

Crustal Structure, Isostasy, and Rheology

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Introduction

This lecture will cover 4 broad topics. First the basic structure of the oceanic and continental crust is provided. The emphasis is on layer thickness and densities and there is little discussion of composition. The second and third topics are the vertical and horizontal force balances due to variation in crustal thickness. The vertical force balance, *isostasy*, provides a remarkably accurate description of variations in crustal thickness on the earth based on a knowledge of the topography. The horizontal force balance provides a lower bound on the force needed to maintain topographic variations on the earth. The basic question is what keeps mountain ranges from spreading laterally under their own weight?

The fourth topic is the rheology of the lithosphere; how does the lithosphere strain in response to applied deviatoric stress? We will see that the uppermost part of the lithosphere is cold so frictional sliding along faults governs the strength while at greater depth, the rocks can yield by non-linear flow mechanisms. The overall strength versus depth profile is called the yield-strength envelope. The integrated yield strength transmits the global plate tectonic stress field. Moreover, the driving forces of plate tectonics cannot exceed the integrated lithospheric strength. This provides an important constraint on the geodynamics of oceans and continents.

The yield-strength-envelope formulation will also be used in the following lecture on flexure. It provides an explanation for the increase in the thickness of the elastic layer as the lithosphere ages and cools. In addition, it is used to understand the depth of oceanic trenches. The first moment of the yield strength versus depth provides an upper bound on the magnitude of the bending moment that the lithosphere can maintain. This model strength estimate can be checked by measuring the bending moment of the trench/outer rise topography. There is remarkably

good agreement assuming mantle dynamics does not play a large role in the support of subduction zone topography. Throughout these two lectures, the deviatoric stress levels are typically 100-300 MPa since this is the level of stress needed to maintain the topographic features on the earth. In the following lectures on earthquakes, the magnitudes of stresses are typically less than 10 MPa. Part of this order-of-magnitude stress reduction is due to the fact that many earthquakes are shallow. However, there is still a major unresolved issue of why the crust appears weak in regard to earthquakes and strong in regard to topography and flexure. Since this is a major unresolved issue, it is perhaps a good topic for research.

Oceanic Crustal Structure

The basic structure of the oceanic crust has been established through seismic refraction and reflection experiments, seafloor dredging/drilling, gravity/magnetics modeling, and studies of ophiolites (*Magmatic systems*, edited by Michael P. Ryan. San Diego : Academic Press, c1994. xxii, 401 p.). Figure 1 from *Kent et al.* [1993] illustrates the current model of crustal generation at a fast spreading ridge. Partial melt that forms by pressure-release in the uppermost mantle (~40 km depth) percolates to a depth of about 2000 m beneath the ridge where it accumulates to form a thin magma lens. Beneath the lens is a mush-zone which develops into a 3500-m thick gabbro layer by some complicated ductile flow. Above the lens, sheeted dikes (~1400- thick) are injected into the widening crack at the ridge axis. Part of this volcanism is extruded into the seafloor as pillow basalts. The pillow basalts and sheeted dikes cool rapidly as cool seawater percolates to a depth of at least 2000 m. This process forms the basic crustal layers seen by reflection and refraction seismology methods.

