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CRUSTAL AND UPPER MANTLE STRUCTURE IN THE REGION OF THE GULF OF MEXICO*

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RESUMEN

Se describen los estudios sísmicos de refracción de la corteza y del manto en la región del Golfo de México. La conclusión principal de los estudios corticales indica que la corteza que subyace a los sedimentos en la parte profunda del sineclise de la Costa del Golfo, está delgada, en comparación con la corteza de la parte central de los Estados Unidos. Se discute el problema de que gruesos cuerpos de sedimentos pueden acumularse.

ABSTRACT

Seismic refraction studies of the crust and mantle in the Gulf of Mexico region are described. The principal conclusion of the crustal studies was that the crust underlying the sediments in the deep portion of the Gulf Coast syneclise is thin relative to the crust in the central United States. The question of how thick bodies of sediments can be laid down is discussed.

INTRODUCTION

In this paper I propose to describe some recent studies of crustal and upper mantle structure by myself and my colleagues at The University of Texas at Dallas, and discuss the significance of these in respect of the evolution of the crust and of epeirogenetic processes.

It has long been known that even allowing for isostatic compensation, the maximum thickness of sediments which can be laid down in water of depth d is of the order of 2d to 3d. On the other hand, it is well known that the thickness of the sediments in the Gulf Coast syncline or syneclise is greater than 10 km. The Gulf Coast syneclise is relatively young geologically speaking, but it should be noted that the thickness of the sediments in the

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Witwatersrand System is also greater than 10 km and these sediments are more than 2200 million years old. There appear to be only two possibilities; namely that the sediments were accumulated in shallow water on a continental type crust which subsided as a result of some unknown process or that, despite the shallow water nature of some of the sediments, they were finally deposited in deep water and thus are underlain by an oceanic type crust.

CRUSTAL STRUCTURE

Hales, Helsley and Nation (1970a) reported on the results of a seismic experiment which was designed to determine the thickness of the crust beneath the Gulf Coast sediments. It was found that there were at least 10 km of low velocity sediments (velocity between 2.44 and 3.50 km/sec) overlying material which has a velocity of 5.8 km/sec. On shore, where borehole information is available, the depth to this interface correlates with the top of the Cretaceous as summarized by Williamson (1959). The interpretation shown in Figure 1 was obtained by combining the seismic results with the gravity information of Dehlinger and Jones (1965). The features of this interpretation are that the crust in East Texas is about 50 km thick. This is of the same order as the crustal thickness found in northeastern Arkansas by Steinhart, Meyer and Woollard (1961). It is also similar to that found in the central United States (Pakiser and Robinson, 1966). The crust thins seaward from a point about 100 km inland of the shoreline and stabilizes at about 33 km over most of the continental shelf. The thickness of crust with velocity greater than 6 km/sec on the shelf is about 16 km. The crustal structure found for the shelf is very similar to that found by Cram (1961) for a seismic profile northwest of Houston. The total crustal thickness as determined by Cram was 33.0 km and the thickness of material with velocity greater than 6 km/sec, 13.2 km. Thus, the crust beneath the sediments is too thin to be regarded as continental, but thicker than the usual oceanic crust. Hales, Helsley, and Nation (1970a) concluded that much of the sediments in the Gulf Coast syneclise were deposited in moderately deep water, possibly by a turbidity current-like process after initial deposition in shallow water.

The difference between the crustal thicknesses in the interior of continents and those near the continental margin was noted by Engel and Engel (in press). It leads to the speculation that the crust of the Earth grows thicker with age. Before pursuing this intriguing idea it is worthwhile to describe some results from other seismic refraction studies.

MANTLE STRUCTURE

Recent studies of seismic travel times in the central United States (Green and Hales, 1968; Mereu and Hunter, 1969) have shown that the apparent velocity of the first arrival P phases increases abruptly at a distance of about 650 to 700 km. This change in apparent velocity was interpreted as being due to an increase in velocity at a depth of about 90 km.

