Crustal Structure of the Earth

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1. INTRODUCTION

The boundary between the crust and the mantle was discovered by Mohorovicic in 1909 under the European continent. Subsquent research in this century established the major differences between the continental and oceanic crust; a typical thickness for the continental crust is 30-50 km while a typical thickness for the oceanic crusts is 6 km. In terms of history the continental crust contains a much longer history of 4 billion years, whereas the oceanic crust contains at most 200 million years of history because of recycling of oceanic plates.

Because of its long history, the continental crust has been subjected to various tectonic processes, such as repeated episodes of partial melting, metamorphism, intrusion, faulting and folding. It is thus easier to find systematic relationships between age and structure of oceanic crusts. However, the existence of hotspots as well as changing patterns of plate motion complicate oceanic crustal structure. In this section, we assemble crustal thickness data from various tectonic provinces and discuss their implications.

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2. OCEANIC CRUSTS

2.1. Classic Subdivision and Mean Crustal Thickness

The oceanic crust is classically divided into three layers [52]; Layer 1 is the sedimentary layer, whose thickness varies widely according to sediment sources, and Layer 2 has a thickness of 1.5-2.0 km and P-wave velocity of 4.5-5.6 km/s and Layer 3 has a thickness of 4.5-5.0 km and P-wave velocity of 6.5-7.0 km/s. Combined thickness of layer 2 and 3 is often referred to as the oceanic crustal thickness and we adopt this convention. For the continental crust, we define the thickness from the surface to the Mohorovicic discontinuity (Moho).

The interpretation of oceanic velocity structure is based on two independent sources of information; one is by comparison of seismic velocities in laboratory measurements of rocks from ocean drilling cores with the velocities measured in seismic refraction experiments. The other is based on analogy with structures in ophiolite complexes. A commonly held view (e.g.,[65]) is that Layer 2 starts with extrusive volcanic rocks at shallow depths which grade downward from pillow basalts into sheeted dikes. There is a transition zone at the top of Layer 2 which shows interfingering of extrusive basaltic rocks and sheeted dikes. Layer 3 has properties appropriate to the massive to cumulate gabbro layer seen in ophiolite complexes. The top of Layer 3 has a transitional layer which shows interfingering of sheeted dikes (at the bottom of Layer 2) and isotropic gabbro (at the top of Layer 3). The isotropic gabbro layer is underlain by layered gabbro and harzburgite successively.

The traditional seismic modelling used a few homogeneous layers, which has been replaced by layers which contain velocity gradients in recent studies (e.g., [66]). If the assumption of a few stack of homogeneous

TABLE 1. Average thickness (km) and P-wave velocity (km/s) of layer 2 and 3 in oceanic crusts

	Raitt [52]	Shor et al. [59]	Christensen and Salisbury [9]	White et al.[70]
Thickness				
Layer 2	1.7±0.8	1.5±1.0	1.4±0.5	2.1±0.6
Layer 3	4.9±1.4	4.6±1.3	5.0±1.3	5.0±0.9
P-Wave velocity				
Layer 2	5.1±0.6	5.2±0.6	5.0±0.7	
Layer 3	6.7±0.3	6.8±0.2	6.7±0.2	

layers are used in regions of steep velocity gradient, estimates of crustal thickness can be misleading. Table 1 quotes the thicknesses of layer 2 and 3 from four studies during the last few decades. They are from P-wave velocity structure by refraction studies. Typically, thickness of layer 2 is 1.5-2.0 km and that of layer 3 is 4.5-5.0 km. Table 2 shows a compilation of mean crustal thickness, a sum of layer 2 and layer 3 thicknesses, which is almost uniformly 6 km. The most recent study [70] claims a somewhat higher value of 7.1 km and attributes this difference to underestimation of older studies. They claim that a travel time slope-intercept method of interpretation in previous studies may significantly underestimate the true thickness because it usually does not take into account the velocity gradients. Synthetic seismogram technique alleviates this problem. Note, however, that the difference is relatively small, up to 1 km, although it may be systematic. We thus summarize that the oceanic crustal thickness (excluding layer 1) is 6-7 km.