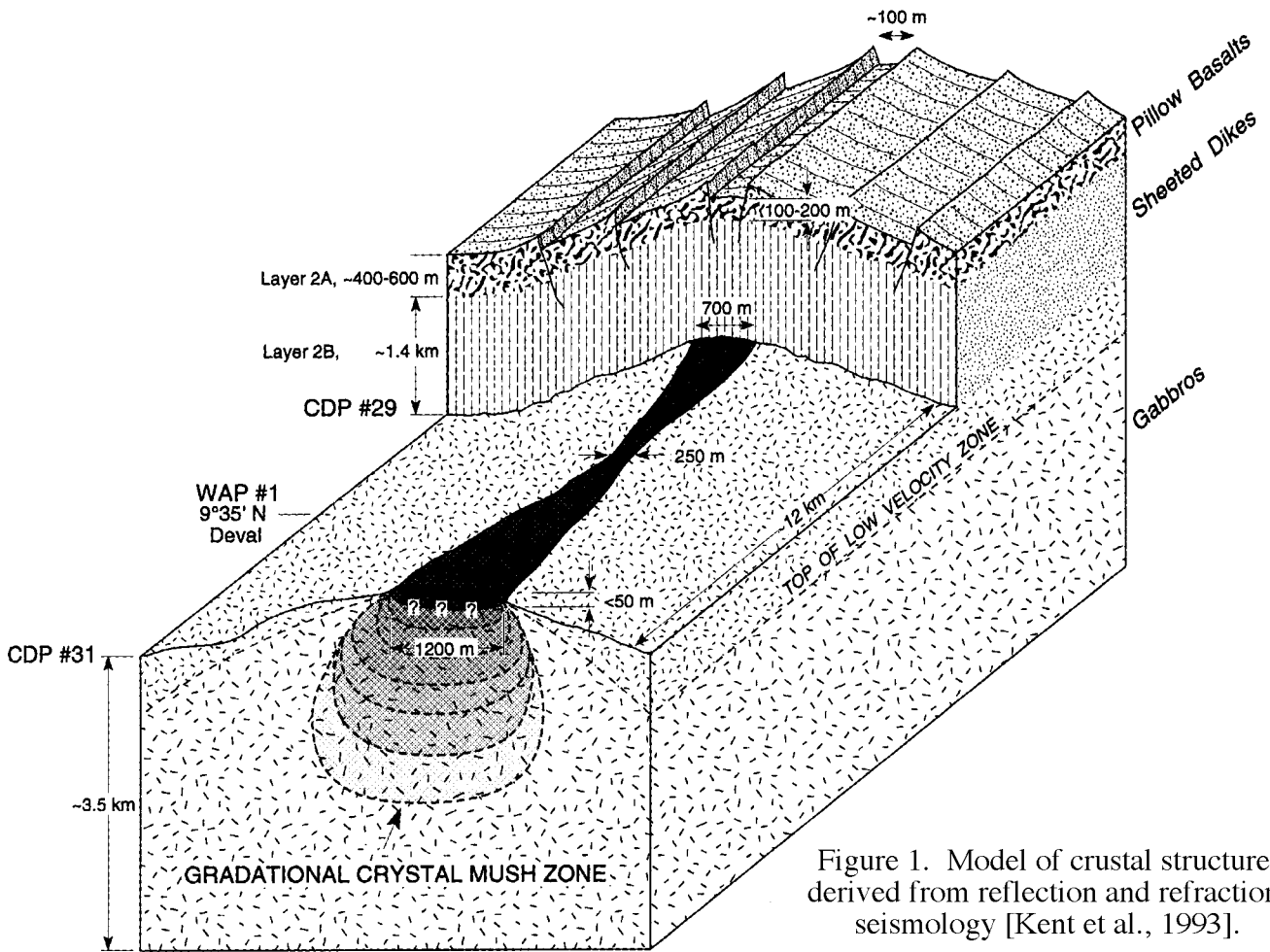


Figure 1. Model of crustal structure derived from reflection and refraction seismology [Kent et al., 1993].

Oceanic Crust		density	velocity	
4 km	sea water	1025 kg m ⁻³	1.5 km s ⁻¹	ocean
5 km	sediment	~2300 kg m ⁻³	>1.65 km s ⁻¹	sediment
7 km	basalt	~2600 kg m ⁻³	~5.0 km s ⁻²	crust
11 km	gabbro	2800 kg m ⁻³	6.8 km s ⁻¹	crust
	peridotite	3325 kg m ⁻³	8.15 km s ⁻¹	mantle

Some key points about the oceanic crust:

- The Mohorovicic Discontinuity (Moho) is defined as the seismic velocity jump from 6.8 km-s⁻¹ to greater than 8 km s⁻¹.
- The Moho corresponds to a change in composition and density. For thick continental crust, it also corresponds to a change in strength.
- The oceanic crustal thickness is remarkably uniform throughout the ocean basins. While the average crustal thickness does not depend on spreading rate, the local variations in thickness are greater for the slow-spreading crust (< 70 mm/yr full rate). For example, the crust is generally thinner near the end of a spreading segment and thicker toward the center of the spreading segment.

Continental Crustal Structure

The basic structure of the oceanic crust has also been established through seismic refraction and reflection experiments, sampling and drilling, gravity/magnetics modeling and studies of exposed crustal sequences. Of course, the continental crust is highly variable in thickness, velocity, density and composition. The diagram below represents an average crustal model for elevations close to sea level.

Continental Crust	density	velocity	
sediment	$\sim 2300 \text{ kg m}^{-3}$	$\sim 5.7 \text{ km s}^{-1}$	
upper crust	2800 kg m^{-3}	6.3 km s^{-1}	
lower crust	2900 kg m^{-3}	6.8 km s^{-2}	
32 km mantle	3200 kg m^{-3}	8.1 km s^{-1}	