In 1969, a seismic refraction study was carried out in the Gulf of

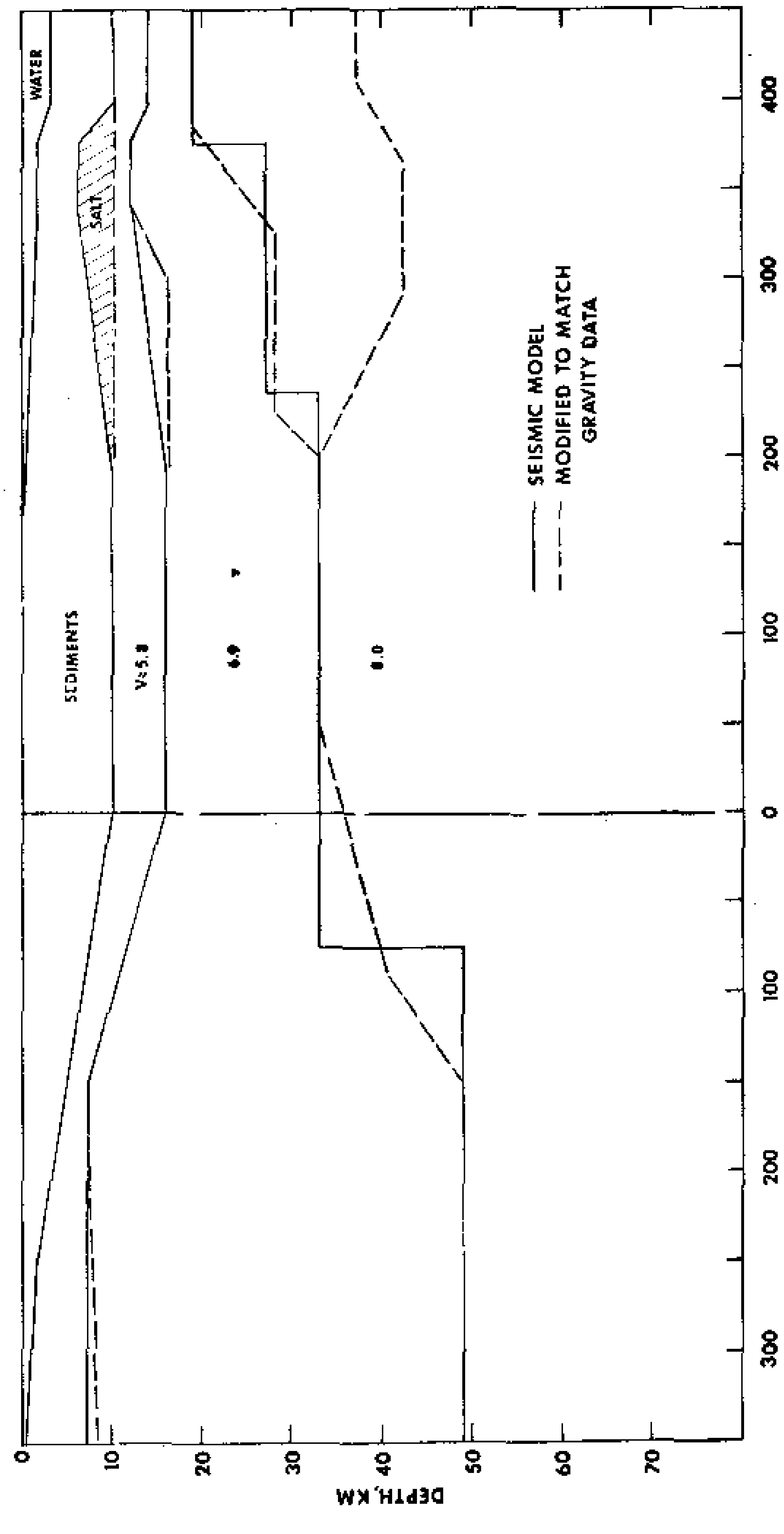

Fig. 1.—Seismic section of the Gulf Coast Syneclise along longitude 94° W.

Mexico by The University of Texas at Dallas in cooperation with the Institutes of Geology and Geophysics of the University of Mexico and the University of Wisconsin and Texas Technological University. Once again it was found that there was a sharp change in apparent velocity, in this case at a distance of about 350 km. This change was interpreted by Hales, Helsley and Nation (1970b) as due to an increase of velocity in the upper mantle at a depth of about 60 km. Hales and coworkers inferred from the fact that the phase had large amplitudes over a considerable distance range that there was a gradient in velocity immediately below the discontinuity and hypothesized that the discontinuity was due to a phase transition. The interpretation by Hales, Helsley and Nation is illustrated diagrammatically in Figure 2. Similarly, Hales, Barrett and Spence (in preparation) found a phase with a velocity of 8.9 km/sec at a depth of 30-40 km below the continental shelf to the south of South Africa. These results vary surprisingly. The depth to the discontinuity varies from 40 to 90 km and the velocity below the discontinuity from 8.9 to 8.4 km/sec. The data are scanty but it appears that the velocity below

