The Structural Features of the Margin of Australasia.

By W. N. BENSON, B.A., D.Sc., F.G.S., F.R.G.S., Professor of Geology, Otago University.

[*Read before the Otago Institute, 12th December, 1922*; received by Editor, 31st December, 1922; issued separately, 26th May, 1924.*]

IN previous papers the writer (1923, 1924) has summarized the various hypotheses concerning the growth of Australasia, the distribution and nature of the Palaeozoic and Mesozoic marine rocks, and the location and conditions accompanying the intrusion of the basic and ultrabasic plutonic rocks. These all indicate the peculiar interest attaching to the northern and eastern margins of the Australasian area. In the present paper it is proposed briefly to discuss the tectonic features and later geological history of this marginal zone, following it down from the East Indies to New Zealand, and to note whether by so doing any new light is thrown on the structure or history of New Zealand itself. Attention will be confined to the western and southern islands of the East Indies, New Guinea, and the other islands of the first Australian arc of Suess (1909), and but little discussion will be given of the area within the Fijian lobe of the Australasian margin indicated by Marshall (1911), or the more extensive regions between the first and third Australian arcs of Suess. Concerning these, however, we shall merely note Suess's comment (1909, p. 517) on the possibility that Vitu Levu may be part of an older segment between the branches of a virgation spreading northwards from New Zealand, to which the Kermadec–Tonga trench forms the foredeep. Consideration will also be omitted of the still more widespread influence of the Australasian tectonic system implied in recent papers by Andrews (1922) and Hobbs (1922) on the growing mountain-ranges on the floor of the Pacific. Such omission does not imply a denial that these areas come within the influence of the Australasian tectonic system, but only that the present writer is unable to add anything of moment to the discussion of the points raised. This discussion is to be found in the work of Woolnough (1903), the authors cited above, and others to which the reader is referred.

Commencing with an account of the Malay Archipelago: It has been shown by recent geological studies—*e.g.*, those of Molengraaff (1921), Wing Easton (1921), and Brouwer (1922)—that the line drawn by Wallace to divide the Malay Archipelago into an Asiatic and an Australian biological province has also a tectonic importance. It separates a western relatively stable region of islands rising from the shallow Sunda and South China Seas, wherein the Tertiary sediments are but slightly folded, from an eastern area of marked instability and intense Tertiary orogeny in which folding continues up to the present era. This second region, again, is bounded by a line drawn round the south-eastern margin of the Banda arc and eastwards through southern New Guinea, separating it from the stable region of the Sahul Bank, Arafura Sea, and southern New Guinea, the outlying portions of the

* Also in Wellington before the sixteenth meeting of the Australasian Association for the Advancement of Science, January, 1923.

FIG. 1.—Bathymetrical map of the Malay Archipelago, &c., based on data assembled by Molengraaff and Tydeman (1921), Sieberg (1910), and Groll (1912).

FIG. 2.—Major tectonic features of the East Indies, New Guinea, and Solomon Islands.

Australian continental massif. Thus the unstable, flexible, or geosynclinal region is compressed between the two continental massifs. Into this yielding area were concentrated the combined or antagonized effects of the circumpacific and Tethyan series of orogenic forces, and the great folding and fracturing in this region results from these forces. According to the views of Volz (1899), Richthofen (1900), and Ahlburg (1913), there has been formed a network of obliquely-intersecting tensional fractures, because the thrusts from the two continental masses exerted a screw-like torsion, acting in directions not actually opposed to one another. This is the view cited by Hobbs (1921); but the investigations of Wanner (1913, 1921), Molengraaff (1913, 1921), and Brouwer (1917, 1922) seem rather to indicate that the dislocations result from intense compression, with orogenic overthrusting or underthrusting at some depth and block-faulting at the surface, a view which is in part followed here.

The Asiatic portion of the Malay Archipelago consists of Sumatra, Java, Borneo, and the regions between them. The Mesozoic rocks are generally of shallow or moderately deep-water origin throughout, though in central Borneo what are held to be abyssal deposits are rather widespread. They are succeeded by a littoral or shallow-water type of Eocene beds with a fauna of a markedly uniform provincial character, and this faunal uniformity throughout the region has been maintained and strengthened up to the present day, and is illustrated, *e.g.*, by the similarity of the fishes in the rivers of north-eastern Sumatra and Java and of western Borneo, the valleys of which have been found to unite beneath the South China Sea, which covers a submerged peneplain (Molengraaff, 1921).* Crust-folding was relatively small in this region during Tertiary times. The whole area is ridged into a broad festoon of arcuate anticlinal folds, convex towards the south, and converging into a knot in the north-eastern portion of Borneo, and again in the north-western point of Sumatra (see figs. 1 and 2), whence the outermost of the anticlinal axes, which runs through the islands off the west coast of Sumatra, may be traced northward through the Nicobar and Andaman Islands into the Arakan Yoma. The chief folding occurred in Cretaceous times; the Permian, Triassic, Jurassic, and older Cretaceous strata are greatly disturbed, considerable overthrusting having occurred, and are invaded by plutonic rocks. Permian (?)† limestones are found superposed on Cretaceous sediments, or on Cretaceous granite, without any evidence of contact-metamorphism. The eroded surface of this complex is covered by Eocene littoral conglomerates and sandstone, with coal-measures followed by nummulitic limestone, Oligocene-Miocene foraminiferal limestones, and sandstone, on which lie unconformably younger Miocene marls and tuffs with Pliocene

* According to Molengraaff (*op. cit.*), this submergence was due to the general rise of the sea-level subsequent upon the melting of the extensive ice-sheets of the Pleistocene glacial period, a feature which Daly has discussed. The Sunda Sea is rarely more than 30 fathoms deep. In the absence of much definite information Molengraaff has suggested tentatively a like explanation for the Sahul Bank, which lies at about the same depth.

† Professor Wanner, however, has informed the writer (22nd May, 1923) that Van Es's correlation of the Palaeozoic limestones of northern Sumatra with the Permian formation of Timor, cited in the previous paper (Benson, 1923, p. 34), is not, in his opinion, supported by a sufficient faunal similarity, and Fliegel's determination of them as Upper Carboniferous should stand.

sandy claystones and lignites. Very important crust-warping and block-faulting occurred in Upper Pliocene times, which determined the form and position of the present coast-line, the raised coral-reefs, the main *graben* river-valleys, and many minor topographic features. The most marked of these *graben* extends almost throughout the length of Sumatra, and is separated by a relatively narrow range from the south-western coast. These latest structural lines often cross obliquely the older anticlinal axes, and are themselves intersected by many transverse and oblique fracture-lines, on which, as on the longitudinal fractures, there have been many points of volcanic eruptions.

Analogous conditions exist in Java. The area of exposed Cretaceous sediments and plutonic rocks invading older sediments is very limited. The varied nature of the Cainozoic sediments indicates that considerable geographic changes occurred during the Tertiary period. Verbeek and Fennema (1896) held that two unconformities occur, Oligocene-Miocene and Lower-Upper Miocene respectively. Tobler (cited by Van Es, 1917) holds that the greatest movement both here and in Sumatra was at the close of the Tertiary period, the folding preceding the deposition of the extensive Pleistocene sediments; but Van Es considers it was in progress during and after the Tertiary times.* It is more marked in the older central geanticlinal portion than in the younger flanking sediments, the steeper dip of the southerly-dipping beds indicating the southward (outward) direction of superficial thrust. The periods of greatest movement appear to him to have been in Miocene and post-Tertiary times. By the latter, Pleistocene coral-reefs have been raised as high as 2,500 ft., and the maximum uplift occurs where the Tertiary folding is most marked, the parallelism in location and direction being such as to indicate the intermittent action of a single group of forces of long duration. The outermost of the geanticlines is seen in the long submarine ridge rising to a depth of less than 1,000 fathoms, and separating an off-shore synclinal trough 1,500–2,000 fathoms deep from the foredeep over 3,000 fathoms deep. Continued to the west of Sumatra, however, this outermost geanticline rises above the surface to form a string of islands including the Mentawei Group.† As in Sumatra, so in Java, longitudinal, transverse, and diagonal fracturing was accompanied by block-faulting and volcanic eruptions at various times from middle Tertiary to the present date, and was instrumental in determining the present topography.

East of Java the main geanticlinal axis, with the volcanoes thereon, no longer forms a gently accentuated ridge marginal to a partially submerged plateau with the deep sea on one side only, but instead is a high and narrow ridge rising from considerable depths and broken by cross-fractures. It runs through Bali, Lombok, Sumbawa, Flores, and that string of islands, from Dammer to Banda and Gunong Api, forming the innermost of a series of discontinuous arcuate ridges separated by similarly interrupted troughs. The structure of this arc is not very clearly known, but,

* Martin (1919) states, however, that the recognition of the various subdivisions of the Tertiary rocks in Java has rarely been based on palaeontologically satisfactory evidence, and the stratigraphical relationships of the several formations to one another are only exceptionally known. He therefore counsels caution in the acceptance of such generalizations as these.

† Molengraaff (1922) suggests that another anticlinal ridge existed still farther to the south-west, which has since subsided isostatically into the depths of the Indian Ocean, leaving Christmas Island as its sole representative above sea-level. Andrews (1900) has shown that this remnant consists of volcanic rocks and littoral calcareous formations, coral-reefs, &c., ranging in age from Oligocene to Recent.

at any rate in Sumba, between it and the outer arc there is no evidence of the occurrence of Miocene overthrusting. It is overlapped by an outer arc which, beginning at Savu, runs through Rotti, Timor, Letti, Babber, and the Tenimber Islands, and, according to the Dutch geologists, it continues thence by the Kei Islands to Ceram and Buru, though alternative conceptions have been entertained by other writers. Throughout this whole zone very extensive crust-movements have occurred and are still in progress.

While Suess's diagram (vol. 3, p. 235) of the trend-lines of the Philippine and Sunda Archipelago, "based on the writings of Drasche, Molengraaff, Hooze, Wichmann, Martin, Koto, and others," illustrates this conception of a continuous geanticlinal ridge, he was not himself convinced of its correctness, for he remarks as follows (vol. 3, p. 243): "It is in itself scarcely probable that the cordillera which comes from Sumba and Timor should reappear here [in Ceram and Buru] in full development after having been broken up into a series of small islands and reefs. I am therefore inclined to regard the arc of Timor as uniting with another independent chain striking east and west, and believe that Buru and Ceram should be looked upon as the continuation of the southern peninsula of [north-western] New Guinea." This view was supported in some degree by Boehm (1906) and lately by Gregory (1923, 1923A), and it must again be considered after the general structure of the Banda region as conceived by the Dutch geologists has been described.

Consideration will now be given to the outer arc and the Banda Sea, which whole region, according to Molengraaff (1921) and Brouwer (1917, 1922), illustrates conditions analogous to those which existed in the Alpine regions of Europe during Mesozoic and early Tertiary times. Brouwer's (1922) most recent statement may be cited: "The tectonic features of the East Indian Archipelago as they now exist are the result of orogenic forces which have been acting during long periods of time and have caused movements in a horizontal direction in many places. Where the lands were high above the strand-lines of the surrounding seas the ranges were cut down, and the deeper parts were uncovered by erosion; where at the same time the crust was moving below sea-level no denudation took place, and no unconformities and disconformities in the succession of strata are found. The latest crustal movements are only a younger stage and a direct continuation of the Tertiary crustal movements. The Tertiary folds and overthrusts, which were formed at relatively great depth, are now visible at the surface, but the fissured and faulted crust that once lay above them has been removed by erosion. On the other hand, the tectonic features due to late deformation near the earth's surface during the younger stages of mountain-building have remained visible, and are manifested in the fissured and faulted crust, while the accompanying folds and overthrusts remain invisible at greater depths. In the parts of the earth's crust now visible in the different islands the erosion-intervals are not found at the same place in the geological time-table. For the major tectonic features it is sufficient to describe the visible traces of two stages of crustal movements, the late Mesozoic and Tertiary stages, and the youngest stage, which still continues. The youngest stage is definitely known to be limited to certain parts of the present archipelago, while the distribution in time and place of the older stage is not definitely known." In the Alps the early Mesozoic formation and accentuation of anticlines and synclines was succeeded in Cretaceous times by strong horizontal movements, which "reached their maximum in the Tertiary period. As the overthrust sheets moved at greater depth, the sea-basins became narrower, and the masses of the geanticlines were pushed forward in a nearly horizontal direction. . . . [Such] horizontal movements of the curving rows of [East Indian] islands are proved by several features now observable on these islands, and as these movements proceed the sea-basins will be narrowed, and eventually the masses of the present geanticlines may be pushed over the Sahul shelf of the Australian continent."

This may be illustrated by summarizing the stratigraphical succession and the tectonics of certain islands in this Banda arc. From Timor to south-western New Guinea the Permian sediments are of shallow-water origin, and are locally interstratified with basic igneous rocks. Probably much of the region was dry land in Permian times. In Timor the Permian sediments pass unbrokenly into Lower Triassic rocks, but the absence of the latter in other regions bears witness to a general marine regression of the sea in Lower Triassic times, followed by a very widespread Upper Triassic transgression. The sediments were largely of deep-water origin, being foraminiferal and radiolarian deposits, with some manganese-nodules, like those in modern abyssal ooze. These pass laterally into littoral formations, indicating diversified conditions of deposition on the synclines and anticlines of Upper Triassic times, the two facies of Triassic rocks being often brought into close apposition by the subsequent overthrusting. The Jurassic conditions resembled those of Upper Triassic times: the Jurassic sediments are partly those of deep-sea origin, but shallow-water deposits only occur in Misol and the Sula Islands. These general conditions continued up into Lower Cretaceous times, with apparently numerous local lacunae in the sequence of strata, the diversity of sedimentary facies resulting from the constant formation of geanticlinal ridges on which neritic sediments were deposited, and which were thrust forward along gently inclined planes of faulting at geosynclinal depths. These crust-movements were very marked in Cretaceous times, when the sea retreated from much of the present East Indian land-areas. The free connection between the eastern Australasian region and the Tethys was broken (Martin, 1914), and numerous plutonic intrusions were formed. It is difficult to state exactly the directions of strike of these late Mesozoic folds, for they have been greatly modified by the later Miocene orogeny. The orogenic stresses being temporarily relieved, a general subsidence occurred with the transgression of a shallow sea over Rotti, Timor, Letti, Ceram, and Buru, depositing Upper Cretaceous foraminiferal marls, accompanied by the formation of more littoral deposits in Celebes. This transgression was further extended in early Tertiary times, and the deposits formed were more diversified—littoral conglomerates, sandstones, and clays predominating in the western part of the archipelago, foraminiferal limestones in the eastern, while associated with these in Bali, Sumbawa, Flores, and Sumba is a large amount of andesitic débris. The formation of the present deep-sea basins and other crust-movements began in Miocene times.

The older Tertiary rocks in Timor, and continuing thence into the Banda arc, have been intensely folded into a mountain-chain and overthrust outwards. The directions of these Middle Tertiary anticlinal axes are often oblique to the present coast-lines or the trend of the later Tertiary geanticlines. The phenomena of *klippen* (or, as the Dutch geologists prefer to call them, *fatus*, using the local Malayan term) are clearly developed: "Groups of deposits of the same age but of different palaeontological and petrographical character are found one on top of the other, and isolated rock-masses of older formations are found resting on younger oceanic deposits; as is clearly visible among the deep ravines cut on the recently elevated islands, Timor and Babber. The structure is usually chaotic, and is similar to that of the higher overthrust sheets of eastern Switzerland, which were moved in the near-surface zone, where the rocks yielded to pressure not by flow, but mostly by fracture. The comparative method of study leads to the supposition that on Timor the deeper complicated but less chaotic overthrust structures such as are found in the Western Alps have not here been uncovered by erosion" (Brouwer).

