SEISMIC RAY THEORY APPLIED TO REFRACTION SURVEYS OF THE EARTH'S CRUST IN MISSOURI

Samuel Woods Stewart, A.B., M.S.

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CHAPTER I

INTRODUCTION

Definition of the Earth's Crust

The concept of an earth crust is an old one, yet ambiguity still exists as to the meaning of the word in present-day use. Its modern usage derives originally from the theories of the origin of the earth stated in the 18th and 19th centuries. At that time most scientists believed the earth was at one time a fluid, molten mass. The word crust described the cooled, crystalline outer portion of the earth, as compared to the still warm and, perhaps, fluid inner part of the earth. Arguments for a hot interior were based upon the known increase of temperature as one descends into a deep mine or lowers temperature measuring devices into deep bore-holes, and upon natural thermal phenomena as exhibited by hot springs and volcanoes (Fisher, 1889). Various estimates of the thickness of this cooled crust ranged from 16 to 25 miles (26 to 40 km).

In the latter half of the 19th century and the early part of the 20th century, the classical gravity and isostatic studies of Pratt, Airy, Bouguer, Hayford, and others served as a new influence on studies of the nature and behaviour of the earth's crust. Analysis of measurements of the force of gravity and deflection of the vertical near large mountain ranges showed that these ranges were not simply an additional load on the crust, supported wholly by the crust. Rather, the lower density mountains seemed to approach a condition of "floating" on a more dense but weaker sub-stratum, much as an iceberg floating in the sea. The crust was identified with the lithosphere, an outer shell possessing considerable strength, while the underlying sub-stratum was identified with the asthenosphere, a region with such little strength that it permits a certain amount of material flow under relatively small stress differences. The thickness of the crust (i.e., the lithosphere) based upon interpretation of gravity, geodetic and topographic data, and upon estimated densities for the crustal and sub-crustal materials, was calculated to be 50 to 60 km beneath the continents and 20 to 30 km beneath the Atlantic and Arctic Oceans (Bucher, 1933, p. 49).

The influence of seismology upon the study and, indeed, the definition of the earth's crust, has been great. In 1910 A. Mohorovicic first reported and correctly interpreted the traveltimes of seismic waves at relatively short distances. He determined that the earth had an outer layer about 50 km thick with compressional wave velocity of 5.7 km/sec, overlying a sub-stratum with compressional wave velocity of about 7.75 km/sec.

He recognized that the surface at 50 km depth must be of major importance: "At this surface there must occur a sudden change in the material of the earth's interior, for here there must occur a sudden jump in the velocity of propagation of earthquake waves" (Mohorovicic, 1910, p. 39). The essence of Mohorovicic's observations has stood the test of greatly improved theoretical, laboratory and field studies of the outermost portion of the earth. The seismic boundary discovered by him is today referred to as the Mohorovicic discontinuity, the "Moho," or the "M-discontinuity." Although this boundary is referred to conveniently as a discontinuity, the nature of the velocity transition across the boundary is not clear. Because the seismic data have not yet yielded on the question, the routine interpretation of such data is simplified greatly if the velocity across the boundary is assumed to increase discontinuously, rather than if it is assumed to increase continuously over a zone of finite thickness.

At the present time most seismologists and many earth scientists define the lower boundary of the earth's crust to be identical with the M-discontinuity (e.g., Gutenberg, 1959a, p. 21). Some, however, prefer to omit any implication as to the nature of the velocity transition, and instead apply an operational definition to the problem. For example, Steinhart and Meyer (1961, p. 2) suggest the following definition: "The base of the crust of the earth will be taken to be that depth at which the compressional wave velocity first exceeds 7.8 km/sec." Definitions of this type are interesting, but not always applicable. This definition will be mentioned again in Chapter III.

Even today not all earth scientists place the lower boundary of the earth's crust at the M-discontinuity. For example, Benioff (1954, p. 395) takes as the crust the depth down to which the deepest earthquakes are known to occur. This depth, about 700 km, is 10 to 20 times greater than that to the M-discontinuity below continents. DeSitter (1956, p. 506-507) uses the word crust such that in one context its thickness is at least 300 km, and in another context its thickness is 30 km. Gutenberg (1959a, p. 21) states: "It is important that the word crust be defined by every author using it."

In the research reported here, the earth's crust is defined in the usual seismological sense. That is, the crust comprises all that material above and including the M-discontinuity. We include the M-discontinuity because of the possibility that the base of the crust is bounded by a velocity transitional zone rather than a velocity discontinuity.

The thickness of the earth's crust ranges from less than 10 km in oceanic regions to more than 50 km in continental regions. The crust constitutes therefore something less than 1% of the total radius of the earth, and about 1.4% of the total volume of the earth. The earth's mantle is taken as that material bounded above by the crust, and bounded below by the core--the other major seismically-determined discontinuity within the earth. The lower boundary of the mantle is at a depth of about 2900 km.

Seismic Interpretation Methods for the Crust and Mantle

The theory for the interpretation of seismic traveltime data as it relates to determining velocity structure within the crust or mantle usually is based upon an earth model characterized either by a sequence of constant velocity layers or by a continuous velocity-depth function that does not vary in the horizontal direction. In studies of crustal velocity structure the layered model is used more widely than the continuous velocity function model, and earth curvature usually is neglected. By contrast, mantle velocity structure most often is determined by assuming a continuous velocity-depth function, and the effects of earth curvature are included. (Carder (1964), however, interpreted mantle traveltime data by assuming concentric spherical shells, each of constant velocity.) In this section we examine briefly some reasons for the differing treatments of crust and mantle traveltime data in determining velocity functions for the earth.

Herglotz (1907) seems to have first treated the problem of calculating directly the velocity-depth function from the experimentally determined seismic traveltime curve. He restricted his problem by requiring (1) that the velocity-depth relation always satisfy the condition $dv/dr<v/r$ (where v is the velocity at radial distance r from the center of the earth), (2) that the increase of velocity with depth be of such a form that the traveltime curve is always a single-valued function and is always concave to the distance axis, (3) that the velocity may not vary horizontally. The resulting solution, in the form of an integral equation, was solved by identifying its form with that of Abel's integral equation. Bateman (1910) solved the same problem independently. He included essentially the same restrictions and solved the problem by similar application of Abel's integral equation. Wiechert and Geiger (1910) simplified the solution to a form more convenient for the numerical computations.