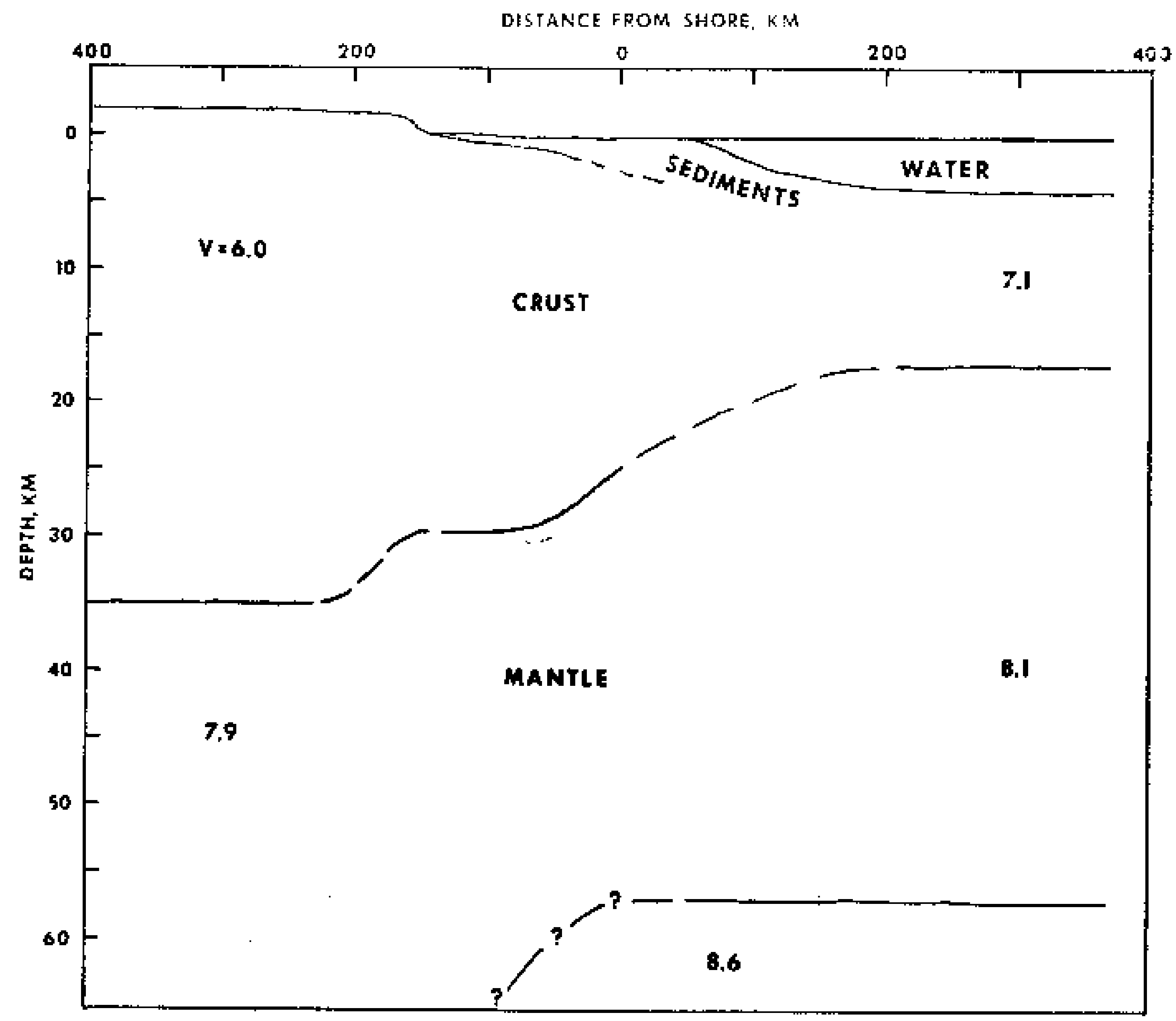

FIG. 2.—Schematic crust and upper mantle cross section through San Luis Potosí and Ciudad Mante, across the Mexican Continental Shelf into the Gulf of Mexico.

the discontinuity may be inversely correlated with the depth of the discontinuity. In all cases in which the discontinuity has been identified it appears to lie above the low velocity zone. The Press (1969, 1970) studies of earth models compatible with the observed periods of the free oscillations all show relatively high densities at depths of 50 to 100 km. Since the surface of the Earth is 70% ocean Press pointed out that his early models were dominated by the structure beneath the oceans. It is probable that the seismic discontinuity described above and Press' high density are associated, and that a change in properties at comparatively shallow depth in the upper mantle is a universal, or at least a widespread, characteristic of the oceans.