2.2 Age Dependence

In general, age dependence of crustal thickness is considered to be weak. In fact, constancy of crustal thickness has been regarded as almost a fact. While it is true that oceanic crust has fairly constant thickness everywhere in the ocean, there exist a few studies which claimed to have discovered the age dependence. Table 3 shows comparisons for crustal thickness between young oceanic region (younger than 30 million years old) and old oceanic region (older than 30 my). There are differences of 0.3-0.6 km between these two regions. Physical mechanism for the age dependence is not clear, however. It indicates somewhat thicker crustal generation in older oceans or gradual evolution of oceanic crust, but detailed mechanism for them are not available. Also, care must be taken before interpreting this difference, since there are a large number of seamounts in the old oceans which tend to biase the estimate toward thicker crusts. In that case, older oceans simply have anomalous crustal thickness due to seamounts and may not have thicker crusts uniformly.

2.3. Regions of Thin Crust

There are three regions where oceanic crust is reported to be thin; they are (i) a slow spreading rate (less than 2 cm/year) region, (ii) non-volcanic rifted margin which underwent extensional tectonics at some point in history and (iii) fracture zones (Table 4). The region (i) probably reflects the fact that an amount of partial melt is small under slow spreading ridges and thus crustal material is not transported from the mantle to shallow depths. Sleep [61] has shown that magma body under slow spreading ridges (less than 1 cm/y) may not be stable due to lateral conduction of heat. A seismic body wave study by Sheehan and Solomon [58] and a surface wave study by Zhang and Tanimoto [74] also showed the evidences for relatively fast seismic velocity under slow spreading ridges which indicate lack of or very little amount of melt under ridge axes. The region (ii) corresponds to an area where extreme extension had occurred in history. An example for this region is near the continental edge of (Central) Atlantic Ocean where extension played the major part in the continental break-up. The reason for thin crusts under fracture zones was recently shown to be caused by an extremely thin layer 3 or a lack of it under fracture zones [68] at least on the slow-spreading, Mid-Atlantic Ridge. This supports the idea that accretion and upwelling at slow-spreading ridges are focused near the center of segments rather than close to fracture zones. Bouger gravity anomaly also shows the so-called Bull's eye (low) gravity anomaly near the center of segments

TABLE 2. Mean Crustal Thickness

	Thickness (km)	Region
Raitt [52]	6.6±1.6	Pacific
Shor et al. [59]	6.1±1.6	Pacific
Houtz [24]	5.6±1.3	Atlantic
McClain [36]	5.8±0.9	Pacific
McClain and Atallah [37]	5.9±0.9	Pacific
Keen et al. [29]	5.8±1.1	Atlantic, Pacific
White et al. [70]	7.1±0.8	Atlantic,Indian,Pacific

TABLE 3. Age dependence of crustal thickness

	younger than 30 my	older than 30 my	Region
McClain and Atallah [37]	5.7±0.9	6.0±0.9	Pacific
White et al [70]	6.5±0.8	6.9±0.3	Pacific
White et al [70]	7.0±0.6	7.6±0.5	Atlantic

TABLE 4. Thin crust regions

	Oceanic Crustal Thickness (km)
Slow spreading region (less than 2 cm/y)	2.1±0.6[a]
Non-volcanic rifted margin	4.9±1.5[b]
Fracture zones	4.0±1.3[c]

Note: a. Jackson et al. [26]
b. Ginzburg et al. [19]
Horsefield et al. [23]
Pinheiro et al. [46]
White et al. [70]
c. Minshull et al. [40]
Whitmarsh et al. [71]
Cormier et al. [11]
Sinha nd Louden [60]
Potts et al. [48][47]
Louden et al. [33]
Detrick et al. [15]

TABLE 5. Oceanic crustal thickness in plume affected regions

Region	Thickness (km)	
Madagascar	21.2	Sinha et al. [60]
Kerguelen	18.5, 20.5	Recq et al. [53]
S. Iceland	20.24	Bjarnason et al. [70][a]

Note: a. as referenced in White et al. [70]

because of thickness variations of layer 3.

2.3. Regions of Thick Crust

Thick oceanic crusts are found where hotspots (plumes) were or are currently under the ridge axes (Table 5). A typical crustal thickness reaches 20 km in such regions. Increased amount of partial melt due to high temperature in the hotspot regions must have been the reason. Some studies report a value of about 10 km, which is higher than the average value of 6-7 km. This can be explained that hotspots were not exactly under the ridge axes but were only in the neighborhood.

