COMMONWEALTH OF AUSTRALIA.

DEPARTMENT OF NATIONAL DEVELOPMENT.

BUREAU OF MINERAL RESOURCES GEOLOGY AND GEOPHYSICS.

RECORDS.

1960/35

AN OUTLINE OF THE GEOLOGY OF AUSTRALIA

by

L.C. Noakes.

AN OUTLINE OF THE GEOLOGY OF AUSTRALIA

by

L. C. NOAKES

With Palaeontological Notes

by

E.M. Smith, J.M. Dickins, G.A. Thomas and D.J. Belford

Record 1960/35

(Commentary prepared for the Geological Map of Australia, Atlas of Australian Resources)

INTRODUCTION

Rocks may be divided into three broad categories: sedimentary, igneous, and metamorphic. Sedimentary rocks such as sandstone, shale, and limestone were laid down in seas or freshwater lakes as sediments which later consolidated. Igneous rocks originated in the depths of the earth; they were pushed up in a molten or semi-molten condition, through the sedimentary and igneous rocks forming the crust of the earth to produce lava flows on the surface, such as basalt and rhyolite, or to cool within the crust as intrusive igneous masses, such as granitic rocks, porphyry and serpentine The third category, the metamorphic or altered rocks such as phyllite, schist and gneiss, comprises rocks which originated as sedimentary or igneous rocks, but whose original character has been changed by heat and pressure within the crust.

The classification of rocks on the accompanying map is two-fold. Sedimentary rocks and most metamorphic and extrusive igneous rocks are grouped according to geological age. Intrusive igneous rocks, which formed masses within the crust and were subsequently exposed at the surface by erosion, are shown separately in distinctive colours; an indication of geological age is provided by letter symbols or in the text of the legend.

The geological ages used here and for the map this commentary accompanies are those of the standard geological time-scale shown in Table I; the names of the various time divisions have been derived from Greek or Latin roots or from localities where rocks of the particular age were studied or first identified during early geological work. The accepted chronological order of the various Periods is the result of more than a century of work and was determined by studying the fossil remains of life found in sedimentary rocks, by observing the chronological order of fossiliferous strata indicated by superposition and then combining all these observations to trace the development of life itself. The 'Period' is the basic time-unit in the scale corresponding to the "System" (Permian System, etc.) - the basic subdivision of strata (rocks).

The determination of the age in years ("absolute age") of the various time divisions results from the development, during the present century, of methods of measuring the radioactivity of minerals within the rocks; because radioactive elements disintegrate at a constant rate to give a known series of decay products, it is possible by careful analyses of some radioactive minerals in rocks to determine the extent of decay and hence the time in millions of years which has elapsed since the mineral was formed in the crust. These methods are constantly being improved and the "absolute" time scale reviewed and adjusted; that given in Table I will doubtless be amended soon, particularly for the Precambrian, in which absolute ages are tentative only.

Until recently, Precambrian time had to be subdivided by comparing the lithologies and degree of alteration of rocks in different areas, because fossil remains are neither numerous nor definite enough to make a good basis for a time-scale. Radioactive minerals are now replacing these shaky criteria, and a more rational Precambrian time-scale is being built up throughout the world.

This summary of the geology of Australia follows the chronological divisions shown in Table I and on the map and is essentially a brief geological history of the continent from about 3,000 million years ago to the present. The growth of the continent is traced through successive periods by deducing the changing distribution of land and sea and the progression of earth movements and of igneous activity which together built up the land as we see it today. Only brief reference to mineral deposits is made because these are the subject of another map and commentary in this series.

Widespread Quaternary unconsolidated deposits are shown on the map in the central portions of the continent; and they are in fact equally well developed in Western Australia; but this portion of the map was compiled from regional maps which show 'solid' geology only, and omit unconsolidated surface deposits.

PRECAMBRIAN

Precambrian rocks in Australia are commonly divided into Archaean (or Archaeozoic - 'first life') and Proterozoic ('early life') following overseas practice. These divisions are best regarded as Eras within which Periods and Systems will in time be defined.

There are in fact three recognizable divisions within the Australian Precambrian, although geologists differ in their definition in terms of 'Archaean' and 'Proterozoic'. The common practice in eastern Australia is to divide the Proterozoic into 'Upper' and 'Lower' to embrace two of the three divisions. Geologists in Western Australia and South Australia reserve Proterozoic for the younger division only (Nullagine and Adelaide Systems) and place older divisions in Upper and Lower Archaean. Eastern Australian practice is followed in this commentary.

The history of the Precambrian, which accounts for some 5/6ths of the whole of geological time, is largely obscure because the sequence of rocks and of events is difficult to establish. Studies by astronomers suggest that the earth came into existence about 4,500 million years ago and has probably been cooling down from that time. However, the oldest rocks established by reliable radioactive dating are about 3,000 million years old so that the state of the earth between about 4,500 million and 3,000 million years ago is entirely conjectural.

The rocks of the Archaean Era, from more than 3,000 million years to perhaps 2,000 million years ago, include some recognizable but altered (metamorphosed) sedimentary rocks, lavas, and many other types of igneous rocks. But the geological history is very obscure; indeed it is not certain that the geological processes controlling the formation of these early rocks were entirely the same as those which have clearly operated since: the crust of the earth in Archaean time may have been thinner and hotter than it has since become.

The record of Proterozoic rocks is more understandable than that of earlier times; the grade (or degree) of metamorphism is less and deposition of normal sediments in troughs and basins by recognized geological processes can be more easily traced. However, the interval of time in the Proterozoic is too long and the events are too obscure to indicate the changing pattern of land and sea in Proterozoic time on a palaeogeographic map. The probable distribution of the three divisions of the Precambrian is shown on the geological map.

Outcrops of Precambrian rocks are widespread in Western Australia, South Australia, and the Northern Territory; this great area of Precambrian rocks is loosely referred to as the Australian Precambrian Shield; it extends into western and north-eastern Queensland and into western New South Wales. Areas between outcrops of these old rocks are occupied by a thin cover of younger sedimentary rocks, sand, or alluvium, or by thicker sediments deposited in basin-like depressions in the Precambrian basement; the names of these various basins, which are of particular interest in the search for oil and water, appear on Plate 1.

The history of the Precambrian is essentially that of the growth and consolidation of this Shield, which has been fairly stable since the end of Precambrian time.

The original distribution of Archaean rocks can only be conjectured; they probably extended eastward from the known outcrops, perhaps to form an Archaean "continent". The principal process in the consolidation of the Shield may have been a repeated breaking up of the crust into huge blocks and the deposition of new sediments in the troughs and basins formed over sunken blocks. This process can be deduced from the record of Proterozoic rocks, which filled troughs and basins between older blocks and were folded and consolidated by subsequent movements; the process was virtually complete by the end of the Proterozoic.

Archaean

Rocks considered to be definitely of Archaean age, particularly well exposed in Western Australia, are everywhere severely folded and compressed. The most representative rock types are "schist" and "gneiss" - metamorphic rocks in which compression has so oriented the mineral constituents in an altered sediment as to give a parallel or platy structure which may have no relationship to original bedding. This structure is termed 'foliation': rocks showing marked foliation, with platy minerals visible, are called schist; rocks in which specific minerals have been concentrated into distinguishable bands parallel to the foliation are called gneiss. Schist and gneiss can be formed from either sedimentary or igneous rocks and in many places their origin is obscure.

Slate, quartzite, and volcanic rocks are also found in the Archaean; "greenstones", altered basic lava flows, are prominent in Archaean sequences in the Kalgoorlie and Pilbara Goldfields of Western Australia. The iron-ore beds of the Middleback Ranges in South Australia are currently shown as Archaean, although they may well be Lower Porterozoic.

Some belts of folded metamorphic rocks in Western Australia and the Northern Territory, labelled A/B on the map, appear to be similar to Archaean rocks, but could as well be of Lower Proterozoic age.

Proterozoic

Lower Proterozoic rocks are at present best known in the Northern Territory and western Queensland; rocks of the same general age are probably represented in some areas shown as A or A/B in South Australia and Western Australia. In most places these rocks occur in fairly well defined belts and include many little-altered sediments like sandstone, greywacke(1), shale, and limestone, deposited in 'geosynclines'(2); but some have been metamorphosed and resemble Archaean rocks. The rocks have been folded to varying degrees, but in general are much less deformed than Archaean rocks.

In general, Upper Proterozoic rocks provide a marked contrast to the older Precambrian; they consist mainly of unaltered sediments and lavas deposited in broad basins within the older rocks; they have been little folded, and in many places rest almost horizontally on steeply-dipping older beds. This applies particularly to Western Australia and to the Northern Territory where consolidation of the Shield was well advanced in Upper Proterozoic time; local, severe folding of Upper Proterozoic rocks occurred in a few places, notably at Yampi Sound in the far north-west(3).