There is, however, a marked variation in the intensity of disturbance. In Sumba there is no trace of overthrust-folding, and this forms the backland to the Timor zone of overthrust. Approaching the Australian foreland, also, the folding-structures in Timor are of somewhat simpler character, for the southern coast-range of this island has merely an imbricated structure with fairly uniform dip. The Aru Islands, believed by the Dutch geologists to be on the margin of the continental massif, form but a swelling thereon. They exhibit only Pleistocene (and Upper Pliocene ?) marine limestones, &c.

Again, in north-western New Guinea north of MacCluer Gulf normally folded Tertiary rocks occur, as also in the Misol-Obi-Sula chain of islands, in which even the Jurassic strata, which are of shallow-water origin, are sometimes nearly horizontal, though locally sharp folding without overthrusting may occur (Boehm, 1906; Brouwer, 1921B). This region then seems to have been comparatively stable, and at least adjacent to a landmass during the Cretaceous and Tertiary periods of folding. The schistose pre-Jurassic rocks of the Sula Islands, the strike of which is markedly oblique to that of the Tertiary folds, may perhaps represent a portion of that ancient block. This block, thus relatively stable during the Cretaceous and Miocene foldings, seems to have been in some measure like a foreland to the great outward-moving superficial thrusts of the Miocene folding in Ceram. According to the views of the Dutch geologists, the strike of these folds is in the main the continuation of the Banda arc, but is complicated in regard to details. It is not parallel, but oblique, to the coast of this island, running south-east - north-west through middle and eastern Ceram, bending into an east-west direction in western Ceram, and inclining to the south-west into the terminal Huamoal Peninsula. These directions of strike are displayed both by the crystalline schist and gneisses along the southern side of the island, and the fossiliferous Triassic and later Mesozoic sediments along the north. Crossing Manipa Strait, however, the strike bends sharply to the north-west, as is shown by the schists of Manipa Island itself, and by the several zones of formations which cross Buru. These zones are, in succession from north-east to south-west, as follows: Crystalline schists, &c.; Triassic sandstones and shales; fossiliferous Triassic,* later Mesozoic, and early Cainozoic sediments; and they are therefore arranged in the opposite order, as regards the Banda Sea, to that displayed in Ceram. According to the Dutch geologists, there is an outward or northern thrust

* Professor Wanner has informed the writer (22nd May, 1923) that the supposed Upper Cretaceous molluscan fauna of Buru characterized by *Tissotia*, mentioned in the previous paper (Benson, 1923, p. 50), is really Upper Triassic (Noric), the characteristic form, when better specimens were examined by Krumbeck, having proved to be *Neotibetites*. The Upper Cretaceous form *Trigonosemus*, reported to have been found in Obi, is a Belgian shell, and was probably brought there by a Belgian prospector. Wanner himself found no trace of Cretaceous rocks in this island.

of the various formations in Buru as well as in Ceram; but this Wanner (1921) opposes, holding that in Buru the thrust was directed from the north-east towards the south-west. He compares this apparent reversal of the direction of thrust of a geanticlinal axis where a sharp kinking has occurred with the conditions on either side of the Straits of Sunda, believing, with Van Es (1917), that the direction of thrust in western Java is to the south; while, according to Tobler (1906), it was towards the north-east in the adjacent portions of Sumatra. According to a verbal communication made to the writer by Professor Brouwer, however, there is not a general acceptance of this conclusion of Tobler's. Wanner and Brouwer (1922) also suggest that the further continuation of the axis of Buru occurs in the neighbourhood of Sula Besi, the crystalline schists of which resemble those of Buru, and strike in a north-westerly direction, except for a single instance of an east-north-easterly strike which has been recorded, and he remarks that such a connection accords better with the zoogeographic evidence than the extension south-westwards to Tukang Besi, which Molengraaff (1921) has supposed might have existed.

Some comment may here be made on the rôle played by the Sula Islands, Obi, and Misol, which we have stated were in some measure like a foreland to the folds in Ceram, following Suess's conception, originally accepted by Wanner. As the result of continued investigation, Wanner (1921) now doubts the propriety of considering Misol at least as portion of a continental platform, for the moderately folded Mesozoic rocks which lie upon the crystalline rocks are similar in all essentials to the coeval formations that occur much more highly folded or even overthrust in Ceram*—so much so that they must be considered as having been deposited in the same geosynclinal depression. The relations of Misol to Ceram are indeed much more marked than its relation to Obi and the Sula Islands. It may be best to consider it as an outer portion of the geosyncline which has suffered relatively slight folding, rather than part of a foreland massif.

In attempting to trace the Miocene folding farther to the west the structure of Celebes must briefly be considered. This is a matter concerning which very diverse views have been expressed by Koto (1899), Sarasin (1912), Ahlburg (1913), Abendanon (1917), and others. According to Abendanon (1917), the whole region from south-eastern Asia to Tasmania in Palaeozoic times formed a single continental massif, which he termed "Aequinoctia." Thus he explained the apparent absence of pre-Permian marine fossils from the East Indies, though the occurrence of *Spirifera verneulii* (*S. disjuncta*) has recently been discovered in Celebes (Brouwer, 1919),† and may indicate the presence of Upper Devonian beds. There are widespread phyllitic rocks, possibly Palaeozoic, among the older formations invaded by the granites, &c. The presence of some such land-mass which would divide the stream of Asiatic forms migrating towards Australia might perhaps account for the difference between the later Palaeozoic faunas of the eastern and western regions of Australia noticeable in Devonian and Permian times (*cf.* Benson, 1923A, pp. 27, 31). Abendanon held that this land-mass was broken up in Carboniferous times, when an extensive submergence took place, and in the central region (now the

* A point of special interest to New Zealand geology is the occurrence in both Misol and Ceram of dark greywacke sandstones containing *Terebellina* ("*Torlessia*") *McKayi*, as noted by Wanner (1921).

† Some obscurely preserved brachiopods, &c., found recently in the north-western peninsula of New Guinea may be of like age, according to a verbal communication from Professor Brouwer.

Banda Sea) orogenic forces commenced to act, and have affected the region intermittently and more or less powerfully up to the present day. The present islands are considered by him to rest on disrupted fragments of this older platform, which, with their covering of Permian, Mesozoic, and older Tertiary rocks, have been greatly dislocated and folded during the subsequent orogenic epochs. The crystalline schists and gneisses of Borneo, western and central Celebes, Buru, Ceram, and north-western New Guinea are held by him to be the exposed portions of this ancient platform, and he states that they exhibit a dominantly east-west strike varied to some extent by the post-Permian crust-movements.* Wanner (1919) is of the opinion, however, that the known instances of an east-west strike in the crystalline rocks of Celebes are far too few to establish definitely the existence of a pre-Miocene trend-line in this direction, and notes that the strike of the Miocene folding and the extension of the plutonic intrusions connected therewith (which frequently exhibit gneissic marginal facies) is usually in a north-westerly to north-north-westerly direction. Thus the trend of the Miocene folds in western, central, and south-eastern Celebes would appear to overlap, coulisse-like, the trend of the coeval folds in Buru. A like north-westerly or north-north-westerly strike is exhibited by the crystalline schists, &c., which form the base of the largely volcanic mass of the Minahassa Peninsula. In eastern Celebes strikes to the north-east have been noted in the slightly folded late Tertiary beds, but the main mass of the eastern peninsula consists, according to Wanner (1910), of massive horizontally-lying Eocene and Oligocene limestones, marls, and sandstones, locally upturned along a north-westerly strike. Here also Hotz (1913) has found grey-blue shales, containing belemnites, which resemble the Jurassic rocks of the Sula Islands. Thus the eastern arm of Celebes may perhaps form an outlying portion of the more stable region north of the zone of intense folds sweeping through Buru, south-eastern and central Celebes. It is noteworthy that basic intrusive rocks are particularly abundant in the margin of the folded rocks. A vast mass of peridotite occurs in south-eastern Celebes associated with diabasic rocks, and these extend to the north along the western side of the fault-bounded series of depressions extending through Tomori Bay from Tolo to Tomini Gulf These ultrabasic rocks were injected apparently during the late Mesozoic orogeny, and the late Cretaceous-Eocene marine sediments rest on their eroded surfaces, but there are, in addition, a series of Middle Tertiary intrusions of gabbros, &c.

The trend-lines of the Malay Archipelago are thus traced in accordance with Brouwer's (1922) charting (fig. 2). A point of detail should, however, be noted concerning the direction of the individual fold-axes. Brouwer (1922) points out that where the general trend of the geanticlinal zone is sharply bent, as in Babber, the individual fold-axes cross the main trend-direction almost perpendicularly. This is believed to result from differences in the amount of horizontal movement of the geanticline at depth and at the surface. The obliquity of the strike-line of the Mesozoic rocks of the Tenimber and Kei Islands to the direction assumed for the Banda arc in that region has had a very different interpretation, as will appear below.

* It is conceivable, however, as Professor Brouwer verbally indicated to the writer, that the crystalline schists of the region assumed by Abendanon to be the pre-Cambrian basement of the supposed Palaeozoic continent may be really the highly altered representatives of a long series of Palaeozoic geosynclinal sediments metamorphosed during the later Palaeozoic orogeny.

These orogenic movements were followed by long-continued denudation and widespread transgression of the sea, with the deposition of the petroliferous later Tertiary rocks, *Globigerina* limestones, and terriginous sediments, marls, clays, sandstones, and conglomerates, with increasing diversity of lithologic facies as the later Tertiary crust-movements became pronounced. These are succeeded by oyster-banks and (especially) coral-reef formations making a concordant series of deposits, followed, after further warping, by locally-widespread late Pliocene or Pleistocene reef-limestone, such as that which covered the greater part of Timor.

A considerable amount of volcanic activity occurred during the later Tertiary period, though it is not always easy to differentiate its products from those of earlier Tertiary age. Thus in south-western Celebes, "probably a short time before the deposition of the Tertiary limestone ('partly Eocene and partly Miocene') had completely terminated, eruptions began all along the western side . . . which gave rise to the high western mountains; for the greater part they consist of tuffs, breccias, volcanic conglomerates, of andesites, basalts, and also of leucite-rocks," while intrusive essexitic and shonkinitic rocks also occur. Farther north in the same island, however (the Latimodjong Range), the eruptions seem to have stopped before the newer Tertiary period. Leucitic rocks are also known to belong to the younger Tertiary formation in Sumbawa (Brouwer, 1917B).

The disposition of these formations renders clear the extent and nature of the Plio-Pleistocene crustal movements. The presence of uplifted fringing reefs is seen in nearly all the islands, where they sometimes form definite "reef-caps," the amount of the uplift being occasionally as much as 4,000 ft. "The uplift of islands has not, however, been simultaneous, nor equally intense, while periods of temporary subsidence have probably interrupted the general elevation since the Plio-Pleistocene period." The appearance of tilting presented in certain islands where raised coasts on one side of the island contrast with the subsidence observable on the other may not, however, really involve mere tilting of crust-blocks. Brouwer (1918) urges that in the forward wave-like propagation of a geanticlinal crest there would naturally be a depression on the rear slope of the crest related to the uplift on the forward limb, which depression might extend beyond the limits of that portion of the crest remaining above sea-level, thus giving rise not merely to differential uplift of the forward and rear coast-lines, but actually to features indicative of coastal drowning. Other things being equal, the greatest uplift will be seen in the widest islands. Thus in the case of Timor, which by the end of Pliocene times had been reduced by erosion to a cluster of low islands rising from a shallow shelf-sea, the sheet of reef-limestone then formed has since been arched upwards asymmetrically to a maximum height of 4,000 ft., contrasting thus with the arching that reaches a height of 1,300 ft. in the narrower island of Rotti, and only 460 ft. in Jamdena (the largest of the Tenimber Group). This group indicates another phenomenon. It consists of an eastern and a western portion, the former including Jamdena, and the latter a row of much smaller islands, in which, however, the elevated reef-caps stand at heights of up to 700 ft. This appears to result from the development of a small synclinal fold separating the two islands on the main geanticlinal ridge. The sharpness of this ridge is well marked at the Kei Islands, a short distance farther north, which rise between depths of 3,300 and 1,600 fathoms to the west and east respectively.

The main trend-lines of the later stage of mountain-making are now accurately known, and coincide approximately with the longer axes of the islands, while the deep-sea basins are found to be elongated arcuate synclines parallel to the adjoining rows of islands. The continuation of such movements is shown by the frequency of earthquake-shocks along the trend-lines, while they are notably absent from the stable region of eastern Sumatra, northern Java, Borneo, and the southern China Sea. A very noteworthy feature is the obliquity of the modern geanticlinal axes to the strike of the Tertiary folds, which want of parallelism Brouwer explains by the supposition "that the rows of uplifted and fragmented island-blocks indicate the places where at a greater depth folding continues, and that there is motion in a vertical direction as well as considerable motion in a horizontal one. The vertical movement will cause gradual erosion, and the exposed surface of the geanticline will in time consist of rocks which were in the zone of flow during an earlier stage of mountain-building. The rate and direction of the movement of the deeper-lying rocks as they approach the earth's surface may differ more and more from the rate and direction of motion of the rocks that lie at still greater depth."

Of noteworthy significance in connection with these movements is the distribution of the ancient and modern volcanic centres. During the recent crustal movements in the outer row of islands around the Banda Sea, where the crust has been thickened as a result of overthrusting, the magma has not reached the earth's surface, while the inner row, with a thinner crust, is characterized by a great number of volcanoes on the top of the geanticline. Where the two rows are nearest to one another, just now at Timor, there are no active volcanoes on the inner row, and the volcanoes on this row appear to have become extinct at a later and later period as their distance increases from this point and thus also from the stable Australian massif. The horizontal movements then progressively so increased the thickness of the crust in this zone as to stop up existing vents and prevent the formation of others. "We see in the inner row of islands of the south-eastern archipelago an instance of extinction of volcanic activity on the top of the geanticline during a renewal of the mountain-building process" (Brouwer, 1917).*

* It may be permissible to cite a few more sentences from this work (pp. 803–4): "If tangential pressure reveals itself in the formation of normal folds the molten magma will, under compression from all sides, force its way through the crust, with unequal strain first near the top of the anticlines where tension takes place. . . . In the case of disruption . . . the tension of the anticlinal and synclinal tops disappears or decreases, and the vents of the volcanic magma leading to the surface, maintained by the tension, can gradually be stopped up. Movements on a large scale will give rise to overthrust sheets, [and] the earth's crust *in situ* will increase in thickness, an additional reason for the stopping-up of the volcanic vent. A new way is opened for the magma to reach the surface along the thrust-planes. Most often the magma, if it reaches the surface, will appear on a lower level—*i.e.*, in the region here discussed, below the surface of the sea along the outer margin of the row of islands—and movements in the direction of the 'Vorland' will cause the volcanic products to be gradually overlain by the moving masses." In discussing the origin of the "green rocks" of the Alps and the older basic volcanic rocks of the Malay Archipelago the writer (Benson, 1924) independently put forward a view very similar to the above, adding that by the consolidation of the later drafts of basic magma rising along the thrust-plane, between the overthrust crust-flake above and the overridden submarine lavas below, there may be produced those intimate associations of gabbro-peridotite and pillow-lava that form so noteworthy a feature in the Mesozoic rocks of Switzerland—*e.g.*, in the Engadine—and in those of the Malay Archipelago.

