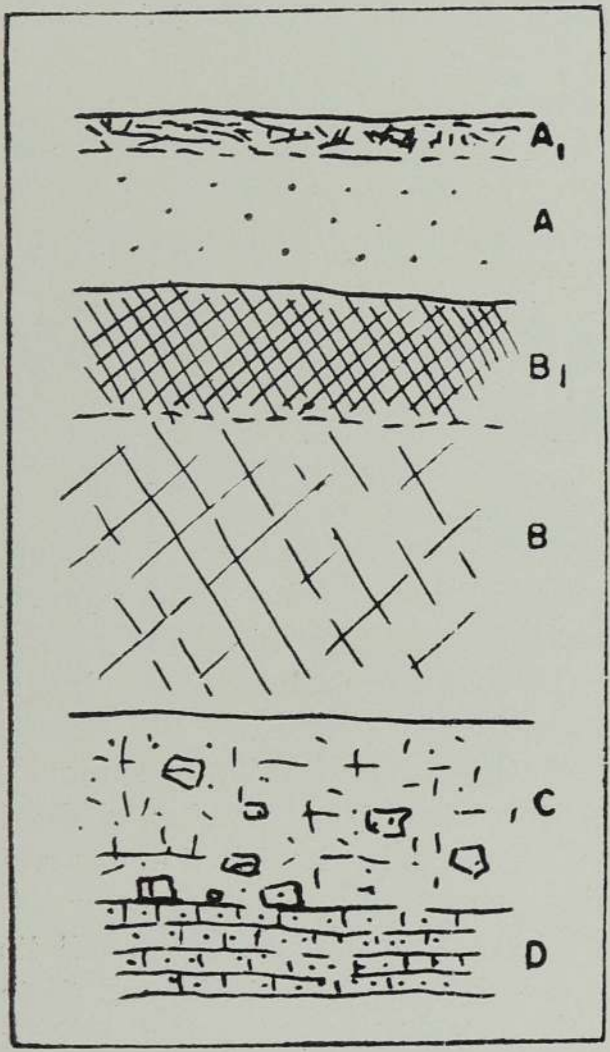


Fig. 100. Diagrammatic sketch of the soil profile. (*Modified from A. Holmes*, 1965.)

A—zone of leaching, covered by layer of humus (A1).

B—zone of accumulation, especially of iron and aluminium; location of *hardpans* and of *kankar* in B1.

C—decomposed bedrock, parent material of soil.

D—fresh bedrock.

A—the *zone of leaching*, B—the *zone of enrichment*, and C—the *parent material* (Fig. 100). Zone A lies at the surface and is generally covered by a layer of *humus*. Iron compounds and clay particles (aluminium compounds) are leached out from Zone A by descending soil water and concentrated in zone B. Zone B is thus called the zone of accumulation and it is here that hardpans and kankar nodules develop in soils of the arid and semi-arid regions such as the Dry Zone. Zone C is decomposed bedrock, the parent material of the soil.

GEOLOGY AND SOILS

A soil is named only after the arrangement of its soil horizons have been recognized and when their form as well as chemical and physical properties are known. It is then fitted into one of the *Great Soil Groups* which are the main classes of soils recognised by soil scientists all over the world. When a soil does not fit onto any one of the already recognised classes, a new soil group is named after it. The Reddish Brown Earths of Ceylon (see below) are such a new class.

The Soils of Ceylon

Fourteen Great Soil Groups have been recognised in Ceylon[75], and the interplay of various soil-forming factors can be seen to some extent in their distribution (Fig. 101). It is clear that the major factor influencing soil formation in Ceylon is climate, parent material being generally a subordinate factor ; the boundaries of the major soil groups follow closely the main rainfall divisions in the island. The soils in the Dry Zone, for example, are distinctly different from those in the Wet Zone, even when developed on the same type of parent material such as charnockite. The influence of the other factors cannot be so easily recognised, except by a trained observer, but there are appreciable differences between soils on a stable landscape and an unstable one, or between soils on the crests of a ridge and those at the bottom of the slope.

Of the fourteen Great Soil Groups found in Ceylon, only the following eight need be considered here :

(1) Reddish Brown Earths
(2) Non-Calcic Brown Soils
(3) Red Yellow Podzolic Soils
(4) Red Yellow Latosols
(5) Reddish Brown Lateritic Soils
(6) Regosols
(7) Alluvial Soils
(8) Solodized Solonetz

1. *Reddish Brown Earths.* This is one of the Great Soil Groups of the semi-humid tropics and is best developed in the Dry Zone of Ceylon where the annual rainfall is less than 75 inches. Although these soils are developed on a variety of parent rock materials, such rocks must have a sufficiency of the ferromagnesian minerals mica, hornblende, pyroxene, or garnet. The Reddish Brown Earths are best developed over the lowest peneplain of Ceylon, that is, in most of the Northern, North Central

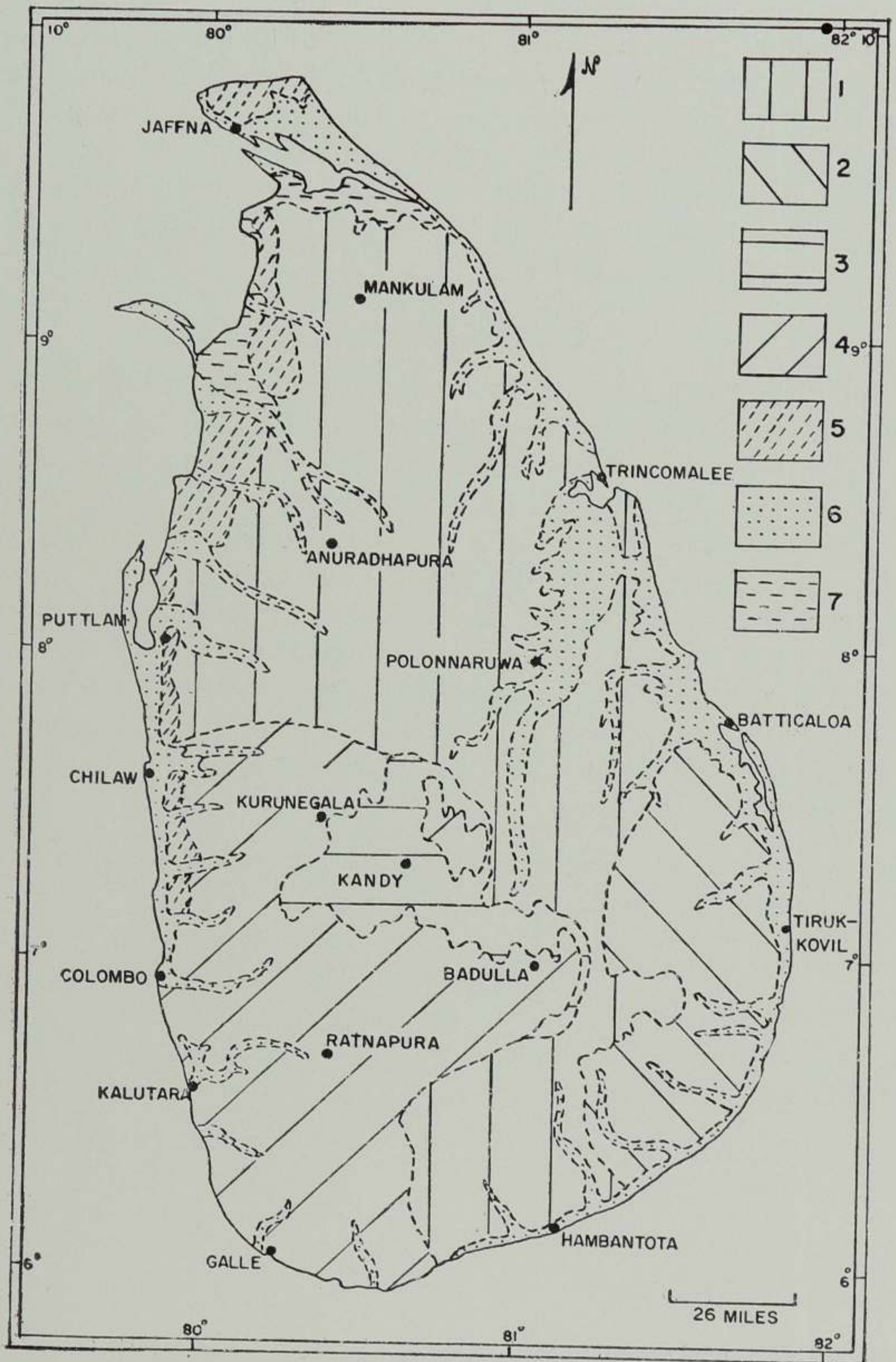


Fig. 101. Simplified map of the Great Soil Groups of Ceylon. (*Modified from F. R. Moorman and C. R. Panabokke,* 1961)

(1) Reddish Brown Earths, (2) Non-calcic Brown Soils, (3) Reddish-brown Lateritic Soils, (4) Red Yellow Podzolic Soils, (5) Red Yellow Latosols, (6) Regosols and alluvial soils, (7) Solodised solonetz and solonchaks.

Eastern, and Southern Provinces, where biotite and hornblende-bearing gneisses of the Vijayan Series are present; but they also develop on Highland Series rocks (metasediments and charnockites) in the area between Polonnaruwa and Trincomalee that lies in the Dry Zone. The commonest vegetation on these soils is dry mixed evergreen forest.

2. *Non-Calcic Brown Soils.* These soils develop within the same areas as the Reddish Brown Earths but only where there is a deficiency of ferromagnesian minerals in the parent rock. They are specially prominent in the Eastern Province, on the highly acid, quartz-rich gneisses with little biotite and hornblende that are common in the area.

3. *Reddish Brown Lateritic Soils.* Within the Central Hill Country of Ceylon, where the rainfall is over 100 inches annually, is a region where the rainfall is between 75 and 100 inches per year. This is the Kandy Plateau, physiographically made up of sharply rolling country which appears to have been recently uplifted. As a result of this uplift there has been rapid erosion and dissection of the land, both processes having resulted in the removal of the earlier formed soil; insufficient time has elapsed since then for the development of new, mature soils. The Reddish Brown Lateritic Soils found within the Kandy Plateau contain remnants of the early mature soils and side by side with them are reddish brown loams which are full of weatherable minerals, a sign of their comparative youthfulness.