A major fold-belt of Upper Proterozoic rocks is the Adelaide Geosyncline in South Australia, where an immense pile of sediments was deposited in a trough which existed through Upper Proterozoic and part of Cambrian time. The Upper Proterozoic sediments, constituting the Adelaide System, have been divided into four Series of which the second youngest includes sediments derived from glaciation of the land surface in late Proterozoic time.

The sequences of Upper Proterozoic rocks in Western Australia and the Northern Territory can be broadly correlated with the Adelaide System, although they cannot yet be split into four Series. However, in the Kimberleys and in the Northern Territory the Upper Proterozoic can be divided into two. The lower sequence consists mainly of sandstone, with lava flows and some iron-ore beds (red beds); the upper includes sandstone, dolomite, shale, and red beds, with glacial sediments which may be broadly correlated with those of the Adelaide System (see Plate 1.) Upper Proterozoic rocks were also deposited in the Officer Basin which lies north of the Eucla Basin and extends into both Western Australia and South Australia. The sequence is little known but includes both Upper Proterozoic and Lower Proterozoic rocks and, in places, is 15,000 to 20,000 feet in thickness.

---

(1) A sedimentary rock with the same grainsize as a sandstone but consisting of angular to rounded grains of a number of minerals including rock fragments, set in a matrix of fine-grained material.

(2) Very large depressions of the earth's surface - commonly long and narrow, and subject to submergence and sedimentation.

(3) The folded rocks of the Davenport Range, Northern Territory, referred to the lower division of the Upper Proterozoic on the map, are now known to be Lower Proterozoic in age.

In several places in Western Australia, Northern Territory, Queensland, and Tasmania, Proterozoic rocks cannot be confidently subdivided and are shown as undifferentiated. In north-eastern Queensland and western Tasmania, these folded Proterozoic rocks constitute the only outcrops of the basement rocks of the Tasman Geosyncline, in which sedimentation began in Palaeozoic time.

IGNEOUS ROCKS

Acid and basic* lava flows and instrusive masses are represented in the Archaean and Proterozoic; indeed granitic rocks are more prominent in the Precambrian than in any other division. Many granitic rocks, intruded in Archaean time, are no longer recognizable because of alteration; most of the unaltered granites in the Precambrian Shield are of Lower Proterozoic age. The vast area of 'granite' shown in Western Australia is, in fact, a complex of granite, gneiss, and other metamorphic rocks of Archaean age.

In the Northern Territory, at least two ages of granitic intrusions are known from radioactive age determinations - one about 1,600 million years and another about 1,440 million years ago.

Across the greater part of the Shield, Upper Proterozoic rocks are not intruded by granite, but in places in the Adelaide Geosyncline granites of Cambrian age intrude rocks of the Adelaide System.

PALAEONTOLOGY

Records of life in the Precambrian are meagre. This does not mean, of course, that life did not exist previously; very few Precambrian rocks are so untouched by alteration that fossils would be preserved in quantity, and in any case, few of the primitive forms of life were able to leave recognizable traces in the rocks.

In the Northern Territory, rocks assigned to the Lower Proterozoic and known to be over 1,600 million years old have yielded "Collenia-like"** forms regarded as very primitive marine plants (algae). Other markings in Proterozoic rocks resemble worm-burrows, and in Upper Proterozoic rocks in South Australia and Northern Territory impressions of jellyfish have been identified.

All forms of primitive life of which we have record existed in the sea; indeed there is no record of terrestrial forms (land plants) until the Silurian.

---

* Igneous rocks are commonly classified on the content of silicon dioxide (SiO_2). Those containing more than 65% are termed 'acid'; rocks of 'intermediate' composition contain 55-65% and 'basic' rocks contain less than 55% SiO_2.

** Readers requiring more information of the animals and plants mentioned in these notes should consult an encyclopedia or a text book on Palaeontology such as "Principles of Invertebrate Palaeontology" by Shrock and Twenhofel published by McGraw Hill, New York.

ECONOMIC GEOLOGY

In Australia, as in other part of the world, the Precambrian Shield provides the richest mineral provinces. The greater part of Australia's total production of gold, lead, zinc, iron, and uranium has been won from the Shield, mainly from Archaean and Lower Proterozoic rocks.

Upper Proterozoic rocks are largely unmineralized and have contributed much less than the older Precambrian; they provide some uranium in the Northern Territory, but their main contributions to date are the iron-ore beds at Yampi Sound and those currently being explored in the Constance Range in western Queensland; these ores originated as iron-rich sediments in Upper Proterozoic time.

In general, Archaean and Lower Proterozoic rocks provide only meagre supplies of underground water; in places these are saline. Gently folded Upper Proterozoic rocks yield useful supplies in places in South Australia and in the Northern Territory; the cattle industry of the Barkly Tableland (western Queensland and Northern Territory) is dependent on abundant supplies of sub-artesian water stored largely in the Camooweal Dolomite, which is either Upper Proterozoic or Lower Cambrian in age.

Even the youngest of the Upper Proterozoic basins appears to offer no real prospect for oil accumulation, although occurrences of bitumen in at least three places indicate that some petroleum was generated in late Precambrian rocks.

CAMBRIAN

The Cambrian Period, which extended for some one hundred and ten million years, saw many changes in the growing continent. Some of these changes can be reconstructed by tracing the distribution of fossils that flourished during known short periods within the long Cambrian Period; but the reconstruction is far from complete because some Cambrian rocks have been removed by erosion and others in eastern Australia particularly, which are thought to be Cambrian, are unfossiliferous.

The approximate distribution of land and sea in Lower, Middle, and Upper Cambrian time is shown in figure 1. The greater part of Western Australia and South Australia was land throughout Cambrian time; parts of the Northern Territory and Western Australia were inundated several times, particularly in the Middle Cambrian, and eastern Australia was apparently inundated by sea at least from Lower Cambrian onwards.

In Lower Cambrian time sedimentation continued in the Adelaide Geosyncline, where limestone, shale, and sandstone, some containing Lower Cambrian fossils, have been found. The Lower Cambrian sea extended, probably in a long northerly arm, into central Australia, where fossiliferous limestone and sandstone were deposited in the Amadeus Basin. No Lower Cambrian rocks have been identified north of this Basin, but the sea probably continued northwards across the continent in a long and narrow strait.

The situation in eastern Australia in Lower Cambrian time is obscure; thick sequences in the Tasman Geosyncline, evident in the Middle Cambrian, may have commenced in Lower Cambrian time, particularly near Brisbane and in Tasmania, but the metamorphic and volcanic rocks in these places are unfossiliferous.

In the Middle Cambrian the continent was widely inundated by a band of sea across the middle of the continent, and by an eastern sea from which it was separated by a north-south ridge. The two seas contained different faunas; so the ridge was a major barrier between them, and not just a local one. Fairly early in Middle Cambrian time the sediments of the Adelaide Geosyncline were uplifted and folded, and the western sea retreated northwards.

The western sea was mainly shallow and deposits consist of limestone, shale, sandstone, and chert. The eastern sea, shallow at its western limit, deepened eastward and occupied a gradually subsiding trough - the Tasman Geosyncline - in which ridges and islands probably existed. Fossiliferous Middle Cambrian greywacke, other sediments, and volcanics occur in Tasmania and Victoria, where submarine volcanic activity was intense at this time; similar, but unfossiliferous, rocks cropping out farther north in the Geosyncline, as at Brisbane, are believed to be Cambrian; these are included in rocks labelled P_z and Pz1 on the map.

In Upper Cambrian time, the eastern sea persisted, as did sedimentation and some valcanic activity. The western sea, which had retreated to the north before the end of Middle Cambrian time, was replaced by a great arm of the eastern sea which crossed the dividing ridge into the Amadeus Basin in central Australia and probably continued north westward to bisect the continent. This marine link between central Australia and the eastern sea first appeared before the end of Middle Cambrian time. Sedimentation in the shallow western arm across the shield, like that of Middle Cambrian time, consisted mainly of limestone and sandstone and persisted into Ordovician time.

The contrast shown by marine conditions and type of sediment between eastern and western seas appears also in the structural history. The comparatively thin sandstone and limestone sequences deposited in shallow seas on the Shield were little folded; in contrast, the thicker sequences of greywackes and volcanics laid down in deeper water and under conditions of crustal unrest in the Tasman Geosyncline were severely folded during "orogenies" - episodes of structural deformation - beginning, in Tasmania, about the end of Cambrian time (Tyennan Orogeny). The comparative stability of the Precambrian Shield in contrast to the Tasman Geosyncline, first apparent in the Cambrian, persisted as a basic feature of the structural evolution of the continent.

