there is a change of phase, it seems that the velocities in dunite will be considerably lower at the appropriate temperatures than the velocities ascribed to a depth of 40 km in Southern California, and very much lower than the velocities at 36 km in New England. Eclogite may fit somewhat better, but it looks as though its velocity also will be too low. About the only silicate which appears to be possible for this deep layer is some variety of garnet, for which we have no measurements at present on the effect of temperature.

Harvard University,
Cambridge, Massachusetts

WAVE-ANALYSIS AS A CLUE TO THE MECHANICS OF EARTHQUAKES

L. Don Leet

No abstract or manuscript was submitted for this paper.

Harvard University,
Cambridge, Massachusetts

TECTONIC PROCESSES NOW IN ACTION

B. Gutenberg

(Balch Graduate School of the Geological Sciences, California Institute of Technology, Contribution No. 313)

Tectonic processes may act either gradually as in connection with plastic flow, or as sudden movements connected with earthquakes. The first sort of movements requires that in a layer the stresses are larger than the strength of the material in opposing plastic or pseudo-plastic flow; the second that somewhere they surpass the breaking strength. In three papers [see 1, 2, 3 of "References" at end of paper], one of them jointly with Dr. Richter, the author recently has investigated such processes. In the present paper, it is intended to give a summary and to draw certain conclusions.

From the fact that mountains apparently have not changed their height appreciably in historic times and also from laboratory experiments it follows that in the uppermost layers (at least 30 km thick) the strength is of the order of 10^9 to 10^{10} dynes per cm^2. Isostasy and post-glacial uplift, on the other hand, indicate that below this depth the strength decreases rapidly. A disturbance of the equilibrium corresponding to the weight of an extended layer of rock with a thickness measured in several tens of meters produces subcrustal flow reaching probably down to the core of the Earth [1]. Seismic observations [4], since confirmed by unpublished results, lead to the conclusion that at a depth of about 70 km there is a small but definite decrease in the wave-velocity, possibly indicating the transition from the crystalline to the vitreous state of the material there. This would explain a decrease in strength at this depth.

The order of magnitude of the strength below a depth of 70 km is not known. Its value is of importance for an estimate of the minimum stresses required to maintain plastic flow. The relatively small stresses required to produce changes in marginal areas of post-glacial uplift suggest the possibility that forces even as small as the "Polfluchtkraft" may produce noticeable plastic flow over long periods. On the other hand, it seems safe to conclude that the relatively large gravity-anomalies in tectonically active regions are connected with subcrustal movements extending to the core of the Earth. The velocity of these subcrustal currents depends mainly upon the viscosity of the material and the stresses. In areas of post-glacial uplift, it takes thousands of years to reduce deviations from the equilibrium to one-half, which denotes an average viscosity of the order of 10^{22} poises.

Gravity-anomalies at the surface of the Earth indicate stresses acting at an unknown depth at present or very recently. In many regions, they at least serve to maintain the deviation from the equilibrium. The seismic activity in such regions shows that the stresses frequently surpass the breaking strength of the material. Deep-focus earthquakes furnish proof that in certain areas down to a depth of 700 km the stresses are accumulating faster than plastic flow can reduce them. On the other hand, all evidence indicates that a larger part of the tectonic activity of the Earth occurs in relatively narrow belts surrounding the Pacific Basin [2]. The sequence of phenomena observed in these belts is quite persistent, although data are incomplete in most of them. Proceeding from the ocean towards the continent, usually the oceanic basin descends into a deeper trench. No seismic activity is found there. Earthquakes with focal depths less than 50 km occur chiefly beneath the steep slope extending upward from this trough to the continent. Moreover, along this slope is a belt of maximum negative gravity-anomalies. On land the gravity-anomalies become positive and are frequently associated with volcanism and shocks at increasing depths, usually not exceeding 150 km. Still farther inland under mountain ranges of about tertiary age, there is sometimes a belt of foci at depths exceeding 150 km, sometimes even approaching 300 km. Farther inland still, shocks may be found at depths ranging from 300 to 700 km but without clear relationship to surface structures in the immediate neighborhood. In some regions the foci of the earthquakes appear to fall on a surface dipping at various angles downward away from the ocean. However, in no region is there conclusive evidence that this whole surface is active. Possibly, it is a surface of maximum stress.

There is no evidence thus far of earthquakes originating at depths appreciably exceeding 700 km. Either the stresses decrease there noticeably, or the viscosity decreases, permitting a more rapid plastic flow, or there is a noticeable increase in the breaking strength. The fact that the very deep shocks frequently exhibit large energy might be a consequence of a larger breaking strength which also could be expected from the theoretical conclusions of Goranson [5].