4. *Red Yellow Podzolic Soils.* These soils are predominant in the Wet Zone of Ceylon, that is, in the Hill Country and the south-west region of the island, where the annual rainfall is over 110 inches. Metasediments and charnockites of the Highland Series are the main rock types. Rainfall is the overriding factor in the formation of the Red Yellow Podzolic soils; they develop equally on a variety of crystalline schists and gneisses, quartzites, and crystalline limestones.

5. *Red Yellow Latosols.* The Red Yellow Latosols are found within a belt which runs along the north-west of the island, a few miles inland from the coast. This belt stretches from Puttalam to Pooneryn and parts of the Jaffna Peninsula are also included within it. The occurrence of the Latosols corresponds roughly with the distribution of the Older Quaternary formations, namely, the Red Earth and the ferruginous gravels (see p. 149). The soils are bright red in colour and appear to have developed under previously existing climatic conditions different from those of the present. They are called 'old' or 'relic' soils which have been preserved from erosion by the relative stability of the existing landscape. The parent materials of these soils are of sedimentary origin (either wind borne or

river deposits) and have undergone previous cycles of weathering: the soils are thus poor in weatherable minerals but rich in quartz.

6. *Regosols*. Regosols are soils that are so young that a recognisable soil profile has hardly had time to develop. Such soils are found extensively on the unconsolidated sands and sand dunes found round the coasts of Ceylon. Included in this group are the shallow, stony or gravelly soils present on rock outcrops; they are sometimes known as *lithosols*.

7. *Alluvial Soils*. A variety of soils found in the river valleys and flood plains of the island fall within this group. The development of soil profiles in alluvial material is not strong, largely because there is constant addition of new layers of alluvium to those recently laid down. Alluvial soils are younger than all other soils except the regosols.

8. *Solodized Solonetz*. These soils occur along the sea coast in the Dry Zone and on the more clayey parts of tidal flats and estuaries. They are characterised by the presence of salts in the parent material. The typical vegetation on such soils is grass or halomorphic plants; bare patches are common.

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I

On the Use of the Term ‘ Highland Series

The name *Highland Series* was first used by the author in 1961[6] to include the metasediments of the *Khondalite Group* (previously known as the Khondalite Series) as well as *charnockites* (earlier said to be intrusive into the metasediments) found in the Rangala area. These two groups of rocks are very closely associated in the field in this area, they have a common metamorphic history, and are thought to belong to a single succession of rocks laid down during the same period and formed during the same metamorphism.

This close association of metasediments and charnockites is now known to occur throughout the Central Highlands of Ceylon where it has, in recent years, been found to be present in the entire Hatton, Ratnapura, and Rakwana sheets, and in the eastern portions of the Gampaha, Avissawella, Horana, and Alutgama sheets[76]. The fact of this association was also recognised by J. S. Coates in 1935 when he labelled the central belt in his geological map of Ceylon the *Charnockite-Metasedimentary Series*[13], by P. W. Vitanage in 1959 when he named the central zone of the Polonnaruwa sheet the *Charnockite-Khondalite Metasedimentary Belt*[14] and by R. L. Oliver and D. K. Erb in the northern part of the Kirindi Oya Basin[20].

The name Highland Series was extended, in 1962[77], to cover almost the entire area shown in the Provisional Geological Map of Ceylon of 1948 to be occupied by the Khondalite Series. The same practice is followed in this book, though it should be noted that the name has not yet been officially recognised by the Geological Survey Department, except when applied to the Rangala area.

II

Isotopic ages of Minerals from Ceylon

Although nearly thirty isotopic age determinations have so far been carried out on minerals from Ceylon, not all of them are equally reliable. For instance, the ages of micas and feldspars from the Polonnaruwa and Balangoda areas are now known to be too high, and others are of doubtful values owing to the nature of the samples. The most reliable ages known at present are those carried out on zircon and thorianite crystals, and these ages, together with the mica ages determined in 1962 at the Institute for Pre-Cambrian Geology, Leningrad, are given in Table 19[78]. The localities of the samples are also shown in Fig. 98.

The most remarkable feature of the Table is that no mineral has yet given an age that is undoubtedly Pre-Cambrian, that is, more than 600 million years. Further, micas from crystalline limestones of the Khondalite Group (Nos. 5, 6, 7), which has always been presumed to be Pre-Cambrian in age, are seen to have formed between 538 and 512 m.y. ago. This apparent anomaly can be explained in one two ways. Either

(*a*) the oldest known metamorphism was not of Pre-Cambrian age at all but rather took place during Cambrian times; in which case the remarkable similarity of metasediments and charnockites of the Highland Series to khondalites and charnockites of the Eastern Ghats which were formed 1650 m.y. age is purely accidental. Or,

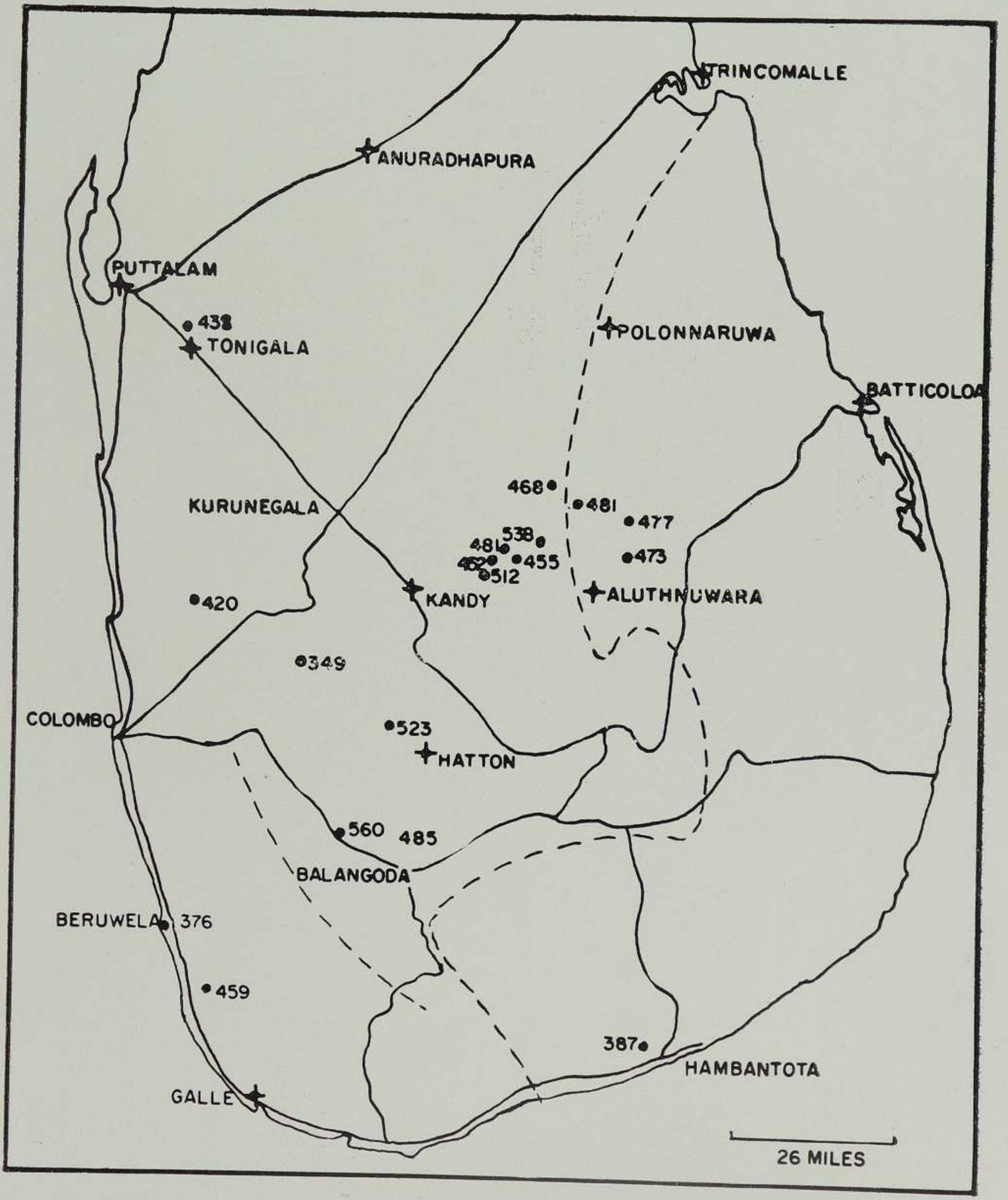

Fig. 102. Map showing localities of minerals whose isotopic ages have been determined.