The distinction here introduced between those parts of the archipelago in which the crust is still thin and those which have become thickened by overfolding recalls the new orogenic conceptions of R. T. Chamberlin (1919, 1921), who distinguishes between thick-shelled mountains (characterized by open gentle folding, a moderate crustal shortening affecting a relatively deep zone and strong uplift with vertical movement and normal faulting) and the contrasted thin-shelled mountains affected by intense deformation, leading to great overthrusting, especially in the marginal portions. Applying these conceptions to the eastern portion of the Malay Archipelago, it would seem as if the mid-Tertiary movements were characteristically of the thin-shelled type, and the overthrusting resulting therefrom thickened the crust sufficiently to cause the later movements to have more of the features of those in thick-shelled regions. The Plio-Pleistocene folds are broken by very many fractures. In opposition to Richthofen's view, cited by Ahlburg (1914) and Hobbs (1921), that these fractures result from tensional strains in a region nipped between the diversely thrusting Australian and Asiatic continental masses, Brouwer holds they are the surface expression of the vertical and horizontal movements which result from compressional stresses, and occur where there are important differences in the rate of movement in the underlying rock-masses if the fissures are approximately longitudinal, while transverse fractures result from a difference of velocity of horizontal movement in neighbouring parts of the geanticlinal axis. These fractures have broken across the geanticline, in many places separating the ridge into a number of separate islands. A very notable instance of this is the narrow Manipa Strait, over 2,000 fathoms deep, between Ceram and Buru. It occurs at a point of sharp flexure in the geanticlinal axis, which Brouwer (1921) points out should naturally be a point where fracturing might be expected owing to the differential movement of adjacent portions of the anticlinal ridge. Wanner (1921) accepts this view, and thinks it probable that the differential movement may here be measured in several tens of kilometres.

Among the regions hitherto discussed, however, it is in Celebes that the thick-shelled type of crust-movement is most in evidence. Here Plio-Pleistocene dislocations both in the region of crystalline rocks and elsewhere have formed a regular network of high mountain-blocks, which alternate with more or less depressed blocks in which are preserved the slightly-folded remnants of the formerly extensive covering of late Tertiary marine sediments, which were laid down on the submerged Middle Tertiary peneplain. The general direction of the main fracture-lines is approximately meridional, tending to the north-north-west, but these are crossed by an important series of east-west fractures, and by others with an approximately north-west trend. Ahlburg's (1914) map, reproduced by Hobbs (1921), indicates the position of these. By the fracturing and block-movement, the drainage system and the outline of the island have very largely been determined. On the western side, between Macassar Strait and the high ranges of crystalline rocks, there is a region of irregularly and often rather strongly folded Miocene sediments, with oil-bearing sandstones and shales and intercalated leucitic lavas, together with probably late Tertiary sandstones and conglomerates, which have a general north-easterly strike and are truncated obliquely by the coast-line. The crust-movements, indeed, have continued up to the present time, for Abendanon noted that a small plain had been uplifted not less than 16 ft. in the last fifty years (Wanner, 1919). The significance of this latest phase of crust-movement in Celebes becomes greater when it is compared with the similar late Tertiary and Pleistocene movements in New Guinea and New Zealand.

It seems desirable here to note Professor Molengraaff's most recent generalizations (1922) concerning the tectonics of this region, as they show the manner in which Wegener's (1920) views have been applied to its explanation. (See also Wing Easton, 1921). Molengraaff holds that the arcs of the Malayan Archipelago originally formed a much more regularly curved series of arcuate folds concave towards Asia, of the structure of which they formed the marginal parts. On the basis of Tydeman's bathymetrical charts he would trace the easternmost anticlinal fold in Mindanao into the north-eastern arm of Celebes, and thence by the south-eastern arm into the Tukang Besi Islands, crossing a deep and narrow strait marked by sharp fracture and lateral dislocation of the anticlinal axis. He follows it from here with a sharp change in direction into Buru and Ceram, and thence by way of the Banda arc through Java and Sumatra into Burma, noting a certain resemblance between the occurrences of serpentine in south-eastern Celebes, Amboina, Moa, Letti, and Timor. Admittedly, however, the linking of the many diverse elements between Buru and the north-eastern peninsula of Celebes into a single anticlinal axis involves many difficulties, and does not commend itself to all the geologists who have studied this region. The suggestion is therefore put forward tentatively only.

Following Wegener's hypothesis, it is then supposed that Australia (inclusive of New Guinea) "moved horizontally in a westerly or north-westerly direction, and the portion of the arc between Buru and Rotti, and especially the particular stretch between East Timor and Buru, was gripped in the concavity of the coast-line (Arafura Bight)"—*i.e.*, the margin of the continental mass as indicated by the position of the hundred-fathom line. "Through this [movement] the folding arcs of the Moluccan geosyncline were thrust on to one another, so that one now sees that underthrusting directed outwards from the continent might act on the high islands of Ceram, Timor, Babber, &c., apparently like a system of overthrustings going out in a centrifugal direction from the central Banda Sea" (*cf.* Molengraaff, 1913). Thus the successive anticlinal ridges and deep synclinal troughs were wrinkled up in front of the advancing continent. In accordance with what has been said above, the kinks, transverse fractures, and dislocations of these anticlinal ridges are explained as the result of differential strains set up during their partial adjustment to the promontories and embayments of the coast-line of the continent of Australia.

Up to the present the conception of the Banda region entertained by the Dutch geologists has been followed, though Suess's objection thereto has been noted. Attention must now be called to Gregory's (1923) recent papers. After citing Suess's opinion and Boehm's general adherence thereto, he adds: "The geological evidence appears consistent with [this opinion]. The Tenimber Islands have been shown by Professor Brouwer to include vertical Mesozoic rocks, which he compares with those of East Ceram, but their strike varies from east-west to 28° north of west, and is therefore that of the island chain extending westward from Tenimber to Java, and is not due to folding on the lines of the Banda arc. In the Kei Islands also the strike of the older and more steeply tilted beds trends east and west (Verbeek, 1908, pl. xv, figs. 421, 431, 440), and is part of the general east-to-west grain of this region, and is older than the

Banda arc. It is true that in the Kei Islands there are some shallow folds which trend from south-south-west to north-north-east parallel to the eastern part of the Banda arc, but they may be explained by a gentle tilt towards the Banda subsidence, and they do not indicate a chain of fold-mountains. . . . The characteristic rocks of the Ceram-Buru line, and of the eastern end of the Timor chain, have not been recorded from the Kei Islands, which form the middle and essential part of the supposed Banda arc." He therefore concludes that "the evidence of the Banda arcs does not accord with the view that they are situated along a meridional mountain-range belonging to the Alpine-Himalayan system and connecting the Sunda and Buru-Ceram lines. The Kei Islands, the central part of the Banda arc, are built of materials that were deposited in the same basin as southern New Guinea. The foundation of these islands was folded in the late Eocene or Oligocene by the same meridional compression that formed the mountain-lines which occur both to the north and south of them, and extend past them both to east and west. This compression was part of the crustal movement which formed the mountains of the Alpine and Himalayan systems and also the fold-mountain chains of New Guinea. After the formation of the fold-mountain belt in the eastern part of the Eastern Archipelago, subsidences within it and fractures across it, similar to those frequent along the Alpine-Himalayan belt, happened in the Banda area. The subsidences formed the Banda and Weber Deeps, and cross-fractures broke up the land into islands and separated the Molucca Islands from New Guinea. These earth-movements, in accordance with the evidence so well interpreted by Professors Molengraaff and Brouwer, are probably still in progress; they have been very uneven, subsidence having occurred in one place while uplift was in progress elsewhere" (Gregory, 1923A).

In opposition to this conclusion may be cited the verbal comment of Professor Brouwer that as a result of laboratory investigation of his collections from Jamdena it now appears that much formerly assigned to the Tertiary should be relegated to the Mesozoic; and, considering the strike of these formations as well as of those previously held to be Mesozoic, it would appear that the balance of the very varying direction of strike lies more nearly meridional and in the direction of the Banda arc than at right angles thereto; and, further, the lines of strike shown by Professor Gregory running eastwards to east-south-eastwards through the peninsula south of MacCluer Gulf do not take note of the very sharply marked deflection to the south-east which actually occurs here, and appears to be concentric with the Banda arc, and to run thus for a short distance before bending back to the east-south-east along the line of the Snow Mountains.

In support of his view Gregory cites the comment of Suess (1908, p. 237) that "we might regard the whole zone of the Tenimber, Kei, and Watubele Islands, together with Ceram and Buru, as resting on an arc-shaped horst, and this would be separated on the north by a trough subsidence from New Guinea, Misol, and Obi"—though it is clear from a later remark (p. 243) his preference is to look on Ceram and Buru as the continuation of the southern peninsula of New Guinea, as does Professor Gregory. Professor David (1914) is cited in further support thus: "[Papua] is part of the Himalayan-Burmese arc prolonged through the Malay Peninsula, Sumatra, Java, and Timor. Its trend-lines are continuous with those of the Malay Peninsula [? Archipelago], and the direction and age of the folding . . . . agree with those of the Burmese arc." Kober (1921, p. 157) is also of the view that a uniform marginal chain runs around the Indian and Australian foreland from the Indus, through Timor and New Guinea, to New Caledonia, and terms it the Indo-Australian branch of the Mediterranean orogen. On his interpretation, the Sunda and Ceram-Buru chains would be respectively the outward-thrust lateral chains of a single but widened orogen, the central portion of which had subsided to form the Banda Sea, while New Guinea would represent the restricted portion of the same structure.

This diversity of interpretation of the structure of the eastern end of the Banda Sea naturally involves a corresponding variety of conceptions of the structural relationships of western New Guinea, to which attention must now be given. Converging towards north-western New Guinea are two arcuate lines of strongly folded mountains, the Buru-Ceram line already described and that running south-eastwards from Halmahera. The structure of this island, which Suess (1909, p. 308) assigned entirely to the Asiatic framework, is as yet but little known, but is perhaps essentially similar to that of Celebes, though the lesser elevation and dissection have not permitted the exposure of any crystalline schists in the foundation. So far as this is visible beneath the covering of late Tertiary and modern volcanic rocks, it consists of sharply upturned Tertiary and recently discovered Mesozoic sediments with infaulted pre-Tertiary basic igneous rocks (Wanner, 1913; Brouwer, 1922 and private communication). It seems to lie at the meeting-point of an Asiatic arc extending south-westwards from Yap and the Pelew Islands, with that running south-east into New Guinea. Between the latter and the Buru-Ceram arc is the resistant wedge made up by the crystalline rocks of eastern Celebes, the Sula Islands, and Obi, and the rather more yielding Misol mass. According to Brouwer's view, illustrated in fig. 2, the south-eastern Halmahera arc strikes across the southern peninsula of western New Guinea, and is here shown by steeply dipping Eocene *Alveolina* limestones, which appear to be drained by strike-streams, and bends round to the east and east-south-east into the Snow Mountains. It separates, therefore, the crystalline rocks of the Sula Islands from those of the northern peninsula of western New Guinea (the "Vogelkop") and the adjacent regions about Geelvinck Bay and farther east. In Suess's view the Buru-Ceram trend-line (though it may be locally deflected to the south-east in the southern peninsula) is continued into the Snow Mountains, while he groups into a single series not only the crystalline rocks of the Sula Islands, Obi, Misol, the northern peninsula, and Geelvinck Bay, which are overlain by nearly horizontal shallow-water marine Jurassic rocks, but also those which extend farther east, along the north coast and highlands of New Guinea as far as the Louisiade Islands, beyond its south-eastern extremity. Stanley (1921A) is of the opinion that the Halmahera arc swings into Waigeo Island, the northern peninsula, and Jappen Island, and thence extends along the north coastal ranges. On the view of Gregory (1923) it would seem as if the Snow Mountains and their eastward prolongation must be considered as a complete bilateral orogen, and to correspond with both the northward-thrust Ceram trend and the southward-thrust Timor trend, with a narrow central zone corresponding to the widened depression of the Banda Sea. No evidence yet advanced seems to indicate the existence of such an arrangement in the Snow Mountains only, though the structure of the whole of New Guinea as viewed by Suess and Kober may approximate thereto.

There is, however, a very remarkable series of depressions which separate, by a trough-faulted zone twelve hundred miles long, a narrow strip of the northern-coast ranges from the great central ranges, throughout the whole length of the island. The relation of the topography of New Guinea to the Australian continental massif on the one hand and the Pacific Ocean on the other thus bears more than a passing resemblance to the relation of the topographic features of Sumatra to the stable Sunda region on the one hand and the Indian Ocean on the other, though this resemblance is lost as the eastern extremity is approached. The effect of east-and-west fault-lines in determining the direction of streams is seen in the headwaters of the rivers draining the northern Vogelkop Peninsula. The main rift-valley commences in the MacCluer Gulf, is continued by the valley of the Waiponga Stream draining westwards into Geelvinck Bay, and thence eastwards by the Rouffaer and Idenburg Rivers, which unite and enter the sea by way of the Mamberamo River, traversing the Van Rees Range. These two rivers have a flood-plain up to twenty miles in width at a height of about 160 ft. above the sea, and lie in a depression running for nearly five hundred miles parallel to the coast about eighty miles to the north. The headwaters of the Idenburg lie in a similar but smaller depression about sixty miles from the coast and seventy miles in length, and at an elevation of about 600 ft. Low gaps lead from these into the depression occupied by the Sepik (or Kaiserin Augusta) river-system, the broad alluvial plains of which cover elevated Pleistocene marine beds (Stanley, 1924). These depressions run approximately due east, but at the mouth of the last-named river opens another long trough depression, bounded by fault-scarps, which is occupied by the Ramu River, and leads across an indefinite divide, only 1,200 ft. above sea-level, into the Markham River valley, which opens into the Huon Gulf. On the north- and south sides of this depression the Finisterre and Bismarck Ranges rise to heights of over 10,000 ft. In the valley itself somewhat dislocated late Tertiary or Pleistocene sandstones appear beneath the modern river-alluvium (Stanley, 1923). The southern fault-scarp of this depression continues for over three hundred miles to the south-east, forming the north coast of British Papua, and is recognizable in the truncated spurs of the various promontories, such as the Cape Vogel Peninsula. A series of volcanic rocks capping such promontories have been emitted along this line of fracture, and the active volcanoes of the D'Entrecasteaux Group may perhaps be considered as rising from a submarine extension of the Ramu-Markham zone of fracturing.

It will be best to describe separately the several structural zones of New Guinea from south to north. The lowland of southern New Guinea traversed by the Eiland, Digul, and Fly Rivers is composed of horizontal late Tertiary lignites and clays, through which appears the granite of Mabaduan, the outlying member of the series of granite-intrusions of Cape York Peninsula (Haddon, 1894). This is the stable portion of New Guinea, a portion of the Australian massif. Heldring (1909) suggested that this formed with the Arafura Sea and Gulf of Carpentaria an elliptical area of depression, the Gulf of Papua being a similar but more pronounced feature, and pointed to several features as evidence of such movements of depression, faulting, or warping; and David (1914) has entertained a similar view. Verbeek (*fide* Brouwer, 1917) doubted the validity of this evidence.

