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On the Growths of Continents*

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With eight figures

SUMMARY

A mechanism for the formation of arcs on the earth's surface is put forward. A physical cause for this process based upon the contraction hypothesis as stated by Jeffreys is stated and physical reasons given why the process should give rise to arcs. It is shown that the geology, the volcanism, the distribution of earthquakes and the whole pattern of existing active mountain ranges may be explained in terms of this process.

The question of how it has acted in the past and the causes of the changes in the pattern along which it is applied is discussed. So is the rate of volcanism.

The contributions of new and of secondary or eroded material to form continental shelves and the material for new marginal mountain ranges is estimated.

It is concluded that the proposed mechanism is physically valid and would serve to explain the growth during geological time of continents, oceans and atmosphere on a planet initially uniform and lacking these surface features.

INTRODUCTION

The physical characteristics of the earth may be described in several ways. The existing features may be defined; their history may be told; the processes which caused the earth to have a history may be discussed. A great deal is already known about the first two categories, the earth's features and the latter part of its geological history. Much less is known about the third, but it is with this search for a primary process which causes the earth to have internal motions, and to change its surface features that this paper is chiefly concerned. In this respect the earth is an engine. It does work to build mountains and cause earthquakes. Its horsepower has been estimated to be of the order of 10^{10} h.p.

For the purpose of the analysis to be made in this paper of the earth's internal processes three classes of information are available. They are observations made by the methods of field geology, analysis made by mathematical treatment based upon the fundamental laws of physics and observations made by physical, that is geophysical, methods. Assistance in the problem may also be obtained from the fields of geochemistry, geodesy and cosmology.

The methods of field geology have been adequate in order to describe the earth's surface as it is and to tell a great deal about its history, but they have not disclosed the cause of the earth's internal movements and there is no indication that they are likely to do so. In order to discover the processes that have given the earth a history, a consideration of physical laws is necessary, for one must

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assume that the earth, like all other matter which has been observed, is subject to the fundamental laws of gravitation, electromagnetic theory, heat conduction, radioactive decay, elasticity and fluid motion. The processes operating within the earth must both obey these laws and also be such as to produce the observed geology of the earth. This assumption is generally agreed upon, but the combined approach by both the geological and the mathematical methods at once, has not been extensively put into practice because geological maps and descriptions are so complex that until recently it was not apparent either to geologists or to mathematicians how the fundamental physical laws could be applied to them.

For more than a century a body of sound geological observation has been growing together with another of established physical laws, but this irreconcilable impasse has existed between them. It is on account of this temporary limitation that geology is often classed as a 'natural' rather than a physical science.

More recently a third class of information has become available in the form of a body of geophysical observations which promise to bridge the gap and make possible the eventual transfer of geology into the group of precise sciences with a sound theoretical basis. These observations include measurements in different parts of the earth of gravity, radioactivity, heat flow, location of earthquakes, age of rocks, layering of the earth's interior. These physical data promise to enable physical theory and geological observations to be reconciled, because on the one hand the geophysical results are relatively simple and amenable to mathematical analysis, and because on the other hand for the first time they tell something precise about the nature of the earth's interior which can be correlated with the surface geology. In this paper published geological and geophysical observations are interpreted in terms of the theoretical analyses of the earth's behaviour advanced by H. Jeffreys (1929) and A. E. Scheidegger (Scheidegger and Wilson, 1950).

The method of approach used has been to examine some existing mountain ranges and island arcs. It has been found that their essential features can be approximated to by simple forms and that the arcs and ranges can be divided into a few classes of elements. These arcs and mountains are generally almost circular arcs. They presumably represent zones where failure has occurred in the outer spherical shells of the earth.

The properties of spherical shells making up various possible earth models of increasing complexity have been examined by Scheidegger to see how such models could fail so as to produce forms similar to those actually observed. Only one has been discovered which would give rise to the required shapes.

It has been shown that there are logical physical reasons why this type of failure not only could, but should, occur. In this manner a mechanism has been derived, which is believed to be physically sound and which appears to be capable of producing arcuate thrust failures at the earth's surface.

This mechanism derived for a single arcuate element is then applied to each part of the present mountain system to demonstrate that its repeated application is consistent with observed geological and geophysical data. Finally, the attempt is made to show that the repeated application of this process in the past might have been sufficient to have built past mountains and to have given rise to continents in a manner consistent with their geological structure.

The paper thus aims to present a coherent theory of the growth of terrestrial features. The theory appears to meet many requirements, but is only a first approximation, for it does not explain the cause of any but the largest structures. An attempt has been made to show that it is quantitatively compatible with the data available from field geology, from geophysical observation and from the pertinent laws of physics. A number of ways in which it may be checked are pointed out.

CHARACTERISTICS OF ACTIVE PRIMARY ISLAND AND MOUNTAIN ARCS AND OTHER ELEMENTS OF OROGENETIC SYSTEMS

It is one of the great achievements of field geology to have shown that mountain building is concentrated in mobile active belts which have moved about the earth from time to time. Two belts, each roughly along a great circle, make up the system which is at present active. One of these belts extends across the Mediterranean, Southern Asia, Indonesia, and Melanesia to New Zealand. The other surrounds the Pacific Ocean from Indonesia clockwise to Antarctica. The recognition of this system was largely the work of Suess (Bucher, 1933, p. 33).

It has long been known that many of its elements are arcuate ranges or chains of volcanic islands. Sollas (1903) and Lake (1931) are among those who have suggested that some of these arcs are approximately circular.

In this paper the whole of the present system is regarded as being made up of elements, which may be divided into five classes. Four of these are approximately circular arcs. These five types of arc meet in junctions which also fall into classes, again five in number. These types of elements and junctions will now be described.

Single Island Arcs

Most island festoons such as those of East Asia, the South Sandwich Islands or the greater part of the Aleutian or Lesser Antilles Islands form single island arcs. The essential topographical and geological feature is a regular arcuate chain of active volcanic islands, concentric with which on the outer or convex side is an ocean trench. (Umbgrove, 1947, pp. 173-174.)

Double Island Arcs

If the Aleutian Island arc be followed towards Alaska the single volcanic island arc develops into a double arc; the place of the ocean trench is taken by Chirikof and Kodiak Islands and the Kenai Peninsula, which are all predominantly composed of sediments. The essential topographical and geological feature thus becomes two separate, but parallel arcs of islands, the inner one volcanic, the outer one sedimentary. The arcs near Trinidad in the West Indies and near Timor in the East Indies are other examples of double arcs. (Umbgrove, 1947, pp. 175-177.)

Double Mountain Arcs

If the double island part of the Aleutian Islands be followed still further east, it can be seen to become a double continental mountain system in which the valley occupied by Cook Inlet separates the volcanic (and batholithic) inner arc of the Aleutian Range from the sedimentary outer arc on Kenai Peninsula and in the Chugach Mountains. (Fig. 1.)

Bostock (1948) has illustrated this three-fold division of the western Cordillera for the whole British Columbia coast. Vancouver, Queen Charlotte and Alexander Archipelago Islands are predominantly sedimentary. The main Coast Range in Canade is batholithic and volcanic while between it and the islands is a trough occupied by channels of the sea and patches of flat-lying young sediments.

In the United States a similar double arc divided by a trough is also apparent. The sedimentary Coast Ranges are divided from the volcanic and batholithic arc of the Cascade and Sierra Nevada Mountains by Puget Sound and the Great Valley of California. The whole west coast of North America affords good examples of double mountain arcs, but others are discernible on other continents, as will be shown.

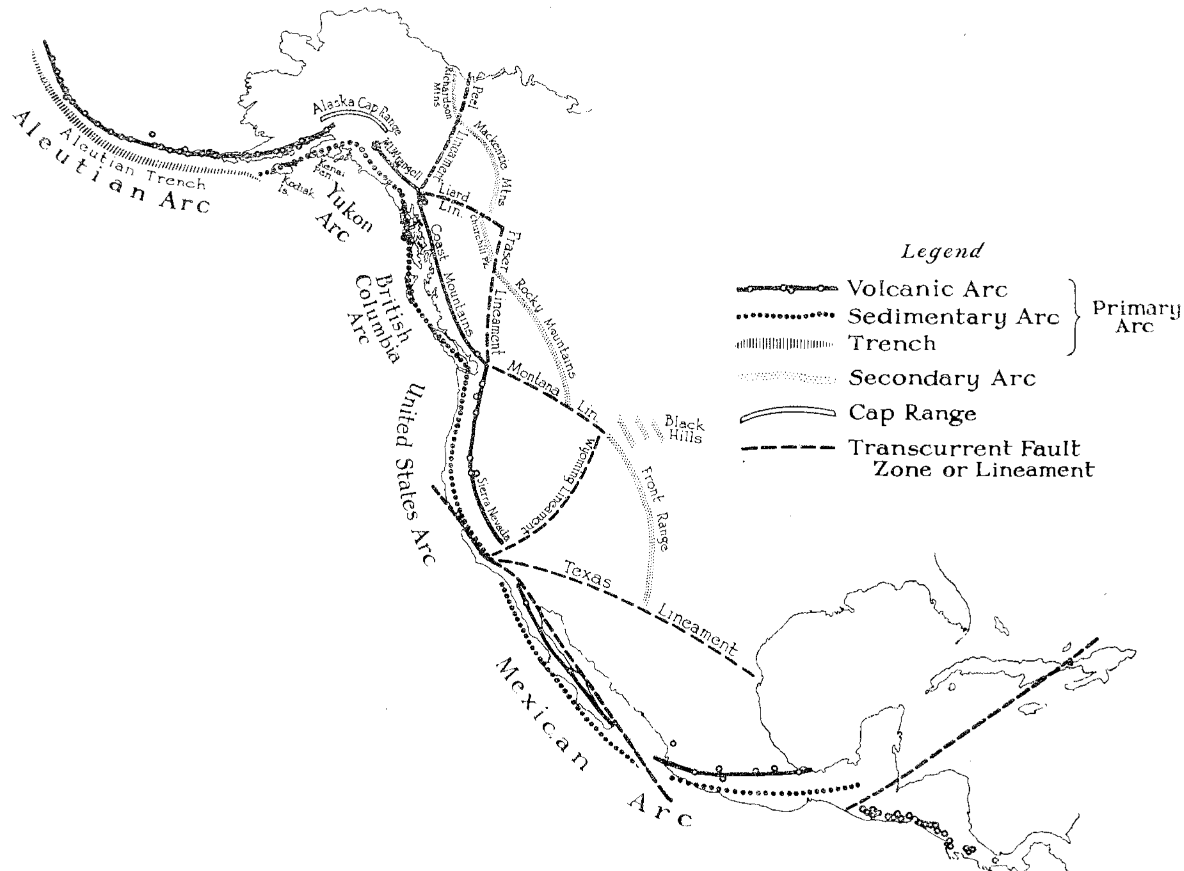

FIG. 1.—The North American Cordillera, showing five primary arcs along the coast, the secondary ranges in the interior, and the medianland which separates them.