TABLE 20.—Isotopic Ages of Zircons, Thorianites, and Micas from Ceylon

No.	*Locality*	*Mineral*	*Age in million years*			*Rock and geological setting*	*Source*
			U^{238}-Pb^{206}	Pb^{206}-Pb^{207}	K-Ar		
1	Not available	ZIRCON	574±32			Average of 21 gem-quality crystals. (Pegmatites in Highland Series)	Gottfried et. al. (1956)
2.	Not available	ZIRCON		570		Not available	A. Nier (1939)
3.	Ratnapura	EKANITE	560±50			Gem gravel. (Pegmatite in Highland Series)	E. Gubelin (1962)
4.	Not available	ZIRCON		555±20		Not available	Tilton & Aldrich (1957)
5.	Nitre Cave, Rangala	PHLOGOPITE			538	Diopside-mica clot in cryst. 1st. (K. 3072) of Highland Series	Obruchev & Gerling
6.	Norton Bridge, Hatton	PHLOGOPITE			523	Mica-spinel aggregate in cryst. 1st. (M. 126) Highland Series	Obruchev & Gerling
7.	Naranpanawa, Rangala	PHLOGOPITE			512	Mica schist lens in cryst. 1st. (K. 3100 E.) Highland Series	Obruchev & Gerling
8.	Balangoda District	THORIANITE	490			Average of 8. (?Pegmatites in Highland Series)	Holmes (1955)
9.	Rest of Ceylon, excluding Balangoda District	THORIANITE	490			Average of 10. (?Pegmatites in Highland Series.)	Holmes (1955)
10.	Balangoda District	THORIANITE		485		Not available (?Pegmatites in Highland Series).	A. Nier (1939)
11.	Wilgomuwa, Rangala	PHLOGOPITE			481	Mica vein in calc granulite (K 753). Transitional Zone between H.S. and Vijayan Series	Obruchev & Gerling
12.	Tunisgalla Estate, Rangala	PHLOGOPITE			481	Diopside-mica rock in calc granulite (K. 640). H.S.	Obruchev & Gerling
13.	Mahawelakandia, near Dambane, Rangala	BIOTITE			477	Migmatitic granite gneiss (K.3156B) Vijayan Series	Obruchev & Gerling

14.	Mavaragala, near Dambane, Rangala	BIOTITE			473	Biotite gneiss with granitic veins (K. 3142). Vijayan Series	Obruchev & Gerling
15.	Madumana, Pallegama, Rangala	PHLOGOPITE			468	Pegmatite (M. 330) in H.S.	Obruchev & Gerling
16.	Magala, Alutgama	BIOTITE			459	Granitoid rock with monazite (K. 3400). South-western region.	Obruchev & Gerling
17.	Kaladuria Estate, Rangala	BIOTITE			455	Pegmatite (K. 631) in H.S.	Obruchev & Gerling
18.	Arratenne, Rangala	BIOTITE			452	Mica schist associated with graphite vein (K. 634). H.S.	Obruchev & Gerling
19.	Uriya Wewa, near Tonigala, Galgamuwa	PHLOGOPITE			438	Mica schist band in pre-Tonigala migmatitic gneiss. Vijayan Series	Obruchev & Gerling
20.	Walpita, Gampaha	BIOTITE			420	Biotite-garnet-cordierite gneiss. South-western region.	Obruchev & Gerling
21.	Hambantota	BIOTITE			387	Mica selvage to granite vein. V.S.	Obruchev & Gerling
22.	Beruwela, Alutgama	BIOTITE			376	Granite, with monazite and zircon (K. 3491A). S.W. region	Obruchev & Gerling
23.	Bogala Graphite Mine, Gampaha	BIOTITE			349	Mica schist band in gneiss, associated with graphite veins. S.W. region	Obruchev & Gerliug

(*b*) rocks of the Highland Series were, in fact, formed during a Pre-Cambrian metamorphism about the same time as the E. Ghats metamorphism, but the micas in some of the rocks give much younger ages than the original metamorphism. The presence of pegmatites in the Highland Series with ages older that the micas (see below) lends some support to this alternative, but the question will finally be settled only when more ages of other minerals are known. For the present we shall accept this view as most likely.

Micas from the granitic gneisses of the Vijayan Series on the east of Rangala (Nos. 13 and 14) and mica-bearing pegmatites in the Highland Series (Nos. 15 and 17) group closely around 465 m.y., with a range from 477 m.y. to 455 m.y. Micas from two calc granulites, one in the Transitional Zone (No. 11) and one in the Highland Series (No. 12) have identical ages of 481 m.y.

Gneisses from the south-western region have ages of 459 m.y. and 420 m.y. (Nos. 16 and 20), but a granitic rock from the same region (No. 22, 376 m.y.) has almost the same age as a granitic vein from the Vijayan of the south-east region (No. 21, 387 m.y.).

The youngest known age is 349 m.y., given by a mica schist from Bogala graphite mine (No. 23).

Most of the zircons and thorianites on which ages have been determined have undoubtedly originated in pegmatites, and the results indicate that the presence of two distinct groups of pegmatites [64a,84]. These are ;

(*a*) a group of zircon-bearing pegmatites, of which the Balangoda Granite is the best known, intruded about 570 m.y. ago ; this has been called the *Balangoda Cycle*.

(*b*) A group of thorium-rich pegmatites containing thorianite, intruded about 485 m.y. ago ; this in the *Late-Cambrian cycle*, and it may include monazite- and allanite-bearing pegmatites.

The significance of the ages of these two groups of pegmatites lies in the fact that similar pegmatitic activity took place at about the same time in other parts of the pre-Gondwana continent. The older, zircon-bearing pegmatites are similar in age to zircon -and monazite-bearing pegmatites from East Africa which have an age of 550 m.y. The younger, thorium-rich pegmatites are similar in age to pegmatites with thorianite from Madagascar (490 m.y.), cheralite from Travancore (485 m.y.), xenotime from Western Australia (450 m.y.), and uraninite and monazite from Brazil (450-500 m.y.).

We can now, using the above data, make some preliminary deductions about the ages of the major plutonic events that led to the formation of the crystalline rocks of the island. Some of these deductions may later be proved to be incorrect, when the age determinations of a large number of rocks now being made by R. Crawford at the Australian National University, Canberra, become known, but they are given here for what they are worth, in the present state of our knowledge. These deductions are :

(i) That the Highland Series rocks were formed during a Pre-Cambrian geological cycle at about the same time as the Eastern Ghats belt, that is, about 1650 m.y. or more .ago

(ii) That zircon-beating pegmaties were intruded into these rocks after a long interval, about 570 m.y. ago.

(iii) That a late metamorphism, possibly connected with an orogeny but with no clear evidence of previous sedimentation took place from about 540 to 475 m.y. This late metamorphism caused (*a*) a recrystallisation of micas in the crystalline limestones of the Highland Series, (*b*) the formation of new mica from pyroxene and hornblende in the granitic gneisses of the eastern Vijayan Series, and (*c*) the intrusion of mica-bearing pegmatites in the Highland Series. The migration of F and Cl somewhat earlier may have caused the recrystallisation of mica veins and pockets in calc granulites within the Transitional Zone and in the Highland Series. The thorianite-bearing pegmatites were intruded during this episode.

(iv) That plutonic activity continued to about 350 m.y. ago (or middle Palaeozoic times), during which period the granites and granitic gneisses of the south-eastern Vijayan, the south-western region, and possibly the Tonigala Complex were formed.

It should be said here that the results of Crawford's work are not known, at the time of writing this, but they are awaited with great interest.

III

List of fossils recorded from Ceylon

JURASSIC

(Those marked * from Andigama, all others from Tabbowa)

Plants

Pteridophyta	_Cladophlebis zeylanica_ Sitholey
	Cladophlebis reversa (Feist.) Seward and Holttum
	Cladophlebis denticulata (Brogn.) Seward and Holttum
	Cladophlebis cf. _browinana_ Jacob
	*_Cladophlebis_ sp.
	Sphenopteris wadiai Sitholey
	Coniopteris hymenophylloides (Brogn.)
	Fern-like fragments
Cycadophyta	_Taeniopteris spatulata_ Mc Clelland
	Nilssonia fissa (Feist.) Seward and Sahni
	Nilssonia schaumburgensis
	Anomozamites (_nilssonia_) sp.
	Ptilophyllum sp.
	?_Otozamites_ sp.
Coniferales	*_Elatocla dusplana_ (Feist.) Seward and Sahni
	Elatocladus sp.
	Araucarites cutchensis (Feist.) Seward and Holttum
	Brachyphyllum mamillare (Brogn.) Seward and Holttum
	Desmiophyllum (?_Podozamites_) sp.
Plantae incertae sedis	Stem fragments

MIOCENE

Localities: **A**—Keerimalai, Jaffna Peninsula; **B**—north of Pomparippu, north-west coast; **C**—Puttalam, north-west coast; **D**—east of Kankesanthurai, Jaffna Peninsula; **E**—near Pallai, Jaffna Peninsula; **F**—Minihagalkanda, south-east coast; **G**—Nirukiri, Jaffna Peninsula; **H**—Arnakallu (Aruakalu), north-west coast.

Invertebrates

Gasteropoda	_Callistocypraea_ (_Miolyncina_) _prunum_ (J. de C. Sowerby) (**A, F**)
	?_Conus_ (_Lithoconus_) _litteratus_ Linné (**A, D, F**)
	Conus (_Lithoconus_) _subbrevis_ d'Archiac and Haime (**A**)
	Cypraea (_Lynsina_) _jenkinsi_ d'Archcia and Haime (**F**)
	Euspirocrommium oweni d'Archiac and Haime (**A, F**)
	Natica rostalina Jenkins (**A**)
	Olivancillaria (_Anazola_) _nebulosa_ (Lamarck) var. _pupa_ J. de C. Sowerby (**A**)
	Phalium (_Semicassis_) _booleyi_ G. B. Sowerby
	Ptychocerithium archiaci (Vredenburg) _pseudocorrugatum_ (d'Orbigny) (**A**)
	Strombus spinosus minihagali Deraniyagala (**F**)
	Tectus loryi d'Archiac and Haime (**A, F**)
	'_Xenophora_' sp.
Lamellibranchia	_Amusium subcorneum_ d'Archiac and Haime (**F**)
	Anadara peethenis d'Archiac and Haime (**A**)
	Antigona puerpera (Linné) var. _granosa_ J. de C. Sowerby (**F**)
	Chlamys senatoria Gmelin (**A, B**)
	Chlamys sp.(**F**)
	? _Discors triforme_ (J. de C. Sowerby) (**A**)
	? _Macrocallista_ (_Costacallista_) _pseudo umbonella_ Vredenburg (**F**)
	Ostrea (_Lopha_) _virleti_ Deshayes (**F**)
	Atrina (_Atrina?_) _pachyostraca_ (Davies) (=_Pinna pachyostraca_ Davies) (**F**)
	Spondylus aff. ?_tallavignesi_ d'Archiac and Haime (**A**)
	Spondylus waylandi A. M. Davies (**F**)
	Trachycardium picteti d'Archiac and Haime (**F**)
	Venericardia sowerbyi d'Orbigny (**F**)

