2. THE PRIMARY MECHANISMS OF BASIN SUBSIDENCE

A. ISOSTASY

The application of Archimedes' principle to the earth suggests that continents are buoyed up by a force equal to the weight of the displaced mantle (Turcotte and Schubert, 1982). Adjacent blocks of different thickness and/or density structure will have different relative relief (Fig. 2.1). Typical lithospheric structure beneath the continents and the oceans are shown in Figure 2.2, these values will be used in most of our discussions. Below some depth, there is no density contrast between the two adjacent columns, and asthenosphere of equal density underlies both columns (Fig. 2.2). The weight of the columns above this depth of compensation must be equal.

In this model of isostasy, we can calculate the relative relief between two adjacent continental columns of differing density structure (Fig. 2.3):

If Z is filled with water (density = 1.0 g/cm^3):

$$\text{mass of column 1} = \text{mass of column 2}$$
$$30\,(2.8) + 90\,(3.4) = Z\,(1.0) + 15\,(2.8) + 45\,(3.4) + (60-Z)\,(3.3)$$
$$390 = Z\,(1.0) + 15\,(2.8) + 45\,(3.4) + (60 - Z)\,(3.3)$$
$$390 = Z + 42 + 153 + 198 - 3.3\,(Z)$$
$$3.3\,(Z) - Z = 393 - 390$$
$$2.3\,(Z) = 3$$
$$Z = 1.3 \text{ km}$$

If Z is filled with air (density = 0 g/cm^3) instead of water:

$$3.3\,(Z) = 3$$
$$Z = 0.9 \text{ km}$$

If Z is filled with sediment (density = 2.3 g/cm^3):

$$Z = 3$$

Therefore, a basin filled with water will be about 1.5 times deeper than the same basin filled with air. Also, a basin filled with sediment will be about 2.3 times deeper than the same basin filled with water, depending upon the densities used.

Isostasy will be an important factor in basin subsidence if you change the thickness or density structure of the lithospheric column. These changes can take place if you stretch the lithosphere or just the crust (the above example shows lithosphere that was stretched by 100%), remove the crust by erosion or tectonic processes, emplace dense material into the column (e.g., inject dikes, thrust ophiolites), or fill a hole in with denser material (e.g., replace water with sediment). Similarly, uplift will occur if you remove the mantle lid and replace it by relatively lighter asthenosphere, or add more buoyant crust to the column.

B. FLEXURE

Isostasy, as previously discussed, assumes local compensation as if the earth consists of a series of free-floating pistons (Fig. 2.4) and adjacent pistons are compensated at a common depth. However, the lithosphere has finite strength and so is relatively rigid. When a load is placed upon the lithosphere, the plate bends as an elastic beam (Fig. 2.4). The underlying mantle is displaced, and following Archimedes' principle, the bent plate is buoyed up by the weight of the displaced mantle. The region beneath the load is held up by the strength of the surrounding lithosphere, and the surrounding lithosphere is held down by the weight of the nearby load. The net effect is for the entire region affected by flexure to be in regional isostatic balance.

The lithosphere behaves approximately as an elastic beam of some assumed or calculated rigidity (Fig. 2.5). The more rigid the beam, the broader but shallower the basin. The less rigid the beam, the deeper but narrower the basin. Emplacing identical loads on two plates of differing rigidity will result in two basins of differing geometry but identical volume (Fig. 2.5).

C. THERMAL

Thermal effects lead to subsidence by changing the density structure of the lithosphere so that the isostatic balance is changed. The lithosphere can heat up quite quickly (e.g., via intrusions) but cools more slowly by conduction. If conduction is the primary means of cooling, the lithosphere cools first as a function of the square-root of time ($t^{1/2}$), and then after a few tens of millions of years it cools as an exponential ($e^{-\tau/t}$). As the lithosphere cools, it subsides because colder rock is more dense and less buoyant than warm rock. The total amount of time for the lithosphere to cool by conduction is about 150-200 My.

