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Comparison of Block and Arc Tectonics in Japan with Those of Some Other Regions.

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§1. Introduction

This paper is expanded from a mimeographed memorandum circulated, and presented for discussion, at the spring meeting of the Seismological Society of Japan, at Tokyo, May 12, 1960. The intention is not to offer any new material, but to bring together more or less well known results in a form suitable for critical comment.

During the remainder of his stay in Japan, the writer continued his study, reading, and discussion along the indicated lines. A few only of his personal indebtednesses are named in the section on Acknowledgments.

The writer's knowledge extends to only a small part of the vast body of seismological, geophysical, and geological data available in Japan. In spite of the great assistance he has received, he is certain that the paper still contains inexactitudes, and even downright mistakes. It is to be hoped that these are minor. Experienced workers will not be misled; but students are cautioned not to accept statements which they are inclined to question, without verifying them from the numerous publications which are more easily accessible to Japanese readers than to the present writer.

The point of view is that of the writer's text-book "Elementary Seismology"; the present paper is in effect a revision of the correspoding discussion in Chapter 30 of the book.

The presentation is with reference to the data of seismicity: accordingly, description and comparison refer to tectonic processes now going on, which in many areas differ significantly from those of the geological past. Moreover, present occurrence of earthquakes in a given small area may be due to special circumstances (either geographically localized, or temporary in terms of the geological time scale). Such local areas may present exceptions to the general tectonic pattern.

§2. Nature of block and arc tectonics

Most of the seismicity of the world is related to two principal environments–those of block and arc tectonics; the latter is found chiefly in the circum-Pacific and Alpide belts. The work of EWING and HEEZEN suggests that the seismicity of the Mid-Atlantic Ridge, and of other analogous oceanic ridges, may represent a third principal tectonic type.

From the viewpoint of historical geology, the distinction between regions of block tectonics and the active arc structures is usually not one of essential character, but of the present stage of development. The materials of most active block structures have been subjected to successive orogenies; at one or more earlier periods such areas presumably presented all the characteristic features now associated with active arcs, such as: (1) high seismicity including shallow, intermediate, and (in typical Pacific arc) deep earthquakes; (2) active volcanoes; (3) large gravity anomalies in narrow belts; (4) a pronounced foredeep. Block tectonics may be considered as a later stage which normally follows the folding and thrusting of a typical orogeny. This stage represents a lower degree of activity (especially when conditions at the greater depths are considered) than the arc stage. Although large shallow earthquakes occur, and some of them break the surface in faulting, intermediate earthquakes are rare and deep earthquakes absent (except when deep earthquakes belonging to an adjacent active arc originate under the shallow block structure). Volcanoes are usually in a late stage of activity or extinct, while foredeeps and gravity anomalies are less pronounced than in active arcs. Such criteria have been used in the following discussion to distinguish the block tectonics of West Japan from the arc tectonics of adjacent areas. The distinction between block and arc tectonics is not perfectly exclusive; some seismic areas appear to be in a transitional condition, and others show characteristics of both kinds due to intersection or to complex geometrical relationship in three dimensions.

Stratigraphy and other geological evidence in some instances suggests, and in others clearly demonstrates, that a present active arc formerly passed through a stage of block tectonics.

This discussion has a definite relation to the concepts employed by the Soviet school of geologists and geophysicists. Active arcs are generally considered as representing active geosynclines. The major geosynclinal belts are marginal to the stable platform areas. The regions of active block tectonics, which occur in the geosynclinal belts in juxtaposition to the active arcs, are classifiable as former platform areas, now involved in the development of geosynclinal movements, and being broken up in consequence. If this process goes far enough, the block structure may be completely destroyed, and the material reconstructed into a typical active arc.

§ 3. Geographical subdivisions of Japan

The exceptional importance of Japan in comparative tectonics derives from the presence, in an accessible, civilized, and well-investigated region, of both block and arc structures, in such a geometrical and mechanical relationship as promises to shed light on the nature of both.

There are five evident subdivisions:

(1) West Japan, including the main islands west and southwest from the Fossa Magna; this is the major area of block tectonics, with only traces of arc features.