Most of the remaining major seismic activity occurs in the Tertiary mountain ranges in southern Asia and southeastern Europe, where shocks at depths not exceeding 50 km follow most structural trend lines of Tertiary age, and where there are also foci at greater depths, but not exceeding 300 km. There are, finally, narrow belts of shallow foci beneath the mid-Atlantic ridge and beneath ridges in the Indian Ocean. These belts, however, differ in so many respects (absence of deep foci, small gravity-anomalies, occurrence under ridges, far from trenches) from the belts surrounding the Pacific Basin that a completely different source for the stresses seems highly probable. Gutenberg and Richter [2] have pointed out the frequent close coincidence of the active zones outside the Pacific Basin with the orogens of Kober. However, this agreement does not include the bottom of the Pacific Basin, which, except for shocks near Hawaii, seems to be one of the least active regions of the world. In general, this area is clearly outlined by petrographic evidence (Andesite line), earthquake-epicenters, and changes in the velocities of seismic waves. Only along the south and southeast is there some doubt about the exact boundary, which, in general, seems there to follow the Easter Island Ridge and its continuation towards southwest and west. There is fair evidence of some outlying patches of Pacific structure, as in the Gulf of Mexico, in the Southern Antillean Region, in the Philippine Basin, and in the Arctic Basin.

The results of investigations of compressions and dilatations at the beginning of earthquake records, as well as geological evidence, leave no doubt that the directions of the crustal movements do not scatter at random. In Japan (according to Ch. Tsuboi) and in the Philippine Islands (according to B. Willis) the continental side is moving southward relative to the Pacific Basin. In Southern California and parts of Central California this is true, too, for the movements along the major faults during recent times; and at present the initial impulses in even the smallest shocks occurring along minor faults generally indicate the same type of movement [3]. Shearing stresses are continually straining this region in a way similar to that when a sheet of paper is deformed by moving two opposite sides in opposite directions. Although this horizontal shear has formed, for example, the San Andreas Rift which has a known length of over 1,000 km, it would be premature to conclude that shearing stresses of this type have produced the large mountain systems and are the cause of all the major tectonic processes at present. These shearing stresses may be due to a minor but permanently acting force, for example, to the "Polfluchtkraft".

The stresses which indirectly are the source of the gravity-anomalies and ocean-deeps around the Pacific Basin, seem to be directed more radially in respect to the ocean and are probably connected with much larger energies than the shearing stresses discussed above. Models of the mechanism of the processes and experiments related to them have been described by Kuenen [6] and by Griggs [7]. From the observations, it seems likely that this mechanism is not symmetric to the boundary-surface of the Pacific Basin. From various points of view, Du Toit, Andrews, and others at the Sixth Pacific Science Congress defended the well-known idea that the continental layers surrounding the Pacific Basin are encroaching on the ocean-bottom and are being warped down. A subcrustal movement returning towards the continent at depth would fit into this picture and would not disagree with the other observations. This might even prove a key to the puzzle of the submarine canyons in the Pacific, whereas in the Atlantic the assumption of thinning of the ocean-bottom could have produced a sinking of the shelf-region (according to Du Toit and Maxson).

The problem of the energy required for these processes is completely unsolved. Differences in temperature between the deeper layers beneath the continents and the Pacific, differences in radioactive content, and chemical processes are among the possible sources. It is not unlikely that the mechanism in tectonic processes in other regions is quite different. Only accumulation of more observations of various kinds including earthquakes, volcanoes, submarine topography (especially submarine canyons), gravity-anomalies, magnetic anomalies, petrographic data, and a careful discussion of all will make it possible to discriminate between various hypotheses in a given region and to arrive at a picture which may be called a first approximation for the tectonic processes at present in action. Only after this goal has been reached, may conclusions be drawn as to the processes involved in the history, considering, however, that the present tectonic processes may not be characteristic of the whole history of the Earth.

References

[1] B. Gutenberg, Changes in sea level, postglacial uplift, and the mobility of the Earth's interior, Bull. Geol. Soc. Amer., v. 52, pp. 721-772, 1941.

[2] B. Gutenberg and C. F. Richter, Seismicity of the Earth, Geol. Soc. Amer., special paper, in press.

[3] B. Gutenberg, Mechanism of faulting in Southern California indicated by seismograms (submitted to the Seis. Soc. Amer.).

[4] B. Gutenberg and C. F. Richter, New evidence for a change in physical conditions at depths near 100 kilometers, Bull. Seis. Soc. Amer., v. 29, pp. 531-537, 1939.

[5] R. W. Goranson, Fracture and flow in stressed solids, Trans. Amer. Geophys. Union 1940, pp. 698-700, 1940.

[6] P. H. Kuenen, The negative isostatic anomalies in the East Indies, Leidsche Geol. Mededeelingen, v. 8, pp. 169-214, 1936.

[7] D. Griggs, A theory of mountain building, Amer. J. Sci., v. 237, pp. 611-650, 1939.

Balch Graduate School of the Geological Sciences,
California Institute of Technology,
Pasadena, California