North of this lowland a series of step-faults have raised a terraced plateau of Pleistocene and probably Lower Miocene coral-limestones (occasionally traversed by basalt dykes) to an average height of 2,000 ft. above sea-level. These show the characteristically jagged surface of karst-lands (Staniforth Smith, 1912; Stanley, 1924A). The limestones occupy especially the regions about the middle course of the Fly River. Farther east the foothill region rises directly from the south coast of Papua. It is composed in part of pre-Miocene formations; contorted semi-crystalline grey or white limestones, which may be Eocene or Mesozoic; more or less silicified limestones with interbedded sediments; and the radiolarian cherts of the Port Moresby series, originally held to be Pliocene, but now considered pre-Miocene, though it lies apparently above the widespread Boioro grey limestone. Farther inland are sandstones with lignites which may be placed in this group. These are considerably crushed, folded, and faulted, and appear to have been overthrust towards Australia. They are succeeded unconformably by the Miocene-Pliocene petroliferous series —limestones, sandy marls, clays, grits, and sandstones with lignite, &c.; volcanic agglomerates, and interstratified flows of andesite. Several minor unconformities appear to be present. The beds undulate, with a general south-easterly strike, but the lowest formations dip much more steeply than the uppermost. They are capped by raised coral-reefs along much of the coast. This foothill zone is succeeded to the north by the high ranges which form the backbone of New Guinea, and are known as the Charles Louis Range, the Snow Mountains, the Star Mountains, the Victor Emmanuel, the Bismarck, and the Owen Stanley Ranges, with various subordinate and spur ranges. In the western end of this central range are dark crinoidal limestones probably belonging to the Permian series, though farther south in the outer portions of the Snow Mountains are littoral Permian (?) sandstones (Heldring, 1911; Martin, 1911; Brouwer, 1917). The structure of the ranges has been investigated by Heldring and Hubrecht (1913). "There is a huge thickness of strata with a fairly uniform dip to the north over long distances, and it does not seem impossible that recumbent folds, imbricated structures, and overthrusts, with a movement directed towards Australia, may occur in these mountains" (Brouwer, 1922). The highest peaks, Carstenz and Wilhelmina Tops, rise to 15,000 ft. in height, and are composed of limestone, possibly Permian, rather than the later age previously assigned (*cf.* David, 1914), though the Eocene *Alveolina** limestone occurs. Crystalline rocks lie beneath these; and serpentines have been collected from the northern flanks of the range in the headwaters of the Rouffaer River (Gelder, 1910); and in the Setekwa, Eiland, and Digul Rivers to the south are pebbles of augite-granite, diorite, more or less gneissic gabbro, and also nepheline-syenite (Heldring, 1911).

In addition to these rocks there is a covering series of Middle Jurassic claystones represented by specimens from the river-pebbles in each of the main streams draining south from the Snow Mountains, and extending into Papua across the upper waters of the Fly and Strickland Rivers.

* The Eocene age of this limestone was originally determined by Martin (1881, 1911) and Schlumberger (1894). It was held by David to be Cretaceous, and a like view was accepted by Stanley up till the present year. Rutten (1914) has again pronounced it to be Eocene, and he is followed in this by R. B. Newton (1916, 1918), in whose papers the earlier work is fully discussed.

Cretaceous rocks are indicated by a usually unfossiliferous but occasionally belemite-bearing grey or blue limestone, which crosses the Purari River; the cherts with *Actinacis sumatraensis* at the junction of the Fly and Palmer Rivers; the fossiliferous sandstones and limestones on Korova Creek, near Kerema; and the ammonites, &c., in the calcareous shale in the Kerabi Valley, to which Dr. P. Marshall verbally assigned a Senonian age. A single development of Eocene coral is reported from the Fly River (Gregory and Trench, 1916). All these formations are stretched along the southern flanks of the great central range, which is essentially a horst, or faulted geanticline, consisting of crystalline rocks, the gneisses and schists of the Owen Stanley series. These are invaded by granitoid rocks, and porphyrites, and a long broken belt of serpentine, and upon them rest unconformably the phyllites, sandstones, and crystalline (Devonian ?) limestones of the Astrolabe - Kemp Welch series, which are invaded by fine-grained basic igneous rocks, and may be in part Palaeozoic. The cover of Eocene *Alveolina* limestone which probably extended over much of this complex has been almost entirely removed (see the generalized sections by Stanley, 1924). The extensive masses of limestone discovered by Detzner (1919) in the vicinity of the Bismarck Range south of the Ramu-Markham depression may be an important outlier of this formation, and be continued in the faulted masses capping the Saruvaged Ranges near the Finisterre Ranges to the north. The south-eastern extension of this central zone is, as previously indicated, bounded to the north by the faulted coast of Huon Gulf. There is a fringing, more or less undulating series of Miocene-Pliocene marine sediments resting on the ancient metamorphic rocks of the basement series, which are continued into the Louisiade Islands. Mount Victory, the only active volcano in Papua, is situated on this fault-line, and has built up the Cape Nelson Promontory.

The north-coast ranges of New Guinea extend north of the above-described longitudinal trench. The scattered data concerning them may be summarized as follows: In the west the northern Vogelkop Peninsula contains some highly dislocated rocks, in which have recently been found brachiopods and Mollusca, apparently of Palaeozoic (Devonian ?) age (*fide* Professor Brouwer). It is, however, difficult to separate these from the complex of crystalline schists and phyllites which make up the bulk of the peninsula and extend along the coast farther to the east. The Van Rees Mountains, as shown by Gelder (1910), consist of undulating late Tertiary lignite beds, sandstones, and marls, overlying older Tertiary nummulitic limestone, and perhaps Jura-Cretaceous rocks, as shown by the occurrence of pebbles containing *Perisphinctes* and *Inoceramus*. These are reported also at several localities farther to the east; and at Walckenaer Bay there are Miocene clays and coal-measures, which dip very steeply, while pebbles of various crystalline rocks in the river-beds near the coast indicate the presence of the basement series in the ranges they traverse. At Humboldt Bay, near the boundary between the Dutch and the mandated territory, the small island of Misotti is made up of serpentine (Suess, 1909, p. 306), while Miocene beds occur at Cape Djar on the mainland near by (Stanley, 1923). The north-western portion of the mandated territory has been studied by Richarz (1910), Reche (1913), and Schultze (1914), and consists of the Bougainville, Bewani, and Torricelli Ranges. On the southern slopes of the Bewani Ranges, drained by the Sepik River system, occurs the crystalline metamorphic series, together with an altered group of phyllites, slates, and conglomerates, with chloritic and epidotized diabases, and porphyrites and keratophyre-tuffs invaded by gabbro and diorite. The Bougainville Range is largely made up of the Oenake serpentine massif. Overlying these older rocks there occur fossiliferous Jurassic sediments in the headwaters of the Sepik and October Rivers, Cretaceous foraminiferal limestones, also older Tertiary (?) glauconitic sandstones and shales invaded by gabbro on the southern slopes of the Bewani Range, with nummulitic and lepidocyclinal limestone, which dips south-south-east at 10°, on the northern slopes. Farther east, in the Torricelli Mountains, are fossiliferous sediments which were referred by Richarz to the Cretaceous period, but which must be considered Lower Miocene (*fide* Wanner, private communication) on account of the occurrence of *Lepidocyclina* and other Foraminifera. These dip at 80°–85° to the north-north-west, a marked local variation from the general strike. These last are followed by the semi-indurated limestones, sandstones, and grits near Monumbo (Potsdamhafen), which dip north-eastwards at 25°–30°, and appear to have been invaded by granodiorite, as is again the case in other points along the coast (Stanley, 1923, p. 24). These rest on older basalts, and overlie unconformably a series of phyllites, &c. (comparable with the Astrolabe - Kemp Welch series), which have been invaded by a large mass of pre-Tertiary peridotite. This series of shattered and metamorphosed sedimentary rocks makes up the coastal Adelbert Range, running hence to Madang (Friedrich Wilhelm Hafen), and is capped here and there by andesite. At the back of it lies the Ramu depression. A similar series of ancient schists, &c., invaded by basic plutonic rocks forms the foundation of the Finisterre Range and the Huon Peninsula. It is reported that the strike here swings from a south-easterly into a easterly direction, though caution must be exercised in deducing the strike of a very dislocated series of rocks from the general elongation of the fault-bounded horst in which they are exposed. Capping the Saruvaged Range at a height of 13,000 ft., and forming the highest portion of the peninsula, are the extensive faulted masses of white limestone discovered by Detzner (1919): this may be, as Stanley (1921) has suggested, an extension of the *Alveolina* limestone which is so widespread farther to the west. Nearer the coast the ancient rocks are covered locally by approximately horizontal carbonaceous sandstone and volcanic agglomerate. Suess notes the abundance of andesites here.

Throughout the whole extent of the northern coast of New Guinea there are very frequent instances of upraised Pleistocene marine deposits and coral reefs.

Summarizing the stratigraphy of New Guinea as deduced from the available data, there must first be recognized an ancient gneissic and schistose group of rocks, together with a somewhat younger but highly disturbed series of sediments and volcanic rocks, possibly in part Palaeozoic. These have been invaded by granites, and especially basic plutonic rocks and peridotites. They are succeeded, probably uncomformably, by Permian, Jurassic, and Cretaceous rocks, the relations of which to one another are not yet clear, though there is as yet no evidence of marked orogeny during the Mesozoic period. Nor, indeed, is there yet any proof of important crust-folding between the time of deposition of these and that of the early Tertiary sediments, littoral sandstones, siliceous radiolarian cherts, and the very extensive Eocene *Alveolina* limestone which covered the greater part of the area, though there seems evidence of some minor unconformities between the successive members of this series. During Oligocene-Miocene times, however, strong movement occurred at several points along the north coast, accompanied by the intrusion of granodioritic rocks, and the general direction of superficial thrust of the older Tertiary beds appears to have been northward along the north coast, but southward towards Australia along the southern side of the central range. The older Tertiary beds are unconformably overlain by the Miocene-Pliocene oil-bearing series of sandy marls, grits, and limestones, with volcanic agglomerates and andesite, these later Tertiary formations occurring on both sides of the axis. Extensive block-faulting and warping occurred intermittently throughout the later Tertiary period, producing minor inter-formational unconformities, and was accompanied by volcanic eruptions, which on the north coast and on the south-east extend to the present day. Planation occurred to some extent during the pauses between the successive crust-movements, and in particular the Mesozoic and early Tertiary covering-rocks were removed from a large part of the central horst region, which had been elevated to some extent before the deposition of the later Tertiary rocks. The post-Tertiary movements were, however, particularly great. The central ranges were elevated as a vast concourse of earth-blocks, with huge scarps, such as that of Mount Suckling, in eastern New Guinea, which faces to the north and is 8,000 ft. high, or the southward-facing scarps of Mount Leonard Darwin and Carstenz Top, in the Snow Mountains, which are estimated to be over 10,000 ft. high—"the most stupendous precipice anywhere in the world" (David, 1914). The lesser displacements near the coast have raised Pleistocene reefs to a height of 2,500 ft.

Preliminary accounts of the course of the structural or trend lines have been given by Suess, Sir Edgeworth David (1914), and Stanley (1921), who has prepared a more extensive discussion (Stanley, 1924A), which the writer has been permitted to consult. According to the former, the main trend runs from west to east through Dutch New Guinea, bending round to pass south-east into the Louisiades, with a probable virgation by way of the Finisterre Range into New Britain. "This strongly marked Burmese trend-line is crossed by minor trend-lines, subordinate folds and faults, more or less meridional, coming from Australia. . . It may be suggested very tentatively that the mainland of Australia has functioned as a 'foreland massif'; Torres Straits, the Gulf of Carpentaria, and the deep Mesozoic and Tertiary basins, with their thick strata, as a senkungsfeld. Possibly the crystalline schists forming the greater part of the backbone of the island have played the part of an inner or 'ruckland massif,' which has helped to roll up the Mesozoic and Tertiary sediments. The chief fracture-zones on which the present active volcanoes of Mounts Victory and Dobu are situated appear to lie on the inner limb of the fold-region, just the portions which have been put in tension as the result of the southerly creep of the Papuan area towards Australia" (David, 1914). Stanley (1920, 1921) added to this view the hypothesis of a further and trident virgation in the south-eastern promontory. The outermost branch runs through Woodlark Island (Murua), and the bathymetrical chart of Groll (1912) suggests that Rennell Island, an elevated atoll probably covering a volcanic cone (Deck, 1921), and perhaps the Loyalty Islands east of New Caledonia, may be a continuation of this trend-line. The intermediate and inner branches consist of the D'Entrecasteaux and Louisiade Islands respectively. In all three branches are ancient schists, and plutonic rocks associated with indurated slates, grey limestones,* sandstone, and conglomerate on Woodlark Island. On this foundation folded Miocene limestones rest. The whole D'Entrecasteaux Group appears formerly to have been united to New Guinea, and to have been separated therefrom and subdivided by east-west rifts accompanied by volcanic activity, and followed by meridional rifting and renewed vulcanicity. In both Woodlark Island and the Louisiades raised and tilted coral-reefs are a characteristic feature (Stanley, 1912, 1915).†

In regard to the trend-lines of the north coast and the Finisterre Ranges (the Tertiary and Mesozoic rocks in which Suess considered "the outer boundary of the folded range which immediately succeeds them to the south"), Stanley (1923) no longer considers them as a portion of the same tectonic zone as the main ranges of the island, but, following a suggestion made by Suess, views them as a separate geanticline "of smaller dimensions, with a probable Asiatic structure, and thereby related to Halmahera, the Philippines, and Japan. This coastal feature is modified by faults or steep folds, which cut obliquely the geanticlinal axis" (*cf.* Suess, 1909, p. 308). This axis, he believes, bends eastwards in the Huon Peninsula, and extends into New Britain (Stanley, 1924A). Parallel to it runs a line of active volcanic islands (the Schouten Group) from beyond the mouth of the Sepik River across Dampier Strait, and this is continued by the great series of volcanoes along the northern coast of New Britain. Kober's view, on the other hand, seems to regard the north-coast ranges as forming the northward-thrust lateral portion of a single orogen comprising the whole of the highlands of New Guinea.

The south-eastern portion of New Guinea thus affords several interesting problems. Suess (1909) groups the whole of this island series, together with New Britain, the Solomons, New Hebrides, New Caledonia, and northern New Zealand, into a single great system, which he terms "the first Australian arc," recognizing, however, an inner and an outer portion. The former, which includes the whole of New Guinea and the islands off the south-eastern extremity, may perhaps be considered to be represented also in New Caledonia; the latter is that containing the Bismarck Archipelago, the Solomons, and New Hebrides. As held by various writers, especially David, Andrews, and Jensen, whose views were summarized in a previous paper (Benson, 1923), Australia grew generally from the south-west towards the north-east and east. It appears in accord with this that the modern crustal activity, both seismic and volcanic, is very marked in the outer portion of the arc, and to a less degree in the inner, and then only near the recently fractured areas of New Guinea, away from which, both to the east and to the west, such activity diminishes. There seems, indeed, reason for recognizing, as Stanley does (1921), two distinct arcs—the outer fairly continuous, broken only by narrow transverse subsidences, the inner very discontinuous and largely submerged. The precise rôle of New Britain is, however, almost as indefinite as that of the Kei Islands, though even if it be no more than an arcuate horst it cannot be considered as exactly analogous with the Kei Islands. As will appear, however, it does seem to be much more probable that it is a definitely folded arc.

* The strike of this limestone is N. 20° E., or approximately at right angles to the general trend of the line, probably indicating a strong local flexure adjacent to a cross-fault.

† For a recent detailed account of the coral-reefs of these islands, based for the most part on a study of the British Admiralty charts, see Davis, 1922.