Many oceanic plateaus, such as the Ontong-Java plateau, also have thick crusts due to a large amount of melt by mantle plumes at the time of its generation. In this case, ridges may not have existed close by but the plume could have had a large flux and melt.

3. CONTINENTAL CRUSTS

3.1. Classical Division

Various tectonic activities have produced a wide range of continental crust during its long history. Structure within a continental crust is complex both in P-wave velocity variations and rock types. There are, however, approximately four layers within the crust and identification is often done with P-wave velocity. The first layer consists of sediment, characterized by P-wave velocity lower than 5.7 km/s. The second layer has P-wave velocity of 5.7-6.4 km/s, the majority of which is considered to be granite and low-grade gneisses. The third layer has P-wave velocity of 6.4-7.1 km/s and the fourth layer has 7.1-7.6 km/s. There are many candidates for the compositions of layers 3 and 4. The P-wave velocity of 7.6 km/s is typically the lowest end of P-wave velocity expected at the uppermost mantle (Pn velocity). Thus a layer with P-wave velocity of 7.6 km/s or higher is considered to be in the mantle. Crustal thickness or depth to Moho is 39 km on average, but it has some variations according to its regions. Conrad discontinuity, which is often found under continents in the mid-crust (about 15 km depth), is found between the first and the second layer in some regions, but it is not universal.

3.2. Shields and Platforms

Shields and platforms have generally thick crusts, typically exceeding 40 km. There are some variations among different regions (Table 6) and among different age provinces within a shield. They have relatively thick lower crust, which often lack clear signals in seismic reflection data (with occasional exceptions). Also the lower crust seems to have smooth velocity transitions from deep seismic sounding studies [38]. They suggest a lack of discontinuities in the lower crust. These features are usually interpreted as moderate level of differentiation in the lower crust.

3.3. Paleozoic and Mesozoic Regions

This region typically has crustal thickness of about 30 km (Table 7). The fourth layer in the classical division (a layer with P-wave velocity 7.1-7.6 km/s) is almost always missing in this region. Consequently, P-wave velocity makes a sharp velocity jump at the Moho. Wide angle reflection from Moho (PmP) is often strong because of it. Also, the Conrad discontinuity is often found in this region. However, most data are biased to European continents, thus requiring some care in generalizing its features.

3.4. Mountain Belts in the Cenozoic Era

The Alpine-Himalaya orogenic belts and the Rocky mountains are the typical regions in this category. Crustal thickness in this region varies between 40 and 70 km (Table 8). Crustal roots which compensate high mountains are found quite often. A thick upper crust which is detached from below, due to low-viscosity lower crust, is often suggested in understanding the tectonics of this region.

3.5. Island Arcs

The data is almost entirely biased to observation from Japan. Crustal thickness is about 20-30 km, which is slightly smaller than the value for the Paleozoic and Mesozoic regions. The region is underlain by a low velocity mantle with Pn velocity of about 7.5-7.8 km/s (Table 9), which indicates a higher temperature under island arcs. A recent tomographic study (e.g., [75]) clearly depicts slow velocity anomalies under volcanic chain in the crust, thus there are some three-dimensional variations being elucidated within the crust in recent studies.

3.6. Hotspots

Afar is one of the few regions studied so far and shows a thin crustal thickness, 15-20 km (Table 9). This is relatively thin for a continental crust, but it is about the same with the crusts under hotspots in the oceanic regions. Since it is at the edge of the continental boundary where the break-up of the two oceans (the Red Sea and the Gulf of Aden) are occuring, it may be natural to have the oceanic structure. Yellowstone hotspot has a normal crustal thickness, but it is substantially smaller than Afar hotspot. It is underlain by a thermal anomaly (e.g. [25]).