IGNEOUS ROCKS

The granites that invaded rocks of the Adelaide System in South Australia probably included both later Proterozoic and Cambrian intrusives, but no Cambrian granites have been recognized elsewhere, though some granitic rocks in Western Tasmania may have been emplaced in Upper Cambrian time. Basalts were poured out over a wide area of the Precambrian Shield in the Northern Territory and Western Australia (see figure 1) in Lower Cambrian time; dolerites intruded as sills into Upper Proterozoic rocks in Arnhem Land, Northern Territory, (Buv) are probably of the same age. Volcanic activity throughout most of the Cambrian in eastern Australia has already been noted.

PALAEONTOLOGY

The earliest forms of life occurring in Australia in rocks attributed without reservation to Cambrian seas are archaeocyathids, algae, and sponges in the Lower Cambrian of South Australia and the southern part of the Northern Territory. Slightly later, but still in the Lower Cambrian, trilobites and brachiopods became important elements in the fauna. Archaeocyathids are extinct creatures which are generally considered to have been more nearly related to the sponges than to any other group of animals living today. Their remains show them to have been more or less funnel-shaped with a wall formed of two hard layers separated by a space and linked by bars. The forms of algae preserved appear to have been of lime-depositing types, building firm layered masses.

Trilobites are also extinct. They were arthropods and periodically shed their external skeletons as modern crayfish do. They are called trilobites because their bodies were indented by two longitudinal furrows so that a cross section shows three lobes, convex upwards. Brachiopods, though not extinct, have only a few representatives in modern seas. They are commonly known as lamp shells, because they resemble the type of lamp used in Ancient Greece. Their shells consist of two unequal valves.

Dendroids are important in places; they were the forerunners of animals which became very important in the Ordivician: the graptolites. The earliest radiolaria are recorded in the Cambrian, and occur throughout the geological column, often in great numbers.

ECONOMIC GEOLOGY

Mineralization of Cambrian age has been recognized only in South Australia, where copper and uranium occur in Cambrian rocks; a deposit of pyrite, from which sulphur is extracted, at Nairne in South Australia, also occurs in Cambrian sediments. Limestone, dolomite, marble, and slate are used in South Australia in the stone and cement industries. Some metalliferous deposits in Western Tasmania and in Victoria occur in Cambrian rocks, but the age of the mineralization is probably Devonian

Cambrian rocks in South Australia, Northern Territory, and Western Australia, including the Lower Cambrian volcanics, provide important supplies of underground water; in addition, areas supporting the highest cattle population in the Northern Territory owe their productivity to the lime-rich soils derived from Cambrian or late Proterozoic limestone and dolomite or from Cambrian volcanics.

Cambrian sediments in South Australia, north-western Queensland, Northern Territory, and Western Australia are of interest in the search for oil; petroliferous limestones, which are possible source-beds, have been found, and a show of oil was discovered in one small basin of Cambrian rocks in the Northern Territory.

ORDOVICIAN

The pattern of land and sea in Ordovician time (Figure 1.) was little changed from that of the Upper Cambrian. Widespread deposition continued to divide the shield into two large islands. The Ordovician sea impinged on the continent in the Bonaparte Gulf region, Western Australia, forming either an embayment or a narrow strait leading to the wide seaway to the south. The Carnarvon and Perth Basins, which were marine basins for much of later time, may have been first submerged in Ordovician time, but this has not yet been confirmed by fossil evidence.

The type of sedimentation in both eastern and western seas also shows little change from Upper Cambrian time. In the Tasman Geosyncline rapid sedimentation continued as the Geosyncline gradually sank, but geological history is still obscure in many places because thick sedimentary successions which probably include Ordovician rock are unfossiliferous and have only been mapped as Lower Palaeozoic; these particularly include phyllite, slate, chert, greenstone, and schist, in northern New South Wales and Queensland.

Fossiliferous strata of both Middle and Upper Ordovician age are found in central and south-eastern New South Wales and include greywacke, shale, chert, and sandstone, with rare occurrences of limestone and volcanics. Black carbonaceous shale is dominant in Upper Ordovician beds, which normally contain graptolite remains; Lower Ordovician strata have been identified by fossils in only one locality, but they are probably present elsewhere in unfossiliferous successions.

In central Victoria a succession of Ordovician strata is found consisting of sixteen thousand feet of alternating thin-bedded slate and greywacke; remains of graptolites are found throughout the succession. Upper Ordovician rocks are widespread in eastern Victoria, where they have been mostly metamorphosed to phyllite and schist. In Tasmania more than ten thousand feet of strata, representing the greater part of Ordovician time, occur in the western part of the island; they include conglomerate, sandstone, siltstone, and limestone, and are fossiliferous in part.

Although deposition was widespread in the Tasman Geosyncline in Ordovician time, the entire Geosyncline area was not covered by sea at any one time; details emerging in many places indicate that ridges and islands existed within the Geosyncline and that sedimentation probably took place in smaller troughs and basins. At different times and places, supplies of sediments apparently came from the west, from island ridges, and from land which formed the eastern boundary of the Geosyncline, now submerged in the Tasman sea. All these Ordovician rocks have since been fairly strongly folded and in most places intruded by granite, but the age of the folding and intrusion is different from region to region and in most places younger than Ordovician. In eastern New South Wales, in particular, Ordovician rocks were subjected to three and possibly four orogenies between Ordovician and Lower Carboniferous times.

In the western sea, in the Amadeus Basin and beyond, probably including the Officer Basin, sandstone, limestone, and shale with some dolomite were laid down. The Ordovician sequence in the Amadeus Basin is the thickest so far known on the shield and totals some seven thousand feet of sandstone, siltstone and limestone.

Thinner sequences of similar rocks have been recorded from the Bonaparte Gulf Basin, from the north-eastern corner of the Canning Basin, and from a bore near Broome. Unfossiliferous sandstone and siltstone in the Carnarvon and Perth Basins, Western Australia, could be in part Ordovician.

Except in the Amadeus Basin, Ordovician sediments of the western sea have been little folded or deformed. No igneous intrusives have been found in these sediments.

PALAEONTOLOGY

The Australian Ordovician is chiefly noted for its fine zoning by means of graptolites, which are especially abundant in Victoria, where 9 zones have been distinguished. These tiny animals formed branched colonies, many of them provided with floats which ensured them a wide distribution. They are now extinct, but the remains of their chitinous bodies show as impressions or carbonized markings in the finer-grained rocks such as slates, which are especially suitable for their preservation. Because of their wide distribution and comparatively rapid evolution they are very useful in correlating and dating the rocks in which they occur.

Trilobites were also an important element of the Ordovician faunas, and together with cephalopods (related to modern squids and cuttlefish), brachiopods, gastropods (snail-like shells), and corals, have proved very useful in areas where graptolites are not so abundant, such as Tasmania and central and northern Australia.

In Australia ostracods are first recorded from the Ordovician of the Fitzroy Basin, W.A. They occur in both marine and non-marine beds from the Ordovician to the present day.

IGNEOUS ROCKS

No Ordovician igneous rocks are known in Central and Western Australia, and little igneous activity has been recorded for certain in the Tasman Geosyncline. Some greenstone in Queensland and volcanics on the southern coast of New South Wales may be of Ordovician age, but elsewhere there is little record of vulcanism.

Some granites in south-eastern New South Wales are regarded as probably Upper Ordovician: they accompanied a period of folding and uplift called the Benambran Orogeny - the first of a series of major orogenies which gradually brought about the stabilization of eastern Australia.

ECONOMIC GEOLOGY

Ordovician rocks are important hosts for mineral deposits in the Tasman Geosyncline, particularly for gold reefs in Victoria and New South Wales, but all the mineralization is linked with granitic rocks of younger age. Ordovician limestone is quarried for flux and for supplies of lime in Tasmania.

In western Queensland and central and Western Australia Ordivician sediments provide important supplies of groundwater in places and possible source or reservoir rocks for oil.

SILURIAN

Deposition in the Tasman Geosyncline continued throughout Silurian time, but uplifts about the end of the Ordovician drained the seaway stretching westward through central Australia. Sedimentation took place in the Carnarvon and, possibly, Perth Basins along the seaboard of Western Australia, but the sea had retreated from the Bonaparte Gulf Basin.