Echinodermata	*Clypeaster* (*Paleanthus*) *depressus* J. de C. Sowerby (**F**)
Foraminifera	*Alveolinella* (*Flosculinella*) sp. (**A, B, E**)
	Amphistegina sp. (**G**)
	Austrotrillina sp. (**G**)
	Borelis sp. (**G**)
	Carpentaria sp. (**G**)
	Eponides sp. (**G**)
	?*Flosculinella* sp. (**G**)
	Gypsina sp. (**G**)
	Miliolidae (**A, B, E**)
	Nephrolepidina sp. (**G**)
	Operculina sp. (**F**)
	Quinqueloculina sp. (**G**)
	Taberina (=*Orbiculina*=*Archais*) *malabarica* (Carter) (**A, B, C, E**)
	Rotalia sp. (**G**)
	Textularia sp. (**G**)
	Triloculina sp. (**G**)
	Sorites sp. (**F**)
	Spiroclypeus orbitoideus H. Douville (**F**)
	Spiroclypeus sp. (*?*) cf. *S. Pleurocentralis* (Carter) (**A**)
Anthozoa	*Flabellum* sp. (**F**)
	Hydnophora plana (*?*) Duncan (**F**)
	Montlivaltia brevis Duncan (**F**)
	Porites sp. (**F**)
	Solenastrea sp. (**F**)
	Staminocoenia plana Duncan (**F**)
Hyalospongiae	*Pheronemo* sp. (**F**)
Bryozoa	Cheilostome (**F**)
Calcareous Algae	*Lithothamnium* sp. (**A, B, G**)
	Lithophyllum sp. (**G**)

Vertebrates

(All from Locality H)

Chondrichthyes	*Isurus* sp.
	Glyphis minor Agassiz
	Galeocerde articus Faber
	Hemipristis serra Agassiz
	Myliobatis sinhaleyus Deraniyagala
	Aetobatis sinhaleyus Deraniyagala
Osteichthyes	*Labrodon sinhaleyus* Deraniyagala
	Callyodon sp.
	Diodon sinhaleyus Deraniyagala

PLEISTOCENE

(from the Ratnapura Beds)

Vertebrates*

Reptilia	*Geoemyda trijuga sinhaleya* Deraniyagala
	Trionyx granosa sinhaleya Deraniyagala
	Crocodilus sp.
	Crocodilus porosus minikanna Deraniyagala
Mammalia	*Homo sinhaleyus* Deraniyagala
	Homo sapiens balangodensis Deraniyagala
	Hystrix sivalensis sinhaleyus Deraniyagala
	Globicephala macroryncha Gray
	Cyon javanicus sinhaleyus Deraniyagala

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* The desirability of listing so many species and sub-species as recorded by Deraniyagala[15] is doubted by several other workers.

Felidae	*Leo leo sinhaleyus* Deraniyagala
Elephantidae	*Hypselephas hysudricus sinhaleyus* Deraniyagala *Palaeoloxodon namadicus sinhaleyus* Deraniyagala *Elephas maximus sinhaleyus* Deraniyagala
Rhinocerotoidae	*Rhinoceros sinhaleyus* Deraniyagala *Rhinoceros kagavena* Deraniyagala
Suidae	*Sus sinhaleyus* Deraniyagala
Hippopotamidae	*Hexaprotodon sinhaleyus* Deraniyagala
Cervinae	*Muva sinhaleya* Deraniyagala *Rusa unicolor* Erxleben *Axis axis ceylonensis* Fischer
Bovinae	*Bibos gaurus sinhaleyus* Deraniyagala *Gona sinhaleya* Deraniyagala
Bubalinae	*Bubalus bubalis migona* Deraniyagala

Plants

Bambusa vulgaris Schrader
Ochlanda stridula Thwaites
Onchiosperma fasciculata Thwaites
Caryota urens Linné
Elaeocarpus subvillosus Arnott
Myristica dactyloides Gaertner
Canarium zeylanicum Blume
Coscinium fenestratum Colebrook
Wrightia flavidorosea Trimen

SOURCES

Jurassic

1. K. Jacob (1938)[85]
2. M. S. Krishnan (1960)[86]
3. E. H. Pascoe (1959)[87]
4. A. C. Seward and R. E. Holttum (1922)[88]
5. R. V. Sitholey (1944)[23]
6. D. N. Wadia (1940)[89]

Miocene

1. F. Eames (1950)[27]
2. P. E. P. Deraniyagala (1961)[29]
3. B. S. Tewari and K. K. Tandon (1960)[90]
4. E. J. Wayland and A. M. Davies (1923)[24]
5. J. Rosewater (1961)[90a]

Pleistocene

1. P. E. P. Deraniyagala (1958)[15]
2. G. S. Puri (1941)[91]

IV

CHEMICAL COMPOSITION OF SOME ROCKS AND MINERALS FROM CEYLON

TABLE 21—Chemical Analyses of some Typical Rocks from Ceylon

	METASEDIMENTS						CHARNOCKITES & AMPHIBOLITE				GNEISSES			GRANITES		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
SiO_2	57.96	58.84	74.71	94.18	.51	46.42	73.11	61.56	48.43	45.45	68.44	71.00	77.70	64.86	73.20	SiO_2
TiO_2	1.38	1.01	nil	.06	.02	.22	.97	1.65	.84	.19	.40	.07	.07	.38	.14	TiO_2
Al_2O_3	24.01	18.23	14.69	3.56	.31	10.30	14.19	13.30	18.30	12.26	17.41	14.51	11.42	14.62	14.75	Al_2O_3
Fe_2O_3	3.51	2.52	.03	.16	.03	6.61	.82	.56	.23	4.10	nil	.91	.62	.37	.78	Fe_2O_3
FeO	6.16	7.14	1.46	.51	.17	3.84	1.03	9.25	9.88	9.03	4.37	1.75	.37	5.98	.90	FeO
MnO	.24	.28	trace	.04	.02	.29	.05	.60	.75	.75	.07	.17	.01	.07	.01	MnO
MgO	1.05	4.03	.47	.14	21.03	7.02	.50	1.71	7.58	9.44	1.53	.95	1.08	.78	.08	MgO
CaO	.68	4.07	2.03	.92	31.37	22.26	2.26	6.93	10.97	11.78	1.68	1.70	3.09	3.64	1.46	CaO
Na_2O	.35	2.50	3.39	trace	trace	1.75	3.12	1.80	2.39	1.83	3.62	3.58	1.55	3.10	5.04	Na_2O
K_2O	2.13	2.04	3.26	trace	trace	.37	3.32	1.40	.49	1.11	2.48	5.46	3.85	5.25	4.02	K_2O
H_2O+	2.17	.07	.11	n.d.	n.d.	.59	.31	.54	.35	.39	.09	.59	.39	.77	.12	H_2O+
H_2O-	.40		.04	.04	n.d.	.05	.13	.11	.10	.15	.04	.04	.10	.11		H_2O-
P_2O_5	.11	trace	.02	.02	trace	.05	trace	.38	.02	.07	.02	n.d.	n.d.	.16	trace	P_2O_5
CO_2	n.d.	nil	n.d.	n.d.	46.04	.43	n.d.	n.d.	n.d.	1.32	n.d.	n.d.	n.d.	n.d.	n.d.	CO_2
TOTAL	100.19	100.73	100.21	99.63	99.51	99.70	100.08	99.79	100.33	99.87	100.21	100.73	100.53	100.09	100.50	TOTAL
Sp. Gr.		2.80		2.68		3.07	2.66	2.94	3.13	3.11		2.87	2.74		2.60	Sp. Gr.

Descriptions of Specimens

1. Garnet-sillimanite schist (khondalite), 9½ milestone, Passara-Ella road[3].
2. Garnetiferous granulite with biotite, Hattota Amuna, Pallegama[8].
3. Quartz-feldspar granulite, Pelawatte[45].
4. Quartzite, Pitakanda Estate, Matale[92].
5. Crystalline limestone (dolomitic), Naranpanawa[8].
6. Calc granulite, 31½ milestone, Rattota-Laggala road[8].
7. Acid charnockite, 33¼ milestone, Kandy-Weragantota road[8].
8. Intermediate charnockite, Galboda Estate, Rangala[8].
9. Basic garnetiferous charnockite, Lebanon Estate, Madulkele[8].
10. Amphibolite, 22¾ milestone, Kandy-Rangala road[8].
11. Microcline-biotite gneiss, Gal Oya[18].
12. Garnet-sillimanite-cordierite gneiss, Wettewa, Matugama[45].
13. Garnet-biotite granite gneiss, 44 milestone, Kandy-Dambulla road[18].
14. Hornblende granite, Arangala[45].
15. Microcline granite, Tonigala[93].

TABLE 22—Chemical Analyses of some Heavy Minerals from Ceylon

	1	2	3	4
SiO_2	0·04	1·70	26·13	0·51
TiO_2	0·04	0·08	0·30	53·60
Al_2O_3	3·71	0·85	19·76	0·57
Fe_2O_3	0·28	0·54	4·96	21·77
FeO	—	—	9·24	20·45
MnO	—	—	0·17	0·94
MgO	tr.	0·09	1·06	1·38
CaO	tr.	0·64	12·40	—
ThO	71·45	10·04	0·94	—
U_3O_8	22·52	—	0·01	—
Ce_2O_3	0·08	27·60	8·02*	—
La earths	—	30·66	15·08	—
Y "	—	0·56		
PbO	—	0·11	—	—
SnC_2	—	0·01	—	—
ZrO_2	—	—	—	0·19
Cr_2O_3	—	—	—	0·09
P_2O_5	0·01	27·04	0·10	—
P	—	—	—	0·03
S	—	—	—	0·02
H_2O+	nil	nil	1·60	nil
H_2O-	nil	nil	0·08	nil
Loss on ignition	1·0			
TOTAL	99·13	99·02	99·85	99·55

*as CeO_2

1. Thorianite from beach sand, Kaikawala[94].
2. Monazite beach concentrate, Beruwela[59].
3. Allanite from pegmatite, Bogahagoda[94].
5. Ilmenite concentrate, Pulmoddai[59]

V

On Making a Collection of Ceylon Rocks and Minerals

One of the ways in which the beginner can learn something about the geology of Ceylon is by making a collection of rocks and minerals typical of the area in which he lives. He could then enlarge his collection by obtaining specimens from other parts of the island until, finally, he has a collection representative of the whole of Ceylon. In order to make such a collection, all he will need in the way of equipment is a two-pound hammer, (preferably one with a chisel edge on one side of its head), a notebook, and a one-inch topographical map ; a small hand lens would also be useful.