Single Mountain Arcs

In the centre of the west coast of South America between Santiago and Ecuador the coastal mountains are volcanic and face an ocean trench off shore. It will be pointed out that the Andes form a series of arcs convex towards the Pacific Ocean. This central part is similar to single island arcs except that the volcanic chain forms part of the continent and includes batholiths as well as volcanoes. The central Andes are the only examples recognized of this type, and the only coastal mountains facing trench off shore. (Fig. 2.)

Fractured Arcs

It is well-known that the San Andreas transcurrent fault zone cuts the southern half of the United States double mountain arc, but it does so without destroying the double arc pattern. In the case of the Philippine fault zone on the other hand, a great fault is the predominant feature and only some disorganized aspects of arcuate structure exist, such as a deep ocean trench, and scattered active volcanoes. The simple arcuate pattern either never existed or has been destroyed or torn apart by the transcurrent fault zone. Such composite features will be called fractured arcs. The arcs from the Philippines to New Zealand are of this general type. (Fig. 3.)

Characteristics of Single and Double Island and Mountain Arcs

The distribution of the four different types of regular arcs (i.e., those other than fractured arcs) suggests that the type developed depends upon the activity of movements along the arc, the age of the arc and the proximity to continents. Single Island arcs are made of young rocks and occur far from continents; double arcs occur where continents are approached; double mountain arcs which may contain ancient rocks are the usual type found upon continents. The single mountain arcs of the central Andes are exceptionally active and are the only mountains with which deep earthquakes are associated.

Gutenberg and Richter (1949) have divided every arcuate structure into six zones lettered A to F from the convex to concave side. These zones together with their possible properties are listed in the following table in a slight amplification of the original statement. Not all of the features are, of course, observed in any one arc. These features are only found in what are here called primary arcs. They are not associated with rift valley ranges nor with secondary arcs like the Rocky Mountains of the Alberta-British Columbia boundary.

Features of Arcs Reading from Convex to Concave Sides

(A) An oceanic trench

(B) An arc of sedimentary islands or mountains
Young serpentine intrusives in the sedimentary belt
Shallow earthquakes under B or on the concave slope of A
A belt of large negative gravity anomalies

(C) A valley or shallow trough between B and D
Earthquakes at depths near 60 kms., frequently large
A belt of positive gravity anomalies

(D) A volcanic island or mountain arc or a batholithic mountain arc
Serpentine intrusives within the volcanic or batholithic arc
Earthquakes at depths of the order of 100 km.

(E) An older volcanic arc
Older Serpentine intrusives
Earthquakes at depths of 200 to 300 km.

(F) Earthquakes at depths of 300 to 700 km.

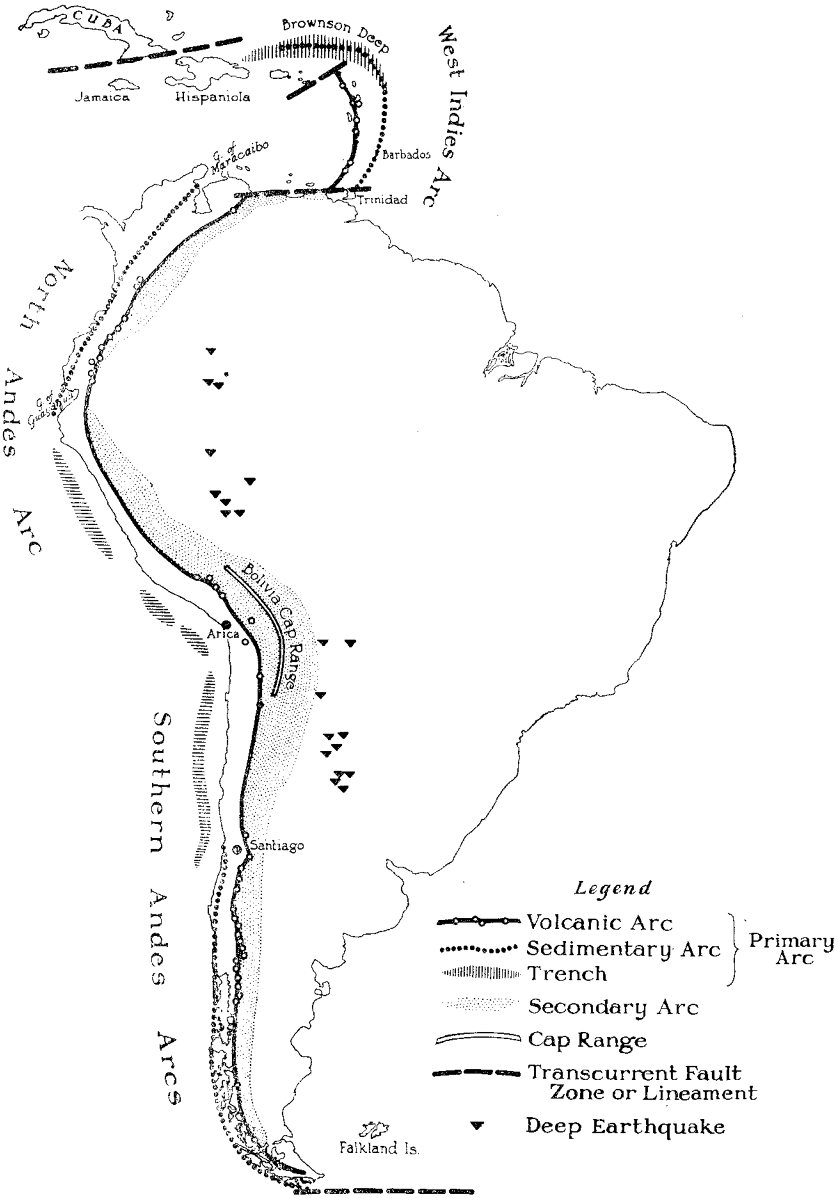

FIG. 2.—The South American Cordillera, showing four primary arcs of the West Indies and Andes and the secondary ranges which adjoin them.

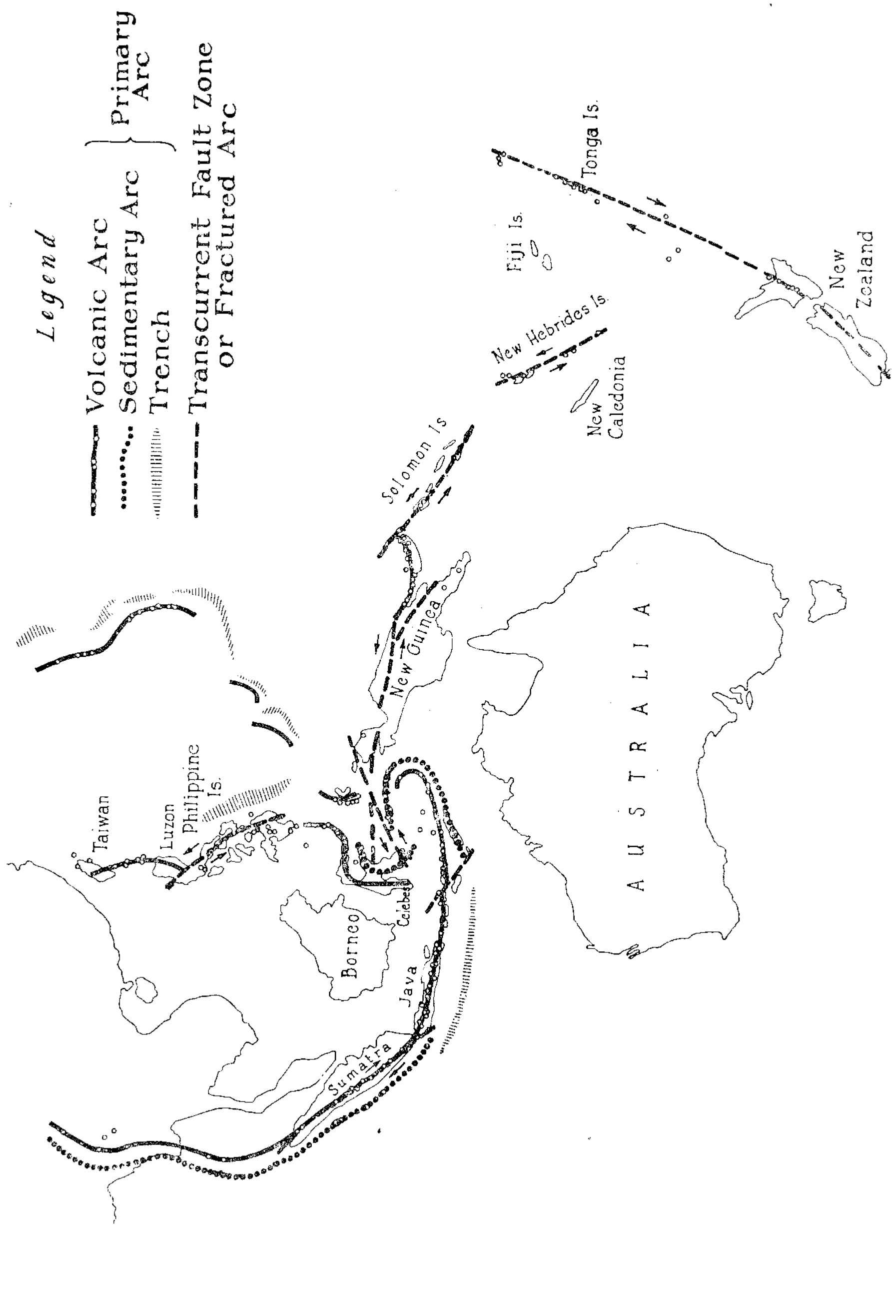

FIG. 3.—The Indonesian junction of orogenic belts and the fractured arcs from the Philippine Islands to New Zealand.