(2) Northeast Japan, including Honshu east of the Fossa Magna, and southwestern Hokkaido. This is part of a major Pacific arc. As in some other such arcs, there is block faulting in the interior; here it is chiefly in a belt adjacent to the Japan Sea.

(3) Northeastern Hokkaido, which is the terminus of the active arc of the Kurile (Chishima) Islands.

(4) The arc of the Ryukyu Islands, which extends into Kyushu, where it intersects and modifies the block structure. KOBAYASHI relates the structures of Korea centrally to this arc.

(5) The Shichito arc, extending southward to the Ogasawara (Bonin) Islands.

These divisions will now be discussed individually, pointing out some of the more interesting comparisons with other regions. Later sections will sketch the block and arc tectonics of several other distant areas, presenting tentative general correlations with the Japanese region.

In addition to the surface features of Japan, geophysical discussion must take into account the belts of deep and intermediate earthquakes discovered by WADATI, as well as the structure of the crust as derived from seismological and gravity data.

The study of most of the active Pacific arcs in hampered by their largely submarine character; often the accessible land area consists of a chain of small islands. This is true of the Shichito, Kurile, and Ryukyu arcs, except at their ends, where they intersect the other block and arc structures. Such areas of intersection are of special importance for investigation. There are three of them in Japan: one including the Fossa Magna and the western Kanto district, one in Kyushu, and one in Hokkaido. All three of these, Professor TSUBOI points out, are associated with large negative gravity anomalies. The next similar critical areas in opposite directions are in Kamchatka and Formosa (Taiwan); findings there should be compared with Japan so far as possible. KOBAYASHI describes the transition from the Ryukyu arc to Formosa rather as a sharp bend in the younger trends than as an intersection; whatever the interpretation, the contrast between adjacent block and arc structures is clear.

§ 4. West Japan

In comparing West Japan with other areas of active block structure, a further subdivision must be considered. The longitudinal separation, along the Median Tectonic Line, into an inner and an outer zone, is of very great importance in studying the geological past of West Japan; but it is not so significant in relation to present tectonic processes. On the other hand, there are important complications at the two ends of West Japan which do not appear in its central segment. At the west, although the block structures and the Median Line cross Kyushu, there is an evident intersection in three dimensions, where these shallow structures cross the Ryukyu arc. Among the known typical arc features are the clustering of shallow earthquakes, associated with negative gravity anomalies, along the Bungo channel, and the central line of active volcanoes followed by epicenters of intermediate earthquakes. Continued study of the deep crustal structure of Kyushu, combining data from earthquake records, explosion seismology, and gravity observations on land and off shore, should clarify the geometrical relation of the intersecting structures. It is highly important to learn how the Mohorovičić discontinuity behaves in such a region.

A somewhat similar three-dimensional relation exists in the North Island of New Zealand, but the trends of block and arc structures are more nearly parallel there than in Kyushu. In the North Island, as in Kyushu, there is a central trough, largely filled with volcanic material; the active volcanoes and the epicenters of intermediate earthquakes follow the trough in both cases. One hypocenter is known at a depth of over 500 kilometers below the central part of the North Island; under Kyushu a few earthquakes are known at depths between 300 and 400 kilometers.

In spite of some significant differences, the middle section of West Japan compares rather closely with other Pacific areas of dominant block tectonics, such as California and central New Zealand. The general level of small seismicity is not high; however, there are occasional very large earthquakes, especially off the southern coast. These earthquakes originate inshore from the Nankai Trench, which thus is comparable in position with the foredeeps of the active arcs. However, the Nankai Trench is much less well marked topographically than the typical foredeeps, such as the Nippon Trench. Middle West Japan has no intermediate earthquakes, and the deep earthquakes are those of the transverse belt, belonging to the Shichito arc structure. The volcanoes are extinct.