The structure of New Britain has recently been summarized by Reed (1921) and Stanley (1923, 1924). On the inner northern side of the arcuate island the sea reaches a depth of 1,400 fathoms, but on the outer plunges steeply down into a narrow trough over 4,000 fathoms deep. There is a core of schists and gneisses invaded by granodiorites and syenite, gabbroid rocks, with diabases and porphyrites. These are associated with Cretaceous (?) grey-white limestone containing *Acteonella*, possibly, however, to be correlated with that occurring on the Purari River (Papua), and other crystalline limestones in New Ireland and the Solomon Islands. There are also steeply dipping older Miocene sediments, overlain unconformably by gently folded Pliocene series of foraminiferal sediments and tuffs. The volcanic eruptions seem to fall into three chief epochs, the first dating back to the close of Miocene time. These periods appear to have significance for the whole of the eastern New Guinea and the adjacent archipelago. Stanley (1924) remarks: "The first phases were associated with the main tectonic zones of faulting, which were more or less parallel to the axis of folding. The second phase was conterminous with subsequent strand-folding, which I consider represented the maximum period of movement in late Tertiary times. The third or final stage is partly connected with the second or coastal fractures, and really commenced as these movements were becoming less in the second set; but these later eruptions are due principally to a second set of fractures—namely, a series of north-and-south rifts, more or less at right angles to the coast-line, which are well in evidence throughout New Britain, and to a lesser extent in the islands of the D'Entrecasteaux Group." An especially good example of this is seen in the Willaumez Peninsula, projecting northwards from the centre of New Britain. The modern volcanic activity is thus greatest along the north coast of this island, and, as has been noted, it extends thence in an arc westwards to the Dampier and Schouten Islands along the north coast of New Guinea. To the north-east the strike swings round into parallelism with that of New Ireland, which runs from north-west to south-east.

In New Ireland, according to Schubert's observations, cited by Stanley (1923), together with those of Sapper and Lauterbach (1910), there is a basement series of gneiss and grey crystalline limestone invaded by plutonic rocks ranging in acidity from granites to gabbros. Diorites are also found in the islands in St. George's Channel between New Britain and New Ireland, and in New Hanover to the north-west of the latter. They are overlain by older volcanic rocks, Miocene-Pliocene foraminiferal limestone, &c., and raised coral-limestones, with abundant Recent volcanic rocks. The presence here of an old folded cordillera is quite clear, and it may be traced from the Admiralty Islands, where ancient rocks have been found beneath modern volcanic accumulations (*fide* Stanley), through New Hanover and New Ireland, in which the strike bends sharply from south-east to due south. This geanticline appears to have subsided for three hundred miles thence to the south-east, but may be recognized again in the south-western islands of the Solomon Group—namely, New Georgia, Gaudalcanar (Gera), and San Christoval. This southernmost island of the group seems to be the meeting-point of two or three slightly diverging geanticlinal ridges, which together make the outer portion of the major structure termed "the first Australian arc" by Suess. The innermost or western member of the three is that which has just been described; the central member runs through the northern and eastern portion of the Solomon Islands, Florida, Ysabel, Choiseul, Bougainville, Buka, and thence along the volcanic islands of the Namatanai chain a short distance east and north of New Ireland and New Hanover, and terminating in St. Matthias Island (Mussau); while the outermost branch may be represented by the shorter ridge diverging northwards from Malaita to the coral-islands of Ontong Java. The cordilleran nature of the Namatanai ridge is shown by the occurrence of diorite in Tabar, one of its constituent islands.

In regard to the structure of the Solomon Islands, little can be added here to Suess's (1909) account of this group. According to Stanley (1923), the latest phase of volcanic activity is represented in Buka and Bougainville Islands; and in Poperang, a small island immediately south of the latter, there is a grey crystalline limestone containing *Rhynchonella*, which Suess thinks may possibly be Mesozoic. In Ysabel, diallage-serpentine is known, and schistose serpentine and granulite in Florida Island. In Gaudalcanar, andesite, dolerite, and porphyry occur, besides Recent volcanic rocks, peridotite, gabbro, serpentine, and a grey slickensided (possibly Mesozoic) limestone. San Christoval is very clearly a portion of an ancient cordillera which has been uplifted after planation. "The mountains are arranged in parallel series of long flat-topped ridges." The island is extensively composed of ancient igneous rocks: diorites, sometimes gneissic gabbros, saussuritic feldspar rocks, and diallage rock serpentine are known, together with indurated slaty rocks and quartzite. Cassiterite has been observed in one stream (*cf.* Marshall, 1912). Diallagic serpentine is also known in Santa Anna, the most southerly member of the group. A series of active volcanoes stand, so far as can be seen, between the isolated remains of this cordillera, and probably rise from portions which have subsided between transverse fractures. In many places the islands are surrounded by coral-reefs elevated to as much as 500 ft., fairly uniform displacements being traceable for nearly four hundred miles (*cf.* Guppy, 1887).

The arc of the Solomon Islands is separated by a deep transverse depression from that of the New Hebrides. Mawson (1905) was unable to confirm the existence of gneissic rocks in the latter, previously reported by Levat, but gave interesting particulars concerning the Tertiary and later history of this island group. An arching of the sea-floor in Miocene times permitted the formation of shallow-water limestones, which were brought above sea-level as the elevation continued, and were invaded by andesite sills. The steep westerly dip of the limestone suggests that the superficial thrust was in the direction of Australia. Fracture and subsidence, especially of the eastern limb of the anticline, were accompanied by the outpouring of basalt and the formation of unfolded Pliocene and Pleistocene foraminiferal tuffs capped by differentially elevated coral-reefs, reaching a maximum height of 2,000 ft. above sea-level in the northern part of the group. This island group does not, however, represent a single simple anticline running to the south-south-east, but, somewhat as in the Solomon Islands, it branches at Efaté (Sandwich Island) in the middle of the group, sending off to the north a series of volcanic islands including active vents. These are not present in the larger islands of the north-north-westerly or main chain of the group, a further instance, possibly, of the easterly retreat from the Australian nucleus of the zones of maximum crustal activity, though the whole region is still unstable. Mawson recognized that this differential elevation of the various islands,

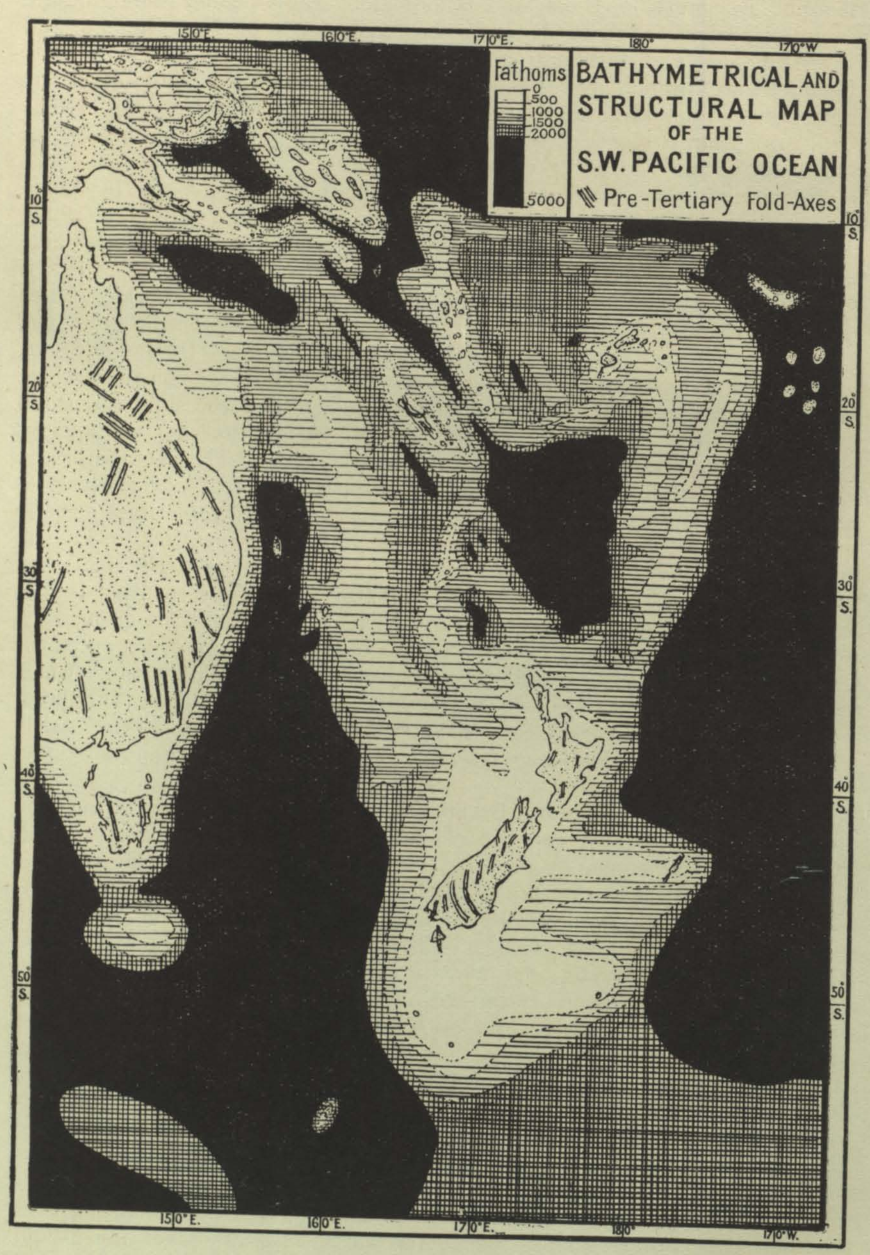

FIG. 3.—Bathymetrical map based on data assembled by Sieberg, Marshall, Groll, and J. K. Davis. Structural features of eastern Australia after David's map.

though superficially one of block-faulting, is essentially a continuation of the Miocene orogeny, and that cross-faulting "of the blatter type," and volcanic eruption, have led to the present distribution and structure of the island masses.

Seismological investigation shows that the crust-movements are still in progress in the outer arc. To the east of the New Hebrides the sea-floor slopes comparatively gently to a depth of 2,000 fathoms, but to the west it sinks rapidly to a depth of 4,490 fathoms (fig. 3), so that the ridge is strongly asymmetric, its steeper slope facing towards Australia, or, more immediately, New Caledonia, from which it is separated by a deep narrow trough. Brouwer's conceptions would lead us to expect here the presence of overfolding at great depth, thrusting almost horizontally south-westwards into a foredeep. In agreement with this is the record of over a decade of seismological observation made by the Rev. E. F. Pigot at Riverview College, Sydney, to whose courtesy the writer is indebted for permission to cite the following unpublished generalizations. The New Hebridean ridge is a region of much seismicity, and the great majority of earthquake-epicentres are situated on the western slope of the ridge, the one facing the deep trough. Moreover, the formation of cross-faults is clearly indicated by the grouping of certain earthquake-epicentres along lines transverse to the main geanticlinal axis. This seismic zone may be traced north-westwards along the western slope of the New Hebrides-Solomon Island ridge, where it plunges down into the Planet Deep, which is apparently the foredeep of the outer and still-growing member of Suess's first Australian arc. Thence it passes through New Britain into New Guinea, and westward through this last island into the Charles Louis Range. It is in northern New Guinea that the seismic activity of this belt reaches its maximum, and here it is apparent that the first Australian arc presses most closely on to the Australian continental massif. Brouwer (1921A), citing, *inter alia*, Visser's work, has remarked on the extension of this zone farther westward into the Moluccas. As in the New Hebrides, the chief epicentres are under water, and lie on the steep slope leading down from the southern coasts of Sumatra and Java into the foredeep which separates the orogenic zone from the submerged portion of Gondwanaland. The movements are there along longitudinal tectonic lines, but in addition there are many shocks occurring along transverse lines, especially in regions where older folds are cut off by the present coast-lines.

Return may now be made to the inner portion of the first Australian arc, consisting of the south-eastern extremity of New Guinea and the adjacent islands, which have already been described, and New Caledonia and the Loyalty Islands. The Loyalty Islands are separated from New Caledonia by a narrow trough, in places more than 1,000 fathoms deep. The islands are elevated and slightly tilted coral reefs, showing several stages of uplift, and nowhere rising more than 400 ft. above the sea. In the island of Marè, around which five terraces are recognized, a small core of volcanic rock is exposed, which suggests that the other islands in the chain are reef-masses covering a string of volcanoes built up from eruptions along a single tectonic line (Davis, 1915). Stanley (1921) has suggested that this is the line which forms the outermost member of the virgation in the south-east of New Guinea, and that it continues through Woodlark Island by way, it has been herein suggested, of Rennell Island. The southernmost of the Loyalty Islands, Walpole Island, is also ringed by five raised reef-terraces (Andrews, 1922), and is of especial interest because of the recent discovery on it of remains of the giant fresh-water tortoise *Miolania*, now being studied by Dr. C. Anderson. This is also represented, though by a different species, in Lord Howe Island, as will be seen later.

The structure of New Caledonia is decidedly complex, and the account given by Suess (based chiefly on the writings of Peletan, Reurteau, Glasser, Deprat, and Piroutet) may be replaced by a summary of Piroutet's (1917) more recent studies. The island falls into two approximately equal portions, the boundary of which is about the line of latitude 21° 15′ south. In each the eastern coast is steep, the land rising into high ranges, while on the west the relief is more gentle, and low hills and plains occur. In the northern portion the ancient crystalline rocks, gneisses, mica- or glaucophane-schists, and less-altered possibly Palaeozoic sericite-schists and quartzites, are arranged in an arcuate fold concave towards the north-east, the strike swinging from nearly N.-S. in the north-western extremity of the island to E.-W. and even E.N.E.-W.S.W., where it meets almost perpendicularly the central portion of the eastern coast of the island. West of these ancient rocks, in the northern half of the island, and in the southern half also, the Permian, Mesozoic, and Lower Tertiary rocks are bent into folds striking much more nearly parallel with the general N.W.-S.E. axis of the island, though numerous departures from this direction, especially two south-westwardly concave arcuate folds, are considered by Piroutet to indicate the presence of relatively rigid blocks of ancient folded rocks concealed beneath the younger Mesozoic and Tertiary formations. Brouwer's interpretation of analogous features may be recalled. Some deflections also may be due to the entry of the vast instrusive masses of ultrabasic rocks. The sedimentary rocks bear witness to continued geographic changes, with intermittent folding or warping, erosion and deposition, from Permian to Recent times, accounting for the many lacunae in the stratigraphical succession. A Permian transgression passed westward over this region, depositing littoral and rather deeper-water sediments. A regression commenced during Lower Triassic times, the marine sediments of this age being sparsely developed, and the crust-movements leading to a complete withdrawal of the sea in Middle Triassic times were associated with or preceded by basaltic eruptions. Depression followed irregularly in Upper Triassic times with a widespread transgression of the sea, followed by a complete retreat of the sea at the close of the period, the region being dry land during the Rhaetic and the greater part of the Jurassic period. These renewed movements were accompanied by further basaltic eruptions. In late Jurassic times a further subsidence took place, when the sea flowed in from the south-west to the centre of the island, depositing Tithonian and early Cretaceous sediments, the latter interstratified with rhyolites and andesites. Before this, however, a certain amount of crust-folding or warping occurred along axes oblique to that of the pre-Permian folding. Up to this time the successive faunas were all closely related to Malayan and Tethyan faunas in general, with some circumpacific elements, but now significant changes took place. Reason has been adduced for a slight modification of Piroutet's (1917) account of the Cretaceous succession (Benson, 1923); but he nevertheless shows that some crust-folding occurred during the middle part of this period, the intensity of which does not appear to have been very great. The direction of the fold-axes is stated to be oblique to the strike of the Jurassic and the Permian folds. This folding was succeeded by the entry from the east of a Senonian marine transgression, which penetrated into regions in which the Lower Cretaceous deposits are lacking. The new immigrant fauna was distinctly of the Indo-Pacific type, and apparently had a definitely marked affinity with that of New Zealand and the American Antarctic regions, though its detailed description is not yet available. The deposition of these Senonian beds was followed by great crustal instability and frequent oscillation, producing a variety of sediments, conglomerates, sandstones, foraminiferal and algal limestones, gypsiferous clays, &c., associated with basic tuffs, basalts, dolerites, &c., abundant in the higher members of the Eocene series, in which several minor unconformities are recognizable. The coastal connection with New Zealand appears to have broken down, there being no community of Eocene marine fauna, though the continuance of connections with the north-west is indicated by the New Guinea, Malayan, and Asiatic relations of the species of Foraminifera which occur in the New Caledonian Eocene beds,* but are unrepresented in New Zealand. These are, however, the latest of the Tertiary deposits of this island. Their formation was followed by the greatest orogeny which is displayed clearly in the island, in which the superficial thrust, coming from the north-east, is again directed towards the Australian nucleus, as in the case of the other regions of mid-Tertiary folding. Though the overthrusting is not developed as extensively as in Timor, the Permian beds in certain areas are thrust above the Upper Triassic, and the Mesozoic above the Tertiary, though not as extensively as Suess supposed (following Glasser's (1903–4) account), (fig. 4). In some regions, perhaps those buttressed by subjacent relatively rigid masses of older folded rocks, the Tertiary folds are more or less symmetrical, but along the east coast a series of subsidences permitted the development of back-folding, the folds being frequently overturned towards the north-east adjacent to that coast.