TYPES OF JUNCTIONS OF ARCS AND OTHER ELEMENTS OF OROGENETIC SYSTEMS

Linkages, Fractured Deflections, Capped Deflections, Reversal Zones and a few Junctions, of which too little is yet known for them to be classified have been recognized.

Linkages were discussed by Suess and are the kind of junction occurring between the north-east Asian island arcs. They are characterized by the extension of one of the arcs past the junction in a nearly straight extension. This extension is, however, marked by much reduced volcanic and seismic activity and only by shallow earthquakes.

Fractured Deflections are the junctions occurring in North America where two arcs meet in an obtuse angle. One conspicuous lineament and probably a second which is less well developed spring from the junction and enter into the continent forming broad valleys through the cordillera. These valleys are believed to be fault zones and across them are changes in geological structure (Fig. 1.)

Capped Deflections occur where arcs meet at an angle that is right or acute. There is a Cap Range of metamorphic rocks of great elevation swinging around the junction. An example of a cap range is the Alaska range at the junction of the Aleutian and Yukon arcs.

Reversal Zones. When Hess described the West Indies he suggested that the arc of the Antilles was linked to Mexico and to South America by zones of transcurrent faults. Since these zones occur where arcs change from facing in one direction to another, they will be called reversal zones. They have no deep or intermediate earthquakes and appear to be shallow fractures only, and to be approximately straight following great circles. They only occur at either end of the Antilles and South Sandwich arcs.

Other Junctions. This group include junctions covered by the sea such as those in Melanesia, of which little is known.

THEORY OF FAILURE OF SPHERICAL SHELLS

The whole of the present system of orogenitic belts might now be described in terms of elements and junctions of the types just defined, but it is considered that this will be clearer if it is deferred until after consideration of the process which is believed to be giving rise to these arcuate and faulted elements.

The simple form which best fits the axis of an island chain or mountain range is not easy to define. Neither topography, geology nor any geophysical measurements yet made give more than an approximate shape. Within these limitations the shape of several arcs has already been analysed. Some appear to be almost straight like the Tonga-Kermadec-New Zealand element, or the Solomon Islands. Most are probably circular, but are possibly spirals not far different from circles. It may be that the centres of most of these circles lie close to one or other of two nearly orthogonal great circles (Lake, 1931, and Wilson, 1949). Certainly most arcs lie at or near the margins of continents. (Fig. 4.)

The development of an arc is presumably due to movement of some kind in one or more of the outer shells of the earth. This can only occur in one of the recognized ways of buckling or failure, that is in an elastic, plastic, creep or flow state or by brittle rupture, sliding fracture or ducile fracture. Shells can fail by expansion or by contraction. The type of failure to be expected has been more fully examined by Scheidegger and the writer from whose paper (Scheidegger and Wilson, 1950) these results are taken.

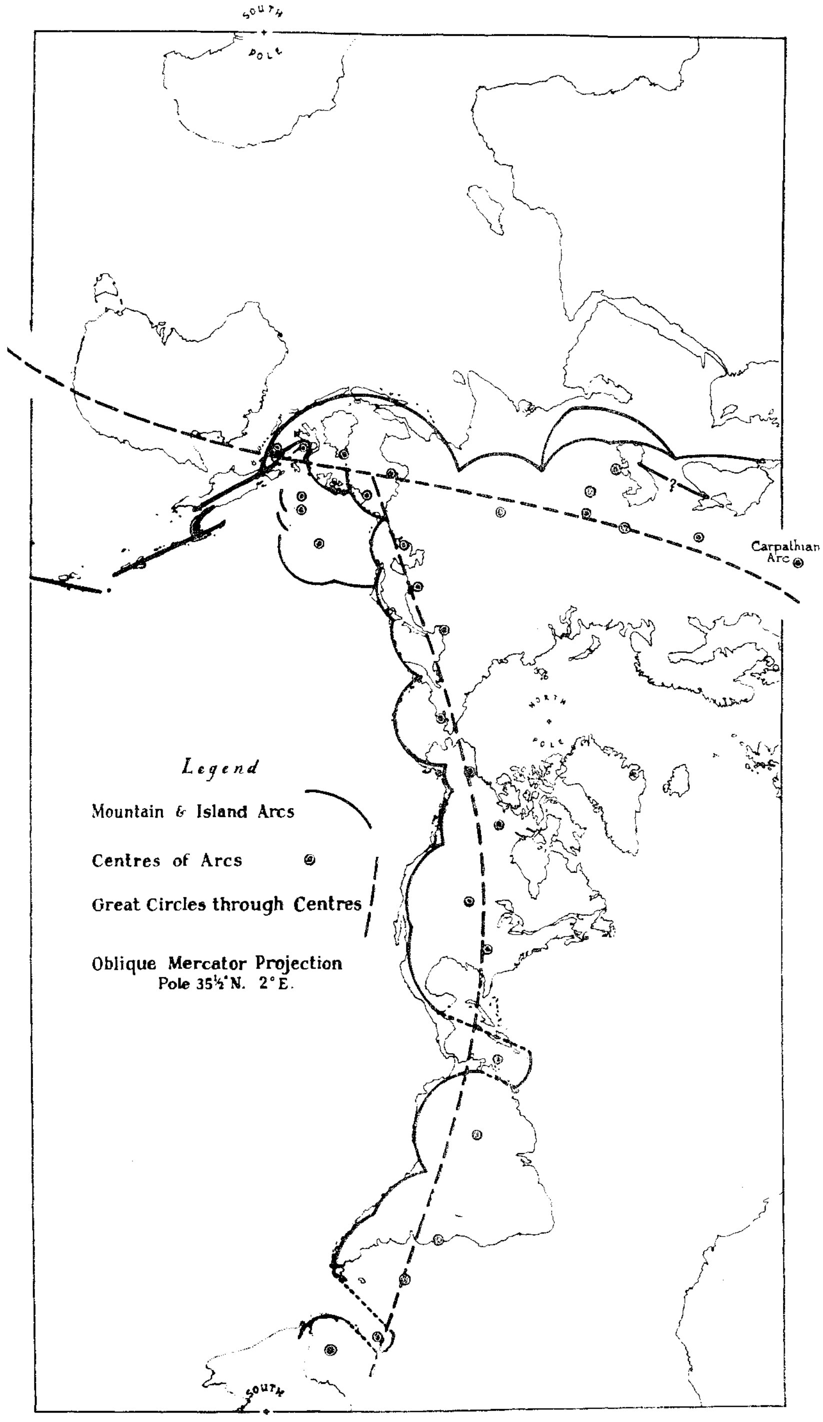

FIG. 4.—The mountain and island arcs of the present orogenic system showing the junction of the two belts in the shape of a "T" at Indonesia.

All possibilities have been investigated for a uniform spherical shell and it has been shown that a uniform shell could not fail so as to form either an arc or a spiral. The earth, however, is not uniform. When the case of aspherical shell with a point of weakness was examined two possibilities were found by Scheidegger which might provide an explanation for the formation of arcs. If a shell with a point of weakness failed in a plastic state it would form a double family of slip lines each with the shape of a logarithmic spiral. These slip lines might be correlated with arcs on the earth's surface, although this is rather doubtful.

However, a spherical shell with a point of weakness could under different stress conditions also fail by sliding fracture, in which case it could break along a conical surface, with the point of weakness as centre, dipping inwards at about 45°. This would be a single fracture not a member of a family, but there could be a number of points of weakness and hence a number of fractures each intersecting the surface along an arc. Such fractures would be ruptures and if their surface expressions took the form of island or mountain arcs then the surfaces of rupture would coincide with the known location of shallow and deep earthquakes and so would be suitable for explaining the cause of shocks. This then appears to be a possible physical explanation and may be tentatively adopted, but it is necessary to show what could cause it. This will be attempted in the succeeding section.

This investigation was not carried further. More complex assumptions could be made, but that is perhaps unnecessary until this simplest explanation has been shown to be untenable.

A reason for the existence of a few irregular elements (Fractured arcs) will be advanced when the whole system is described since their cause depends upon the interaction of parts of the whole system.

The Cause of Failure of Shells Within the Earth

The earth is generally considered to be a heat engine generating about 33×10^9 H.P. as estimated from heat flow and 5×10^9 H.P. as estimated from the energy of earthquakes (Gutenberg and Richter, 1949, pp. 20-21). According to Griggs only two primary mechanisms have been suggested which are adequate to cause mountain building. These are 'compression due to thermal contraction and viscous drag of convection currents in the substratum'. (Griggs, 1939, p. 618.) Many geologists and physicists hold that convection currents provide a likely explanation. Griggs (1939) and Vening Meinesz (1948) have shown very well how convection currents could provide an explanation of the cross section of mountain ranges, but it must be remembered that diagrams of cross sections include various assumptions and that the theory of convection currents is not proven until an explanation is also presented of the development in plan of a series of island arcs. Scheidegger doubts if currents could produce the pattern of arcs. Recent determinations in the Canadian Shield of radioactivity and heat flow are much less than the figures usually taken for the crust. Also large gravity anomalies have been found there which make this theory less tenable than it was formerly held to be.