Analogy between Kyushu and the North Island of New Zealand would logically lead to comparing the outer zone of West Japan with the major part of the South Island. The principal belt of shallow earthquakes in New Zealand, associated with conspicuous surface faulting, follows the coast of the North Island; offshore is the southern end of the Kermadec Trench, belonging to the intersecting arc structure. The earthquake belt crosses Cook Strait and passes down the South Island near its center line, with gradually decreasing seismicity. On the Pacific side of this line is the depression, generally believed to be a geosyncline, underlying the Canterbury Plain; this depression is consequently the analogue of the Nankai Trench. On the opposite side of the earthquake belt are the New Zealand Alps, consisting largely of Mesozoic rocks of geosynclinal type; they are cut marginally by the Alpine Fault, beyond which Paleozoic rocks are found underlying the Tertiary and Cretaceous sedimentary blanket. This western and north-western part of the South Island might thus be compared with a portion of the inner zone of West Japan; the Alpine Fault is in approximately the same situation as the Median Tectonic Line. However, the Alpine Fault, like the San Andreas Fault of California, is primarily a strike-slip feature; in this respect it contrasts sharply with the Median Tectonic Line, which is described as primarily due to thrusting.

To complete the comparison, the wide eastern part of the South Island, including the Canterbury Plain, would correspond to an area south from the Nankai Trench; although far off shore, this area has been suspected by several authors of being continental in character. The volcanoes of Banks Peninsula on the New Zealand coast are closely similar to typically Pacific structures like those of Hawaii, Tahiti, and Samoa; they probably have no close correlatives in the Japanese area.

The two principal orogenies of New Zealand, the post-Hokonui (Mesozoic) and the Kaikoura (late Tertiary) are comparable with those of California and of many other regions, particularly in that the Mesozoic orogeny has left many traces of thrusting and folding in the rocks, while the younger orogeny is chiefly responsible for the present block structure. While a similar remark applies to West Japan, it will not apply to East Japan, or indeed to any of the more active arc structures of the world.

The area of block faulting which includes California is larger than West Japan. Point-by-point comparisons between such widely separated areas are hazardous. California has no offshore trench, nor any clear evidence of the other arc features. However, the structures and seismicity of the Japanese outer zone are perhaps comparable with those of the California Coast Ranges. The Paleozoic and intrusive rocks of the Japanese inner zone are not greatly different from those of the Owens Valley region and the Sierra Nevada. The extinct volcanoes aligned parallel to the Inland Sea suggest comparison with the Pleistocene volcanism of the eastern Sierra Nevada, Owens Valley, and the Mono Basin.

The writer was at first inclined to correlate the Inland Sea with the alluviated geosyncline of the San Joaquin Valley; but it is at least as reasonable to suppose that the Japanese correlative of the San Joaquin Valley was compressed out of existence by the thrusting which established the Median Tectonic Line. Whereas the San Joaquin depression is a downwarp, the Inland Sea is a faulted depression, more strictly comparable with the graben of Owens Valley.

The Great Basin extends from the Sierra Nevada east to the Rocky Mountain structures, which are analogous to those of the mainland of Asia; but it would be rash to suppose that the Japan Sea covers a structure like that of the Great Basin.

There is no known feature in Japan closely resembling the San Andreas Fault of California, or the Alpine Fault of New Zealand. Both are primarily strike-slip features, with strikes generally along the major structural trends, which they occasionally cross at low angles. Those faults in Japan where there is predominant strike slip often are associated with topography like that found along the San Andreas fault; but their attitude toward the major trends, or their shorter extent, differentiate them from it.

In West Japan block faulting breaking the surface has chiefly been observed in the structural belt of the Akiyoshi orogeny, along the Japan Sea coast. This, like similar block faulting in other old structures in many parts of the world, is most readily interpreted as tectonic rejuvenation. Regional stresses of comparatively late geologic age are being relieved along old lines of weakness which were originally developed under a different stress distribution. This circumstance probably accounts in part for the tendency to complex surface faulting, with the development of multiple fault traces in a single event, here and elsewhere in the general region of Japan. Two distinct traces of nearly equal importance were developed in each of the earthquakes of 1896, 1927, and 1943 (and in Formosa, in 1906 and 1935).

The eastern segment of West Japan is anomalous. From Ise Bay eastward, the Median Line curves northward in approaching the Fossa Magna; the structures of the Outer Zone appear drawn out of position accordingly. This local distortion suggests that the crust is weak there, and the results of explosion seismology indicate a special structure. The western limit of the disturbed segment is in the vicinity of the faulting associated with the Mino-Owari earthquake of 1891. Geological maps suggest the Median Line is offset across Ise Bay.