Sedimentation in the Tasman Geosyncline continued the pattern followed by Ordovician time; again the picture is not clear in detail, but troughs and basins of deposition can be seen within the Geosyncline and ridges and islands can be inferred from the geological record. For example deposition of greywacke and claystone with some conglomerate and limestone was continuous from Cambrian to Devonian time within the central Victorian trough, which probably extended north into New South Wales; but the environment was different in eastern Victoria, south-eastern New South Wales and northern Queensland, where areas of land existed at least in early and late Silurian time. Silurian deposits in the south-eastern areas consist mainly of calcareous sediments including great lenses of limestone and a profusion of volcanic rocks which outline a great volcanic arc along the southern highlands. Volcanic activity reached a peak towards the end of Silurian time, but recurred with equal severity in the Devonian.

Farther north, along the coastal areas of New South Wales and eastern Queensland, greywacke, shale, chert and tuff were deposited in a trough. Trough deposits, including shale, sandstone, and greywacke, were laid down in northern Queensland and there is evidence of a system of Barrier Reefs in the southern part of Cape York Peninsula.

The central and western part of the continent was land in the Silurian, probably with moderate relief, and the continent stretched beyond its present limits. Only along the western seaboard of Western Australia is there evidence of sedimentation in the beginnings of the Carnarvon and possibly the Perth Basins; dolomite, limestone, and calcareous sediments of Silurian age have been found in a bore at Dirk Hartog Island, but Silurian sediments have not yet been identified in outcrop.

PALAEONTOLOGY

In some parts of Australia there was no break in sedimentation between the Ordovician and the Silurian, but as conditions of deposition changed, so did the general aspect of the fauna. In Victoria the graptolites, though still important at the beginning of the Silurian, lost their predominance, and the faunal lists show increasing numbers of genera and species of brachiopods, corals, cephalopods, etc. Other areas also show a general picture of abundant and varied animal life during the Silurian, but the most important feature of this time was the appearance of land plants. In Victoria, the vascular plant *Baragwanathia* has been found in association with the graptolite *Monograptus*.

IGNEOUS ROCKS

In addition to the outpouring of acid lavas, particularly in central and south-eastern New South Wales, the Silurian is noteworthy for the widespread intrusion of granites in eastern Victoria, and eastern and central New South Wales.

For the most part, these intrusions came towards the close of a period of major folding called the "Bowning Orogeny" which happened during late Silurian time. This was the second, and one of the most severe, of the major orogenies mentioned in earlier chapters, and it had a stabilizing effect on the rocks of the Geosyncline in those areas in which folding was severe and emplacement of granite widespread; but large areas of the Geosyncline were little affected by the Bowning Orogeny, notably Tasmania, Central Victoria, north-eastern New South Wales, and south-eastern Queensland. In northern Queensland the Bowning Orogeny was probably represented by uplifts but was not accompanied by granite intrusion.

ECONOMIC GEOLOGY

Silurian rocks contain metalliferous deposits in many places in eastern Australia; but it is not always clear whether the lodes or quartz reefs were introduced by late Silurian or by younger granites, both of which intrude Silurian sediments.

Silurian granites probably introduced gold, silver-lead, and copper in central and south-eastern New South Wales; in eastern Victoria some of the richest gold deposits in the State accompanied quartz reefs introduced by late Silurian granites.

Apart from metalliferous deposits, Silurian limestone is widely used for flux, in the manufacture of lime and cement, and for building stone, particularly in New South Wales.

DEVONIAN

The gradual process of consolidation of the Tasman Geosyncline can be clearly seen in events taking place in Devonian time; in fact much of Tasmania, Victoria, and part of New South Wales and Queensland were essentially stablized by one or both of the last two grand orogenies, in these areas, which took place about Mid-Devonian (Tabberabberan Orogeny) and in late Devonian or early Carboniferous time (Kanimblan Orogeny). The volcanic activity prominent in the Upper Silurian in some areas again became widespread and severe in Devonian time.

In the Middle, and even more in the Upper, Devonian, the ancestral Indian Ocean again enroached on the continent and inundated the major sedimentary basins along its western margin, setting a pattern of deposition which continued throughout the rest of Palaeozoic time, and persisted into Tertiary time in the Carnarvon Basin.

After the uplifts at the end of the Silurian, there was probably more dry land in the Tasman Geosyncline in the early Devonian than at any time since the Geosyncline was first formed. Deposition of mudstone and limestone continued in the central Victorian trough, which probably extended southward into Tasmania and northward into New South Wales. Deposition of mudstone, chert, and submarine volcanics continued in the New England trough in north-eastern New South Wales, and south-eastern Queensland.

Mountains pushed up by late Silurian movements in central and south-eastern New South Wales and in eastern Victoria were severely eroded before renewed volcanic activity produced flows of acid lava and tuff in Lower Devonian time; then the volcanic arc began to sink and was largely submerged under the enroaching western sea until, in Middle Devonian time, most of the Geosyncline was again an island-studded sea.

Volcanic rocks gave place to limestone and shale in many places and coral reefs were widespread throughout the length of the Geosyncline, particularly in the Broken River area, north Queensland. The onset of a major orogeny toward the end of Middle Devonian (the Tabberabberan Orogeny) radically changed the picture; deposition ceased and sediments were folded in north-east Queensland, central ans southern New South Wales, Victoria, and Tasmania; north-eastern New South Wales and eastern Queensland were apparently little affected by these movements and sedimentation continued.

Erosion became active in the highlands produced by the Tabberabberan Orogeny, but soon the sinking and sedimentation began again, with the result that most of the Geosyncline was under water in the Upper Devonian. There was, however, a change in the environment and in the type of sedimentation in Upper Devonian time; the Geosyncline was really filling up and gradually reached stability. No enough trough deposition continued in eastern New South Wales and was revived in a few localities in relatively shallow basins and in shallow seas which spread across the Geosyncline. Volcanic activity was prominent in south-eastern New South Wales and in centeal Victoria, but not in the rest of the Geosyncline. Typical sediments were sandstone, grit, shale, and ferruginous siltstone and shale termed "red beds".

Much of the sedimentation took place in fresh water lakes and in general there was little marine sedimentation in the far south of New South Wales and in Victoria and Tasmania. In many places sedimentation continued into the Carboniferous Period.

In the western portion of the Continent, the Bonaparte Gulf, Canning and Carnarvon Basins were submerged by Upper Devonian time; the time of first flooding is not properly known but extends back to Middle Devonian in the northern part of the Canning Basin (Fitzroy Basin).

Devonian sediments in the Bonaparte Gulf Basin are now largely submerged beneath Bonaparte Gulf, but plant-bearing sandstone and overlying thick limestone crop out over a small area near Wyndham. In the Fitzroy Basin, sedimentation was dominated by reefs which fringed the north-eastern margin of the Basin; the reefs, with contemporaneous back-reef and fore-reef deposits, are excellently preserved in many places; siltstone and limestone were deposited over a wide area toward the end of the Devonian. The principal sediments deposited in the Carnarvon Basin in Devonian time were limestone, sandstone, and conglomerate; and here, as in the other two basins, sedimentation continued into the Carboniferous.

PALAEONTOLOGY

In Australia in the Devonian, corals and brachiopods became more important and trilobites and graptolites became insignificant. Straight cephalopods are an important group and ammonoids (goniatites) are useful for zoning the rocks. Stromatoporoids are well represented and make up an important part of the reef masses.

Conodonts, which first appear in the Ordovician, are abundant. The first undoubted foraminifera recorded in Australia are from the Devonian of the Fitzroy Basin. These microfossils continue to the present day, and are a most valuable group for dating the rocks.

Land plants are well established and Lepidodendron australe is common in the Upper Devonian in both eastern and Western Australia. Fish occur in many places. These are the first vertebrates found in Australia and from this group are derived the amphibians, reptiles, birds and mammals.

IGNEOUS ROCKS

The Devonian is particularly noted for its volcanic activity in eastern Australia; most of the lavas were acid varieties - rhyolite, dacite - but in places more basic rocks, such as andesite and basalt, occur. Alkaline lavas around Mount Macedon in central Victoria are of special interest to the petrologist. The Tabberabberan Orogeny was accompanied by fairly widespread granitic intrusion along the belt running from central and south-eastern New South Wales into eastern Victoria; the distribution of these granites follows fairly closely that of the late Silurian (Bowning) granites but the mid-Devonian granites are not so widespread. They may be represented by granitic rocks in eastern Tasmania and in north-east Queensland; but we do not yet know whether these rocks were emplaced in Mid-Devonian or in Carboniferous time, when another major orogeny took place. Porphyritic rocks in western Tasmania may also have been intruded in Mid-Devonian time.

The intrusion of some serpentines - very basic igneous rocks - in New South Wales and Queensland probably took place in the Devonian; they occur as thin, steeply dipping sheets occupying major faults or thrust zones up which they were injected.