TABLE 6. Crustal Thickness in Shields and Platform

Shields and Platforms	Thickness (km)	
Baltic Shield	38,39,40,42	Hirschleher et al.[22]
	45	Korhonen and Parkka [31]
	41,45,47	Meissner [38]
North American Shield	41,45	Cohen and Meyer [10]
	50	Roller and Jackson [55]
	35,40,52	Steinhart and Meyer [67]
	37,38,43,44	Berry and Fuchs[7]
	42	Smith et al. [62]
Australian Shield	32,34,40,41	Hales and Rynn [21]
	50,55	Finlayson [17]
	38,44,,46	Mathur [35]
Indian Shield	40	Hales and Rynn [21]
	34,40,42	Kaila et al. [28]
Western Eurasia (except Baltic)	32	Alekseev et al. [1]
	36,50	Jentsch [27]
	39,46	Sollogub [64]
	39,47	Kosminskaya and Pavlenkova[32]

TABLE 7. Paleozoic and Mesozoic areas

Paleozoic and Mesozoic areas	Thickness (km)	
Caledonian structure (Scotland and Norway)		
	28,32	Assumpcao and Mabform [4]
	29,32,34	Bamford et al. [5]
	28	Payo [44]
Spain	27	Dagniereo et al. [12]
	32	Banda et al. [6]
	28,29,32	Sapin and Hirn [57]
France	28	Ansorge et al. [3]
Germany	26,29	Grubbe [20]
	23,24,25,29	Edel et al [16]
	28	Deichmann and Ansorge [14]
	29,30	Angenheister and Pohl [2]
	30	Meissner at al [39]
	28,30,31	Mooney and Prodehl [42]

TABLE 8. Cenozoic Mountain Belts

Cenozoic Mountain Belts	Thickness (km)	
Alps	38,39	Will [72]
	40,43,45,54	Giese and Prodehl [18]
Caucasus	42,43,44,55	Kondorskaya et al. [30]
Himalaya	66	
Mishra [41]		
	60,64,70	Volvovsky et al. [69]
Rocky	47,51	Prodehl and Pakiser [49]

3.7. Rifts

Various kinds of rift areas show somewhat thinner crust of 20-38 km (Table 9). Recent three-dimensional studies indicate existence of slow anomalies under some rifts, such as East African rift and the Rio Grande rift, while lack of such an anomaly was confirmed under others such as the Rhine Graben (e.g.,[13]).

3.8. Two Well-Studied Continents

Detailed crustal thickness variations have been published for Europe (Figure 1)[38] and for the United States (Figure 2)[8]. Crustal thickness variation within Europe shows thick crust under Scandinavia (the Baltic Shield), thick crust under Alpine-Caucasus orogenic zone, average crustal thickness for Paleozoic and Mesozoic regions (Spain, France and Germany) and relatively thin crust behind the subduction zone (West of Italy). Crustal thickness in the United States has three major peaks; one in the east in the Appalatian mountain region, one in the mid-continent and also the one in the Sierra-Nevada region. There is also a hint of thick crust under the Canadian Shield region, but this map shows only a small portion of it. The Basin and Range region shows a well-known thin crust, a result of extensional tectonics in this region.

For the United States, the map of Pn velocity has been published (Figure 3)[8]. It is not as detailed as the crustal thickness map because the work was done some time ago, but the large scale features in the variations are reliable. Fast Pn velocities are found in mid-continent where the crusts are thick and slow velocities are found in the western United States where the crusts are relatively thin. This of course applies to a large scale feature such as the Basin and Range and the Sierra Nevada mountains show thick crusts due to isostatic compensation.

4. SYNTHESIS

Synthesis of regional studies to construct a global crustal thicness variation map has been attempted by Soller et al. [63]. Their map (Figure 4) has been widely used by global seismologists, because it has been the only one easily accessible. This map, expanded in spherical harmonics up to degree and order 20, shows the depth to Moho, whose global average is 24 km depth. The boundary between the white and dark regions correspond to this depth. Contours

Table 9: Sundry Tectonically Active Regions

Region	Thickness (km)	
Japan(Island Arc)	24,33	Research Group[54]
	30	Yamashina [73]
Afar(Hotspot)	14,15,22,23	Pilger and Rosler [45]
	13,17,25	Ruegg [56]
Baikal (Rift)	28	Puzyrev et al. [50]
	28	Puzyrev et al. [51]
Red Sea (Rift)	32	Makris et al. [34]

Fig. 1: Crustal thickness variations under Europe (after Meissner [38])