Rock and mineral specimens are best collected from quarries and mines, and certain simple rules should be observed when collecting them. These are :—

(i) the specimen should always be of fresh rock and **not** of weathered rock ;

(ii) it should be of reasonable size, showing definite features ; small bits and pieces that are unrecognizable should **not** be collected ;

(iii) the specimen should always be numbered on the spot and the exact locality noted. This can be done on a slip of paper and wrapped up with the specimen ; at the same time the locality and specimen number should be entered both in the note book and on the map. Many a good specimen is rendered worthless by its locality not being recorded at the time of collection.

(iv) the specimen should be trimmed to a convenient size, such as 4″× 3″× 1″, if possible, by using the chisel edge of the hammer.

After the specimens have been brought back from the field they should be prepared for display or for storage in the following manner :—

(*a*) the number of the specimen should be painted in black or white paint at the top right-hand corner, with a distinguishing letter for different types of specimens. For example, rocks can be numbered R. 1, R. 2., R. 3 . . . ., minerals can be M 1, M. 2, M. 3, ..., and fossils F. 1, F. 2, F. 3, . . . This is one possible system but any other would do just as well ;

(*b*) a descriptive card should be prepared for each specimen giving its name, locality, date of collection, and any other details ;

(*c*) the specimen should then be placed in a shallow cardboard tray with the descriptive card affixed to the back of the tray. Sands and other unconsolidated material can be kept either in open trays or in glass bottles ;

(*d*) the labelled specimens can then be kept for display in glass-fronted cupboards or stored in drawers; all specimens must be dusted at regular intervals.

Naming the specimen may present some difficulty to the beginner, but he should be able to describe it, as far as possible, in terms of its structure, mineral composition, and any other visible feature. For example, names like *grey garnet-biotite geneiss, pink granite, garnet-sillimanite schist, white quartz sand,* and *blue lagoonal clay,* are perfectly good names. Alternatively, the specimens, if of reasonable size and fresh, would be readily identified for him by the Geological Survey Department in Colombo. Anyone interested enough in the subject of geology to have read this book so far should, in any case, pay a visit to this Department or to the Colombo Museum, where he will be able to see for himself examples of nearly all the rock types and minerals found in the island.

A representative collection of rocks and minerals of Ceylon suitable for a class or a school science club, is given below:—

A. Crystalline Rocks

Metasediments

1. Quartzite
2. Quartz-feldspar schist
3. Crystalline limestone
4. Calc gneiss or granulite
5. Quartz-feldspar granulite or gneiss
6. Garnet-sillimanite schist or gneiss
7. Garnet-cordierite gneiss.

Gneisses

11. Biotite gneiss
12. Garnet-biotite gneiss
13. Biotite-hornblende gneiss
14. Amphibolite
15. Pink hornblende gneiss
16. Pink biotite gneiss

A. Crystalline Rocks (contd.)

harnockites

8. Acid charnockite
9. Intermediate charnockite
10 Basic charnockite

Intrusives

17. Pink granite
18. Hornblende granite
19. Pegmatite
20. Dolerite
21. Vein quartz

B. Sedimentary Rocks

Jurassic

1. Arkose (feldspathic sandstone)
2. Siltstone
3. Mudstone
3. Mudstone (with fossil plant impressions)

Miocene

4. Jaffna Limestone (with fossils)

Quaternary

5. Littoral sandstone
6. Other sandstone
7. Quartz gravel
8. Dune sand
9. Beach sand
10. Lagoonal clay
11. River alluvium

C. Secondary Formations

1. Laterite
2. Nodular ironstone
3. Chert
4. Kankar
5. Travertine

D. Economic Minerals

1. Graphite
2. Mica
3. Iron ore
4. Gem gravel
5. Gemstones
6. Feldspar
7. Ilmenite sand
8. Monazite sand
9. Garnet sand
10. Kaolin
11. Other clays

E. Other Minerals (preferably crystals)

1. Calcite
2. Feldspar
3. Garnet
4. Magnetite
5. Pyrite
6. Rutile
7. Zircon
8. Thorianite
9. Tourmaline
10. Quartz

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GLOSSARY *

A

Accessory minerals. Minerals that occur in minor amounts in rocks and are not essential to their classification, e. g. *zircon, apatite, magnetite, graphite.*

Acid rock. A light-coloured rock containing more than 65 per cent silica (as free quartz or combined in silicate minerals) and poor in ferromagnesian minerals, e. g. *granite, rhyolite, quartz–feldspar granulite.*

Alluvium. Mud, silt, and sand brought down by a river and deposited on the surrounding plain during periods of flood.

Allanite. A feebly radioactive mineral of the *epidote* group. Hydrated silicate of calcium, cerium, and lanthanum, with a little thorium, but of variable composition. Monoclinic, often **metamict**.

Almandine, Almandite. Reddish-brown garnet with iron and aluminium; common in metamorphic schists and gneisses.

Amphiboles. Family of rock-forming minerals, mainly hydrated aluminium silicates of magnesium, calcium, and iron. Mostly monoclinic. Chief varieties are *hornblende* and *tremolite.*

Amphibolite. Lustrous, black, hornblende-plagioclase schist; formed by regional metamorphism of basic igneous rock or of impure calcareous sediment.

Anticline. A fold in rocks in which the strata dip outwards from the axis; older beds are in the centre.

Antiform. In the form of an anticline but without the implication that the structure is simple and the right way up.

Apatite. $Ca_5(PO_4)_3(Cl,F)$, calcium phosphate with chlorine or fluorine. Hexagonal; blue or green in colour. Common accessory mineral in igneous and metamorphic rocks, particularly in crystalline limestones.

Aquifer. A water-bearing stratum.

Archaean. A term sometimes used to include the crystalline rocks (igneous, metamorphic, or migmatitic) of Pre-Cambrian age.

Arenaceous. Sandy (sediments and sedimentary rocks).

Argillaceous, Clayey (sediments and sedimentary rocks).

Arkose. A coarse-grained sandstone rich in undecomposed or partly decomposed feldspars probably derived from weathered granite. Predominant member of the *Tabbowa Beds.*

Artifact. Implement of flint or chert made by Prehistoric man.

Augen. Lenticular crystals of feldspar or aggregates of quartz and feldspar in metamorphic rocks.

Axis, fold. A term used in many senses. In a loose sense, the line on a map that divides a fold as symmetrically as possible or the trend of the crest of an anticline or trough of a syncline.

Axial plane. The plane that divides a fold symmetrically.

B

Banded. The texture of rocks having thin and nearly parallel bands of different colours minerals, or textures.

Barrier bar, beach. Elongate sand ridge rising slightly above high-tide level, extending generally parallel to the coast and separated from it by a lagoon.

Barytes. $BaSO_4$, barium sulphate. Orthorhombic, whitish rather heavy mineral often found in veins. Principal ore of barium. Sometimes called *barite.*

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* Definitions mainly from *A Dictionary of Geology* by J. Challinor (1961), and *Glossary of Geology and Related Sciences* by the American Geological Institute (1957).

Basalt. An extrusive, fine-grained basic igneous rock, dark in colour, composed of calcic plagioclase, pyroxene, and sometimes olivine; often porphyritic or vesicular in texture. Most abundant type of lava.

Basic rock. A dark-coloured rock withless than 55 per cent. silica (with little or no free quartz) and rich in ferromagnesian minerals like pyroxene, amphibole, mica, and olivine, e.g. *basalt, amphibolite*.

Batholith. A large intrusive body of granitic composition, larger than a stock or a *boss*.

Bed. The smallest division of a stratified series, limited above and below by bedding planes.

Bedrock. Any solid rock exposed at the surface or overlain by unconsolidated material such as soil, sand, and clay.

Beryl. $Be_3Al_2Si_6O_{18}$, beryllium aluminium silicate, generally with small amounts of sodium, lithium, calcium, and water. Hexagonal; green. Occurs mostly in granite pegmatite. Gem varieties are *aquamarine* and *emerald*.

Biotite. $K(MgFe'')_3(AlFe''')Si_3O_{10}(OH)_2$, hydrated potassium-aluminium silicate with iron and magnesium ; member of the *mica* group. Monoclinic, dark brown or green, often black when thick. Common rock-forming mineral.

Block uplift. Vertical uplift of extensive blocks of the crust between large faults.

Boss. A small igneous intrusion, roughly circular in shape.

Breccia. Rock composed of angular blocks and fragments mixed with finer material ; may be of sedimentary origin, or formed by crushing along faults.

C

Calcite. $CaCO_3$, calcium carbonate. Hexagonal-rhombohedral; generally white, sometimes pink. Chief constituent of limestones.

Calcareous. Containing or partly composed of calcium carbonate.

Calc granulite, c. gneiss. An impure, calcareous metamorphic rock containing calcium silicate minerals like *diopside, scapolite, wollastonite;* and *sphene*.

Cataclastic. A texture in metamorphic rocks in which the minerals are crushed and granulated by pressure.

Chalcopyrite. $CuFeS_2$, copper-iron sulphide. Tetragonal. An important ore of copper.

Charnockite. A greenish-grey or bluish-grey rock with a greasy appearance, varying from acid to basic in composition, in which the mineral hypersthene is always present.

Chert. A dense, hard, cryptocrystalline rock containing opal, chalcedony, or quartz, or a mixture of all three. Occurs in many colours and has a tough, splintery to conchoidal fracture.

Chondrodite. $Mg_5(SiO_4)(OH,F)_2$, hydrated magnesium silicate with fluorine. Monoclinic orange-coloured mineral; occurs in some crystalline limestones.

Clastic. Consisting of fragments of rocks and minerals.

Clay. A natural material with plastic properties, composed of particles of very fine, hydrous aluminium or magnesium silicate minerals like *kaolinite* and *montmorillonite*.

Columnar jointing. A type of jointing typically developed in igneous rocks (basalts especially) in which the rocks develop planes of parting which are like columns possessing hexagonal cross sections.