Besides the three well-defined periods of folding noted, minor crust-movements may have occurred at other periods, especially at the close of Lower Triassic times and in the Middle Eocene. The last great movement of approximately Miocene age was accompanied by the injection into the crust of vast amounts of ultrabasic magma, which is now exposed in large or small masses of peridotite throughout the island.

Concerning the subsequent movements of the crust little detailed information is available to the writer. Coral-reefs, raised from 6 ft. to 20 ft., surround the island, and in general there seems to be a slight tilting movement in progress, a subsidence in the partially drowned western coast, and (at least in earlier Pleistocene times) an elevation on the eastern. This is further exemplified by the uplift of the coral-limestone of the Isle of Pines in the south-eastern extremity (Compton, 1917), and of the Loyalty Islands still farther to the east. This elevation Andrews (1922) believes to be due to Recent crust-movements independent of and more vigorous than those of New Caledonia. Thus the whole New Caledonian ridge can

---

* As the list of the Eocene fossils of New Caledonia is not readily accessible in New Zealand, it may be useful to give it here, as compiled from the work of Deprat (1905) and Piroutet (1917). The forms marked with an asterisk (and possibly others also) are known in the Eocene rocks of New Guinea and the Malay Archipelago: *Orthophragmina* cf. *chudeaui*,* *O. discus*, *O. dispansa*,* *O. javana* var. *minor*,* *O. lanceolata*, *O.* cf. *multiplicata*, *O. nummulitica ?*, *O. pentagonalis*, *O.* cf. *pratti*, *O.* cf. *sella*,* *O. stella*, *O. stellata*, *O. umbilicata*,* *O.* cf. *varians*, *Nummulites baguelensis*,* *N. nanggoulini*,* *N. jogjakartae*,* *N. striatus*, *N. variolarius-herberti*; also various species of *Alveolina*, *Discocyclina*, *Miliola (Pentellina)*, and *Operculina*, together with some bryozoa, *Prenaster* cf. *alpinus*, *Spatangus*, and *Lithothamnium nummulitica*.

be considered in the main as a geanticline which has been developing intermittently from Permian times, the diverse strikes of the successive foldings resulting, probably, from the apposition of the folds formed at the surface in strata lying on the eroded surface of those formed at depth. Further, though active orogenic movement has ceased, a slight warping of the ridge is still in progress. The foundering of the north-eastern coast may suggest the occurrence of block-movements in association with the Tertiary folding; but Davis (1918) is of the opinion that the generally rectilinear, cliffed yet embayed, north-eastern coast is not a fault coast, but has resulted from an extensive and very recent submergence of a series of wave-cut cliffs formed after an earlier period of long-continued emergence. No late Tertiary or Recent volcanic activity has been recorded in connection with these crust-movements.

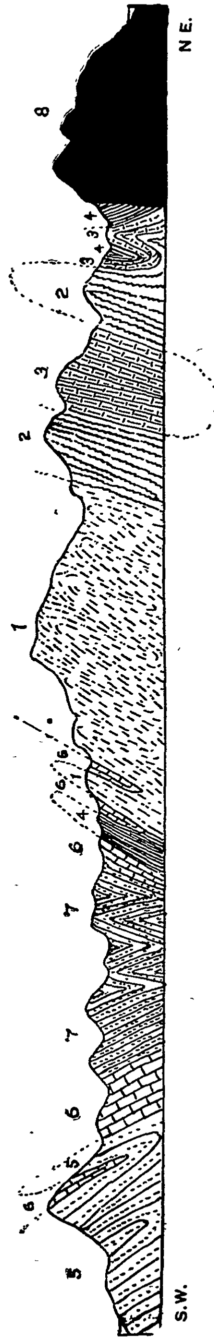

FIG. 4.—Section across New Caledonia (after Piroutet, 1917). 1, sericite-schists; 2, quartz-schist and phyllites; 3, Permo-Triassic; 4, Upper Jurassic-Cretaceous coal-measures; 5, Middle Eocene; 6, 7, older and younger Upper Eocene; 8, serpentine.

It is now possible to contrast the structure of the Australasian margin as displayed on either side of New Guinea. Though Kober (1921) has classed the whole into a single orogen, and Gregory (1923A) has supported in some degree his conception of the Banda region as a bilaterally outthrust structure with a subsided central zone, it is by no means clear that such an arrangement is continued into the central ranges of New Guinea, as Gregory suggests in his diagram, and the actually observed trend-lines in the western portion of that island do not accord with the suggestion that might be raised by Suess's phrasing that New Guinea as a whole, with its outthrust coastal ranges and longitudinal depression, should be regarded as the continuation of the Banda structures. Still further difference is seen to the south-west, where (omitting New Britain), in place of a bilateral arrangement, the structure is that of a series of parallel unilateral chains, running concentrically about the Australian nucleus and superficially thrust in that direction. It might perhaps be argued that the deep west of the Solomon-New Hebrides chain is not a true foredeep, as its seismic characters would indicate, but essentially the subsided central portion of the orogen towards which the eastern flank has been turned back, while in the normal case the thrusting would have been in the opposite direction—*i.e.*, to the north-east—symmetrically with the south-westerly thrusting of New Caledonia. In support of this view might be cited the overturning of the folds in the east of New Caledonia itself towards this depression, which Piroutet (1917) has pointed out. The alternative suggestion that the deep is a true foredeep, and the New Hebrides-Solomon ridge is but the marginal fold of the former continent now represented by the submerged platform which rises above the sea in the Fiji Islands, would seem to remove that ridge from the tectonic control of the Australasian structure rather more than would be in accord with the conceptions entertained by Suess and Andrews (1922). Further divergencies from the Moluccan type of structure of the Australasian margin will be seen below in the account of New Zealand, where the folded arc passes into a more or less continental platform.

Passing farther to the south, it is noted that the New Caledonian-Loyalty Island ridge is not continued far beneath the ocean, but is cut off by a depression between 1,000 and 1,500 fathoms in depth, beyond which, but some distance west of the prolongation of the New Caledonian axis, the Norfolk ridge rises to within 500 fathoms of the sea-surface, and continues with a slightly sinuous but generally south-south-easterly direction towards the centre of the North Island of New Zealand, meeting it to the west of the short submarine prolongation of the North Auckland Peninsula. The basaltic mass of Norfolk Island, rising from this ridge, contains a volcanic tuff with fragmental crystal-grains possibly derived from a plutonic source (Speight, 1913). Stretching west of the narrow New Caledonian trench is a large submarine plateau, situated at a depth of less than 1,000 fathoms, reaching almost to the coastal shelf of Queensland, from which it is separated by a deep, narrow trench. From this a second wider and more continuous ridge extends south-south-easterly to the neighbourhood of Cook Strait. Lord Howe Island (composed of relatively ancient and probably late Tertiary basalts and agglomerates) rises from the western side of this long submarine plateau-ridge, which is separated from the Norfolk ridge by the New Caledonian trench, between 2,000 and 3,000 fathoms deep; and a like depth, the Thompson Trough, divides it from Australia. The special interest attaching to Lord Howe Island lies in the occurrence in it of the remains of the giant tortoise *Miolania*, which is also known in the Pleistocene rocks of Walpole Island, of Queensland, and Cretaceous (?) of Patagonia. "As *Miolania* must have been a land-animal, its discovery in regions so remote is sometimes cited as one proof of the former existence of a great Antarctic continent uniting the lands in question."* This, and the position of the broad suboceanic ridges, suggest a continuance of a general south-south-easterly grain in the structure of the floor of the Tasman Sea, which may thus be the foundered former continental land. Such an indication, however, clearly does not approximate to a proof.

The geological formations of New Zealand may be classed broadly into a pre-Cretaceous and a Middle Cretaceous - Tertiary series. The following tectonic details concerning it may now be noted. The most ancient rocks are visible along the western slopes of the South Island. According to recent ideas, they are crystalline schists and gneisses lying unconformably below the Ordovician sediment; but the possibility that they are (partly at least) an extremely altered facies of the Ordovician rocks cannot be held to have been excluded. Their strike is very variable, ranging from W.N.W. to N.N.E., and is not noticeably different from the strike of the Ordovician rocks. Its varying trend is possibly due to the refolding along approximately meridional lines of rocks originally folded on a north-westerly strike. A limited area of Silurian sediments also

---

* *British Museum Guide to the Fossil Reptiles, &c.*

occurs, but their structural relationships are not clearly known, though their strike appears in general to be approximately parallel to that of the Ordovician beds. The earlier north-westerly folding was accompanied by the intrusion of more or less gneissic granites according to Park (1921), who has revived the belief that this occurred in Devonian times. By some writers the intrusion of the gneissic diorites has been assigned to this period, but recent work shows that a much later date is probable. The relation of the older Palaeozoic to the later Palaeozoic and Mesozoic sediments which presumably rest unconformably on them is not clearly exhibited. At one time these later rocks were classed into one continuous series (Maitai series) of supposedly Trias-Jura age, but they are now known to range from the Permian to basal Cretaceous, and to contain several lacunae and probably disconformities. These were the littoral sediments on the western margin of the Pacific of that period. Diversity exists in the interpretation of the structure of these rocks. It has been affirmed (on grounds the writer considers inadequate) that an extensive orogeny, accompanied by the intrusion of the gneissic diorites of the south-west, occurred between Permian and Triassic time, but, though, as Marshall has now recognized (1917A), some break may occur here, which would account for the absence of the Lower and Middle Triassic fauna, no angular conformity has been shown between the two series, and probably a simple retreat of the sea, to be correlated with the general regression throughout the Malay Archipelago in Lower Triassic times and resulting disconformity of Upper Triassic on Permian or basal Triassic annelid beds, was the essential feature of that interval. Indeed, it may have been partly bridged by the time of deposition of the large series of unfossiliferous greywackes which intervene between the two fossiliferous formations.

The gently undulating Jurassic beds of eastern Southland certainly contrast sharply with the steeply folded Maitai rocks of western Southland, but do not come into contact with them. Instead, they pass down conformably into the strongly folded Triassic rocks of the Hokonui Hills, which, when traced to the north-west, could scarcely be separated by Hutton from the Maitai rocks of western Southland; and, though he returned (1885, 1900) to his first impression that there was a concealed unconformity here, he believed for a time (1875) that a perfect conformity existed. The strike of these beds in the southern flank of the Hokonui Hills is towards the north-west, but, as was shown by Cox (1878), it bends very sharply but continuously 'round into a southerly direction parallel to the strike of the Maitai rocks of western Southland, and thus encloses a wedge-shaped area of gently undulating Mesozoic sediments which cover much of south-eastern Southland. The significance of this will be discussed later. On the northern side of the Hokonui Hills the fossiliferous Triassic rocks appear to pass down into the flat-lying micaceous schists of Central Otago, to which further reference must be made.

The early Cretaceous orogeny is the most marked of the tectonic disturbances which have affected New Zealand and produced very intense folding and dislocation. The strike of the Permian, Triassic, and Jurassic rocks varies considerably, though chiefly within the same limits as those of the older folded strata. The variability is most marked in the shattered earth-blocks in the north-western peninsula in the North Island. Approximately meridional strikes, varying somewhat to the east or west, are common in the main ranges of this Island, and the plication is most intense in the eastern half, though without extensive overfolding; but on the western side it is more open, and the strata are undulating except where they are shattered by the broad crush-zones as shown by the recent investigations of Henderson and Ongley (1923). The same trend continues through the Kaikoura Mountains of the South Island, though a north-easterly strike is marked near the line of separation between the Palaeozoic rocks in the north-western portion of that Island and the Permian to Mesozoic rocks which make up the Southern Alps. Mr. Morgan (1911) has suggested that here the north-easterly-striking Mesozoic rocks have been thrust over the north-north-westerly-striking Palaeozoic foreland. A zone of shattering invaded by plutonic rocks sometimes separates the two masses. The ultrabasic rocks of the Dun Mountains, and the gneissic granodiorites of the south-west, appear to have been erupted at this period, proof of the intrusion of the granodiorite into the annelid-bearing Permian or Triassic sediments having recently been obtained by Moir and also by Park (1921).

In the southern half of the South Island of New Zealand the main ranges bifurcate. One branch, containing the Palaeozoic sediments and granodiorites, continues to the south-south-west through Fiordland, bending later to the south-east into Stewart Island; the other range bends directly to the south-east, running through Central Otago, and consists of the problematical Otago schists. These form a broad anticlinal mass of sericitic schist, usually appearing to pass laterally and vertically into fossiliferous Permian (?) and Triassic greywackes, &c., though rectilinearly bounded masses of greywacke appear to be sometimes rather sharply distinct from the adjacent schists. On the south-west boundary of Otago a syncline (largely covered by Recent alluvium) and a sharp anticline of fossiliferous Triassic greywackes (forming the Hokonui Hills) separate this region of nearly flat schists from the gently undulating unaltered Mesozoic sediments of Southland, which are wedged in between the two branches of the bifurcating range, as indicated above. Suess terms this bifurcation the meeting of two unilateral chains in syntaxis; but the writer would suggest that it resembles rather a virgation of a single range with a general westward superficial thrust forced by the presence of a rigid block underlying the gently undulating Mesozoic strata. In the north of the Hokonui Hills the gradual passage of the greywacke into the schist, and the complete absence from the greywackes of any detritus derived from the schists on which they rest, as demonstrated by Marshall (1912, 1918), inclines the writer to Marshall's view that the schists are but the metamorphosed form of the greywacke. In the Otago region, as has been suggested by Wilckens (1917), the superficial thrust seems to have been so great as to produce overfolding, so that the flat-lying schists may really be a packet of recumbent folds. This explanation was also independently conceived by the writer (Benson, 1921), with the addition that the Hokonui anticline was considered as a Parma-like forefold separating the overfolded area from the resistant massif beneath Southland; and, further, the existence of fault-blocks bringing the slightly altered upper recumbent folds down among the lower folds and more metamorphosed rocks was suggested as a means of explanation of the occurrence of rectilinearly and rather sharply bounded areas of greywacke among the micaceous schists. The lack of recognizable horizons, however, will long prevent the adequate testing of these hypotheses. It is to be noted that plutonic intrusions are almost entirely absent from the region supposed to consist of recumbent folds, but they are abundant in the western branch of the forced virgation—*i.e.*, western Southland and Fiordland.