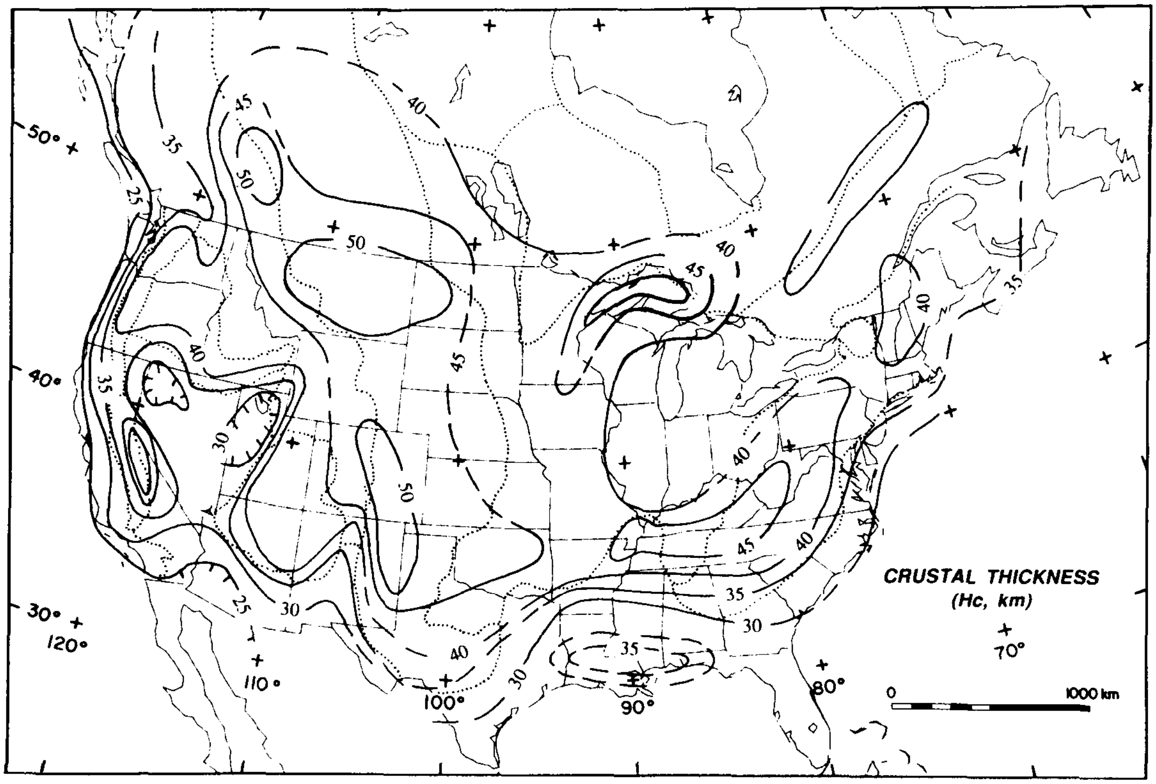

Fig. 2: Crustal thickness variations under the United States (after Braile et al. [8]