Everything else being equal, the total amount of subsidence during cooling is exactly equal to the total amount of uplift during heating. Therefore, there is no net subsidence (Fig. 2.6A). Other events must occur to create a basin by thermal processes. These processes include: erosion of uplifted areas (Fig. 2.6B), thickening of the mantle lid during cooling, or thinning of the crust.

An example of thermal effects can be described qualitatively here (Fig. 2.7) but will be dealt with in a more quantitative manner later in the course. Our example starts prior to time 1 with a lithospheric column of one-unit height composed of crust (C), mantle lid (L), and asthenosphere (A). The column has a simple geothermal gradient from the surface to the base of the lithosphere below which the temperature stays relatively fixed at about 1300°C (Fig. 2.5, top row). At this time, the basin has not yet subsided. If between time 1 and time 2 we stretch the lithosphere by some factor β, the lithosphere thickness will thin to $1/\beta$ (McKenzie, 1978). The geothermal gradient will become steeper, and the column will subside due to the isostatic effects of thinning the lithosphere and replacing dense mantle lid with slightly less dense asthenosphere (see Fig. 2.3). This subsidence is not thermal subsidence but local isostatic compensation to thinning of the lithosphere. Following time 2, the lithosphere cools and thickens (Fig. 2.8) as warm asthenosphere converts to cool lithosphere. At the end of this process, the original geothermal gradient is restored. As less dense asthenosphere converts to slightly more dense mantle lid, the column will continue subsiding until the original geothermal gradient is obtained. The rate of cooling will be exponential and so will the subsidence.

In this example (Fig. 2.7) there are two stages of subsidence. An initial phase of subsidence occurs during extension of the lithosphere. The rate and amount of this subsidence directly follows the rate and amount of extension. The second phase of thermal subsidence occurs at an exponential rate, following the cooling of the lithosphere once extension is complete. Thus, the total amount of subsidence is a function of isostasy, the net effect of thinning the crust and mantle lid, but the rate of subsidence is controlled by the thermal decay equation.