In this paper an explanation of many features of the earth's surface has been developed which is believed to be physically sound. It has been found that it can be based upon Jeffrey's statement of the contraction hypothesis (Jeffreys 1929, pp. 138-160), but not upon any idea of convection currents.

If the earth is cooling and contracting by conduction and radiation there must be a level of no strain above which the rocks are in compression and below which they are in tension. Jeffreys placed the level of no strain very approximately at 100 km and the limit of appreciable cooling at 700 km.

Recently, Benioff (1949) using data supplied by Gutenberg and Richter has shown that the earthquakes occurring beneath the Andes and Tonga-Kermadec Islands not only lie on surfaces extending to depths of 700 km., but also may be divided into two sequences lying respectively above and below a discontinuity at 70 km. across which he gives reason to believe that there is no effective mechanical coupling. If Jeffrey's very approximate estimate of 100 km. is equated to Benioff's observed depth of 70 km. an explanation of Benioff's observations is provided by the supposition of a cooling earth with a level of no strain at that depth separating the deep and shallow shocks. (Fig. 5.)

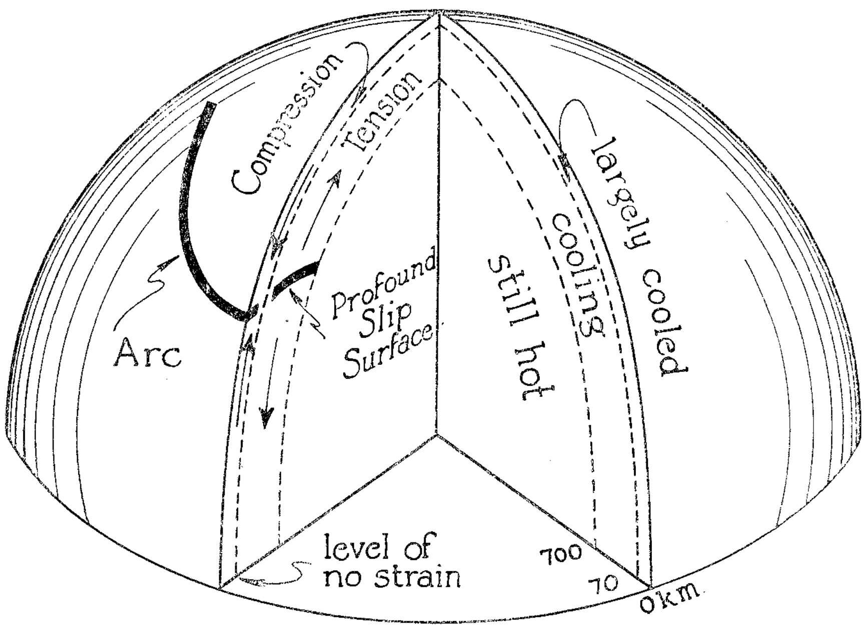

FIG. 5.—Sliding fracture along two conical surfaces centred about a weak point as the cause of arcute failure upon the surface of a cooling earth.

The shell from 70 to 700 km. would be contracting due to cooling, which would cause it either to be in tension or subject to a relief of pressure and hence to fail by sliding rupture producing normal faults with a conical form centered about points of weakness and with a dip of over 45°. It is the cooling of this deeper layer which is regarded as the prime cause of the earth's motions. Above 70 km. the shell would be in compression and would fail by thrust faults with a dip of less than 45°.

Where there are deep and shallow earthquakes their position shows that, in general, failure in the shallow zone overlies failure in the deeper zone. This is not coincidence and apparently the upper failure is constrained to lie over the lower in spite of the theoretical and observed lack of mechanical coupling between the earthquakes occurring in the two layers (Benioff, 1949, p. 1844). The distinction between the forces which are uniform in all directions in the lower layer and the directed forces in the upper layer is important and will be discussed later.

According to the analyses already made arcuate failure must be due to forces which are uniform in all directions. On the other hand, some of the smaller structures and notably the echelon folds and lines of volcanoes on the Japanese islands are not arcuate. They are straight and parallel, and strike not around each arc but along the orogenetic belt as a whole (Tokuda, 1926, and Wilson, 1950).

An explanation of this difference is afforded if one considers the primary cause of mountain building to be world wide cooling, with resultant tensions by forces uniform in all directions in the deeper layer. Deep fracturing having occurred, the shallow fracturing is not due to a world wide and uniform system of forces but is due to local forces which constrain it to occur above the deep fractures and to be oriented with a major axis of stress perpendicular to the deep fractures. In this case failures would not be expected to be arcuate. They would be straight and would appear either as a series of small folds constrained to lie along an arc over the deeper fractures, with each fold axis normal to the major axis of stress in the upper layer, or else as a series of approximately 45° transcurrent faults such as those forming the lineaments connected with fractured deflections. In any case the occurrence in the same arcuate element of large scale features due to tension and also smaller features due to compression is easily understandable. This occurrence of tension and compression features in the same mountain range has been noticed by many previous writers (e.g., Bucher, 1933). The above explanation which places them one above the other avoids having to devise a mechanism involving alternating periods of tension and compression.

Thus, an explanation has been advanced for the building of arcuate, folded mountains and for the occurrence of earthquakes beneath them. Shallow and deep earthquakes occurring on the same arc should have opposite directions of first motion being due to thrust and normal faults respectively. This has been observed and is capable of being further checked (Byerley and Evernden, 1949).

It is considered that ocean trenches are due to overriding by the inner block up-thrust at the surface. If the fault zone is active and far from continental sources of detritus the trench may remain open, but in other circumstances the trench may become filled and subsequent motion may push up the sedimentary filling in the form of thick, contorted, marine beds which may rise above the sea to form an outer sedimentary arc. The same overriding and underthrusting probably suffice to explain the occurrence and position of the belts of negative and positive gravity anomalies. This explanation appears to be very similar in appearance to that shown by Umbgrove (1947, Fig. 114, p. 174) although the postulated cause is different. Certainly Vening Meinesz' concept of the downward root or tectogene has been most valuable.

The cause of the persistent occurrence of volcanoes over that part of the fault surfaces lying about 100 to 150 km. deep is not known, but it is possible to imagine an explanation compatible with the rest of this theory.

The General Characteristics of an Orogenetic System

The principle characteristics of the arcs of the present active orogenetic system will now be described. The six features of a primary arc which were lettered A to F by Gutenberg and Richter have already been mentioned (see Table, p. 89), but primary arcs are only one of several parts that may be present in an orogenetic system. In any cross-section of the North American Cordillera from west to east the following zones are present separated in the manner indicated.

Foreland. The Pacific Ocean basin

Boundary. Sole of thrust fault zone of primary arc dipping east.

Primary Arc. The Coast Range Mountain System including the St. Elias and the Coast Ranges, Cascade Mountains and Sierra Nevada.

Boundary. Indefinite or unknown boundary.

Medianland. The Central Plateau and Basin and Range Province.

Boundary. Faults of the Rocky Mountain Trench.

Secondary Arcs. The Rocky Mountain system.

Boundary. Sole of thrust fault zone of secondary arcs dipping west.

Hinterland. The covered shield and Canadian Shield.

All these zones, or at least the first, second and last ones, will be shown to be present in every section across an orogenetic system which is taken in the direction from the convex towards the concave side of the primary arc.

The foreland is always on the convex side of the primary arc. It is often an ocean, but may be a shield as in the case of India, Arabia and Africa.

The medianland corresponds to the Zwischengebirge or median mass and may or may not be present. If not, the primary and secondary arcs fit together as do the western (primary) and eastern (secondary) Andes.

The secondary arcs may always be distinguished from the primary arcs by reason of their lack of any appreciable volcanism or igneous intrusion, which are indispensible features of any primary arc. They are younger than primary arcs and have no deep earthquakes as can be observed when they are separated from primary arcs by a medianland.

The hinterland is always a shield, usually largely covered, to which the secondary but not the primary arc is convex.

It is suspected that Kyrnine's three classes of sedimentary rocks often fit this structural classification and that his greywacke, arkose and quartzite classes are associated respectively with primary arcs, secondary arcs and thinly covered hinterlands. (Kyrnine, 1948.)

THE PRESENT OROGENETIC SYSTEM

North American Arcs

The Foreland is the Pacific Ocean Basin.

The Primary or Western Arc of the North American Cordillera between Alaska and Honduras consists of four double mountain arcs. These are the Yukon, British Columbia, United States and Mexican arcs which meet in fractured deflections opposite to Skagway, Seattle and Los Angeles. They are illustrated in Fig. 1 and the principle features are self-explanatory. The position of the Mexican arc was established with the aid of the locations given by Gutenberg and Richter (1949, p. 36) for shallow earthquakes and for the position of the large negative gravity anomalies which have been found by submarine off the Lower California coast.

The Medianland is present in North America and forms the Interior System of Yukon and British Columbia (Bostock, 1948) and the Basin and Range and the Plateau Provinces in United States. It is, of course, a very complex area in which metamorphic and igneous rocks are abundant.

The Secondary Arcs are the Eastern System, Rocky Mountains or Front Ranges of the Cordillera and are divided into six ranges or groups of ranges all without appreciable recent igneous activity. The three principle of these form great circular arcs well shown on the tectonic maps of Canada and United States (King, 1944, and Derry, 1950) and are the Mackenzie Mountains, the Rocky Mountains of British Columbia-Alberta-Montana and the Front Ranges of Wyoming, Colorado and New Mexico. Alternating with them are the smaller Richardson Mountains, Churchill Peak Rockies and the complex of mountains in southern Montana. All these features are probably confined to the shell above the level of no strain.

The Hinterland is the Canadian Shield together with covered parts of it in the Interior Plains.