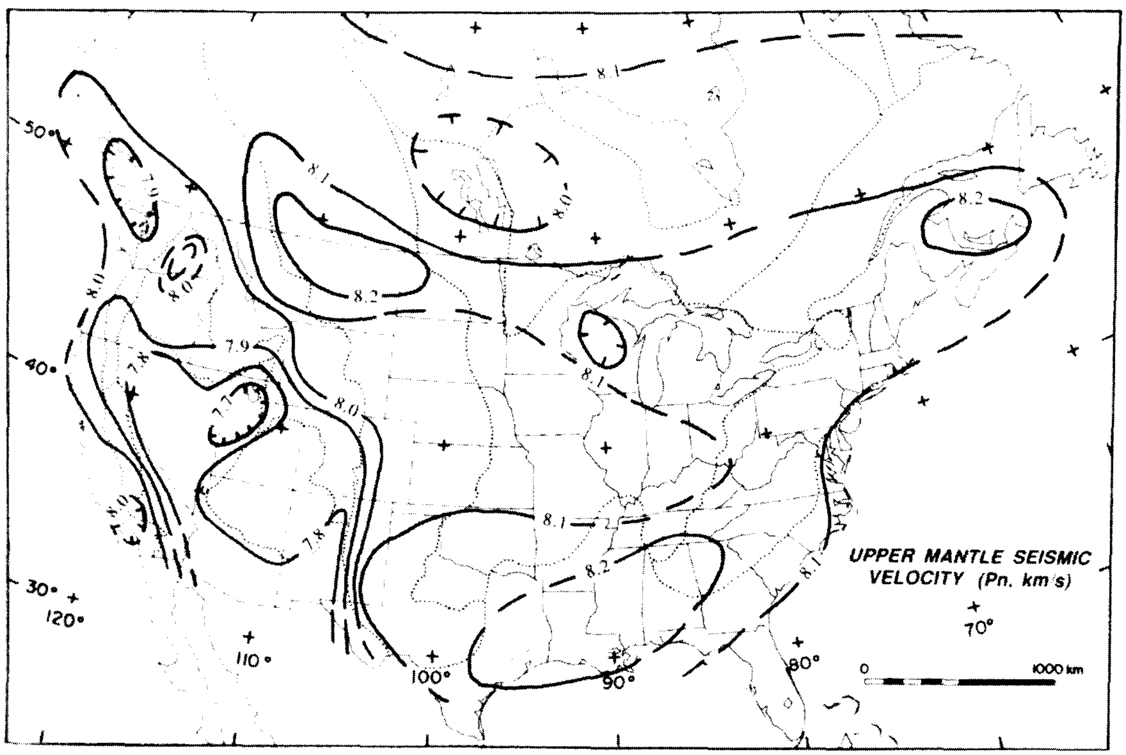

Fig. 3: Pn velocity variations under the United States (after Braile et al. [8])

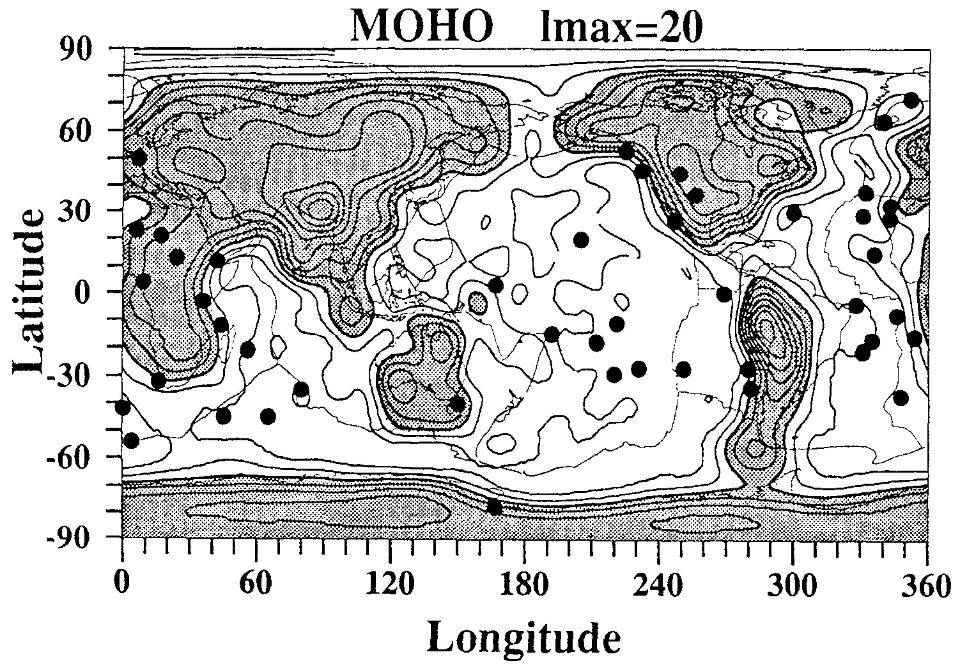

Fig. 4: Global Moho depth variations. Contours are at 5 km interval. The boundary between dark (thicker) regions and white regions is 24 km depth. Filled circles are locations of hotspots from the list of Morgan [43].

are given every 5 km. The peak at Himalaya, for example, corresponds to 65 km in depth. Some precaution in interpreting this map is required, since there are regions that have not been studied and the map contains some extrapolated results. Further work is clearly desired to improve this situation.

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