Conglomerate. A cemented sedimentary rock consisting of rounded, water-worn pebbles or boulders more than 2 mm. in diameter.

Conchoidal. The shell-like form of surface produced by the fracture of a brittle substance.

Continental deposit. Sedimentary deposit laid down within a landmass by water or by wind, as distinct from *marine deposits* laid down in the sea.

Cross bedding. The arrangement of laminations of strata transverse or oblique to the main planes of stratification of the strata concerned. Also known as *current bedding* and *false bedding*.

Crystalline limestone. A metamorphosed limestone; when pure known as *marble*.

D

Delta. A triangular-shaped alluvial deposit formed either within the sea or a lake at the mouth of a river.

Detrital matter (detritus). Fragments of minerals or rocks produced by the weathering and disintegration of rocks.

Diopside. $CaMgSi_2O_6$, a calcium-rich pyroxene. Orthorhombic; green. Common in crystalline limestones and calc gneisses.

Dip. (a) The degree of inclination of an inclined plane from the horizontal; (b) the direction of true dip.

Dolerite. A medium-grained basic igneous rock of the same composition as basalt and gabbro, composed essentially of plagioclase, pyroxene, olivine, and magnetite. Occurs commonly as dykes.

Dolomite. $CaCO_3.MgCO_3$, calcium-magnesium carbonate. Hexagonal-rhombohedral; whitish. Occurs in dolomitic limestones.

Dune. A mound or ridge of blown sand, commonly crescentic or linear in shape.

Dyke. A wall-like or tabular body of intrusive rock, cutting across stratified or massive rocks and generally vertical or highly inclined.

Dyke swarm. A set of dykes, either parallel or radially disposed.

E

Earthquake. Gentle or violent vibrations at the earth's surface caused by the sudden displacement of rocks at depth, normally along a fault plane.

Escarpment. Any line of cliffs or steep slopes breaking the continuity of a surface.

Estuary. That portion of a river or stream which is influenced by the tides of the sea.

Exfoliation. The breaking off or peeling off of concentric layers of bare rock surfaces by the action of physical changes combined with some chemical action.

Extrusion (extrusive rock). The outpouring of magnatic material such as lava at the earth's surface; rock formed by the solidification of such material.

F

Fault. A fracture in the earth's crust along which there has been relative movement, the displacement of the two sides being either vertical, or lateral, or both, and extending for a few inches or for many miles.

Feldspar. A group of common rock-forming minerals, aluminium silicates with potassium, sodium, calcium, and sometimes barium. Varieties include *orthoclase, microcline, plagioclase*, and *anorthoclase*.

Ferruginous. Containing a large proportion of iron compounds; generally rusty coloured.

Ferricrete. A near-surface crust of material cemented together with iron oxide.

Ferromagnesian minerals. A general term for the dark-coloured silicate minerals rich in iron and magnesium, e.g. *olivine, pyroxene, amphibole, mica.*

Fissure. An extensive fracture or crack in the rocks, generally larger than a joint.

Flint. A special variety of chert, generally occurring as nodules.

Flinty crush rock. A black, flint-like product of dynamic metamorphism; a partly-fused variety of *mylonite.* Also known as *pseudo-tachylyte.*

Flood plain. The flat portion of a river valley adjacent to the river channel that has been built up by sediments laid down by intermittent floods.

Flow structure. A structure in igneous rocks in which the flow of the magma is indicated by layers of different composition or by the orientation of elongate minerals.

Fluvial. Of or pertaining to rivers.

Fold. A bend in stratified rocks.

Foliation. The layered arrangement of minerals such as mica in metamorphic rocks.

Foraminifera. Unicellular animals (or Protozoa), mostly of microscopic size, possessing chambered shells made up of calcium carbonate or of sand grains cemented together.

Formation. An assemblage of rock strata possessing common characteristics, chiefly lithological.

Fossil. The remains, impression, or trace in the rocks of animals or plants.

G

Galena. PbS, sulphide of lead. Cubic ; grey, heavy mineral with a metallic lustre. Principal ore of lead.

Gangue minerals. The non-valuable minerals like calcite and quartz that are often associated with ore in veins.

Garnet. A group of minerals, silicates of aluminium, iron, magnesium, calcium, and chromiums Cubic; red, brown, or green in colour. Occur mainly in metamorphic rocks. Varietie. are *almandite*, *pyrope*, *spessartite*, *andradite* and *grossularite*.

Gasteropoda. One of the three chief classes of the phylum *Mollusca* having asymmetrically coiled shells but without internal chambers, e.g. the common garden snail *Helix*.

Geochemistry. The study of (a) the relative and absolute abundance of the elements in the earth, and (b) the chemical reactions and movements of elements in the earth (crust, hydrosphere, atmosphere) during geological processes.

Geochemical prospecting. The search for hidden deposits of metallic ores by examining the chemical properties of rocks, soils, surface waters, and vegetation for abnormal concentrations of metals.

Geomorphology. The study of the character, origin, and evolution of the surface features of the earth.

Geophysics. The study of the physical state of all parts of the earth from the core to the atmosphere, and of the physics and mechanics of geological processes.

Geophysical prospecting. The art of searching for concealed deposits of useful minerals by physical measurements from the earth's surface; these include seismic or electrical phenomena, the gravitational or magnetic fields of the earth, and thermal distribution.

Geosyncline. An elongate trough or basin subsiding for a considerable length of time in which a thick succession of sediments and some volcanic rocks accumulates. Generally located adjacent to a landmass from which the sediments are derived.

Gneiss. A coarse-grained, foliated or banded crystalline rock, usually of metamorphic origin. Varieties include *banded gneiss*, *veined g.*, *streaky g.*, *augen g.*, *granitic g.*

Gneissic structure. The coarse foliation or banding characteristic of gneisses.

Goethite. FeO(OH), hydrous iron oxide. Orthorhombic. Most *limonite* is impure goethite.

Gondwanaland. An ancient continent, believed to have consisted of parts of present-day India, Australia, Antarctica, South Africa, Madagascar, and South America, which broke up at the end of the Mesozoic Period to give the present distribution of these landmasses.

Gondwana System. A series of strata, mostly sandstones and shales, containing abundant plant fossils and extending from the Carboniferous to the Cretaceous, laid down within Gondwanaland. The term is strictly applied to the rocks of India, but broadly includes equivalents outside it, particularly the Karoo System of Africa. Thickness of the Gondwana System varies from 20,000 to 30,000 feet.

Gorge. A narrow, steep-sided river valley, often in solid rock.

Grade of metamorphism. The degree to which rocks have been subjected to metamorphic-agents such as temperature and pressure.

Granite. A coarse-grained, acid, plutonic rock consisting essentially of quartz, orthoclase feldspar, and mica.

Granitic gneiss, granite gneiss. A coarsely crystalline rock of banded or streaky appearance and granitic composition, generally of metamorphic origin.

Granulite. A metamorphic rock composed of even-sized, interlocking granular minerals generally formed under high grade metamorphic conditions.

Graphite. C, native carbon. Hexagonal; black to steel grey, soft. Also known as *plumbago*.

Gravel. Loose, detrital material, composed chiefly of small, rounded pebbles mixed with sand and clay.

Grikes. Narrow ridges formed on the surface of limestone by weathering along joints.

Grit. A sandstone composed of coarse, angular grains and small pebbles, and with a rough surface.

Gypsum. $CaSO_4.2H_20$, hydrated calcium sulphate. Monoclinic ; soft, white mineral occurring chiefly as an evaporite. Varieties are *selenite, alabaster, satinspar.*

H

Haematite. Fe_2O_3, a reddish-brown iron oxide with a metallic lustre and red streak. Hexagonal-rhombohedral. Chief ore of iron.

Heavy minerals. The accessory detrital minerals with densities more than 4.0, e.g. *ilmenite rutile, zircon.*

Highland Series. One of the two major crystalline rock systems of Ceylon, the other being the *Vijayan Series.* Made up chiefly of the Khondalite Group of metasediments and of charnockites.

Hornblende. The chief mineral of the *amphibole* group. Monoclinic. Common rock-forming mineral.

Hot spring. A thermal spring in which the temperature of the water is higher than body temperature (98°F).

Hydrology. The science that relates to the water of the earth.

Hydrogeology. The geology of underground water supplies.

Hydrothermal. Pertaining to magmatic emanations rich in hot water or steam.

Hypersthene. An orthorhombic *pyroxene* ; characteristic mineral of charnockites.

I

Igneous rock. A rock resulting from the solidification of molten or partially molten magma.

Illam. Gem-bearing gravel.

Ilmenite. $FeTiO_3$, oxide of iron and titanium. Hexagonal ; black, opaque mineral. The principal ore of titanium.

Impermeable. Having a texture that will not permit water to pass through it. Also *impervious.*

In situ. In place. Implies that a visible rock is part of a larger rock mass outcropping at a particular point, and not a loose block brought there from some distance away.

Incised meander. A river meander that has cut deep into the flood plain so that the river, flows in a winding gorge.

Inclined fold. A fold in which the axial plane is not vertical.

Intrusion, intrusive rock. A body of rock that invades pre-existing rocks.

Invertebrates. Animals without backbones or spinal columns.

Ironstone. A rock composed essentially of iron compounds. Commonly a sedimentary rock but also a secondary deposit formed by chemical action, e.g. *nodular ironstone.*

Isoclinal fold. A fold in which the limbs have parallel dips ; may be vertical, overturned, or recumbent.

Isotopic age. Age of a mineral or rock determined by the ratio of the daughter element to the parent radioactive element within the mineral or rock, using known rates of decay.

J

Joint. A fracture or parting in rocks along which there has been no displacement ; generally occurs in one or more parallel sets.

K

Kabook. see *Laterite.*

Kankar. Nodular calcium carbonate, white or creamy in colour, occurring below the surface in soils of dry regions.

Kaolin. Clay produced by the weathering of feldspars in feldspar-rich rocks like pegmatite and granite ; composed mainly of *kaolinite*, a hydrated silicate of aluminium. Also known as *china clay.*

Khondalite Group. A group of metamorphosed sediments, including quartzites, crystalline limestones, garnet-sillimanite rocks, and graphite-bearing schists, which form part of the Pre-Cambrian Highland Series of Ceylon. Earlier known as the Khondalite Series.