Lineaments

The two lineaments springing from each of the three fractured deflections are shown on Fig. 1, p. 89. In each case that one striking ESE is the only one to be well developed. Of these six lineaments the two most southern were described by Ransome (1915), the Montana lineament is well known to those working in Montana (e.g., W. T. Thom and E. S. Sampson) and there is evidence along some of the faults along this last lineament that the south side moved east. The three marked in Canada possess similar properties and directions to those in United States but have not been so widely recognized.

All six are valleys, marked by rivers and transportation routes. Along the better known there are evidences of fault zones. Where they cross the Cordillera many other structures either change direction or end abruptly. One of the strongest reasons for believing in the validity of these large indefinite features is the marked changes which occur in the secondary arcs of the Rocky Mountains where the lineaments cross these secondary mountains. The precision with which the secondary arcs stop at lineaments and with which changes in direction of the Rocky Mountain trench occur at lineaments can be checked on the tectonic maps of Canada and United States.

The pattern illustrated in Fig. 1 has such astonishing regularity that it cannot be due to chance. Some geologists may claim that it is only obtained by gross over simplification and by associating features not of precisely the same age and of such dissimilar nature as the Sierra Nevada and Cascade Mountains. On the other hand, a physicist would be likely to suspect any explanation that was not fundamentally simple. This may therefore serve as a first approximation whose discrepancies from the complexities of geology need further explanation.

We have already suggested that the reason for the arcuate nature of the primary arcs lies in contraction below 70 km. which is uniform in all directions and symmetrical about weak points and that failure occurs on conical fractures. Once this deep failure has occurred a major principle axis of stress is set up normal to the belt, which gives rise to vertical sliding fractures cutting the belt obliquely. This is suggested as the cause of the lineaments. If true their directions of motion are known from theory and can be checked in the field. It is suggested the lineaments only occur in the upper shell. Deep earthquakes do not occur along them.

It has been shown that the same forces normal to the orogenetic belt would also explain the echelon structure of the Japanese islands as folds or thrusts. Such an echelon arrangement of the volcanic peaks of the Cascade Range is quite apparent on the Tectonic map of United States. (Wilson, 1950, pp. 147-150, and King, 1942.)

On the other hand, directional surface forces would not explain the plainly circular shapes of the three main secondary arcs. This is an anomaly which is not understood, but it may be pointed out that these three main secondary arcs have their centres approximately at the centres of the fractured deflections which might conceivably have acted as points of weakness.

THE ANDEAN ARCS

The Foreland is the Pacific Ocean (Fig. 2).

The Primary Arc consists of three mountain arcs in the Andes. One junction at about 19° south is obvious enough and Benioff (1949, p. 1854) has pointed to a change in earthquake distribution there. The other at Santiago is 33° S is marked by eastward branching folds (Oppenheim, 1948), shallow earthquakes in the interior (Gutenberg and Richter, 1949, p. 42) and a pass. The northern junction is a capped deflection with the Puna block of high (21,000 feet) metamorphic mountains forming the cap. The southern junction is perhaps a fractured deflection.

There is an interesting division of the Andes into single and double types of arc. From Tierra del Fuego to Santiago there is an outer fringe of island or a coastal range composed of in large part of metamorphic or sedimentary rocks, and partly of unexplored nature.

North of Santiago 'longitudinal structural depressions such as the Vale of Chile do not exist and highlands continue unbroken though with gradually decreasing elevation from the Andean front westward to the ocean' (Rich, 1942, p. 165), but from the Gulfs of Guayaquil to Maracaibo there is again an outer sedimentary arc. The central region of single mountain arc is fronted by an ocean trench and is the only part that is underlain by deep earthquakes. There are large negative gravity anomalies off shore approximately over the trench (Gutenberg and Richter, 1949, p. 40).

The Medianland is not present. In the Andes there is clearly no Medianland and the primary and *Secondary Ranges* lie side by side, the reversed convexity and alternating cusps allowing them to fit closely together.

Oppenheim divides the whole length of the Andes into two provinces of which the western ranges are those we have described. They are 'formed totally, or in some instances partly, by great masses of igneous rocks' and were uplifted mostly by block faulting in Upper Mesozoic and Tertiary stages. 'In contrast with the western Cordilleras the eastern ranges of the Andes are formed mainly by sedimentary and metamorphic rocks with the crystalline core appearing in long stretches . . . The structure of the eastern ranges is also predominantly normally faulted and folded; however, moderate thrust faults evidently occur in the easternmost ranges mainly facing the basin plains to the east . . . The age is mainly late Tertiary and Quaternary'. This description suggests that the eastern ranges are the secondary ranges corresponding to the Rocky Mountains in North America and like them younger, sedimentary, and overthrust towards the east. (Oppenheim, 1947, pp. 171-172.)

The Hinterland is the shield areas of eastern South America and their covered extensions adjoining the Andes.

THE EAST ASIA FESTOONS

Off the east coast of Asia between Alaska and the Philippine Islands are the best developed systems of island arcs in the world. The principle of these form the five regular festoons of the Aleutian, Kurile, Japanese, Ryukyu (or Nansei) Islands and the arc from Taiwan (Formosa) to Luzon. Hess (1948, p. 442) has stated that the three southern arcs underwent a major deformation in mid-Mesozoic time.

In late Cretaceous time the pattern of failure changed and since then the most active zone has followed the Kurile Islands, crossed Japan by the Fossa Magna and followed the Bonin, Marianna, West Caroline and Palau Islands. (Fig. 6.)

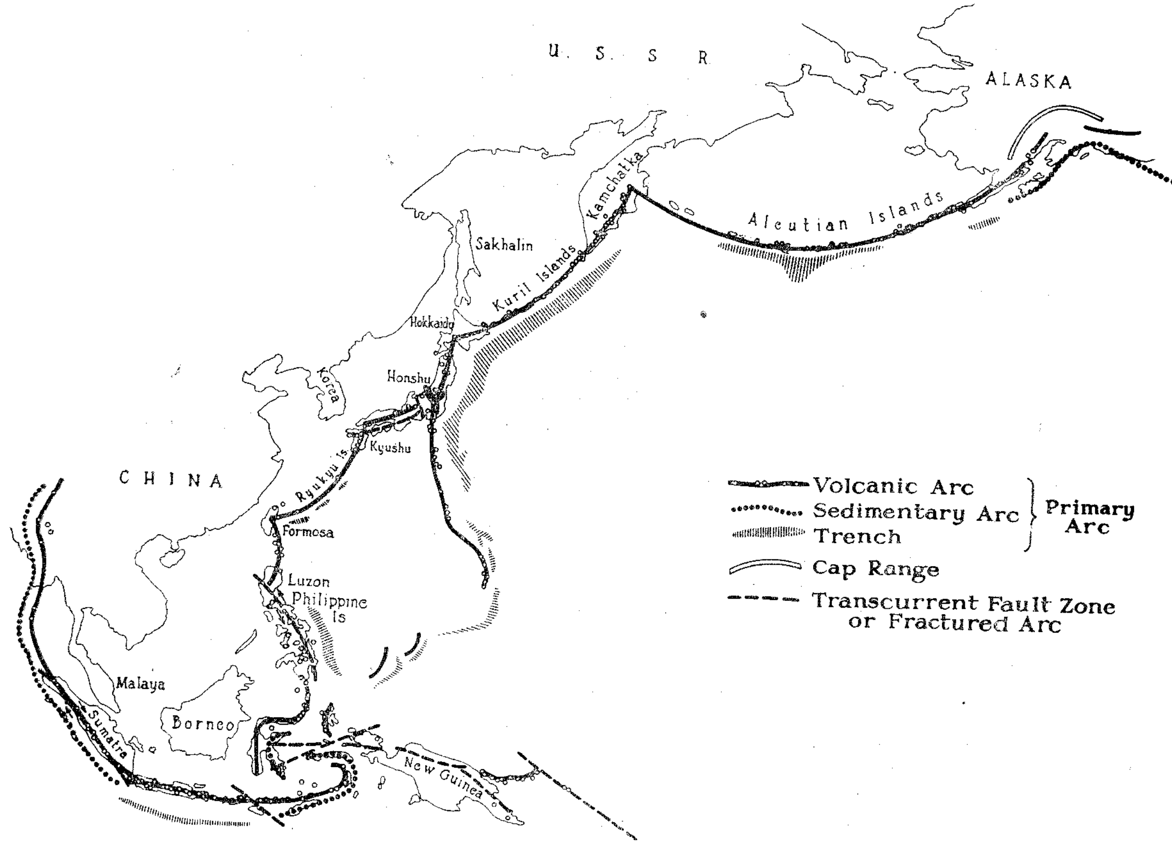

FIG. 6.—The East Asian primary arcs and the Indonesian junction.

Consider first the older belt and notice the similarities and differences between the five arcs. It will be assumed that the Kurile and Aleutian arcs did form in mid-Mesozoic time when the Japanese and North American arcs between which they lie underwent great deformations. There is no evidence known to the contrary. Symmetry suggests it for at the present time the belts of young and active mountains form continuous unbroken belts around major parts of the earth. Therefore it is reasonable to assume that in Jurassic time also the belts were continuous.

The five older arcs, with the possible exception of Japan, appear to be single volcanic arcs and all lie along the margin of the continental shelf about the same distance offshore, between oceanic deeps and moderately shallow water. The form of union between them in each case is linkage with a knot of volcanic mountains at each point of union. These knots are respectively the Sopka Klyuchevskaya volcanoes (15,912 feet) of eastern Kamchatka and the islands of Hokkaido, Kyushu and Taiwan.

Systematic differences between the northern and southern arcs are that the arcs grow smaller towards the south and the knots become increasingly detached from the continent. In regard to these connections with the continent it has already been indicated that the Aleutian peninsula and mountains are part of the volcanic arc right up to the Alaska cap range, but that in the case of the Kamchatka and Hokkaido junctions the active earthquake zones follow the arcs and that there is little seismic activity and no deep activity along the northern half of Kamchatka nor along Sakhalin. It is considered that these extensions in northern Kamchatka and Sakhalin correspond to the lineaments of the fractured deflections in North America and very likely have transcurrent fault zones with left hand (anti-clockwise) displacements along them. This supposition could be checked.