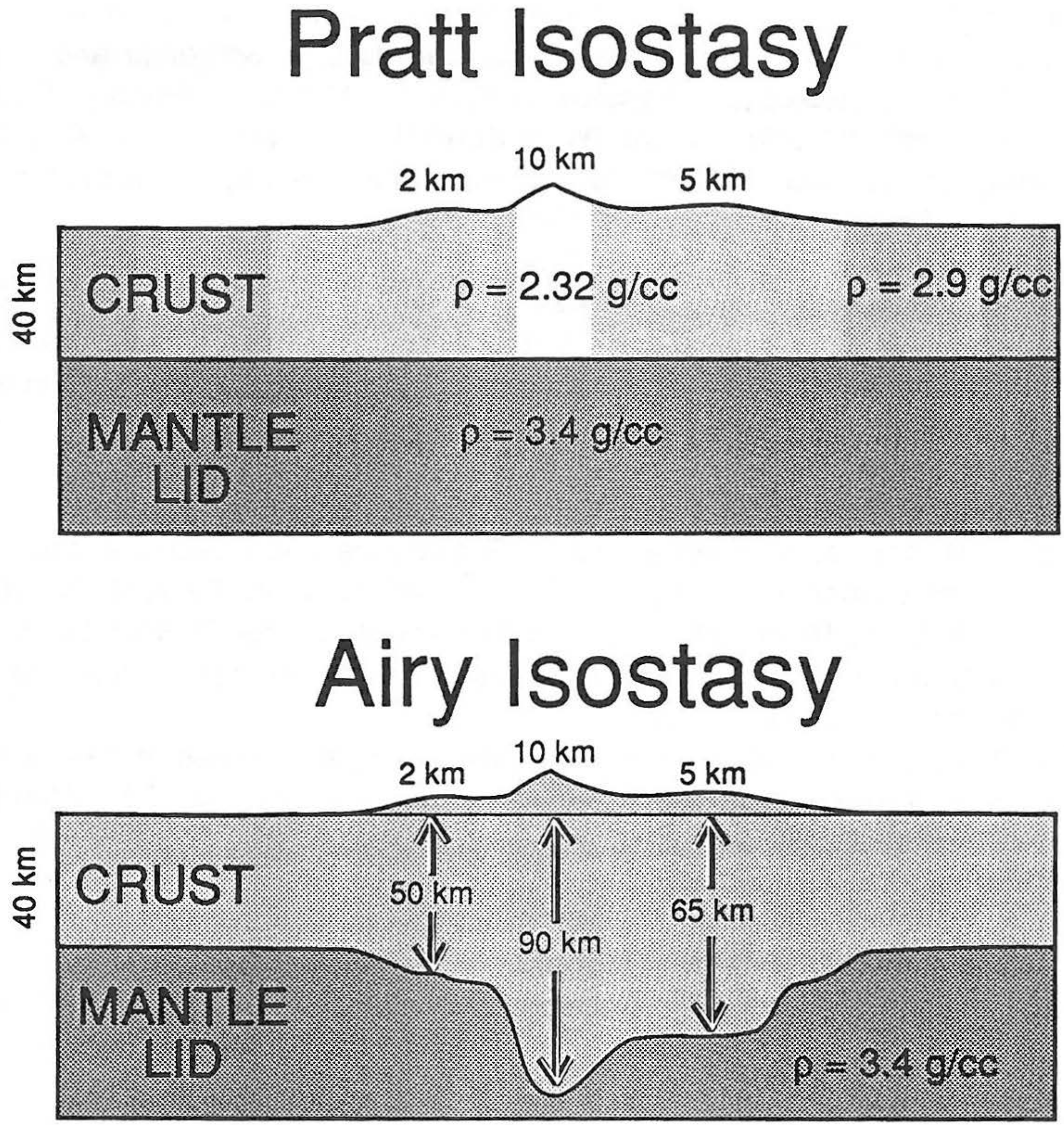

Figure 2.1 Pratt versus Airy isostatic compensation of the crust (modified from Molnar, 1986).

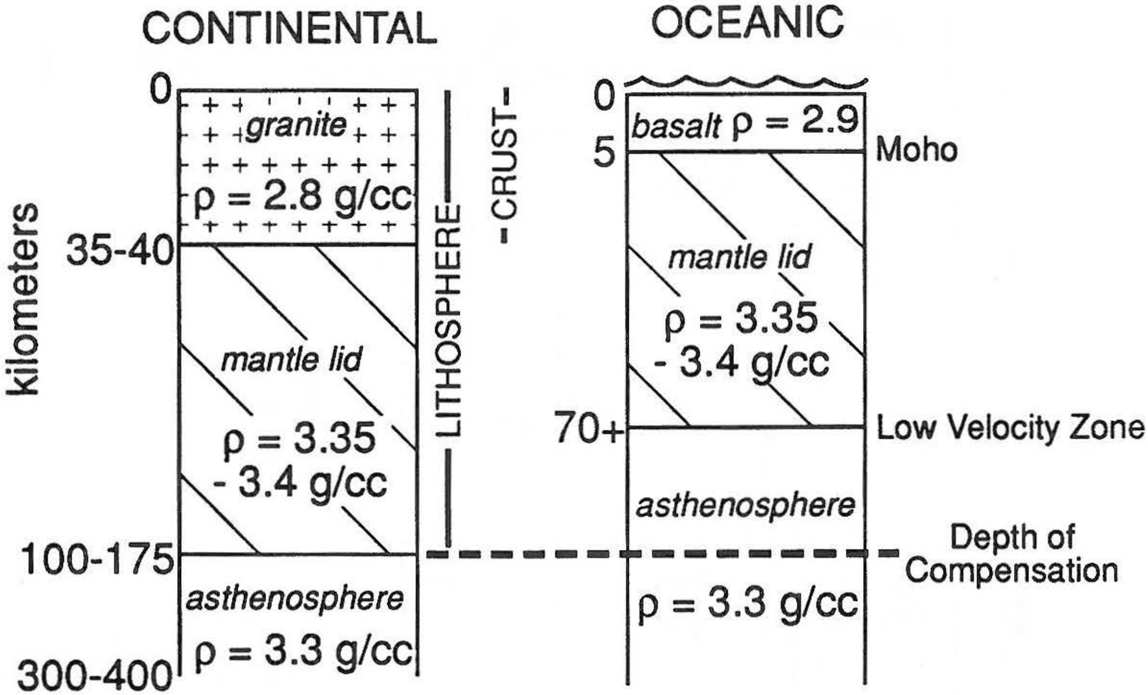

Figure 2.2 Idealized columns for continental and oceanic lithosphere.