ECONOMIC GEOLOGY

Some mineralization accompanied the Mid-Devonian granites in eastern Australia; but as large quantities of metals were introduced with the younger Carboniferous granites which, in many places, occurred within the same belts, it is commonly difficult to decide what mineralization can be attributed to Mid-Devonian granites. This applies particularly to deposits of copper, lead, and zinc in western Tasmania, to copper, tin, and tungsten in north-eastern Tasmania, and to gold and copper in north-eastern Queensland.

Gold and copper deposits in the Cobar area of central New South Wales are believed to have been introduced in the Middle Devonian, and some silver-lead ores in south-eastern New South Wales and some gold in central and eastern Victoria may stem from Middle Devonian granites. Chromite and some nickel were introduced by serpentines in the Lower Devonian in North Queensland.

Devonian limestones are used in the manufacture of lime and cement, and Upper Devonian sandstones are used as building stones and in the making of refractory bricks.

Devonian sediments in the Western Australian sedimentary basins are of importance in the search for oil, because they may provide both source and reservoir rocks; in particular, the reef limestone of the Fitzroy Basin is a likely reservoir for oil.

CARBONIFEROUS

In early Carboniferous time the pattern of sedimentation in both the Tasman Geosyncline and in the Western Australian basins apparently remained the same as it was in the late Devonian; changes which may have taken place in the Tasman are not discernible because some of the early Carboniferous sediments were subsequently removed and because Upper Devonian and Lower Carboniferous sediments cannot everywhere be distinguished. The palaeogeographic map for the Lower Carboniferous is therefore tentative; the evidence is more definite for the Upper Carboniferous when deposition in the Tasman Geosyncline was restricted to the eastern part of the trough following a major orogeny (Kanimblan Orogeny) which took place in Lower Carboniferous time. These movements presumably raised most of the western Australian basins above sea level because there is no record of Upper Carboniferous strata except in a part of the Fitzroy Basin and possibly in part of the Bonaparte Gulf Basin.

The Kanimblan Orogeny in eastern Australia separates the sediments deposited in this Period into Lower and Upper Carboniferous: folding and emplacement of granite interrupted sedimentation everywhere except in the New England trough in north-eastern New South Wales.

Lower Carboniferous rocks - limestone, sandstone, shale, chert, and volcanics - lie conformably on Upper Devonian sediments in basins in eastern and northern Queensland. The sediments are both marine and fresh water. The sea at that time certainly covered eastern Queensland, with ephemeral lakes along its western shore-line, which was apparently constantly changing in response to minor earth movements; thousands of feet of sediments deposited in basins are still preserved, but thinner sequences, deposited between the basins have no doubt been removed.

The extent of the Lower Carboniferous sea in New South Wales is not known; mudstone with some sandstone, conglomerate, and lava flows was laid down in the New England trough, and, although no record of it remains, a shallow sea may well have covered much of central and western New South Wales. Shallow seas and estuaries, and some freshwater lakes, covered much of Victoria, and sediments of probable Lower Carboniferous age - sandstone, red beds, shale, and conglomerate - are preserved in the Grampians in western Victoria and in the Mansfield area in central Victoria. The highlands of south-eastern New South Wales and eastern Victoria probably formed a major ridge at this time. There is no record of the Lower Carboniferous sea in Tasmania but some inundation probably took place.

The Kanimblan Orogeny, the last of the grand orogenies to have widespread effects throughout the Tasman Geosyncline, interrupted sedimentation except in the New England trough. Folding took place towards the end of Lower Carboniferous time in Queesland and, it is assumed, in New South Wales; however, as with other orogenies, the climax of the movement probably occurred at slightly different times in different regions. The movement raised much of the Geosyncline well above sea level once again, and the Upper Carboniferous sea was restricted to the eastern margin of the Continent from Cape York Peninsula to Newcastle. Both marine and terrestrial sediments were laid down in Queensland and New South Wales. These sequences range from Upper Carboniferous into Permian in age, and the boundary between the two Systems is still under discussion, particularly in Queensland; but there is a general tendency to regard as Permian the glacial deposits and the coal seams.

Upper Carboniferous deposits in Queensland certainly include lava flows and marine sandstone, shale, and limestone; and while, in north-eastern New South Wales, mudstone, chert, and lava flows continued to be laid down in the New England trough, thousands of feet of lava accumulated along its south-western margin, north and north-north-west of Newcastle. The lavas are overlain by glacial deposits with plant fossils, and these in turn pass upward into marine sediments of definite Permian age. Some glacial deposits may have been laid down in Upper Carboniferous time; but for convenience, the extent of glaciation will be discussed under "Permian".

In the Western Australian basins, Lower Carboniferous limestone, sandstone, siltstone and calcareous sediments were deposited in the Bonaparte Gulf, Fitzroy, and Carnarvon Basins; except for an area in the Fitzroy Basin where Upper Carboniferous strata have been identified in a bore, these basins were apparently raised above sea level in Upper Carboniferous time, perhaps by movements associated with the Kanimblan Orogeny; sediments within the basins were folded and faulted in places but nowhere was deformation severe.

PALAEONTOLOGY

Important elements in the fauna of the Carboniferous were brachiopods and corals; but many other forms were abundant, such as cephalopods, pelecypods, gastropods, etc. Trilobites and graptolites were rare, but bryozoa or "moss animals" - small colonial forms building and inhabiting calcareous masses of various shapes and sizes - were beginning to make a noticeable contribution to the fauna. Fish remains have been described. In the flora, two distinct aspects can be recognized, one dominated by *Lepidodendron* and the other by *Rhacopteris*. The first is particularly prominent in the Lower Carboniferous and the second in the Upper, but there is some overlap. Many of the plants in the *Lepidodendron* flora attained the dimensions of trees and numerous specimens may have been drift wood.

IGNEOUS ROCKS

The widespread folding and faulting of Lower Carboniferous and older rocks of the Tasman Geosyncline during the Kanimblan Orogeny was closely followed by the emplacement of granite in many places; Kanimblan granites are probably represented in north-east Queensland, north, central and south-eastern New South Wales and in much of Victoria. Some basic and granitic intrusives in Tasmania are believed to be Kanimblan in age, although they could also be mid-Devonian and associated with the Tabberabberan Orogeny.

Volcanic activity was again widespread in the carboniferous, although the belt of major activity within the Geosyncline shifted to the east, particularly in Upper Carboniferous time, and trended north from Newcastle through north-eastern New South Wales and eastern Queensland. Vulcanism occurred also in northern Queensland. Both basic and acid lavas are present in many places, but lavas of acid or intermediate composition generally predominate.

Acid lavas were poured out in the Bonaparte Gulf Basin, in Western Australia, but these are the only known volcanics of Upper Palaeozoic age in the central and western parts of the continent.

ECONOMIC GEOLOGY

Intrusives accompanying the Kanimblan Orogeny were responsible for a metallogenetic epoch which was unsurpassed in eastern Australia. Gold, molybdenum, tungsten, tin, bismuth, and antimony, with some lead, copper, and zinc, were introduced in Queensland, particularly in the north-eastern sector, and in many places in New South Wales. Copper deposits in the Chillagoe area, northern Queensland, were introduced by Kanimblan granites. Kanimblan granites in Victoria are thought to be responsible for most of the major gold reefs in the State, particularly in the central region (including Bendigo, Ballarat, Castlemaine, and Stawell); other metals such as antimony, tin, and tungsten were also introduced.

In Tasmania, granites thought to be Kanimblan were particularly rich in tin and wolfram, and basic rocks, presumably of the same age, were responsible for the introduction of osmiridium.

Sediments added to the Palaeozoic succession in the Western Australian basins during the Carboniferous improve the prospect for oil and provide storage for underground water.

PERMIAN

The Permian Period is noteworthy for two events: a widespread glaciation of the continent and the deposition of the major coal measures of the Commonwealth.

There is evidence of two stages of glaciation, a severe glaciation in the Lower Permian (apparently starting in late Carboniferous time in eastern Australia) and a milder glaciation later in Permian time.

These glaciations are represented in the geological record by glacial sediments which take three main forms. Material dumped on the land by retreating and melting glaciers, forming deposits of badly sorted boulder-clay, is termed "tillite"; similar material dropped from melting icebergs and flows in the sea forms part of the marine deposits collecting on the sea floor and is termed "periglacial sediment" or "aqueo-tillite". A third form of glacial sediment results when rivers transport the debris left by glaciers and deposit it in lakes or in the seas as a conglomerate: these deposits, called "fluvo-glacials" or "outwash", show better sorting than do tillites and some of the boulders bear striations or grooves caused in glacier transport.

The Permian seas inundated mainly the eastern seaboard of the Continent and the Western Australian basins, but many low-lying areas within the continent received a mantle of terrestrial sediments mainly derived from glaciated mountain ranges.