The deviation of the Median Line as it approaches and crosses the Fossa Magna is one of the major problems of field geology in Japan. Discussion revolves around points similar to those raised in California with reference of the deflection and possible breaking up of the San Andreas Fault, descending from the northwest to intersect the east-west structures of the Transverse Ranges (for details see the writer's "Elementary Seismology"). Another similar problem exists in New Zealand; the Alpine Fault is deflected eastward on approaching Cook Strait, and diverges into branches which have been variously correlated with the faults of the eastern North Island.

The zone of deflected trends is sharply limited on the east by the Fossa Magna, beyond which we should speak of fragmentation rather than of deflection. The western limit is in the narrowest part of Honshu. The faulting of 1891 is somewhat east of this limit; on the surface it is not a single fracture, but a complex of fractures with varying trends. In the field, the writer saw topographic features, west of the faulting of 1891, which strongly suggest geologically young displacements along known faults.

The presence, in the western part of the disturbed segment, of the epicenters of the transverse belt of deep-focus earthquakes, indicates a major transverse fracture belt, extending to great depth, but reaching the surface in a complicated and perhaps shifting series of breaks. This is essentially the interpretation of EHARA, in his paper on the geotectonics of central Honshu. With a wealth of geological detail, he represents the facts in terms of a relative northward displacement of the Shichito arc structures, with fracture at the surface indicated by the Fossa Magna, dipping westward as indicated by the belt of deep earthquakes.

The Fossa Magna is a structural boundary not obviously like any other known feature. There is every evidence of considerable difference in tectonic and geophysical conditions on opposite sides. However, this does not appear to be tectonic "contrast" in the sense used by Soviet geophysicists, since there is no clear indication of a sharp difference in the rate of displacements now going on. This agrees with the fact that the Fossa Magna is not a line of seismic activity.

§ 5. Northeast Japan

Northeast Japan is perhaps the most favorable region in the world for studying a Pacific-type active arc. It represents a different stage of development from that of West Japan. The distinguishing features of Northeast Japan are:

(1) Three-dimensional structure. Instead of block structure with vertical faults, we find the typical active surface of a Pacific arc, dipping from the offshore troughs under the land, and continuing downward and northwestward into the belts of deep-focus earthquakes. In reality this is not a thin surface, but an irregular thick sheet, of probably complicated structure. It is not active throughout, but (just as in block structures) seismicity is confined to limited regions and to belts traversing it. The dip is partly responsible for the circumstance noted by TSUBOI, that epicenters, even of the shallower earthquakes, do not align so clearly here as in West Japan, but show areal rather than linear distribution. Gravity anomalies, active volcanoes, and epicenters of intermediate earthquakes, are aligned longitudinally as in other arcs.

(1) In contrast with the relatively simple alignment of the volcanoes and the other principal arc features is the chaotic character of the surface geology. Studies by KOBAYASHI and others indicate that this was once a region continuous with and much like West Japan, crossed by the Median Tectonic Line; but in later geological time it has been displaced relatively east or southeast, breaking into blocks which did not all move simultaneously nor in the same direction. Consequently, the line between areas formerly on the inner and outer sides of the Median Line may be drawn differently if different criteria are used, particularly, if the data are of different age.

(3) Along the Japan Sea coast is a strip now associated with block faulting, which broke the surface in 1847 (Zenkoji earthquake), 1896 (Riku-U earthquake), and probably in 1894 (Shonai earthquake). The existence of this active tectonic belt was pointed out by OMORI.

Shallow earthquakes and block faulting occur in the interior of some other active arcs, in both Pacific and Alpide belts.

(4) A difference in mechanism of strain accumulation and release is indicated by TSUBOI's finding that the proportion of small to large earthquakes is higher here than in West Japan. This may be interpreted as due to breaking into smaller units as in other regions where small earthquakes and earthquake swarms are relatively common.