L

Lacustrine deposits. Material deposited in lakes, generally by rivers, and often containing organic constituents of freshwater or terrestrial origin.

Lamellibranchiata. One of the chief classes of the phylum Mollusca, having a shell of two hinged valves, with beaks. Also known as *Pelecypoda.*

Lamina (pl-ae). A thin separable layer in stratified rocks, generally less than 1 cm. thick.

Laterite. A reddish weathering product of many rock types in wet tropical regions, resulting from the leaching out of silica, alkali and alkaline earths and the concentration of hydrated oxides of iron and aluminium ; hardens on exposure to air. Known in Ceylon as *kabook.*

Laurasia. A hypothetical landmass of the northern hemisphere which is thought to have broken up at the end of Carboniferous times to give the present northern continents.

Lava. Igneous magma extruded through volcanoes and fissures. Also the rock formed as a result of its solidification.

Limestone. A bedded sedimentary rock consisting chiefly of calcium or magnesium carbonate e.g. the *Jaffna Limestone.*

Limonite. A general term for brown, hydrous iron oxide, consisting mainly of *goethite.*

Lineation. A descriptive term for any kind of linear structure within or on a rock.

Lithology. The general character of a rock, particularly as seen in field exposures and hand specimens, including its mineral composition, texture, and structures.

Lithomarge. An iron-rich clayey weathering product, generally in shades of red, brown or yellow.

Littoral. Belonging to the shore, between tide marks.

Loess. An accumulation of wind-borne dust, yellowish in colour, and derived from desert, and glacial deposits.

M

Macroscopic. Rock characters that can be seen with the naked eye, in contrast to those seen with a microscope.

Magma. Molten rock material ; a silicate melt, with or without solid particles, occurring within the earth's crust or poured out on the surface.

Magnesite. $MgCO_3$, magnesium carbonate. Hexagonal-rhombohedral ; white, usually massive to compact and earthy.

Magnetite. Fe_3O_4, magnetic iron oxide. Cubic, octahedral ; black. Important ore of iron and common accessory mineral in rocks.

Mantle. The layer between the crust and the core of the earth ; thought to be ultrabasic in composition, and either crystalline or vitreous.

Marble. A rather pure, metamorphosed limestone.

Marine deposit. Material laid down in the sea, as distinct from a *continental* deposit.

Marl. A calcareous clay.

Metamict. A term for minerals that have lost their crystalline structure and become amorphous owing to molecular rearrangement caused by radioactive emanations from such elements as thorium, uranium, or zirconium contained in them.

Metamorphism. The mineralogical and structural changes in solid rocks that take place in response to physical and chemical conditions different from those under which they were originally formed.

Metamorphic rocks. Rocks formed in the solid state in response to pronounced changes of temperature, pressure, and chemical environment.

Metasediments. Metamorphosed sedimentary rocks.

Mica. Family of rock-forming minerals, silicates of aluminium and potassium with magnesium and iron, all with hydroxyl (OH). Monoclinic, with perfect cleavage, splitting into thin elastic sheets. Varieties, *biotite*, *muscovite*, *phlogopite*.

Microcline. $KAlSi_3O_8$, a potassium feldspar. Triclinic ; white, pink. Common mineral in granitic rocks, e.g. Tonigala Complex.

Migmatite. Used loosely for a gneissic rock of mixed appearance in which a granitic component is usually present.

Mineral. A solid inorganic substance having a definite homogeneous chemical composition, and occurring naturally in the earth.

Mohorovičić Discontinuity. The boundary between the crust and the mantle of the earth. at which there is a sudden increase downwards in the velocities and regularity of seismic waves ; situated about 35 km. below the continents and about 10 km. below the oceans Also known as the ' Moho '.

Molybdenite. MoS_2, sulphide of molybdenum. Chief ore of molybdenum.

Monadnock. An isolated residual rock, hill, or mountain standing above a peneplain and as yet not worn down to the general level of the plain ; an erosion remnant.

Monazite. $(Ce,La)PO_4$, cerium of the rare earths cerium, yttrium, and lanthanum, and commonly containing some thorium. Monoclinic. Chief ore of rare earths and of thorium ; Ceylon monazite has about 9 per cent ThO_2.

Moonstone. A semi-precious variety of feldspar (orthoclase, albite, or labradorite), commonly transparent or translucent, which exhibits a delicate, pearly, opalescent play of colours.

Mudstone. A hardened mud or clay ; an indurated argillaceous rock. One of the three chief classes of sedimentary rocks, the others being *sandstone* and *limestone*.

Muscovite. $KAl_2(AlSi_3)O_{10}(OH)_2$, potassium mica.

Mylonite. A very fine-grained and often banded rock resulting from the small-scale grinding down of rocks during movement along fault planes. Also *flinty crush rock*.

N

Neolithic. The later (New) or polished Stone Age, a period characterised by beautiful weapons and instruments made of flint and other kinds of stones. Roughly equal to the Recent and extending from about 10,000 to 4,000 years ago.

Nodule. A general term for a rounded concretionary body which can be separated as a discrete mass from the formation in which it occurs.

Nose. The plunging end of a fold as seen in plan on the ground.

Normal fault. A fault in which the inclination of the fault plane is steep and dips to the downthrow side ; includes vertical faults.

O

Olivine. $(Mg,Fe)_2SiO_4$, magnesium-iron silicate. Orthorhombic ; olive green–mineral. Important constituent of ultrabasic and basic rocks and of crystalline limestones. Gem variety, *peridot*.

Open fold. A fold in which the limbs diverge at a large angle.

Open-cast mining. Mining of the surface after removal of superficial cover, as distinct from *underground mining*.

Ore. A mineral from which a metal or non-metal can be mined and extracted with profit.

Orogeny. The processes of mountain building brought about by compressive forces in the earth's crust.

Orthoclase. $KAlSi_3O_8$, a potassium feldspar. Monoclinic; white or pink in colour. Commonly present in granites and other acid igneous rocks.

Outlier. An outcrop of a newer rock surrounded by older rocks.

Overturned fold. A fold in which the steeper limb is overturned beyond the vertical.

P

Palaeogeography. The historical reconstruction of the physical geography of past geological ages.

Palaeontology. The science of the life of past geological ages as revealed by fossils.

Patanas. Rolling grasslands.

Peat. A superficial accumulation of partially decomposed vegetable matter, dark brown to black in colour ; used as low-grade fuel.

Pegmatite. A very coarse-grained acid rock of granitic composition, made up chiefly of quartz and feldspar, and occurring as dykes, veins, and irregularly shaped patches.

Peneplain. A nearly flat surface of country produced by long periods of subaerial erosion ' almost a plain '.

Percolation. The movement, under hydrostatic pressure, of water through the interstices of a rock or soil, but not movements through large openings like caves. Generally used for the movement of rain water downwards from the surface.

Permeability. The capacity of a rock to transmit fluids, depending on the size and shape of the pores and on the number and nature of interconnections. Also *perviousness.*

Petrology. A general term for the study, by all available methods, of the natural history of rocks, including their origins, present conditions, alterations, and decay. *Petrography* and *petrogenesis* are branches of petrology.

Phlogopite. A member of the mica group with magnesium and iron. Common in crystalline limestones.

Photogeology. Geological interpretation through aerial photographs.

Photomicrograph. Photograph of an enlarged object as seen through a microscope.

Placer deposit. A deposit of gravel, sand, or similar material containing valuable minerals like gold, tin, or gemstones, brought about by the weathering and erosion of rock masses and veins.

Plagioclase. A mineral group of aluminium silicates with sodium and calcium, ranging from *albite* to *anorthite.* Triclinic. One of the commonest rock-forming minerals.

Plastic deformation. A permanent change in shape of a solid that does not involve failure by rupture.

Plateau. An elevated area of comparatively flat land usually bounded by abrupt slopes.

Plumbago. see *Graphite.*

Pleistocene. The earlier of the two epochs comprising the Quaternary Period ; from about 1 million years ago.

Plutonic rocks. Rocks formed deep in the earth's crust usually by the action of heat ; include igneous, migmatitic, and some metamorphic rocks.

Poikilitic. A texture in igneous rocks in which small granular crystals are scattered within larger crystals of another mineral.

Poikiloblastic. ' Poikilitic ' texture in metamorphic rocks.

Porosity. The ratio of the aggregate volume of interstices in a rock or soil to its total volume ; usually expressed as a percentage.

Porphyritic. A texture in igneous rocks in which large crystals (or phenocrysts) are set in a finer groundmass (or matrix) which may be crystalline or glassy.

Porphyroblastic. ' Porphyritic ' texture in metamorphic rocks.

Pre-Cambrian. All rocks formed before the Cambrion and found below rocks of that age ; generally subdivided into *Early Pre-Cambrian* (formerly Archaean) and *Late Pre-Cambrian* (or Proterozoic) ; lasted from about 4,500 to 600 million years ago.

Pumice. Cellular or sponge-like glassy lava, generally of acidic composition, and extremely light in weight due to the large amount of pore space.

Pyrite. FeS_2, iron sulphide. Cubic; brassy yellow mineral with a metallic lustre, and sometimes known as 'fool's gold'. An important ore of sulphur.

Pyroxene. A family of minerals, silicates of magnesium, calcium, and iron. Orthorhombic and monoclinic. Varieties are *augite, enstatite, hypersthene, diopside, aegirine.*

Pyrrhotite. Magnetic *pyrites.* Hexagonal. Occurs usually as brown to reddish-brown masses.

Q

Quartz. SiO_2, crystalline silica or oxide of silicon. Hexagonal. Hard, glassy-looking mineral, one of the commonest rock-forming mineral of all types of rocks. Coloured varieties are semi-precious gemstones, e.g. *citrine* (yellow), *cairngorm* (smoky or brown), *amethyst* (purple), *rose quartz* (pink).

Quartzite. A metamorphosed sandstone consisting of an interlocking mosaic of quartz crystals.