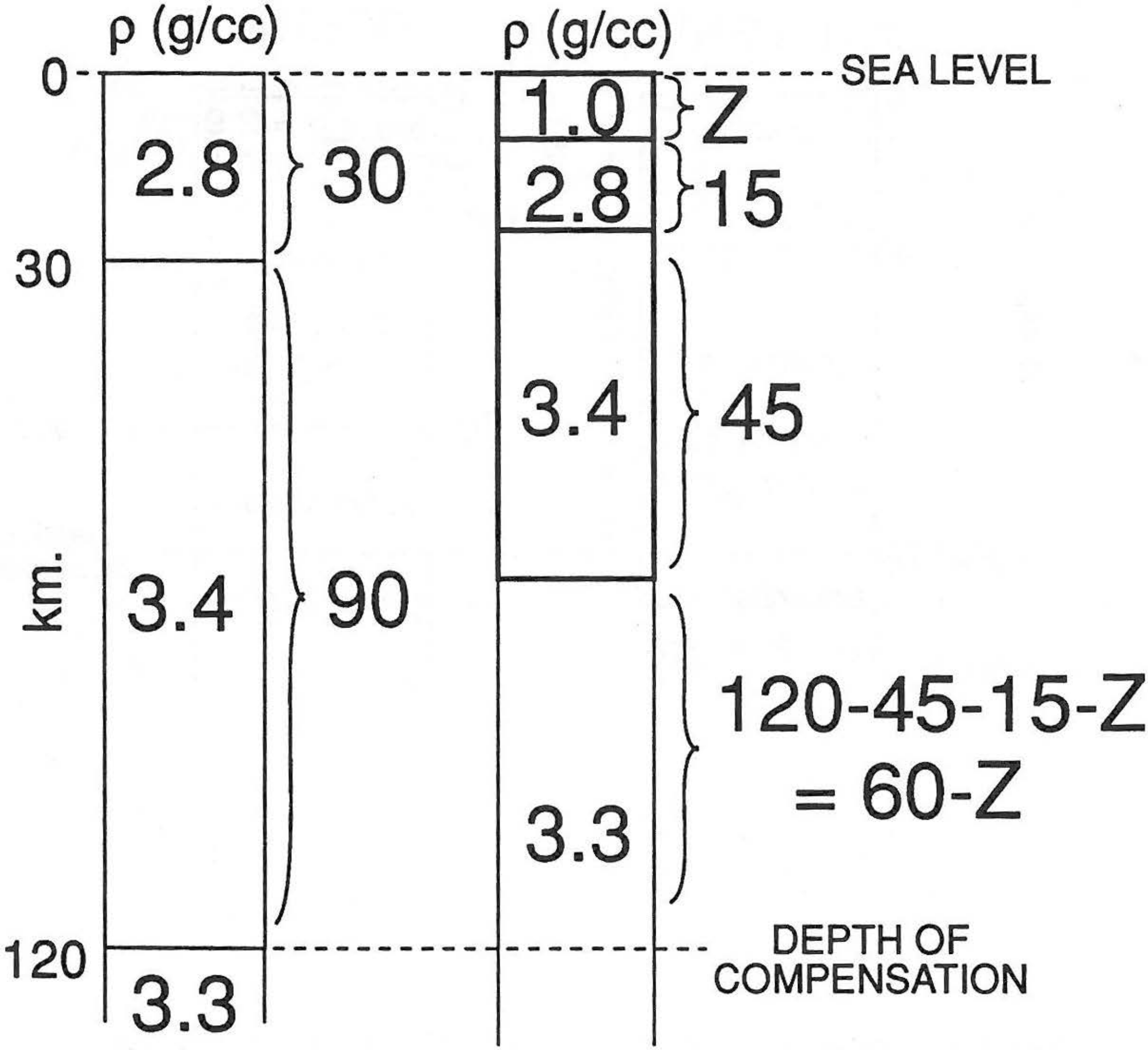

Figure 2.3 Isostatic balance of two adjacent continental blocks.