(5) The high seismicity off the Pacific coast is cut by a belt of low activity, very clear in TSUBOI's mapping, which includes the epicenter of the great Sanriku earthquake of 1933. Probably this belt follows a resistant transverse structure, composed of relatively unfractured rocks which yield only occasionally, under strain sufficient to produce a great earthquake and numerous aftershocks. The block of the Kitakami Mountains appears to represent this structure on land.

(6) The Kanto district, extending west to the Fossa Magna, occupies the area of intersection of two arcs: the principal Honshu arc and the Shichito arc. The former accounts for relatively high seismicity in the Kanto district. In accordance with the three-dimensional arc structure, most of the numerous epicenters on land correspond to foci at depths of 40 km. or more. Hence, even when a great earthquake like that of 1923 occurs there, no evident main fracture reaches the surface. The many small faults formed in 1923 were incidental to the general surface distortion of the Kanto region, which was shown clearly by geodetic observations. This high degree of surface complexity recalls that of the great Indian earthquake of 1897, when faulting and complex warping of the surface took place over a wide area.

§ 6. Hokkaido

The intersection of two arcs in Hokkaido offers a promising field for geophysical investigation of crustal structure, provided that the difficulties of working in that terrain can be successfully overcome. There are interesting analogies with the North Island of New Zealand, even in geographical outline. The central tectonic division has suggestive similarity to the Auckland Peninsula. However, the active volcanism of southwest Hokkaido does not compare well with the Pleistocene volcano, Mt. Egmont, of New Zealand; and there is in Hokkaido no clear correlative of the coastal mountains of the North Island, with their active block faulting. In brief, the North Island is a region of intersection of block and arc structures, rather than of two arcs; it resembles Kyushu rather than Hokkaido.

§ 7. Branching

The two principal western branches of the circum-Pacific active belt diverge in central Honshu; they approach closely again between northern Celebes and Halmahera, then diverge again. West Japan may be assigned to the western branch; lying between the Honshu and Ryukyu arcs, its position is like that of the great region of dominant block faulting which includes California, between the Alaskan arc and the Mexican arc. The oceanic area between the two branches is of special interest; at the north it lies between the Shichito and Ryukyu arcs, although the deep arc structures of the former, extending into the transverse deep-focus belt, pass under it. This area includes the Nankai Trench; continental structure probably extends much further south, although the Mohorovičić discontinuity may be found to stand near the oceanic level.

§ 8. Comparison with the East Indies

If Indonesia could be investigated thoroughly by present geophysical and seismic methods, the results would probably go far toward clarifying the nature of both block and arc tectonics. The results reached by past investigators there must be considered carefully for correlation with work in Japan and in all active regions.

The belts of negative gravity anomaly, discovered by Vening MEINESZ, have commonly been held to indicate the location of contemporary active orogeny. The islands (such as Nias, Timor, Ceram) included in or traversed by these belts were involved in intense folding-during the Miocene. Presumably the zone weakened at that time is now yielding under the general regional stress; this agrees with the fact that the Meinesz belts include the epicenters of many shallow earthquakes, some of them large. Shallow earthquakes elsewhere in Indonesia are mostly associated with block tectonics.

The principal Meinesz belt follows the Sunda arc, which is the least complex structure of the region; the arc extends from Sumatra and Java along the chain of the Sunda islands and round the Banda Sea. Broadly speaking, it is a typical active arc, with all the characteristic features; but some of these features are better developed in one part of the arc, and some in another. In certain respects the Sunda arc compares better with the arc of the Ryukyu Islands than with that of Honshu. Thus, the islands of the Sunda arc form a double chain; the inner arc, including Sumatra, Java, and smaller islands, is actively volcanic, but the islands of the outer arc, in the Meinesz belt, are non-volcanic. The Ryukyu arc has a similar double chain, but off the Pacific coast of Honshu there are no small islands in the belt of gravity anomalies.

The Honshu arc, in fact, is more closely comparable with the Java sector of the Sunda arc. Off Java there are no small islands in the Meinesz belt (although there is a submarine ridge); and the Java Trench, though not as significant as the Nippon Trench, is the principal foredeep feature of the Sunda arc. Large shallow earthquakes are not frequent in the Java sector; but active volcanoes, and epicenters of intermediate earthquakes, are numerous, and the corresponding deep earthquakes originate north of Java.