The Tasman Geosyncline was now so far consolidated that earth movements produced broad basins rather than abrupt troughs and, apart from the filling of the New England trough, sedimentation in the Permian everywhere took place in basins.

Along the western margin of the Permian sea in eastern Australia, and in part of the Perth basin in Western Australia, lay great swamps choked with vegetation, from which developed by subsequent compaction the major coal measures of the continent. From time to time, these swamps became fresh-water lakes or were inundated by the sea; normal lacustrine or marine sediments were deposited, and in the Permian sequences coal seams alternate with marine or lacustrine sandstone and shale. The sediments were thickest in the basins and, in places, thinner sections between basins have been eroded

The great Bowen Basin in Queensland and the Sydney Basin in New South Wales originated in Permian or in late Carboniferous time and received some 23,000feet and 17,000 feet of sediments respectively. The deposits in these basins consist of sandstone, shale, limestone, glacial sediments and coal seams; in both eastern New South Wales and eastern Queensland there are considerable thicknesses of volcanic rocks. Isolated swampy basins in southern-central and in north-eastern New South Wales gave rise to coal seams in the Coorabin and Ashford areas respectively.

Much the same type of sedimentation took place in the Western Australian basins as those near the eastern seaboard, but vulcanism was absent and the only economically significant development of coal was at Collie; thin coal seams were deposited in the Bonaparte Gulf, Carnarvon and Fitzroy Basins.

Deposits in the Carnarvon and Canning Basins consist of limestone, sandstone and shale with glacial sediments prominent in the lower part of the Permian sequence; Permian sediments in the Carnarvon Basin total 14,000 ft. in thickness. The Canning Basin was extended far to the south-east where marine sediments pass into terrestrial glacial deposits. Similar glacial deposits found in South Australia and remnants found in the Northern Territory complete the evidence for widespread glaciation in Permian time. A thick, but local sequence of conglomerates, along the northern flanks of the Macdonnell Ranges west of Alice Springs is tentatively regarded as a torrential, but not glacial, deposit of Permian age.

Trough deposition in the Permian was restricted to the New England region in north-eastern New South Wales, extending northwards into Queensland; in these areas considerable thicknesses of sandstone, chert, shale, mudstone and limestone were laid down.

Towards the end of Permian time an orogeny (Hunter-Bowen) took place along the present eastern seaboard; this folded and uplifted the Permian and older sediments in the New England trough and in eastern and north-eastern Queensland; granites were emplaced in the same areas but the orogeny had little effect farther west and south. In Western Australia, uplifts about the same time restricted the sedimentary basins and drained the Carnarvon and a large portion of the Canning Basin; some gentle folding occurred in places in Late Permian and in Triassic time.

PALAEONTOLOGY

The brachiopods appear to have been the most important animal group in the Permian, although other forms are also numerous. In some areas, certain kinds of bryozoa made up most of the fauna and a particular horizon in Western Australia is noted for fossil cephalopods. Crinoids (sea lilies), pelecypods, and gastropods were also important elements of the fauna, but trilobites and graptolites finally became extinct. The Upper Carboniferous Rhacopteris flora passed up into a flora dominated by Glossopteris; the micro-flora consisting of spores from many plants has been studied. Many insects have been described from the freshwater deposits associated with the Permian coals.

IGNEOUS ROCKS

Volcanic activity, noted in the Upper Carboniferous along the present margin of the continent north of Newcastle, continued in Permian time, but with less severity; in the Upper Permian, volcanic activity extended south of Sydney and flows appeared with the sediments deposited in the Sydney Basin. Volcanic flows in the Permian included a wide range of rock types from acid rhyolite to basic basalt. Granitic rocks emplaced towards the close of the Hunter-Bowen Orogeny were restricted to north-eastern New South Wales and south-eastern and north-eastern Queensland, but small granite bodies were intruded near the southern margin of the Sydney Basin. The serpentine belts of north-eastern New South Wales and south-eastern Queensland were also introduced at this time.

ECONOMIC GEOLOGY

The Hunter-Bowen granites gave rise to the important tin provinces of north-eastern New South Wales and of south-eastern and north-eastern Queensland (Herberton and Mt. Garnet); they also introduced other metals including molybdenum, tungsten, bismuth, and antimony. In Queensland metals were introduced by granitic and volcanic rocks in three phases between Upper Permian and Upper Triassic time. The copper-gold deposits of Mount Morgan and some gold and silver-lead deposits from elsewhere in Queensland are late Permian to Triassic in age. Asbestos minerals are mined from serpentine in north-eastern New South Wales.

However, the principal economic interest in the Permian lies in the vast reserves of bituminous coal, mainly in the Bowen and Sydney Basins in eastern Australia and at Collie in Western Australia. Permian coals are of minor importance in Tasmania; attempts have been made to develop deposits of Permian oil shale in New South Wales and Tasmania. From a broader viewpoint, the initiation in Permian time of sedimentary basins along the eastern coast of the continent, which were not subsequently subjected to severe folding or intrusion, was the starting point of real prospects for oil in the Tasman Geosyncline; oil was, no doubt, generated in some of the older rocks but, in all probability, it did not survive the heat and deformation accompanying the orogenies.

TRIASSIC

The Hunter-Bowen Orogeny caused uplifts which probably restricted the great Bowen Basin in Queensland and drained the belt running southward into north-eastern New South Wales, which had been under the Permian sea. The Sydney Basin and the western portion of Tasmania were little affected, and in early Triassic time sedimentation contined with very little break in large freshwater lakes which were apparently separated by bars from the Triassic sea to the east. Deposits in these areas consisted mainly of sandstone and shale with plant fossils, but in Tasmania useful seams of coal were also developed.

Isolated lakes existed just west of Melbourne in Victoria and at Leigh Creek in South Australia; only a remnant of sandstone, too small to appear on the map, records the Victorian lake, but in the small basin in South Australia some 2,000 feet of shale and sandstone with coal seams are preserved.

The sea retreated from much of the Western Australian basins in Triassic time, but early in the Period arms of the sea inundated part of the Fitzroy and Bonaparte Gulf Basins and at least the northern part of the Perth Basin, where marine shale and sandstone were laid down. Marine shale in the Fitzroy Basin was followed by lacustrine and estuarine sandstone as the sea withdrew; in Upper Triassic time, apparently all of the basins were drained.

With the passage of time in the Triassic, changes took place along the eastern seaboard of the continent: high ground in north-eastern New South Wales and south-eastern Queensland in the early Triassic was gradually worn down, and eventually a new basin - Ipswich-Clarence - was initiated. Deposits consist mainly of freshwater sandstone and shale, but include useful coal seams, particularly in Queensland. Volcanic activity in the Triassic was but a faint echo of the tremendous outbursts in previous Periods; eruptions accompanied the sinking of the Ipswich-Clarence Basin, particularly in Queensland, and early Triassic beds in the Sydney Basin record mild vulcanism. Only a few small igneous intrusions of Triassic age are known in eastern Australia.

PALAEONTOLOGY

In the Triassic, the fossil flora is better represented than the fauna. The Glossopteris flora of the Permian gave place to one more or less dominated by Thinnfeldia, the change being quite abrupt. The freshwater lake deposits have preserved tracks of reptiles as well as insect and fish remains, but signs of animal life are not plentiful in Triassic rocks. A few tiny forms of marine animal life such as foraminifera have been recorded, but as stated above, most deposits of this age are freshwater. The marine Triassic of the north part of the Perth Basin contains ammonites.

ECONOMIC GEOLOGY

The introduction of some metalliferous deposits in Queensland, mainly by volcanic rocks, in the Triassic was mentioned under "Permian". Of chief economic interest in the Triassic are the coal measures in Queensland, Tasmania, and South Australia; in these three States the most important supplies of coal come from the Triassic. Triassic sediments supply building stone in Queensland, New South Wales and Tasmania; Triassic shale is used in the manufacture of bricks, tiles and pottery in Brisbane and Sydney.

Little sediment was added to the Western Australian basins in the Triassic, but mild folding in parts of these basins in Late Permian and Triassic time gave rise to structures in which petroleum may subsequently have been trapped.

JURASSIC

The Jurassic Period is most noted for widespread crustal sagging between the stable shield in central and Western Australia and the present eastern seaboard of the continent; this resulted in a very large area of swamps and lakes over much of Queensland and part of New South Wales and South Australia, in which began the deposition of sediments in the Great Artesian Basin. In many places over two thousand feet of sediments was deposited in Jurassic time; the greatest thickness recorded is over 8,000 feet, in the Queensland portion of the Clarence-Ipswich Basin.