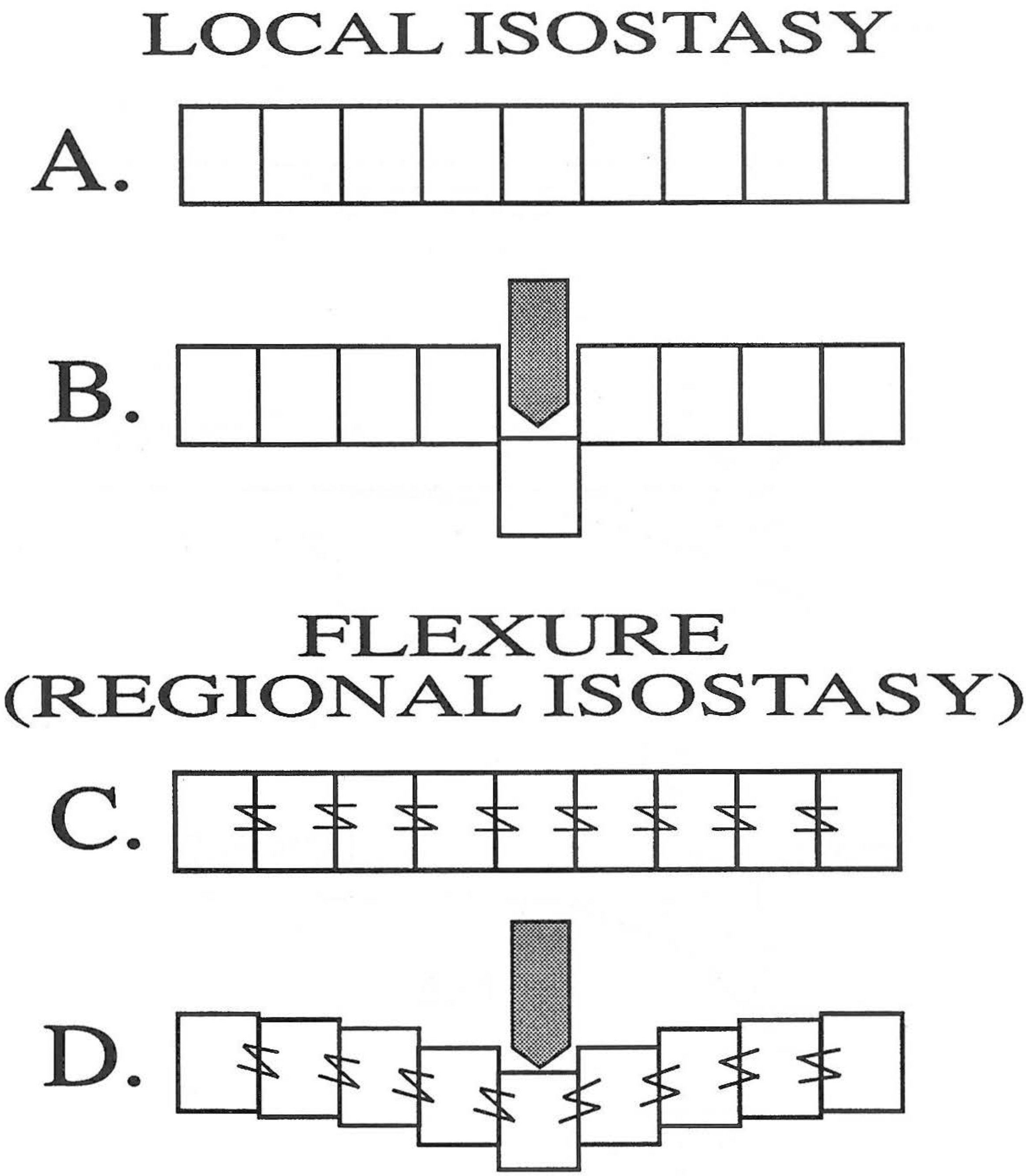

Figure 2.4 Conceptual comparison of lacal isostasy versus flexure (regional isostasy). In local isostasy (A), the lithosphere is composed of separate blocks. As a load is placed on the surface of the earth (B), only the block immediately beneath the load subsides. In reality the earth has lateral strength (C), as if the blocks are attached to each other by springs. Emplacement of a load on the surface of the earth causes subsidence (D), but is compensated over a larger area due to the rigidity of the lithosphere.