The relation between Sumatra and Java is somewhat like that between West and Northeast Japan; however, Sumatra is more comparable to an arc structure like that of the Ryukyu Islands. Sumatra has some definite characteristics of block tectonics, such as the high scarps along the southern coast, and the longitudinal internal rift, which the displacements in the earthquake of 1892 indicate is a right-hand strike-slip feature. (However, this rift is largely filled with volcanic products, and resembles the rifts in the North Island of New Zealand and in Kyushu).

North of the Sunda arc there is an important tectonic division, across a line passing through central Celebes. To the west and northwest is a large stable area, with relatively few earthquakes, except near the coasts of the Strait of Macassar, which is an internal fracture in the stable mass. All the earthquakes on this side of the division are shallow, except for deep earthquakes belonging to the Sunda arc. On the other side is the terminal section of the Sunda arc, in the Banda Sea; and another active arc descends from the northeast along the volcanic eastern peninsula of Celebes. Celebes, with its environment, presents a degree of complexity in three dimensions comparable with that of Honshu and its environment. Interpretation in this extremely interesting area is rendered particulary uncertain by the lack of precision attainable in the location of epicenters, as well as the absence of any direct geophysical data on the depth of the Mohorovičić discontinuity or on other details of crustal structure.

§ 9. West Indies

The Caribbean active arc has been much studied by geophysical means. Epicenter locations in this region have become reasonably accurate of late years; but general seismicity is only moderate, so that most of the important large earthquakes are known only from non-instrumental and historical records. The eastern front of the arc is double, with an outer non-volcanic island (Barbados) and an inner volcanic arc.

Negative gravity anomalies follow the outer arc, beyond which there is no deep trench. The northern limb of the arc is quite different; there is a very deep external trench, but there is no active volcanism, and the earthquakes are nearly all shallow. Both northern and southern limbs are classifiable as of block structure, and both are cut by important longitudinal strike-slip faults.

While the eastern front of the Caribbean arc may be compared with the Ryukyu and Shichito arcs, the remainder of the structures differ so much from those of Japan that generalizations about arc tectonics derived from observations in the West Indies can be applied in Japan only with great caution.

§ 10. Himalayan arc

Northern India is potentially one of the most important regions in the world for the study of arc tectonics. The accessible geology has been well investigated, and gravity observations are plentiful. There is still much need for studies of crustal structure by the various seismic methods.

The Himalayan arc strongly resembles those of the Pacific system, except for its generally lower activity; in this it is typical of the system of Alpide arcs of Europe and Asia. The Ganges alluviated depression is a foredeep; along its northern margin is a belt of negative gravity anomalies, in which are located the epicenters of large shallow earthquakes. The proportion of large to small shocks is relatively high, which suggests comparison with regions of block structure. Volcanism is slight, intermediate earthquakes associated with the arc proper are few, and no correlated deep shocks are known.

The remarkable series of intermediate earthquakes under the Hindu Kush are not evidently related to the Himalayan arc. At the other end of the arc, the great earthquakes of Assam and Tibet are related to complicated structures which are still imperfectly known.

Nothing associated with the Himalayan arc suggests close correlation with the tectonics of Japan.

§ 11. Italian arc

Of the arcs of the Alpide system, the Italian arc most clearly shows relation to those of the Pacific. In "Elementary Seismology" it was pointed out that this parallelism is especially evident when referred to double arcs, like the Ryukyu and Sunda arcs. Epicenters of shallow earthquakes follow the chiefly nonvolcanic outer arc of the Apennines; the well-known active volcanoes of Italy are on an inner arc. Intermediate and deep earthquakes are known down to depths of 300 and even 450 kilometers. The depression of the Tyrrhenian Sea is correlative with such interior depressions as the Weber Deep in the Banda Sea interior to the Sunda arc.

§ 12. Correlation with tectonics of the Soviet Union

In section 2 reference was made to the classification of tectonics in terms of geosynclines and platforms. This classification has been applied in detail, and with excellent results, to the tectonic analysis of those parts of the Soviet Union which have been selected for intensive geophysical investigation in the past: the Crimea, the Caucasus, Turkmenia, and Central Asia (especially the region extending from the Tian Shan to the Pamir). The Soviet Union includes typical Pacific active arc structures, in Kamchatka and the Kurile Islands. These were subjected to intensive exploration during the IGY program, but results are only now beginning to be published, so that discussion is premature; the opportunity for comparison with Japan may be awaited with great interest.