These sediments consist mainly of freshwater sandstone, conglomerate, and shale, with some limestone; coal seams were laid down in eastern Queensland and north-eastern New South Wales.

The Sydney Basin, farther south, was apparently drained about the end of the Triassic, but the uppermost beds in the basin could be of Jurassic age. In Victoria a long elongated depression developed across the southern portion of the state, in which sandstone, conglomerate, and shale were deposited in swamps and freshwater lakes; coal seams developed in the south Gippsland area.

In Western Australia, sediments were deposited in the Perth, Carnarvon, and Canning Basins in Jurassic time. In the Canning Basin, the sea slowly invaded the land; coarse-grained rocks were deposited along the slowly advancing shoreline, and finer-grained rocks offshore. The sea probably reached as far east as the Northern Territory border, in the early Cretaceous, after which it slowly retreated to its present shoreline or farther westward. In the Perth and Carnarvon Basins, the deposition of sandstone, shale and claystone was rarely continuous and most beds were terrestrial, indicating that these basins in the Jurassic were the sites of intermittent lakes barred from the sea for most of the time, with infrequent marine invasions from the west. The greatest known thickness of marine sediments, some 11,000 feet of claystone, occurs in a bore in the Carnarvon Basin near North-West Cape.

PALAEONTOLOGY

It is difficult to distinguish the Jurassic flora from that of the Triassic from which it developed. The various species of *Thinnfeldia* lost their dominance and *Taeniopteris* became more important. Freshwater fishes, some insects, a dinosaur from Queensland and footmarks represent the fauna of eastern Australia. A rich marine fauna, recorded from Western Australia, contains many ammonites (a form of cephalopod).

IGNEOUS ROCKS

A few volcanoes were active in Jurassic time in eastern Queensland and in north-eastern and north-central New South Wales. Of greater importance are the masses of dolerite in Tasmania which were intruded as sills, or tabular near-horizontal bodies, into the Permian and Triassic sediments. Many of these sills are now exposed on the surface and cover about half of the State; they form the cliffs and crags of the Great Western Tiers of Tasmania.

ECONOMIC GEOLOGY

Economic interest in the Jurassic lies in the occurrence of bituminous coal in Queensland and Victoria, and in the porous sandstone beds which provide some of the important aquifers in the Great Artesian Basin. Coal seams of the Ipswich-Clarence basin form an important coalfield in the Ipswich area in Queensland, and the Jurassic coal in the Wonthaggi district in south-eastern Victoria provides the only commercial black coal deposits in that State.

CRETACEOUS

The crustal sagging in the Australian continent noted in the Jurassic became more pronounced in the Cretaceous, and the sea flooded in over wide areas. In the early Cretaceous, deposition in the Canning, Carnarvon, and Perth basins in Western Australia, and along the Queensland coast, continued on from Jurassic time, with much the same type of sedimentation - both marine and terrestrial siltstone and sandstone in the Canning Basin and marine claystone, siltstone, sandstone, and calcareous sediments in the Carnarvon and Perth Basins. But crustal sagging to the east initiated two new basins: the Eucla Basin in Western and South Australia and the Murray Basin farther east. About the same time the northern part of the Northern Territory began to founder; a number of freshwater lakes first developed, and these were eventually inundated by a broad but shallow sea. Marine shale, sandstone, calcareous sediments, and some conglomerate were laid down in the Eucla, Murray, and Great Artesian Basins, and thin sequences of freshwater conglomerate overlain by marine shale, commonly containing radiolaria, provide a record of the shallow sea over northern Australia.

About the end of Lower Cretaceous time much of the land began to rise and the seaways to shrink until, in Upper Cretaceous time, the Great Artesian Basin was again a lake-covered depression as it was in the Jurassic; the continent extended southward to include Tasmania and northward to include part of New Guinea. The Canning Basin had been drained, and marine sedimentation was restricted to the Carnarvon and Perth Basins in the west and a strip of the present Queensland seaboard in the east.

In eastern Australia freshwater shale and sandstone with seams of lignite were laid down on the previous marine deposits of the Great Artesian Basin and a similar lacustrine sequence with coal seams developed in swamps in the Maryborough area, from which the sea had retreated. There are traces of a mild orogeny in eastern Queensland (the Maryborough Orogeny) about the end of Cretaceous, in which Cretaceous and some older sediments along the seaboard were folded.

PALAEONTOLOGY

In the Cretaceous, the marine fauna is better represented than the flora or terrestrial fauna. The best known elements of this marine fauna are the cephalopods (particularly ammonites and belemnites), foraminifera, and to a lesser extent pelecypods; in Queensland ammonites have been used to subdivide the Cretaceous. In a small area in Queensland a Cretaceous flora has been recorded, containing, among other things, some dicotyledonous leaves - the oldest flowering plants in Australia. Taeniopteris survived from the Jurassic. Other plants include Ginkgos and Cycads.

IGNEOUS ROCKS

The only volcanic activity of any note occurred in eastern Queensland, but outbursts were minor compared with those of the great volcanic arcs of eastern Australia in earlier time.

Some granitic rocks in south-eastern Queensland probably accompanied the Maryborough Orogeny; they intrude Triassic and Jurassic sediments, but apparently did not rise sufficiently close to the surface to penetrate Cretaceous strata. Granite near Tibooburra, in western New South Wales, and small isolated outcrops to the north-east, near Hungerford in Queensland (not shown on the map) are believed by some to be late Mesozoic and by others to be Palaeozoic in age.

ECONOMIC GEOLOGY

Cretaceous granites were responsible for some minor deposits of gold, silver, copper, and antimony near Maryborough in Queensland; but sediments deposited in the Period are of greater economic interest. Thin but commercial seams of bituminous coal occur in the Maryborough area, and the basal Cretaceous beds provide some of the principal aquifers in the Great Artesian Basin.

Sediments of the Western Australian basins, particularly in the Carnarvon and Perth Basins, provide good storage beds for oil; the oil discovered in 1953 at Rough Range in the Carnarvon Basin was in a Cretaceous sandstone (Birdrong Formation).

TERTIARY

The Jurassic, Cretaceous and Tertiary Periods all show similar cycles of crustal sagging and inundation followed by gentle up-warping to provide, once again, a large continent of dry land. The series of lakes in the Great Artesian Basin toward the end of the Cretaceous apparently continued through into the early Tertiary; the area of depression seems to have extended westward into South Australia, but sediments thought to be of Lower Tertiary age are thin and discontinuous, and as their age is uncertain the boundary of the lakes and swamps in early Tertiary time is vague. Large areas of swampy lakes also developed in South Australia and Victoria, in which sand, clay, gravel, and lignite were deposited; in the central and eastern Victorian swamps, the major brown-coal deposits of Gippsland accumulated.

Similar, but very much smaller, lakes and swamps developed in many parts of the continent; the principal areas are indicated on figure 2. Sand, gravel, silt, and mud, with lignite in places, collected in these depressions; limestone is found particularly in north and western Australia.

In Lower Tertiary time there was a widespread, but generally quiet, outpouring of basaltic lava in eastern Australia (the Older Basalts) In many places, lake deposits and valleys with flats and terraces of stream gravels were over-ridden by basalt; many of these have been preserved below the hard basalt and are termed "deep leads"; the stream gravels commonly contain alluvial gold, which has since been recovered in places.

As the depressions formed on the continent, the sea began to transgress many of the seaboard basins. The Canning Basin received only scattered terrestrial sediments, but marine calcareous sediments were laid down continuously from Cretaceous until Upper Tertiary time in part of the Carnarvon Basin. The Perth and Eucla Basins were again briefly flooded in the Lower Tertiary; the Eucla Basin received extensive limestone deposits, which now crop out over much of the Nullabor Plain and along the coast of the Great Australian Bight. Limestone, sandstone, and calcareous sediments were laid down in the Murray Basin and in coastal basins in western and eastern Victoria; marine sediments were deposited on the north-western tip of Tasmania.

Probably towards the end of the Lower Tertiary, widespread but gentle uplifts drained the sea from the coastal basins, except in south-eastern South Australia and in Victoria, where sedimentation continued until about the end of Tertiary time. Brief incursions of the sea occurred in the Upper Tertiary in the Carnarvon Basin.

The continent, at that time, extended slightly farther east and west than it does now, and probably had land bridges southward to Tasmania and northward to the Gulf Region in Papua. The climate seems to have been temperate to tropical and pluvial throughout and gave rise to widespread "lateritization"* by deep leaching of the soils and underlying rock.

Laterite may have been formed at several different times in northern Australia - in fact it is being formed now, but suitable climatic conditions probably only occurred in Lower to Middle Tertiary time in southern Australia, for it was only at this time that mature laterite was formed. Laterites, with their typical ferruginous crusts are fossil soils and therefore mark the actual land surface at the time of their development.