Quaternary. The youngest half of the Cainozoic Era, including all deposits from the end of the *Tertiary* (that is, the *Pliocene*) to the present day. Made up of *Pleistocene* and *Recent.*

R

Radio-active mineral. A mineral containing an element (e.g. thorium, uranium) which changes into another (daughter) element by the emission of charged particles from its nucleus

Raised beach. An old beach occurring above and separated from the present beach, due to a rise of the land or to a fall in mean sea level.

Rare-earth minerals. Minerals containing one or more of the 'rare' elements thorium, cerium, lanthanum, yttrium, tantalum, niobium, etc. Examples, *monazite, fergusonite, baddelyite, thorite, thorianite, allanite.*

Recumbent fold. A fold in which the axial plane is almost horizontal.

Recent. The last 10,000 years after the *Pleistocene.*

Reef. A ridge of rock at or just above or below the water.

Refractory clay. A clay that can resist the action of heat and chemical reagents.

Regional metamorphism. Metamorphism affecting the rocks of a large region collectively and caused largely by high temperature.

Regression. Withdrawal of the sea.

Relic structure. An original structure that has remained unchanged in a metamorphic rock.

Retrograde metamorphism. The reversal of mineralogical changes that had occurred previously during metamorphism of a rock.

Reversed fault. A fault in which the hanging wall has been raised relative to the footwall.

Rift valley. A valley or depression caused by subsidence of the region between two more or less parallel faults.

Ripple mark. An undulating surface structure produced in loose granular material by wind, wave action or currents. Fossil ripple marks are sometimes preserved in ancient sediments like sandstones and even in metamorphosed rocks like quartzites.

Rock. An aggregate of minerals formed by natural processes.

S

Sandstone. A compacted or consolidated quartz sand. Varieties of sandstone are distinguished by mineral content (*feldspathic sandstone*) or by cementing material (e.g. *calcareons s., ferruginous s.*)

Scapolite. A group of minerals, aluminium silicates of calcium and sodium with chlorine. Tetragonal; white or grey in colour. Generally occurs in impure metamorphosed limestones and calc granulites.

Schist. A medium-grained metamorphic rock with fine-scale foliation resulting from parallel to sub-parallel orientation of lamellar minerals, most commonly the micas.

Scree. Accumulation of rock waste either at the foot of a cliff (=*talus*) or on hill slopes.

Section. A vertical exposure of rock strata, or the representation of such on paper.

Sedimentary rocks. Rocks formed by accumulation of material in water or from the air, generally stratified and deposited in a flat attitude.

Serpentine. A greenish magnesium silicate with hydroxyl (OH) resulting from the hydration of magnesium-rich minerals like olivine, pyroxene, and amphibole.

Shale. A fine-grained, laminated, clayey rock; laminated mudstone.

Sial. The upper, lighter layer of the earth's crust, essentially granitic in composition, underlying continents but absent or thin in oceanic regions.

Silica. SiO_2, silicon dioxide. In its natural crystalline form occurs as the minerals *quartz*, *tridymite*, and *cristobalite;* semi-crystalline and non-crystalline forms are *chalcedony* and *opal*.

Silicate. A chemical compound of silica with one or more metallic oxides.

Sillimanite. Al_2SiO_5, aluminium silicate. Orthorhombic; colourless, needle-like crystals. A metamorphic mineral formed at high temperatures.

Sima. The lower, denser, basic to ultrabasic layer of the earth's crust underlying the sial in continents and forming the floors of the oceans.

Sinkhole. A funnel-shaped hollow developed in limestone regions by solution.

Silt. Material of which the average grain size lies between sand and clay.

Siltstone. A fine-grained, indurated, clastic rock composed essentially of particles of silt grade.

Slate. A fine-grained, indurated metamorphic rock that splits into thin plates.

Sphene. $CaTiSiO_5$, calcium titanium silicate. Monoclinic; brown, wedge-shaped mineral with an adamantine lustre. Common accessory mineral in impure crystalline limestones and amphibolites.

Spinel. A mineral group, oxides of iron, magnesium, zinc, aluminium, manganese, and chromium. Cubic, octahedral; varied colours. Also name of mineral of the group, $(Mg, Fe)Al_2O_4$, a gemstone.

Stalactite. A column of crystalline calcium carbonate hanging from the floor of a limestone cavern.

Stalagmite. A column of crystalline calcium carbonate rising from the floor of a limestone cavern, formed by water charged with calcium carbonate dripping from stalactites above.

Stone Age. A period during which Early Man lived and made implements of stone (chert and flint), such artifacts being evidence of his existence and habits; divided into the Old Stone Age or *Palaeolithic* (which lasted through the Pleistocene) and the New Stone Age or *Neolithic* (lasting through the Recent). The Stone Age was succeeded by the Bronze Age which began about 4,000 years ago.

Stratification. A structure produced by the deposition of sediments in beds or layers (strata), laminae, lenses, wedges, and essentially tabular units.

Stratigraphy. The study of the formation, composition, sequence, evolution, and correlation of the stratified rocks of the earth's crust.

Stratum (pl.–**a**) A layer of approximately the same kind of rock.

Strike. The direction at any point on a surface (particularly a bedding plane) of a horizontal line drawn on the surface through that point; the strike is at right angles to the direction of true dip at the point. Also the bearing of an outcrop on a level surface.

Structure. The relation of the component parts of a rock, rock mass, or region of the crust to each other.

Submarine valley (canyon). An elongated steep-walled cleft running across the continental shelf and slope.

Syncline. A fold in rocks in which the strata dip inwards from both sides towards the axis; younger beds are in the centre.

Synform. The synclinal arrangement of strata, but without the implication that the structure is simple and the right way up.

System. A standard, world-wide division containing rocks formed during a fundamental chronological unit or period, e.g. *Jurassic System*, *Devonian System*.

T

Talus. see *Scree.*

Taprobanian. The earth movements responsible for the folding of the Highland Series of Ceylon; also the folds themselves. Term introduced by Ananda Coomaraswamy in 1906, after ' Taprobane ', an old name for Ceylon.

Tear fault. A fault, usually steeply inclined, in which the movement has been horizontal or nearly so.

Tectonic. Structural, belonging to the structure of the earth's crust.

Terrace. A horizontal or gently inclined bench-like step, often long and narrow, bounded by steep slopes or escarpments.

Tertiary. The earlier part of the Cenozoic Period, comprising the *Palaeocene, Eocene, Oligocene, Miocene,* and *Pliocene.* Also a term for the rocks deposited in that time, e.g. Tertiary lavas.

Tethys. The long east-west extending sea of Mesozoic (pre-Tertiary) times which separated Europe and Africa, and extended across southern Asia; it formed the geosyncline out of which the present Alpine-Himalayan system of mountain ranges was formed.

Texture. The geometrical aspects (e.g. size, shape, arrangement) of the component particles of a rock. See *porphyritic, poikilitic.* etc.

Thermal metamorphism. Metamorphism in which heat is the principal agent causing reconstitution.

Thorianite. ThO_2, thorium dioxide. Cubic; heavy, black mineral first found in Ceylon. Commonly contains some uranium.

Thorite. $ThSiO_4$, thorium silicate. Tetragonal; brownish, flat mineral, commonly altered and metamict.

Thrust. A reverse fault in which the fault plane is nearly horizontal.

Topaz. $Al_2SiO_4(F,OH)_2$, a hydrated silicate of aluminium. Orthorhombic. A gemstone.

Tourmaline. A complex borosilicate of sodium, lithium, mangesium, iron and aluminium commonly found in granitic pegmatites. Hexagonal-rhombohedral; various colours. Delicately coloured varieties are gemstones.

Transverse coastline. A coastline in which the strike of the rocks is at right angles or oblique to the trend of the coast, thus resulting in numerous headlands and bays.

Travertine. Hard, compact calcium carbonate, creamy coloured, deposited from solution by springs or percolating water.

Turtle back. A long, low, bare rock mound, formed as a result of exfoliation.

U

Ultrabasic rock. A rock composed almost entirely of ferromagnesian minerals (e.g. olivine, pyroxene, amphibole), with practically no quartz or feldspar.

Unconformity. A surface of erosion or non-deposition that separates younger strata from older rocks; such sets of strata are said to be unconformable.

Uniformitarianism. The concept that geological processes have been, on the whole, of much the same intensity throughout geological time; in other words that ' the present is the key to the past '.

V

Vein. A relatively thin, tabular concentrate of rock (e.g. quartz vein or pegmatite), or of one or more ore minerals (e.g. graphite vein) between definite boundaries; usually fills fissures and cracks in the country rocks.

Vertebrata. Animals having an internal skeleton of vertebrae, that is, a backbone, to which are usually attached two pairs of skeletonised limbs.

Vesicular texture. Containing many small cavities, generally formed by expansion of bubbles of gas or steam trapped in a rock during solidification; common in volcanic rocks.

Vijayan Series (of Ceylon). A heterogeneous group of gneisses, migmatites, and granites with scattered metasedimentary bands, thought to have resulted from the further metamorphism of the Highland Series, and therefore to have formed at a later stage than the latter. Rocks of the Vijayan Series outcrop on either side of the Highland Series.

Volcano. An opening (or vent) in the earth's crust through which molten lava, pyroclastics, volcanic gases etc. issue, ultimately building a conical hill around the opening.

W

Water table. The upper surface of the zone of saturation below the surface, except where that surface is formed by an impermeable layer.

Way-up. Strata are said to be the 'right' way up if the present upward succession is the original order of deposition, the older beds being below the younger. If the opposite is true and the older beds are above the younger, the strata are said to be 'inverted'.

Weathering. The breakdown of solid rocks into soil by mechanical disintegration, solution and chemical decay, brought about by exposure to the atmosphere.

Wollastonite. $CaSiO_3$, calcium silicate. Triclinic ; a white, silky, fibrous mineral. Commonly formed in contact metamorphosed limestones.

Z

Zircon. $ZrSiO_4$, zirconium silicate. Tetragonal; brown. Common accessory mineral in rocks and constituent of many beach mineral sands. Principal ore of zirconium. Gem varieties are *jargon* and *hyacinth*.

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