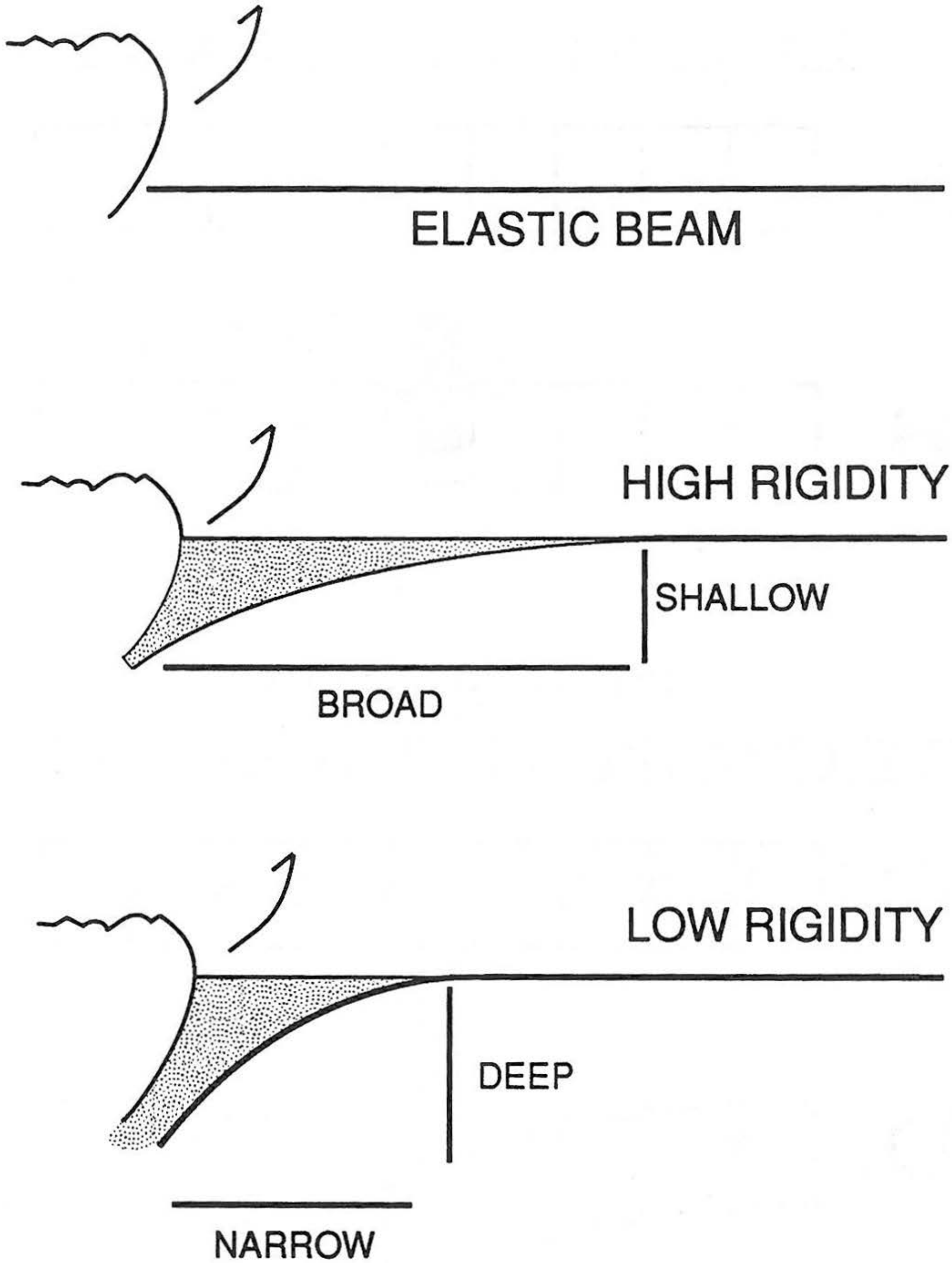

Figure 2.5 Flexural response to emplacement of tectonic loads.