The approximate present shore-line of the continent was established by further crustal movements in early and late Upper Tertiary time (Kosciusko uplift); faulting and down-warping, probably in the earlier of these movements, severed Australia from New Guinea and Tasmania and established the Gulf of Carpentaria and Bass Strait. More basalts poured out in eastern Australia (the Newer Basalts) toward the end of Upper Tertiary time; they were more restricted than those of the Lower Tertiary and occurred principally in central and western Victoria and in south-eastern and northern Queensland

PALAEONTOLOGY

With the coming in of the Tertiary, the fauna and flora begin to assume a familiar look. The marine deposits contain mainly bryozoa, foraminifera, pelecypods, gastropods, and echinoderms (sea urchins), but many other forms of marine animal life are present. At the beginning of the Tertiary nearly all forms differed somewhat from modern forms, but by the end nearly all were almost identical with them. Vertebrates are well represented in marine deposits by fish, reptiles, sharks' teeth, bird and marsupial remains, etc. Freshwater sediments have yielded many leaves and fruits with a very modern appearance, as well as abundant insects and small shells. The study of spores and pollen (palynology), which first becomes important in the Devonian, is very useful in the Tertiary and Quaternary.

IGNEOUS ROCKS

Of particular interest are the Older and Newer Basalts which still cover large areas of eastern Australia; they produce fertile red or grey lime-rich soils and contribute much to the agriculture and pastoral industries. Small areas of Tertiary basalt occur in the south-western corner of Western Australia. The form of extinct craters can be discerned in places in the New Basalts and many breccia necks are related to the Older

---

* Lateritization: A process of deep leaching of surface rocks giving rise to a characteristic soil profile, where the parent rock is chemically suitable. The generalized profile consists of a surface layer of reddish, well-cemented iron concretions (ferruginous zone) underlain by a more clayey zone, mottled in colour (mottled zone); this is underlain by white, leached rock (pallid zone) which passes downward into unweathered rock. Lateritic leaching of rocks containing alumina can give rise to aluminous laterite (bauxite), the raw material for the production of aluminium.

Basalts; however, many of the basalts from both groups seem to have originated from quiet fissure eruptions. Many basalt dykes and minor intrusives, such as sills and plugs, are known in eastern Australia. Another interesting group of Tertiary rocks is the alkaline lavas, tuffs, and intrusive plugs which occur sporadically in eastern Australia. The principal localities are the Glasshouse Mountains in south-eastern Queensland, the Warrumbungle and Canobolas Mountains and Mt. Gibraltar in New South Wales, and Mt. Macedon in Victoria. Similar plugs occur in the Fitzroy Basin in Western Australia. All these alkaline rocks appear to be of Lower Tertiary age.

ECONOMIC GEOLOGY

Of first importance are the extensive brown coal deposits of Victoria which provide most of the State's electric power and solid fuel. Deep leads have been prolific producers of alluvial gold, particularly in New South Wales and Victoria, and have produced alluvial tin in Queensland, New South Wales, and Tasmania. Many of the igneous rocks are useful sources of aggregate and building stone; limestone and clays are used in the manufacture of cement, bricks, and tiles.

Australia's bauxite deposits are the result of Tertiary lateritization. Major deposits at Weipa, Cape York Peninsula, were formed by the lateritization of Tertiary sediments; those at Gove and Wessel Island were derived from Precambrian shales. Very much smaller deposits in southern Queensland, New South Wales and Victoria and Tasmania were formed by the lateritization of Older Basalts.

Tertiary sequences in the major sedimentary basins provide some additional source and reservoir beds for petroleum; but in general Tertiary sediments seem more important as cover-rocks, to confine oil within older sequences, than as producers themselves. Some oil has been found in a Tertiary greensand in eastern Victoria but production was not economic.

QUATERNARY

The principal geological events in Quaternary time were the continuation of some of the crustal adjustments and of volcanic activity noted in the late Tertiary, the Pleistocene ice age, and fluctuations in sea level due to the waxing and waning of polar ice caps. Deposits of the Period include some volcanics, all of the unconsolidated sediments of the coastal plains, sand dunes, and much of the cover of the alluviated inland plains. In many places, these inland plains are labelled "Cainozoic" on the map because they contain deposits of both Tertiary and Quaternary age.

Probably the most spectacular crustal movements in the earlier Quaternary were the faulting and tilting of crustal blocks in central South Australia which produced the large depressions which occasionally flood and become vast lakes (Lake Eyre, etc.). The very gradual sinking of the continental shelf of the north Queensland coast began about this time and initiated the Great Barrier Reef, which continued to build upward as the shelf gradually sank. Smaller crustal adjustments continued on from Tertiary time in many parts of the continent, particularly in eastern Australia, and the earthquakes recorded from time to time within the continent are largely a faint echo of them. Some volcanic activity in the areas occupied by the Newer Basalts continued into the Quaternary, particularly in south-eastern South Australia and northern Queensland, where end phases of vulcanism extended into Recent time.

The third of the major ice ages which have occurred on the Australian continent began about half a million years ago in the Pleistocene Epoch and continued in cycles till about 20,000 years ago. Periods of intense cold and glaciation alternated with "interglacial" periods when the climate was warmer and ice caps shrank. The complete sequence of events has not yet been worked out; but there appear to have been at least three main phases of glaciation, in which the mountains of south-eastern New South Wales, eastern Victoria, and western Tasmania were covered by an ice sheet or sculptured by valley glaciers. The evidence of glaciation - the rounding of valley features by ice and the occurrence of "moraines", accumulation of rock debris carried by the glaciers - persists down to an altitude of about 5,000 feet in the Mt. Kosciusko region of New South Wales and Victoria, and much lower in western Tasmania.

Changes of climate during the ice age, giving rise to glacial and interglacial periods, also caused major fluctuations in the level of the sea. The extension of polar ice-caps in the glacial periods withdrew water from the sea, which fell as much as 300 feet below its present level. During warmer periods the ice caps were partly melted, and the sea rose, at times above the present level. The most recent change came some 5,000 years ago, when the sea gradually fell 10-15 feet, leaving caves, wave-cut platforms, and raised beaches as evidence of its previous higher level. Many features of the Australian seaboard are the result of these fluctuations; the sheltered deep water harbours are drowned valleys, cut when sea level was some hundreds of feet lower than it is now; the coastal flats and lagoons are legacies of the Recent fall in sea level.

PALAEONTOLOGY

The Pleistocene saw the extinction of numerous gigantic marsupials whose remains have been preserved mainly in swamp and cave deposits in association with plants and other animals which differ little if at all from those living today. Some animals and plants now unknown on the mainland, except from cave and swamp deposits, are still living in Tasmania. Pollen grains are an important feature of both Tertiary and Quaternary fossil floras.

ECONOMIC GEOLOGY

Quaternary unconsolidated sediments provide most of the sand supplies, and river gravels supply aggregate. Recent sand deposits along the coasts provide prolific supplies of ground water, which is tapped for domestic purposes in many places and for major industrial use in Newcastle and Sydney.

The concentrations of the heavy minerals - rutile, zircon and ilmenite - in beach sands along the coasts of southern Queensland, central and northern New South Wales and of south-western Western Australia (ilmenite) occurred in Quaternary time.

ACKNOWLEDGEMENTS

Much of the information given in this commentary came from geological literature and particularly from "The Geology of the Commonwealth of Australia" by T.W.E. David, edited by W.R. Browne. A list of the principal references is given below.

Additional and revised information has been obtained from sources within the Bureau of Mineral Resources, Geology and Geophysics, and the writer gratefully acknowledges the help and co-operation of many colleagues, particularly of E.M. Smith, G.A. Thomas, J.M. Dickins, A.A. Opik, M.A. Condon, J.J. Veevers and D.A. White.

The "Australian record of Life" (Plate 1) was prepared by G.A. Thomas.

PRINCIPAL REFERENCES

DAVID, T.W.E. 1950 - The Geology of the Commonwealth of Australia. Edited by W.R. Browne. London, Arnold.

GLAESSNER, M.F., and PARKIN, L.W. (ed), 1958 - The Geology of South Australia. J. geol. Soc. Aust., 5 (2).

McWHAE, J.R.H., PLAYFORD, P.E. LINDNER, A.W., GLENISTER, B.F., and BALME, B.E., 1958 - The Stratigraphy of Western Australia. J. geol. Soc. Aust., 4 (2).

OPIK, A.A., and others, 1957 - The Cambrian Geology of Australia. Bur Min. Resour. Aust. Bull. 49.