The younger belt and its relation to the five arcs just discussed is most interesting. The evidence of deep earthquakes shows that to-day the primary deep-seated failure follows the Aleutian arc (where there is a little intermediate activity and much volcanism) and the Kurile arc, but instead of turning along the Japanese arc as do all of the shallow features (trench, volcanoes, shallow shocks and geological features) the deep shocks continue along an extension of the Kurile arc to the Asiatic coast near Vladivostok where they join with deep shocks lying upon a continuation of the Bonin arc. This arc crosses Japan by the Fossa Magna. The shallow features all follow the Japanese Islands from the Kurile arc to the Fossa Magna where they divide. The more active volcanoes, the deeper trench and the larger shallow shocks turn along the Bonin, Marianna, West Carolines and Palau arcs with the deep shocks, but some weaker features continue to follow the old arc. This is interpreted as a case where transition from one arc to another is only partially completed. The fact that the deep earthquakes follow a different path from the Kuriles to the Bonins from that followed by the shallow shocks seems to support Benioff's observation that there is no mechanical coupling between the shallow and deep earthquakes and that it is not inevitable that shallow failure will be over deep failure. This also is quite in harmony with the interpretation already given.

The cause and occurrence of echelon structures have already been discussed. It is obvious that the change in location of the profound normal faults which took place early in Tertiary time should have been accompanied by the start of a new echelon pattern. Inquiry shows that this pattern exists and is illustrated by Tokuda (1926, Fig. 7B). A series of 3 block mountains cross central Japan along the Fossa Magna and their echelon structure is continued for at least a little way along the Bonin arc by a series of volcanic chainlets. As far as the writer can understand the age of this second echelon pattern is Tertiary and younger in origin than the Jurassic age of the other echelon structures.

Tokuda's interesting experiments in forming similar echelon patterns by pushing his finger tip across wet rice paper is compatible with the explanation given, for his finger tip constrained the echelon folds to form in an arc around it.

The Alpine-Himalayan-Indonesian-Oceanic Belt

The arcs and ranges dealt with thus far have been relatively simple. They form one of the two belts which lie around the earth. The existence and general trend of the mountain ranges and island arcs are so clear and well-known that only details can differ. Whether the right features have been chosen for emphasis and whether the explanations given have been satisfactory are the only points for discussion.

With the other belt of young mountain and island arcs the situation is not comparable. Many of them are so complex and irregular that even the broadest generalizations are difficult and uncertain. The writer has none of the detailed knowledge which would be required to enter into an adequate discussion of the structure of these regions. On the other hand, to have attempted to give an explanation of the simple belt without giving any reason for the complexity of the other one would weaken the whole case which has been put forward.

A very brief attempt will therefore be made to give reasons why complexities exist and to show that some of the irregularity is more apparent than fundamental.

The Himalayan and Alpine mountains will be treated first, then the arcs of the south-west Pacific and finally the Indonesian junction.

The Alpine-Himalayan Mountains. One factor believed to produce complexity of the mountain chains in this region is the abundant supply of sediment available from Asia, India and Arabia in the Himalayan region and from both Europe and Africa in the Alpine region.

Another factor generally considered to be important is the close proximity of older ranges. Reference to Umbgrove (1947, Plates 2 and 4) shows that in the circum-Pacific belt Paleozoic folding is only close to later folding in Bolivia and Japan. On the other hand, the whole Himalayan-Alpine belt parallels a similar important belt of Variscan age that lies immediately to the north.

A third factor is that this belt did not have open ocean on either side of it. All the circum-Pacific belt fronts on the Pacific ocean, but the Tethys geosyncline was a trough between Eurasia on one side and Africa, Arabia and India on the other. At the eastern end the main Himalayan range lies entirely south of the older folding, but at the western end the Alpine folds have been superimposed directly against the Variscan belts. The consequences of this have been dealt with at length by Bucher (1933, esp. Fig. 88, and Law 39, p. 389) and are summed up by Umbgrove (1947, p. 298) as follows: 'Perhaps we may understand the otherwise incomprehensible knot of Alpine chains in the surroundings of the Mediterranean as partly due to the influence of some very old lineaments. Though deeply buried, they still actively exercise their modelling power on the Tertiary mountain chains'.

Unfortunately, we can obtain no guidance about the nature of the deep-seated failure as there are few intermediate and no deep earthquakes. The deep-seated arcs could be more regular than the surface ones. This also has made it more difficult to trace the primary arcs. Nevertheless, as in North America, it has been possible to identify a series of primary arcs each marked by outer sedimentary ranges and inner volcanic and batholithic ones, and also a series of medianlands and a series of secondary shallow-water sedimentary arcs. These features are of course, all well-known.

It is suggested that there are five great primary arcs (Fig. 7), some rather fractured and irregular, but all possessing the usual features and all about the size of the Aleutians. These all meet in capped deflections. The primary arcs are the Indonesian Arc, the Himalayan arc, the Persian arc, the East Mediterranean arc and the West Mediterranean arc. The cap ranges are the Alps, the Caucasus, the Pamir and some of the high curved mountains of the Ta shuch shan on the Burma-China boundary. All these primary arcs are convex to the south and therefore Africa, Arabia and India are forelands whereas Eurasia is the hinterland for all the arcs. Secondary arcs, thrust to the northward and lacking volcanism, are the Pyrennes, Carpathians, Pontic, north Persian and perhaps the Karakoram Mountains. These are naturally connected with some of the cap ranges since cap ranges are but parts of the secondary system.

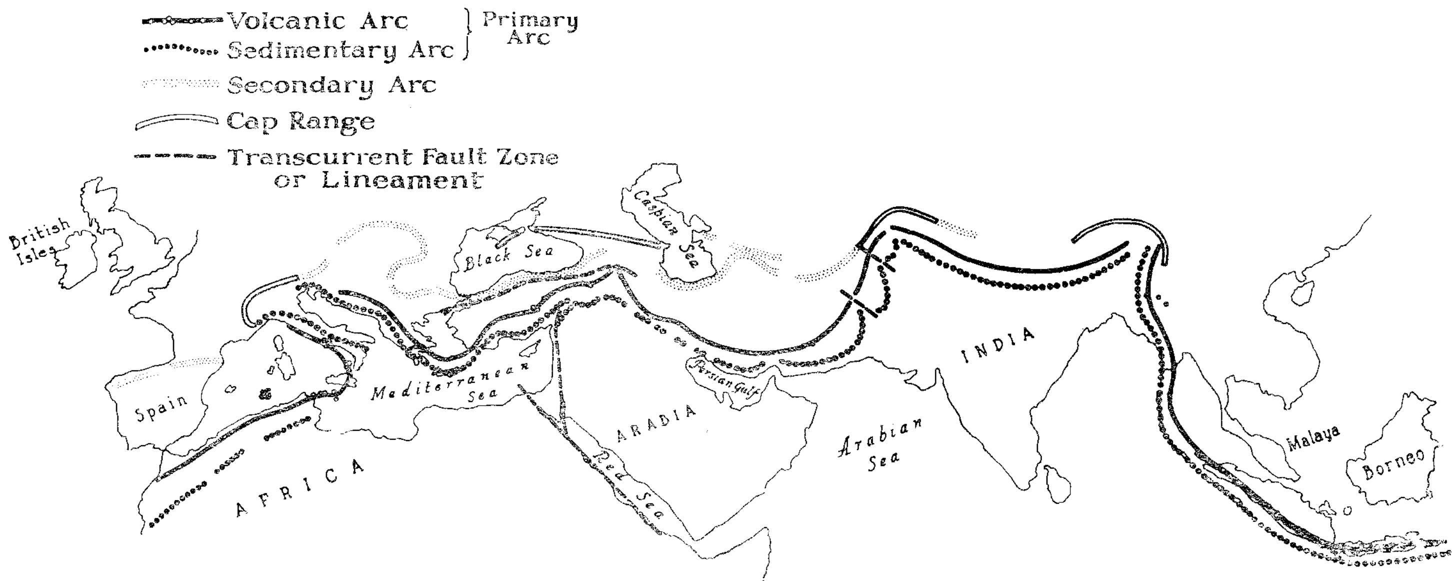

FIG. 7.—The East and West Mediterranean, Persian, Himalayan and Indonesian primary arcs. The rocks of the volcanic arc are andesitic to granitic, those of the sedimentary arc are ophiolitic.

The Melanesian Arcs. These arcs which may be considered to extend from New Guinea to New Zealand include some of the most active seismic regions of the world and certainly the most irregular arcs (Fig. 3). They are not merely compound ones like those discussed in the last section, but some are reversed in direction to others and have ocean deeps on the concave instead of the convex side, and some depart greatly from the normal size by being either very small, like the New Britain arc, or long and almost without curvature, like the Tonga-Kermadec arc.

The three reasons advanced as explanations for the complexity of the Alpine-Himalayan ranges do not apply for there is no evidence of abundant sediments nor of previous orogeny nor of continents on both sides. Some other explanation must be sought.

The one proposed is that the Melanesian arc is part of both the principle belts and has partaken of the fundamental movements of each. The direction of motion in the two belts is nearly at right angles and the interaction of these forces has caused the complexity.

This can be seen by reference to Fig. 8 in which the two belts are shown diagrammatically. Along two of the three limbs of the 'T', shrinking below the level of no strain and compression above can take place without shearing, but along the third side shearing must accompany the shrinkage or compression. This can be seen by arranging three books in the same way separated by one inch gaps and then moving them together or apart.