It may here be remarked that according to Hector (1870), cited by Marshall (1912), the schists of the Chatham Island may be compared and correlated with those of Otago, and have a north-easterly strike; and remnants of a large area of crystalline rocks presumably united into single massif occur in the other islands scattered south-east of New Zealand.*

Authorities have differed concerning the continuity or otherwise of the sequence of late Cretaceous and Tertiary "Notocene" strata which rest on the eroded surface of the late Mesozoic folds. The difficulties attending the solution of this question are particularly great in the North Auckland region, owing to the paucity of recognizable horizons and the dislocation and discontinuity of outcrop of the several formations resulting from the plexus of Pleistocene fractures. Among the lowest of the Notocene strata are marly beds with a Senonian fauna, now under investigation by Dr. Marshall, and apparently comparable with those in New Caledonia, the South Island of New Zealand, Graham Land, and Chile. Newer than these and more widespread are foraminiferal and algal hydraulic limestones, probably for the most part of about Danian age—though it is not at all certain that all the lithologically similar masses of limestone here are coeval. These are followed by tufaceous sandstones with Mollusca, some coal-measures, and a polyzoan limestone of possibly Oligocene-Miocene age, which form the chief distinctive formations in a great thickness of clay or marl above the hydraulic limestone (*cf.* Ferrar, 1922). In addition to these, however, are several interstratified bands of conglomerate, the character of the pebbles in which is being studied by Mr. J. A. Bartrum, and is yielding very significant information, which by his courtesy the writer is permitted to discuss here. As far back as 1884 McKay noticed the intrusion of ultrabasic rock into the hydraulic limestone. This Bartrum has confirmed, finding several instances of masses of normal serpentine, troctolite, or gabbro invading the limestone. The intrusion of such plutonic rocks is characteristically associated with orogenic crust-movements (*cf.* Benson, 1924), so that it may be inferred that the same was true here. Among the above-mentioned conglomerates, however, Bartrum found pebbles of ultrabasic and basic rocks, suggesting that extensive erosion followed the post-Danian orogenic movements before the deposition of the conglomerates and associated claystones, &c.† Thus by a new line of attack upon the obscure stratigraphy of the region the occurrence of a marked unconformity in the Tertiary record in the North Auckland region is seen to be extremely probable; and this unconformity may tentatively be correlated with the much more extensive and vigorous Tertiary orogeny and plutonic intrusion in New Caledonia, and that of the overthrusting in the East Indies, which, as we saw, decreased greatly in intensity when traced

* Observations made by R. S. Allan while these notes were in the press show that the general strike of the schists of Chatham Island runs but little north of due east, though there are exceptional north-easterly, meridional, and even north-north-westerly strikes, apparently in regions of local dislocation. The strike of the schists here is thus approximately parallel to the direction of extension of the shallow bank connecting the Chatham Islands with the mainland. The direction as shown on fig. 3 must thus be modified. The overlying Tertiary marine sediments and volcanic rocks do not appear to show any marked folding.

† The source of the bulk of these pebbles, however, he believes to have been a pressure-affected "terrain which was in existence before and during the deposition of Trias-Jura-sediments." (*Cf.* Bartrum, 1924.)

north-westwards into Sumatra. It is, as yet, quite impossible to indicate the direction of superficial thrust of these crust-movements in New Zealand. The dips of the Tertiary rocks are generally moderate (30°–40°), and the strike is so variable in orientation that it is difficult to pronounce any direction as being that of the prevalent strike. Crust-movement appears to have continued intermittently throughout the Gisborne district (Henderson and Ongley, 1920) during the Cretaceous and Tertiary period, and recently Ongley and Macpherson, during their official geological survey of the East Cape district, have found that the Cretaceous rocks are very strongly folded with a north-west - south-east strike, and are invaded by a pre-Miocene dioritic complex, the source, perhaps, of the dioritic pebbles in the basal conglomerates of the Miocene beds of the Gisborne district. In Hawke's Bay McKay (1877) recorded the occurrence of strongly folded Cretaceous rocks beneath the gently undulating Pliocene beds, and this has been confirmed by Dr. Thomson, who (in a private communication) has compared the Cretaceous rocks lithologically with those of the Middle Cretaceous (Clarentian series) of the South Island. With them he would include the "East Coast series" formerly referred tentatively to the Lower Cretaceous by Morgan (1915) and the writer (1921), and considered to be the latest of that great series of Mesozoic sediments laid down before the Cretaceous orogeny, though the relationship of this series to the characteristic, highly dislocated, and definitely pre-Cretaceous greywackes and argillites has not yet been critically examined. Again, in Palliser Bay, east of Wellington, McKay (1879) recorded the presence of vertically dipping Amuri (Upper Cretaceous) limestone lying unconformably beneath Tertiary marine beds, and Thomson observed pebbles of Cretaceous rocks in the Upper Tertiary sediments in the same region. In the South Island there is as yet no clear evidence of an early Tertiary orogeny, though warpings and block-movements during the period seem to have caused small angular unconformities, disconformities, and overlaps in different localities, not apparently confined to any one period, though probably most pronounced in the early Tertiary and Pliocene periods. The gradually accumulating evidence for these has been summarized by Vaughan (1921) and the writer (Benson, 1921). A few examples of extremely localized overfolding of Tertiary rocks, as at Nelson and on Lake Wakatipu, may be local thrustings connected with the Plio-Pleistocene block-movements.

In Pleistocene times this crust-warping and block-faulting with tilting were extremely important, and were the chief processes by which the present topography was determined. The nature of these movements has been elucidated by Professor Cotton in a succession of important papers (*e.g.*, 1916, 1917, &c.). The chief system of longitudinal fractures and warpings is of those which run north-north-east to north-east, cutting obliquely across the strike of the Mesozoic folds. They have in many regions blocked out the main features of the coast-lines, subsequently modified by the normal processes of marine erosion, so that the strike-ridges meet the coast *en echelon*. In the south, however, where the trend-line of the Otago schists bends to the south-east, the coast truncates the trend-lines almost perpendicularly. The volcanic zone in the centre of the North Island is continued in the same north-easterly direction to White Island, in the Bay of Plenty, and thence into the Kermadec ridge, the origin of which is thus bound up with the structural development of New Zealand. Besides this main longitudinal direction of fracturing there are minor diagonal or transverse fractures and warpings in certain regions.

Since this late Tertiary and Pleistocene climax of block-movement of the crust extensive erosion has taken place; the covering of Cretaceous and Tertiary sediments on the harder pre-Cretaceous greywackes, &c., offering relatively little resistance, has, for the most part, been removed from the higher blocks, but remains in the relatively depressed coastal lowlands, and also in a series of intermontane basins, where it may be covered by the fluviatile gravels derived from the highlands (Cotton, *op. cit.;* Speight, 1915). This recalls in a striking manner the main topographic features of Celebes described above. The latest crust-movements have been in the nature of broad regional warpings, depression or uplift moving equally aggregates of many of the smaller fault-bounded blocks, producing features of coastal drowning or elevation, with consequent revival of river-valleys. The origins of the earthquakes felt in New Zealand (with a few exceptions—*e.g.*, the Cheviot earthquake and the recent Taupo, Wellington, and North Canterbury shocks) are situated not within the land area, but some distance seaward to the east (Hogben, 1914, 1918).

In a previous paper (Benson, 1923, pp. 10–12) the tectonic relationship of New Zealand and Antarctica has been discussed, and support given to the view of Mawson (1911), Gregory (1912), Wilckens (1917), and Kober (1921) that the continuation of the south-easterly trend-lines of Otago will be found in King Edward VII Land and Graham Land, and form part of the folded margin of the Pacific Ocean basin, the continuity of which in Upper Cretaceous times is indicated by an extremely uniform littoral Senonian fauna. In furtherance of this it may be pointed out that there seems a marked similarity in age and petrographical character between the largely dioritic, more or less gneissic rocks of south-western New Zealand and the granodioritic batholiths that are so characteristic of the Antarctandes of Graham Land, the Andes proper, and the coast ranges of British Columbia. Since Upper Cretaceous times, however, the bordering land-masses of this oceanic littoral have been broken up by fracture-systems, the most marked of which, in the New Zealand region, cross the old trend-lines obliquely, running in a north-north-easterly to north-easterly direction. To these may be ascribed the blocking-out of the subsided region forming Ross Sea, and the shaping of the general outline of New Zealand, excluding that of the North Auckland Peninsula, which is due to other fracture-systems. On this conception the New Zealand-Kermadec ridge would appear rather more as a complex fault-horst rising from an extensive submerged platform than as a fold-anticline. Brouwer, however, points out that a geanticline growing at depth is represented at the surface by a fractured ridge, often marked by a line of volcanoes, and separated from a foredeep by a steep submarine slope beneath which earthquakes originate. These are features exhibited to some extent by the Kermadec ridge and Tongan trough, from which the lines of volcanic and seismic activity may be traced respectively southwards into the centre, and off the east coast of the North Island of New Zealand. If New Zealand be regarded as the apex of a virgation, it appears to have become more or less stabilized and continental in character in the broad, largely submerged southern portion, the scanty information concerning the structure of which was summarized in a preceding paper (Benson, 1923, p. 11). The crustal activity increases northwards into the separate arcs. Andrews (1922, p. 20) remarks that the arcs become continental and confluent at their southern extremity. This appears to have been the case also at an earlier epoch, for the evidence of crust-movement during early

Tertiary times in the South Island is much less marked than in the North, where even plutonic intrusion appears to have occurred; and thence follows the immense folding and intrusion of peridotite during the same period in New Caledonia, and the general occurrence of Tertiary orogeny and plutonic intrusion along the zone traced all the way to Timor and its adjacent islands. In much of this, however, the evidence for Cretaceous orogeny and plutonic intrusion is less definite than it is beyond the regions mentioned—namely, in Java and Sumatra at the one extreme, and in the South Island of New Zealand at the other—into which the Tertiary orogeny did not extend. Again, though late Tertiary and Pleistocene crust-movement (block-faulting) accompanied by volcanic and seismic activity extending up into modern times occurs more or less markedly throughout the whole zone, it apparently reaches its maximum in the central region from the New Hebrides to beyond New Guinea, in which last the displacements have been very great indeed. Thus throughout the course of time there seems to have been a progressive limiting of the region of maximum intensity of crustal activities to the area where—to use Andrews's (1922) phrase—the Tethyan and Pacific controls most directly interact. Possibly the diversity of the structure of the Australasian margin, which, as has been pointed out, exists between the western and eastern sides of this central region, arises from some diversity in the nature of these controls, the one a compression between the Australian and Asiatic continental systems, and the other between the Australian region and the Pacific floor. In the latter the effect has been to produce a continuously outgrowing complex, as emphasized especially in Andrews's papers, in which the modern volcanic and seismic activity in the New Hebrides is but the continuation of the action of the same controls which produced the Tertiary orogeny and plutonic intrusion in New Caledonia, and the successive zones of Permian, Carboniferous, Devonian, and early Palaeozoic folding and plutonic intrusion which may be traced in south-westerly sequence through the eastern States of Australia.

In conclusion, the writer has pleasure in acknowledging his indebtedness to several friends for help in connection with the preparation of this paper. Professor Wanner communicated some useful comments on the previous paper and minor corrections. Professor Brouwer kindly read the portion of the manuscript dealing with the East Indies, and made very valuable suggestions. Dr. S. van Valkenburg, of the East Indian Topographic Survey, provided some useful maps, especially the large new "Schetskaart van Nieuw Guinee (Nederlandsch Gebied)." Mr. Stanley, Government Geologist of Papua, discussed many points, and placed at the writer's disposal a large amount of unpublished material, including the manuscript of his forthcoming *Geology of Papua*, and a shorter paper since published by the Australasian Association for the Advancement of Science. The Rev. E. F. Pigot contributed seismic data from the New Hebrides-New Guinea area; Mr. J. A. Bartrum, unpublished information concerning the Tertiary intrusive rocks of the North Auckland Peninsula; Messrs. Ongley and Macpherson, information concerning those of the East Cape district, Dr. Allan Thomson, information concerning the Cretaceous rocks of Hawke's Bay, and Mr. R. S. Allan, observations recently made by him in the Chatham Islands. Mr. G. E. Harris has assisted in the preparation of the diagrams. To all these gentlemen the writer's thanks are due. He desires especially to acknowledge his debt to Professor Sir Edgeworth David, who first aroused his interest in the fascinating problems which have herein been considered.

List of References cited in the Text.

(Papers the originals of which were not consulted by the writer are indicated by an asterisk.)

Abendanon, E. C., 1915. *Geologische en geographische doorkruisingen van Midden Celebes.* Leiden.*

—— 1919. Aequinoctia, an old Palaeozoic Continent, *Jour. Geol.*, vol. 27, pp. 562–78.

Ahlburg, J., 1913. Versuch einer geologische Darstellung der Insel Celebes, *Geol. und Pal. Abhandlungen*, Neu. Folg., Band 12, Heft 7.*

Andrews, C. W., 1900. *Monograph of Christmas Island, Indian Ocean.* British Museum.

Andrews, E. C., 1922. The Present Structure of the Pacific, in Pres. Address, *Proc. Roy. Soc. N.S.W.*, vol. 56, pp. 14–38.

Bartrum, J. A., 1924. An Account of the Riverhead-Kaukapakapa District, Waitemata County, Auckland, N.Z., *Rep. Aust. Assoc. Adv. Sci.*, vol. 16, p. 346.

Benson, W. N., 1921. Recent Advances in New Zealand Geology, Pres. Address, Section C, *Rep. Aust. Assoc. Adv. Sci.*, vol. 15, pp. 45–133.

—— 1923. Palaeozoic and Mesozoic Seas in Australasia, *Trans. N.Z. Inst.*, vol. 54, pp. 1–62.

—— 1924. The Tectonic Conditions accompanying the Intrusion of Basic and Ultrabasic Rocks, *Memoirs Nat. Acad. Sci. Washington* (in litt.).

Boehm, G., 1906. Neues aus dem Indo-Australischen Archipel, *Neues Jahrbuch für Mineralogie*, Beil.-Bd. No. 22, pp. 385 *et seq.**

Brouwer, H. A., 1915. On the Tectonics of the Eastern Moluccas, *Proc. Kon. Akad. van Wetensch. te Amsterdam*, vol. 19, pp. 242–48.*

—— 1917. On the Non-existence of Active Volcanoes between Pantar and Dammer (East Indian Archipelago) in connection with the Tectonic Movements in this Region, *ibid.*, vol. 21, pp. 795–802.

—— 1917a. On the Age of the Igneous Rocks in the Moluccas, *ibid.*, pp. 803–15.

—— 1917b. On Reef-caps, *ibid.*, pp. 816–26.

—— 1917c. Geologisch Overzicht van het Oostelijk Gedeelte van den Oost Indischen Archipel, *Jaarboek van het Mijnwezen in Ned. Oost Indië*, Jahrg. 40, pp. 147–452.

—— 1919. Devonische Afzettingen in den Oost Indischen Archipel, *De Inginieur*, Nov. 29, 1919.*

—— 1919a. On the Crustal Movements in the Region of the Curving Rows of Islands in the Eastern Part of the East Indian Archipelago, *Proc. Kon. Akad. van Wetensch. te Amsterdam*, vol. 22, pp. 772–82.

—— 1920. Fractures and Faults near the Surface of Moving Geanticlines, I, *ibid.*, vol. 23, pp. 570–76.

—— 1921. The Horizontal Movements of Geanticlines and the Fractures near their Surfaces, *Jour. Geol.*, vol. 29, pp. 560–77.

—— 1921a. Some Relations of Earthquakes to Geological Structure in the East Indian Archipelago, *Bull. Seismological Soc. America*, vol. 2, pp. 166–82.

—— 1921b. Geologische Onderzoekingen op de Soela Eilanden, I, *Jaarboek van het Mijnwezen in Ned. Oost Indië* (1920, ii), pp. 1–90.

—— 1922. The Major Tectonic Features of the Dutch East Indies, *Jour. Wash. Acad. Sci.*, vol. 12, pp. 177–85.