Press interpreted the density increase as arising from the basalt-eclogite transition. Hales (1969) suggested that another possibility was the garnet-peridotite transition studied by MacGregor (1970) for the reasons that: (1) Ringwood and Green's (1966) data suggested that the basalt-eclogite transition would be spread out over a considerable depth range whereas the seismic evidence suggested that it was relatively sharp, (2) the Ringwood and Green data suggested that the transition occurred at crustal rather than upper mantle depths, (3) the inclusions in kimberlite pipes are predominantly peridotite (in the sense used by Kuno, 1969) with the exception of the Roberts Victor mine.

Ito and Kennedy (1969) have shown recently that measurements of the density during the transition from basalt to eclogite indicate that the transition takes place in two steps, both relatively sharp. The higher pressure step occurs at the depths appropriate to the seismic discontinuity discussed above. Thus, apart from the difficulty that petrologic considerations imply that "lherzolite and its high-pressure modification constitute the main part of the upper mantle" (Kuno, 1969), it is possible that the transition at 60-90 km is part of the basalt-eclogite transition. In general it would appear that whatever the rock of the upper mantle may be, garnet is a major contributor to the high density and high seismic velocity. One of the difficulties is that the parameters are greatly dependent on the composition as is shown by the data of MacGregor (1970).

There is one point which perhaps has not been emphasized sufficiently. The measurements by Ito and Kennedy were made at temperatures close to the solidus. MacGregor's measurements were made at 1100°C, *i.e.* not far from the solidus. There is ample evidence that at temperatures far removed from the solidus the reactions proceed at a very slow rate - so slow in fact that the high temperature phases may be stable at low temperatures for periods which are long even in terms of geological time. Examples are the diamonds in kimberlite and the garnets in the inclusions. So little is known of the dependence of the reaction rate of the basalt-eclogite transition on temperature that it is possible to hypothesize that the reaction rate decreases with increasing difference between the actual temperature and the melting point, the decrease being such that geological times are required for significant changes at temperatures a few hundred degrees removed from the melting point.

The changes in velocity required by the observations lie between 5 and 10 percent. The percentage change in density found in Press' analysis is of the same order. Thus an increase in the depth of the transition by 10 km would result in a rise of the free surface by 0.5 to 1 km. The slopes of the transition boundary are of the order of 50° per kbar so that a temperature change of 150° - 200° would be required to change the depth of the transition by 10 km. The regional variation in heat flow shows that temperature differences of the required order do occur spatially in the upper mantle and therefore it is not unreasonable to expect temporal changes of the height of the free surface as a result of changes in the depth of the transition (if indeed it is a phase transition).

The response of a phase transition to the loading of the oceanic crust by sediments has been discussed by MacDonald and Ness (1960) and Wetherill (1961). The initial effect is due to the increased pressure resulting from the sedimentary load. The free surface would move down as a result of increased pressure. At a later stage the effect of the thermal blanketing of the sediments results in an increase of temperature which propagates downward. As a result the transition moves down and the free surface up. This effect is of course in addition to that which arises directly from the expansion caused by the rise of temperature. The two effects will have different time constants in general. A mechanism of this kind would make possible the deposition of thick bodies of sediments on a continental crust. However, it seems probable that in some cases thick bodies of sediments were deposited in moderately deep water after initial deposition in shallow water.

The importance of the temperature dependence of near surface phase transitions with respect to tectonic and orogenic processes was recognized by Holmes (1927), Lovering (1958) and Kennedy (1959). These authors suggested that the M discontinuity was the result of the phase transition from basalt to eclogite. The possibility that the M discontinuity beneath the oceans corresponds to this transition has fallen out of favor as a result of the discussions by MacDonald and Ness (1960), Wetherill (1961), and Bullard and Griggs (1961).

In spite of these objections it appears possible that the M discontinuity (or perhaps some other discontinuity in the lower crust), in a continental crust at least, corresponds to the lower pressure step in the basalt-eclogite transition as was suggested by Ito and Kennedy (1969). The temperatures within the crust are several hundred degrees below the solidus. Under these conditions the reaction rates may be slow. If this were the case it would be possible for the continental crust to grow thicker as it grew older.

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