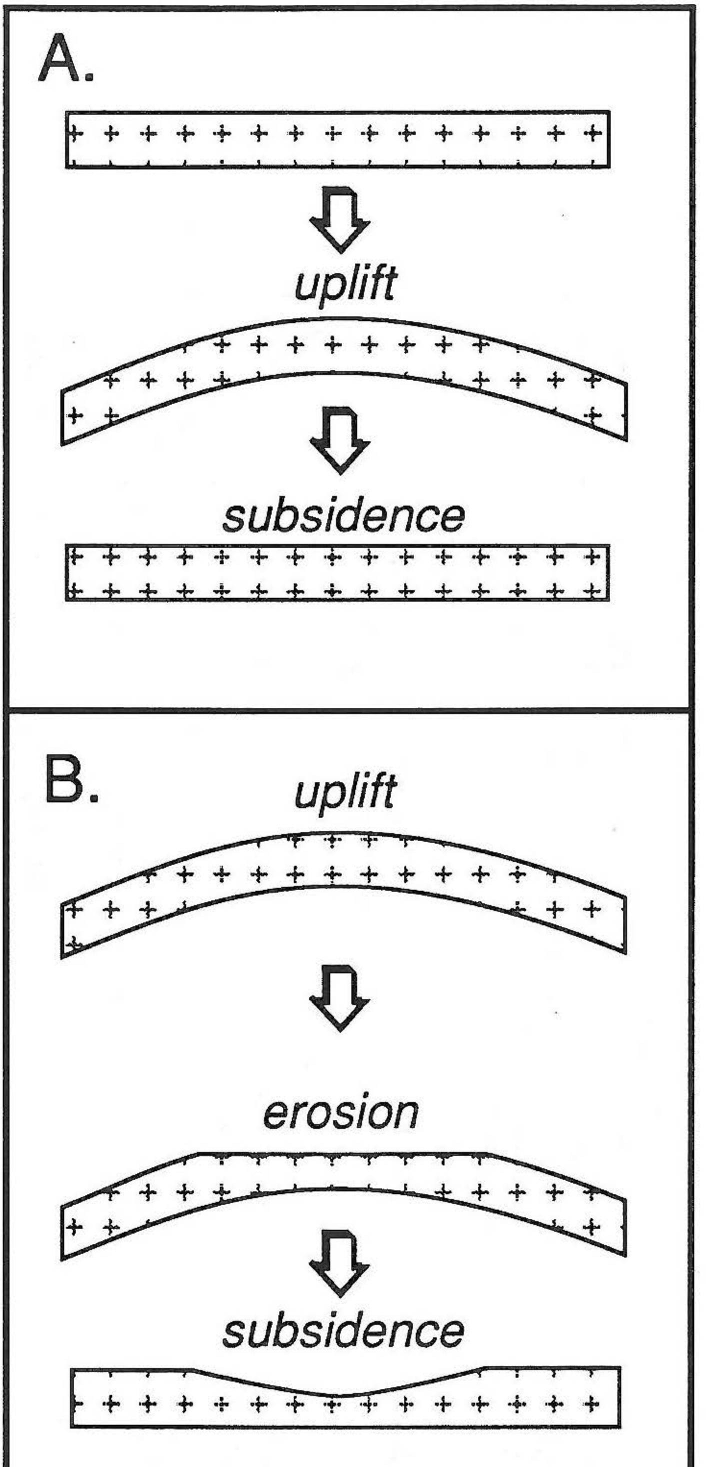

Figure 2.6 Doming associated with thermal perturbation. (A) Thermal event alone. (B) Thermal event with erosion.