—— 1922a. Fractures and Faults near the Surface of Moving Geanticlines, II, Abnormal Strikes near the Bending-points of the Horizontal Projection of the Geanticlinal Axis, *Proc. Kon. Akad. van Wetensch. te Amsterdam*, vol. 25, pp. 329–34.

Chamberlin, R. T., 1919. The Building of the Colorado Rockies, *Jour. Geol.*, vol. 27, pp. 145–64, 225–51.

—— 1921. Vulcanism and Mountain-making, a Supplementary Note, *ibid.*, vol. 29, pp. 166–72.

Chapman, F., 1918. Cainozoic Fossils from the Oilfields of Papua, *Bull. Territory of Papua*, No. 6.

Compton, R. H., 1917. New Caledonia and the Isle of Pines, *Geog. Jour.*, vol. 49, pp. 81–103.

Cotton, C. A., 1916. Structural and Later Geological History of New Zealand, *Geol. Mag.*, dec. 6, vol. 3, pp. 243–49, 314–20.

COTTON, C. A., 1917. Block Mountains in New Zealand, *Amer. Jour. Sci.*, vol. 44, pp. 249–93.

COX, S. H., 1878. Report on the Geology of the Hokonui Ranges, Southland, *Rep. Geol. Explor.*, pp. 25–47.

DAVID, T. W. E., 1911. Notes on some of the Chief Tectonic Lines of Australia, Pres. Address, *Proc. Roy. Soc. N.S.W.*, vol. 45, pp. 4–60.

—— 1914. Papua (in The Geology of the Commonwealth), *Federal Handbook on Australia for the Brit. Assoc. Adv. Sci.*, p. 316.

DAVIS, W. M., 1905. A Shaler Memorial Study of Coral Reefs, *Amer. Jour. Sci.*, vol. 40, pp. 223–71 (esp. 255–56).

—— 1918. The Subsidence of Reef-encircled Islands, *Bull. Geol. Soc. America*, vol. 29, pp. 489–574 (esp. 545–49).

—— 1922. The Barrier Reef of Tagula, New Guinea, *Annals Assoc. American Geographers*, vol. 12, pp. 97–151.

DECK, N., 1921. Rennell Island, *Geog. Jour.*, vol. 67, pp. 474–76.

DEPRAT, J., 1905. Les Depôts Eocenes Neo-Calédoniens, leur Analogie avec ceux de la Region de la Sonde, *Bull. Geol. Soc. France*, ser. iv (5), pp. 485–516.

EASTON, H. WING, 1921. Het ontstaan van der Maleischen Archipel gezien in het licht van Wegeners hypothesen, *Tijdschrift van het Kon. Ned. Akad. Aardrijsk Gen. 2, reeks 38*, No. 4, pp. 484–512. (Abstract in *Geol. Zentralblatt*, Nov. 15, 1921.)

ES, R. J. C. VAN, 1917. De Tektoniek van de Westlijke Helft van den Oost Indische Archipel, *Jaarb. van het Mijnwezen in Ned. Oost Indië* (1914), Jahrg. 40, pp. 7–143.

FERRAR, H. T., 1922. On the Geological Survey of the Whangarei and Bay of Islands Subdivisions, *N.Z. Jour. Sci. and Tech.*, vol. 4, pp. 311–14.

GELDER, J. K. VAN, 1910. Verslag omtrent een Geologische Verkenning van de Mamberamo Rivier op Nieuw Guinea, *Jaarboek van het Mijnwezen in Ned. Oost Indie*, Verhandl, pp. 87–112.

GREGORY, J. W., 1912. The Structural and Petrographical Classification of Coast-types, *Scientia*, vol. 11, pp. 36–63.

—— and TRENCH, J. B., 1916. Eocene Corals on the Fly River, Central New Guinea, *Geol. Mag.*, vol. 63, pp. 381–88, 429–36.

—— and GREGORY, C. J., 1923. The Alps of Chinese Tibet and their Geological Relations, *Geog. Jour.*, vol. 56, pp. 153–74.

—— 1923A. The Banda Arc, its Structure and Geographical Relations, *Geog. Jour.*, vol. 62, pp. 20–32.

GROLL, M., 1912. Bathymetrical Chart of the Pacific Ocean, published by the Institut für Meereskunde der Universität, Berlin.

GUPPY, H. B., 1887. *The Solomon Islands.* Swan Sonnenschein & Co., London.

HADDON, A. C., 1894. On the Geology of Torres Straits, *Trans. Roy. Irish Academy*, vol. 30, pp. 419–76.*

HECTOR, J., 1870. Notes on the Geology of the Outlying Islands of New Zealand, *Trans. N.Z. Inst.*, vol. 2, pp. 176–86.

HELDRING, O. G., 1909. De Zuidkust van Nieuw Guinea, *Jaarboek van het Mijnwezen in Ned. Oost Indie*, pp. 83–203.

—— 1913. Verslag over Zuid Nieuw Guinea, *ibid.*, pp. 40–207.

HENDERSON, J., and ONGLEY, M., 1920. Geology of the Gisborne and Whatatutu Subdivision, *N.Z. Geol. Surv. Bull. 21.*

—— —— 1923. The Geology of the Mokau Subdivision, *N.Z. Geol. Surv. Bull. 24*, pp. 19–20.

HOBBS, W. H., 1921. *Earth Evolution and its Facial Expression.* Macmillan and Co., New York

—— 1922. Les Guirlandes Insulaires et la Formation des Montagues, *Annales de Geographie*, vol. 20, pp. 483–95.

HOGBEN, G., 1914. Notes on some Recent Earthquakes in New Zealand, *Trans. N.Z. Inst.*, vol. 46, pp. 301–3.

—— 1918. A Note on East Coast Earthquakes (N.Z.), 1914–17, *ibid.*, vol. 50, pp. 280–81.

HOTZ, W., 1913. Vorlaufige Mitteilungen ueber geologische Beobachtungen in Ost. Celebes, *Zeits der deutschen Geol. Ges.*, vol. 65, Monalsber, pp. 329–34.*

HUBRECHT, P. F., 1913. Beknopt. Geologischen Meteorologisch Verslag der 3rd Zuid. Nieuw Guinea Expeditie, *Maatsch ter bevordering van het Ond. der Ned Kolonien*, Bull. 68, pp. 37–51.*

HUTTON, F. W., 1875. *Geology of Otago*, p. 43. Mills, Dick, and Co., Dunedin.

—— 1885. Sketch of the Geology of New Zealand, *Quart. Journ. Geol. Soc.*, vol. 41, p. 203.

—— 1900. The Geological History of New Zealand, *Trans, N.Z. Inst.*, vol. 32, p. 165.

JENSEN, H. I., 1906. The Geology of Samoa and the Eruptions of Savaii, *Proc. Linn. Soc. N.S.W.*, vol. 31, pp. 665 *et seq.*

KOBER, L., 1921. *Der Bau der Erde*, Berlin. Gebruder Borntraeger.

KOTO, B., 1899. On the Geological Structure of the Malayan Archipelago, *Jour. Coll. Sci. Imp. Univ. Tokyo*, vol. 2, pp. 1–83.*

McKAY, A., 1877. Report on the Country between Masterton and Napier, *Rep. Geol. Explor. N.Z.*, pp. 67–94.

—— 1879. The Southern Part of the East Wairarapa District, *Rep. Geol. Explor. N.Z.*, pp. 75–86.

—— 1884. On the Occurrence of Serpentinous Rocks as Dykes in Cretaceo-Tertiary Strata near the Wade, Auckland, *ibid.*, 1883–84, pp. 99–101.

MARSHALL, P., 1911. Presidential Address to Section C, *Rep. Aust. Assoc. Adv. Sci.*, vol. 9, pp. 90–99.

—— 1912. New Zealand and the Adjacent Islands, *Handbuch der Regionalen Geologie*, vol. 7, pt. i. C. Winters, Heidelberg.

—— 1912A. Oceania, *ibid.*, vol. 7, pt. ii.

—— 1917. The Geology of the Central Kaipara, *Trans. N.Z. Inst.*, vol. 49, pp. 433–50.

—— 1917A. Permo-Carboniferous Rocks in New Zealand, *Rep. Brit. Assoc. Adv. Sci.*, pp. 108–9.

—— 1918. The Geology of the Tuapeka District, *N.Z. Geol. Surv. Bull. 19*, pp. 27–36.

MARTIN, K., 1911. Palaeozoische, mesozoische, und kainozoische Sedimente aus sudwestlichen Neu Guinea, *Samml. Geol. Reichs-Mus. Leiden*, vol. 9, pp. 84–107.

—— 1914. Wann loeste sich das Gebiet des Indischen Archipel von der Tethys ? *ibid.*, pp. 337–55.

—— 1919. Unsere Palaeozoologische Kenntnisse von Java, mit einleitenden Bemerkungen uber die Geologie der Insel, *Samml. Geol. Reichs-Mus. Leiden*, Beil.-Bd. 9.

MAWSON, D., 1911. The Australasian Antarctic Expedition, *Geog. Jour.*, vol. 37, p. 612.

MOLENGRAAFF, G. A., 1912. On Recent Crustal Movements in the Islands of Timor, and their Bearing on the Geological History of the East Indian Archipelago, *Proc. Roy. Acad. Amsterdam*, vol. 15, pp. 224 *et seq.*

—— 1913. Folded Mountain Chains, Overthrust Sheets, and Block-faulted Mountains in the East Indian Archipelago, *Comptes Rendu du XII^e Congrès Geol. Internat. Canada*, pp. 689–702.

—— and BROUWER, H. A., 1914. De Geologie van het eiland Letti, *Jaarboek van het Mijnwezen in Ned. Oost Indië* (1914), Jahrg. 40, Deel 1.

—— 1921. Modern Deep-sea Research in the East Indian Archipelago, *Geog. Jour.*, vol. 57, pp. 95–120.

—— 1922. *De Zeeën van Nederlandsch Oost Indië*, pp. 272–357. E. J. Brill, Leiden.

MORGAN, P. G., 1911. A Note on the Structure of the Southern Alps, *Trans. N.Z. Inst.*, vol. 43, pp. 275–78.

NEWTON, R. B., 1916. Notes on some Organic Limestones, &c., collected by the Wollaston Expedition in Dutch New Guinea, *Reports on the Collections made by the British Ornithologists' Union Expedition and the Wollaston Expedition in Dutch New Guinea*, vol. 2, No. 20.

—— 1918. Foraminiferal and Nullipore Structures in some Tertiary Limestones from New Guinea, *Geol. Mag.*, dec. 6, vol. 5, pp. 203–12.

PARK, J., 1921. The Geology and Mineral Resources of Western Southland, *N.Z. Geol. Surv. Bull. 23.*

PIROUTET, M., 1917. *Etudes Stratigraphiques de la Nouvelle Calédonie.* Chotat Frères, Macon.

RECKE, O., 1913. Der Kaiserin Augusta Fluss, *Mitt. Deutsch. Schutzgebieten* (?).

REED, F. R. C., 1921. *The Geology of the British Empire.* Edward Arnold, London.

RICHARZ, P. S., 1910. Der Geologische Bau von Kaiser Wilhelmsland nach dem heutigen stand unseres Wissens, *Neues Jahrbuch für Mineralogie,* Beil.-Band 29, pp. 456–536.

RICHTHOFEN, F. VON, 1900. Uber Gestalt und Gliederung einer Grundlinie in der Morphologie Ostasiens, *Verh. der Kais. Preus. Akad. d. Wiss. Berlin,* pp. 916 *et seq.**

RUTTEN, L., 1914. Foraminiferanfuehrende Gestenie von niederlandisch Neu Guinea, *Nova Guinea, Resultats de l'Expédition Scientifique Néerlandaise à la Nouvelle Guinea in 1903,* vol. 6 (ii), pp. 21–51.

SAPPER, K., and LAUTERBACH, C., 1910. Wissenschaftliche Ergebnisse einer amtlicher Forschungsreise nach dem Bismarck-Archipel im Jahre 1908, *Mitt. Deutsch. Schutzgebieten Erganzungsheft No. 3.**

SARASIN, P., 1912. Zur Tektonik von Celebes, *Zeits der deutschen Geol. Ges.,* vol. 64, *Monatsber,* pp. 226–45.*

SCHULTZE, L., 1914. Forschungen in Innern der Insel Neuguinea, *Mitt. Deutsch. Schutzegebiet,* (?) *Erganzungsenheft 11,* pp. iv, 1–99.*

SMITH, STANIFORTH, 1912. Exploration in Papua, *Geog. Jour.,* vol. 39, pp. 313–34.

SPEIGHT, R., 1913. On a Collection of Rocks from Norfolk Island, *Trans. N.Z. Inst.,* vol. 45, pp. 326–31.

—— 1915. The Intermontane Basins of Canterbury, *ibid.,* vol. 47, pp. 336–53.

STANLEY, E. R., 1912. *Report on the Geology of Woodlark Island.* Government Printer, Melbourne.

—— 1915. Report on the Geology of Misima (St. Aignan), Louisiade Goldfields, *Bull. Territory of Papua,* No. 3.

—— 1920. Report on the Geology of Fergusson Island (Moratau), *ibid.,* No. 6.

—— 1921. A Contribution to the Geology of New Guinea, *ibid.,* No. 7.

—— 1923. Report on the Salient Geological Features and Natural Resources of the New Guinea Territory, *Report to the League of Nations on the Administration of the Territory of New Guinea from 1st July, 1921, to 30th June, 1922,* Appendix B, pp. 5–67.

—— 1924. Notes on the Structural Relationships of the Volcanic Rocks, Late Tertiary and Mesozoic Deposits in New Guinea, *Rep. Aust. Assoc. Adv. Sci.,* vol. 16, pp. 284–95.

—— 1924A. The Geology of Papua (to accompany the Geological Map of the Territory of Papua). In MS.

SUESS, E., 1908–9. *The Face of the Earth,* vols. 3 and 4. Oxford Univ. Press.

TOBLER, A., 1906. Topographische und geologische Beschreibung der Petroleum-Gebiete bei Mocara Enim (S. Sumatra), *Tijdschr. Nederl. Aardrijkskund Genootsch,* pp. 199–315.*

VAUGHAN, T. W., 1921. The Correlation of the Later Mesozoic and Cenozoic Formations of New Zealand, *Proc. First Pan-Pacific Scientific Conf.,* part iii, pp. 713–43.

VERBEEK, R. M. D., 1908. Molukken. Verslag., *Jaarboek van het Mijnwezen in Ned. Oost Indie,* No. 37.

VOLZ, W., 1899. Zur Geologie von Sumatra, *Geol. und Pal. Abhandl.* Neu Folg. 6, Heft 2.*

WANNER, J., 1913. Geologie von West Timor, *Geol. Rundschau,* Bd. 4, pp. 136–50.

—— 1913A. Zur Geologie der Inseln Obimajora und Halmahera in den Molukken, *Neu. Jahrb. f. Min.,* Beil.-Bd. 36, pp. 560–85.

—— 1919. Die Geologie von Mittel Celebes nach den neuerer Forschungen E.C. Abendanons und Anderer, *Geol. Rundschau,* Bd. 10, pp. 45–62.

—— 1921. Zur Tektonik der Molukken, *Geol. Rundschau,* Bd. 12, pp. 155–65.

WEGENER, A., 1920. *Die Enstehung der Kontinente und Ozeane.* 2nd ed. Veiweg, Braunschweig.

WILCKENS, O., 1917. Die Geologie von Neuseeland, *Geol. Rundschau,* Bd. 8, pp. 143–61.

WOOLNOUGH, W. G., 1903. The Continental Origin of Fiji, pt. 1, *Proc. Linn. Soc. N.S.W.,* vol. 28, pp. 457–96.