Platform areas in the strict sense are lacking in Japan; they may be observed on the adjacent mainland of Asia, even though some deep earthquakes related to the Pacific active arcs originate under the platforms. The block and arc structures of Japan may be regarded as ancient platform material in different stages of being broken up and transformed by geosynclinal processes.

The geosynclinal zone along the southwestern border of the USSR is on the northern front of the Alpide structural belt. In the Black Sea, under the Caspian Sea, and in Turkmenia, there are tectonic downwarps, in which the Mohorovičić discontinuity descends to 40–50 km below the surface, and there are local areas from which the upper or "granitic" layer appears to be absent. Under the Caucasus the Mohorovičić discontinuity, generally near 40 km deep, descends locally to a depth of 60 km.

In most of these areas typical arc features, and block tectonics fracturing the surface along active faults, are both absent. However, in Turkmenia the Transcaspian depression is in the position of a foredeep north of the

Kopet Dagh arc; and the epicenters of the Ashkhabad earthquake series were located between the mountains and the foredeep as in other arcs. No large gravity anomalies, no active volcanoes, and no intermediate or deep earthquakes are associated with this arc.

The area extending from the Tian Shan across the Garm district to the Pamir is at the southwestern end of the long Pamir-Baikal seismic belt, the trend of which diverges here from that of the series of Alpide arcs. The southern Tian Shan, especially, is a former platform region which in comparatively late geological time has been broken into blocks by the stresses associated with the Alpide geosynclinal movements of the Pamir. (Some recent evidence even suggests considerable strike-slip displacements in addition to vertical movements, in the Tian Shan). The tectonic character of the area is not unlike that of West Japan. Both northern Tian Shan ranges have "roots" represented by depression in the Moho; under the Pamir both the Moho and the intermediate ("Conrad") discontinuity descend.

The Pamir region presents some typical arc features, although volcanism is minor. However, there are large negative gravity anomalies. Intermediate earthquakes at depths of 100–150 km occur under the southern Tian Shan; if referred to the Pamir these seem anomalously placed. As already remarked, the numerous intermediate earthquakes under the Hindu Kush present a very special problem.

The Garm district, between the Tian Shan and the Pamir, is a region of relatively frequent small earthquakes at quite shallow depth. These are apparently connected with a local small-scale block structure; volcanism is not involved.

In "Seismicity of the Earth" it was suggested that the entire Pamir-Baikal seismic belt is at present subject primarily to block tectonics. This corresponds with the statistical result that the proportion of large to small shocks appears to be higher there than in the Pacific arcs.

§ 13. Concluding note

The statistical approach, noted in the preceding paragraph, is likely in future to become a valuable means of distinguishing between areas of different tectonic type. Tsuboi has already applied it with success to the distinction between West Japan and Northeast Japan, and to further more detailed subdivision. Naturally the method can be applied only in areas of high seismicity, or where there are plentiful historical data extending over many centuries.

The critical reader will have noted that there is no sharp distinction between block and arc regions, but rather a gradation. At one extreme are typical Pacific arcs in which the evidence of block faulting is lacking; at the other are regions like that of California in which most of the arc features are absent, and the block tectonics is characterised by large strike-slip faulting which tends to destroy the former alignments. Northeast Japan and West Japan are not quite at these two extremes; but their opposite characteristics are clear enough so that useful future results may be expected by comparing their features with those of arc and block tectonics respectively.

§ 14. Acknowledgments

It would be difficult, however pleasant, to acknowledge all my obligations in preparing this note. I am indebted to publications by many authors, and to personal discussions in Tokyo and elsewhere. Before coming to Japan I found much information and many useful suggestions in publications by Proffessor Kobayashi; since my arrival in Tokyo he has kindly made his publications available for further study, and has been very helpful personally. I have made almost incessant use of "Geology and Mineral Resources of Japan," with accompanying map, published by the Geological Survey in 1956.

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