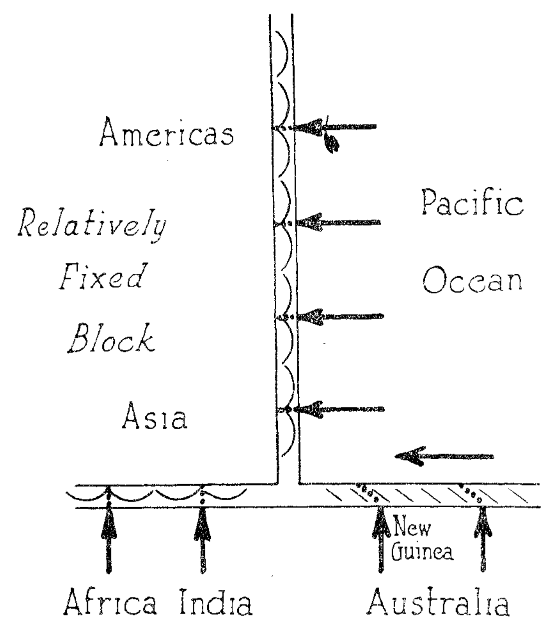

FIG. 8.—Diagram to illustrate the shearing in one limb of the orogenic system, which is believed to be the cause of the fractured arcs from the Philippine Islands to New Zealand. Compare with FIG. 4 (inverted).

We have seen that tension failure alone in the lower shell gives rise to a series of sliding fractures along conical fractures with arcuate outcrops. But if shearing is occurring at the same time conical fractures cannot form and nearly straight fractures take their place.

This is suggested as the explanation of the fractured arcs of the Philippines, New Guinea, Solomon Islands and New Hebrides Islands. It is easy to suggest more precise details of probable direction of motion, but data are limited. The location of active volcanoes and of recent earthquakes is known and they fix the approximate location of the arcs, but the direction of motion of the earthquakes, the distribution of gravity anomalies and the geology are not well known. There is such disagreement about the structural interpretation even among the best informed authorities upon the region. Rather than indulge in speculation, it is just suggested that the occurrence of irregular and straight arcs in this region was to be expected. A mechanism believed to be capable of explaining them in detail when more information is available has been advanced.

Concerning the broad interpretation of the geology of New Zealand and its connection with the Tonga-Kermadec seismic belt and with New Caledonia and other islands there seems to be rather pronounced disagreement at the present time. Suffice it to say that H. Wellman (1950) has identified a longitudinal fault with a lateral displacement of 200 miles. If this is substantiated it is a very large example of the type of structure proposed for New Zealand and the Melanesian fractured arcs.

The Indonesian Junction of Belts. The only thing that can be said briefly about the area of junction of the two belts is that it is complex because two sets of forces acting nearly at right angles have acted upon every part and two belts of failure meet there. It is not surprising therefore, that features often partake of a double nature and that they are broken and irregular.

General Features of the Mesozoic-Cenozoic Pattern of Failure in the Earth

Some of the component arcs and important features of the two Mesozoic-Cenozoic belts have been described. They have three distinguishing features. They are constituted of ranges of folded mountains and volcanic island arcs. They form continuous belts of failure about the earth. They are all generally contemporaneous having been formed during the last 2×10^8 years which is only six per cent of the time since the origin of the earth (Holmes, 1949).

Although these features are the only folded and arcuate volcanic structures of that age, they are not the only features presumed to be due to disturbance of the crust during recent time. There are other kinds of disturbance of which the most important systems are perhaps the African Rift Valleys, the North Atlantic or Thulean volcanic system, the Hawaiian Islands and other linearly arranged Pacific Islands (Chubb, 1934). It is interesting to notice that all of these features have the following points in common. They are all far removed from the arcuate systems; they have only shallow seismic activity associated with them and their volcanic rocks are basaltic, whereas those of the arcs are andesitic.

It is suggested that all these features other than the arcs are due to predominantly horizontal adjustment of the upper part of the crust made necessary by the folding and contraction occurring along the orogenic belts, because the occurrence of shallow but no deep earthquakes in conjunction with these features shows that they have no profound slip-surfaces beneath them. This suggests that they have only extended deep enough to tap basaltic magma and that more profound sources are those which give rise to more acid solutions and magmas. If these are due to horizontal adjustment, that would explain the frequency of long straight faults and lines in their pattern (Anderson, 1942). The Atlantic Ridge could conceivably represent a zone of crustal adjustment also, although, its arcuate shape suggests that it may be a belt of orogenic failure. Its age is not known. Detailed investigation of its structure has only been started (Tolstoy and Ewing, 1949).

The two Mesozoic-Cenozoic orogenic belts are broadly speaking contemporaneous, but there is no evidence that all parts have behaved in the same manner at the same time. On the contrary, those parts where deep-earthquakes are now occurring are considered to be active at present. Other parts like the west coast of the United States are relatively quiescent. It is held with Rutten (1949) and Gilluly that this has been the general rule, that each arc may have had its own history of deposition and erosion and local orogeny and that orogenic epochs within the framework of these Mesozoic-Cenozoic belts have not necessarily been contemporaneous all over the world. As Gilluly (1949, p. 588) stated in his Presidential address to the Geological Society of America 'It seems reasonable to take the California record at its face value, as indicating uplift at one place or another almost continually throughout the Cenozoic. Such movements were doubtless sporadic, like the modern faulting that causes earthquakes. They proceed now quickly, now slowly, now in this area, now in that'.

Benioff's study of earthquakes suggests that in any one arc movements have been contemporaneous, but that there is less regularity in crustal than in profound movements and that there is some connection between adjoining arcs. No doubt there is usually more parallelism in the history of adjacent arcs than between those far apart.

Paleozoic and Precambrian Orogenic Belts

So far only the youngest orogenic belts have been discussed. The idea that the Mesozoic-Cenozoic orogenic episode is but the latest of several is well known. Jeffreys (1929, p. 282-285) has suggested that there may have been of the order of five orogenic epochs. Holmes (1946, p. 109) from geological evidence, which is scarce in the Precambrian, has dated nine, Wahl (1949) and Sonder (1947, p. 941-944) believe there have been a dozen such cycles in the last 2000 million years.

These ideas are followed here and held to be the method by which geological history has unfolded and continents have grown. Only one brief attempt to describe any older belts can be made here. The full story would indeed include all geological history. Sketches of the two Paleozoic belts have been given by Umbgrove (1947, Pls. 1 and 2). Recent views about belts in the Precambrian, have been given for Africa by Stille (1943) and Holmes, Leland and Nier (1950a) for Australia by Hills (1948), for India by Krishnan (1948) and Holmes, Leland and Nier (1950b) and for Canada by Gill (1949) and Wilson (1949b). The idea which has been suggested in different forms by Davison (1887), Andrews (1916) and Lawson (1932) that continents are growing and that they are made up of the belts of past failure is thus well established.

From Umbgrove's maps (Umbgrove, 1947, Plates 1-5) it can be seen that the older belts tended to form on the margins of continental nuclei. These nuclei were smaller and more numerous then. The belts had more branches to fit these smaller nuclei. In some places successive belts paralleled each other, in other parts they were on different coasts and intersected.

The reason why the belts of failure migrated every few hundred million years can perhaps be explained. Orogeny alters and consolidates those marginal shelves which form belts of weakness and initiate one orogenic system, while other coasts are being weakened by deposition. Failure relieves stress along the belt of failure but other stresses may build up elsewhere. These two processes, the formation of new belts of weakness and the creation of stress in new localities, lead to migration. It is not clear to what extent movement of belts is a worldwide movement and to what extent it occurs irregularly. It is certain that in the Triassic period the Appalachian region ceased to be an area of active orogeny. This seems to indicate a sudden and complete movement of the orogenic belt. Following this halt in the east there was great activity in the western Cordillera during the Jurassic.

It is not known how these earlier belts connected from one continent to the next, but until evidence of submerged island arcs is found, it must be supposed that former connections followed those now existing across Indonesia, Bering Strait, the Caribbean region and Drake Strait. The possibility that some former connections were in the form of large reversed arcs makes then harder to locate. The fact that at these places where continents approach one another there are islands with exposures of old rocks suggests that the present connections have been used before (e.g., St. Lawrence Island near Bering Strait and South Orkney Islands near Cape Horn both contain Lower Paleozoic or Precambrian rocks).

The mechanism which has been propounded allows for there to be a broad similarity in the history of each great system of belts, a closer contemporaneity in the events of each arc and between adjacent arcs, but it does not demand any world-wide periodicty of diatrophism.

As Rutten (1949, p. 1769) concluded 'Instead of worldwide, synchronic, orogenetic revolutions, there thus have been periods of long duration, characterized by varying and fluctuating tectonic activity. The active periods are not world-wide. While part of the earth was in tectonic rest, elsewhere tectonic activity was found. The quiet regions may have already been folded during an earlier date, or they will be folded at a later date, or they may remain ultimately undisturbed. Differences in time of folding may be found not only in different continents, but also along one and the same orogenitic belt'.

It is considered that the continents are entirely built up from the roots of former primary orogenies. The idea that they have grown thus since Precambrian time is already widely accepted. (Holmes, 1946, p. 401). The principle of uniformitarianism suggests that the same processes went on in Precambrian time (Sonder, 1947). In three papers preliminary to this one the writer has endeavoured to show that the concept that continents have entirely grown during geological time is compatible with the geological, cosmological and geophysical evidence in the Canadian Shield. (Wilson, 1949b, 1949c, and 1950.) The old idea that the continental basement is an original sialic block finds no support from Precambrian geology.

Since it is well known that mountains usually form in thick geosynclinal deposits of sediments it will be well to examine next the rate at which such belts have originated and been changed into ranges. We must, in fact, examine the source, and rate of accumulation of the material that enabled continents to grow.

The Rates of Erosion and of Deposition

It has been estimated that erosion reduces the surface of the United States by one foot in 9000 years. (Dole and Stabler, 1909.) If this process had continued at the same rate throughout the length of geological time a layer about 17 km. thick would have been removed since the beginning of Paleozoic time (5×10^8 years) and 110 km. thick since the probable time of origin of the earth (33×10^8 years). For comparison, the thickness of the whole crustal layer above the Mohorovicic discontinuity is only about 30-40 km.

It has been suggested that the present rate is high, so that a better measure is provided by figures recently published by Murray (1950), giving the volumes of sediment deposited on the Gulf Coast in Mesozoic and Cenozoic time.

If we accept from Murray's data that the emerged and off-shore portions of the Gulf Coastal Plain together contain at least 500,000 cubic miles of Cretaceous and later sediments and also that this was accumulated during 130 million years from an area of 1½ million square miles then the rate of erosion would have been about 1 foot per 85,000 years. But this takes no account of the sediments swept out to the deep ocean and the floor of the Gulf of Mexico. Kuenen (1941, p. 174) has shown that the volume of deep sea deposits may be three times as great as the corresponding volume of continental sediments.

We need not discuss this in more detail but can safely conclude, that the rate of erosion is such that it removes a foot in not more than each few tens of thousands of years off continents in a similar state to North America.

The important point is that if erosion at all comparable to that of Mesozoic and Cenozoic time had taken place in Paleozoic and Precambrian time then there would exist shelves of those ages around North America many times as extensive as those of the Gulf coast. Of course, no such shelves exist. Except for the Atlantic and Gulf Coast shelves there are virtually none at all except in the Arctic where the Coppermine Series might be regarded as a very small example. To suggest (Shepard, 1948, p. 159 and 173) that the Atlantic and Gulf Coast shelves have only a veneer of young sediments over older is to contradict the evidence from deep wells quoted by Murray. To maintain that no similar Precambrian and Paleozoic shelves ever existed is to deny the existence of an average rate of erosion which was only a fraction of that of to-day.

It seems quite untenable to suggest that there was so little erosion before Mesozoic time. It is also quite unnecessary because Kay (1948) and Eardley (1947 and 1949) have pointed out that the Appalachian and Cordilleran Mountains were formed out of precisely such shelves as are now forming on the Gulf and Atlantic Coasts. This seems to be an entirely satisfactory explanation. The Jurassic age of the oldest rocks known in these shelves suggests that they only started to form after the Appalachians had been built. Lawson (1942) has even suggested that the process will soon be repeated on the Gulf coast. On the Pacific coast there has not yet been time to form a shelf since the Cordillera was built.

This suggests that the mechanism of growth is already known and indeed it is widely accepted for recent time, but it is often coupled with the idea that there was throughout Precambrian time a continental block, formed in some other undefined manner. Perhaps this idea is widely held because even after the idea had been accepted that continents are growing it was felt necessary to have a pre-existing block to supply the sediments by which growth proceeds. But is that so? A shelf must be formed only by erosion, but once failure has occurred volcanism supplies abundant lava, ash and intrusive rocks from the interior of the earth to add to the continent. Rubey (1950) has suggested that during the earth's history " conceivably the hydrosphere and atmosphere may have come almost entirely from the earth's interior '. Could not the continental material have done so also?

Rate of Volcanic Extrusion

The surface of the continental blocks is approximately 50,000,000 square miles and they are about 20 miles thick. If the earth is somewhat over 3 billion years old (Holmes, 1949) then all that is required in order to build the continents is that an average of one-third of a cubic mile of new sialic rock should have been extruded each year.

It would be difficult if not impossible to estimate precisely the rate at which such contributions have been made, but it will perhaps suffice to show that the known contributions are such as to make the rate appear to be a reasonable one.

There are three kinds of igneous rock which are known to be quantitatively the most important. These are granites, andesites and basalts. They will be discussed in turn.

The rate and method by which granite is formed cannot be observed in recent rocks as it takes place at depth. Much granite and more granite gneiss has been formed in the past and it is increasingly abundant in the older rocks. But it is doubtful how much of the contributions of granite should be included in this calculation. Admittedly, in areas of young rocks like the United States and central Europe there is evidence of the intrusion of granite magma, but its source is a matter of debate. If it came from the depths as granite the answer to our problem is easy, but erosion should expose more granite in the older rocks. A cursory examination of maps of old areas suggests that this is the case, but it is not. The old shield areas are not composed of granite, but of well foliated granite gneiss showing abundant evidence of containing great amounts of metamorphosed sediments as has been maintained by geologists in every shield area. The disappearance of the shelves rather than indeterminate petrological arguments force one to believe that the roots of mountains are formed of sediments to which only small additions of materials have been made. These additions have chiefly been water and heat which are supplied during primary mountain building along the great arcuate fractures from the depths. The contributions of new continental material in the granites and gneisses may thus be largely illusory and will not be included, but to take the opposite view would enlarge the source of continental material.

The rocks which are added along the island areas are predominantly andesites, dacites and latites so that they have an average composition similar to granodiorite. At present there are about 500 volcanoes listed as active. To form one-third cubic mile of new rock each year each volcano would have to emit a sheet of lava a square mile in area and about 4 feet thick. Probably most volcanoes do not contribute this much each year, but the most active like Paricutin extrude much more. Fenner (1923) has estimated that the tuff in the Katmai Valley of Ten Thousand Smokes is more than one cubic mile in volume and represents one principle sandflow. That would equal the contribution necessary from the whole world for three years and it is not the largest single eruption known.

Turning to basalts and pyroxene andesites the quantities known to have been formed are very great. Von Tillo estimated that 2,000,000 square miles on continents and islands were covered by 'young' (Tertiary?) volcanic masses (Daly, 1933, p. 138). Great volumes have been formed under the oceans, for examples 500,000 cubic miles in the Hawaiian Islands alone (Zimmerman, 1951). Of course, oceanic eruptions contribute nothing to continents to-day, but the continents may include rocks poured out in the ocean. Lawson (1932) has argued that the action of sea water is breaking down basalt leaves a more siliceous residue which would be of sialic composition.

These figures do not establish the rate of volcanic out-pouring, and it is not known whether adequate data to establish that rate exists, but they perhaps suffice to show that the formation of continents by extrusion of volcanic rocks and to a greater or less extent by the intrusion of plutonic rocks is a reasonable proportion. Naturally, most of the rocks now exposed have been reworked through succeeding cycles of erosion, deposition and metamorphism so that they are no longer in their original form.

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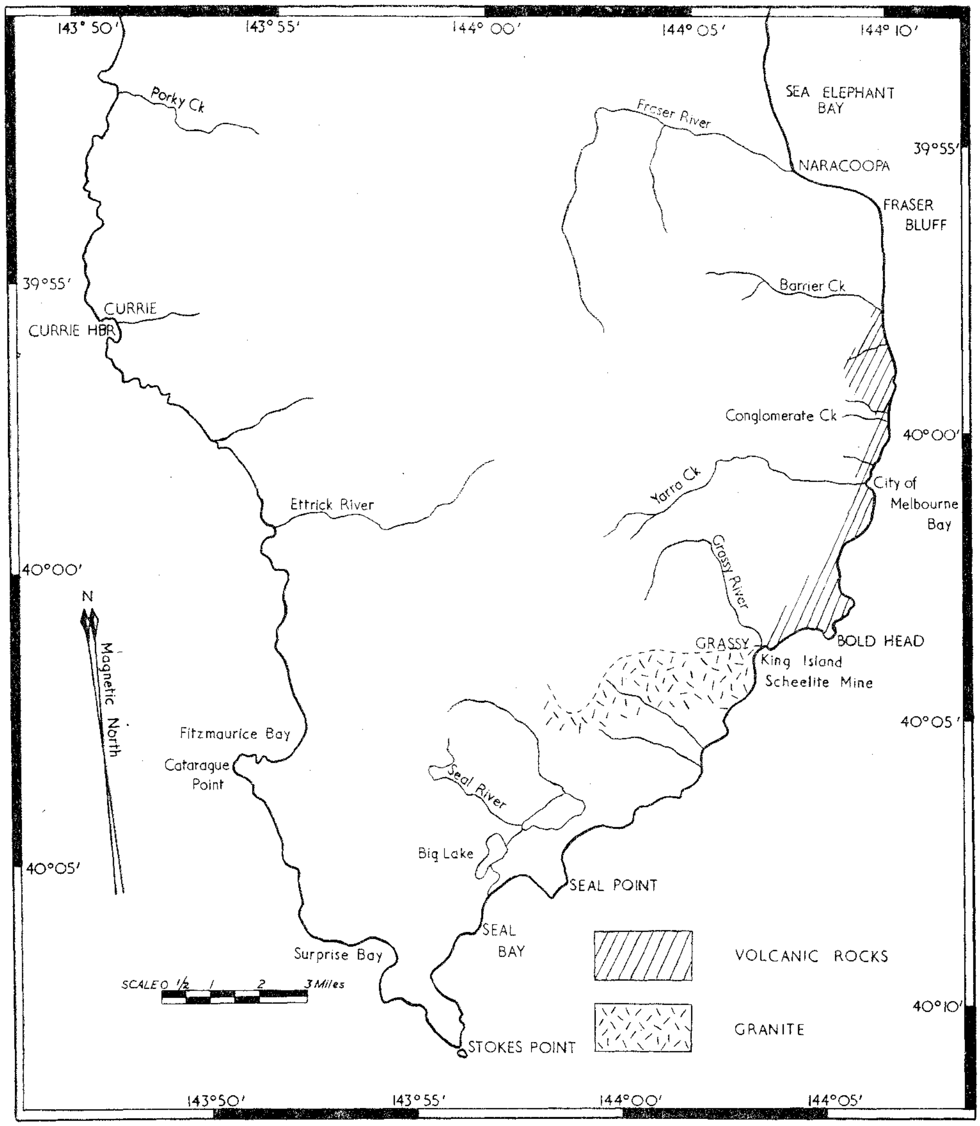
Fig. 1.



Southern portion of King Island showing the locality of the Volcanic Suite.