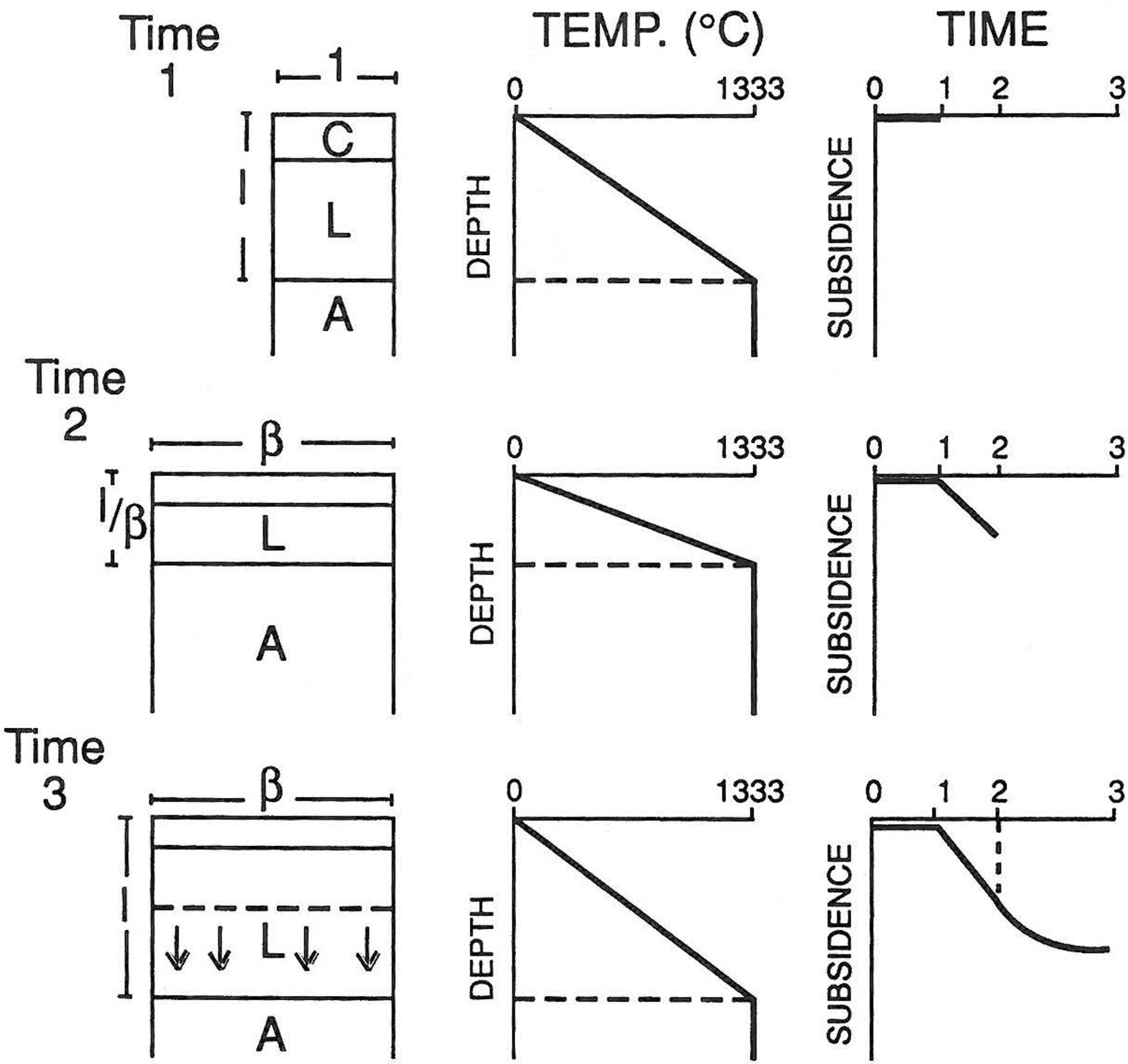

Figure 2.7 Thermal and subsidence effects of lithospheric extension. See text for explanation. Modified from McKenzie (1978).

OCEANIC LITHOSPHERE

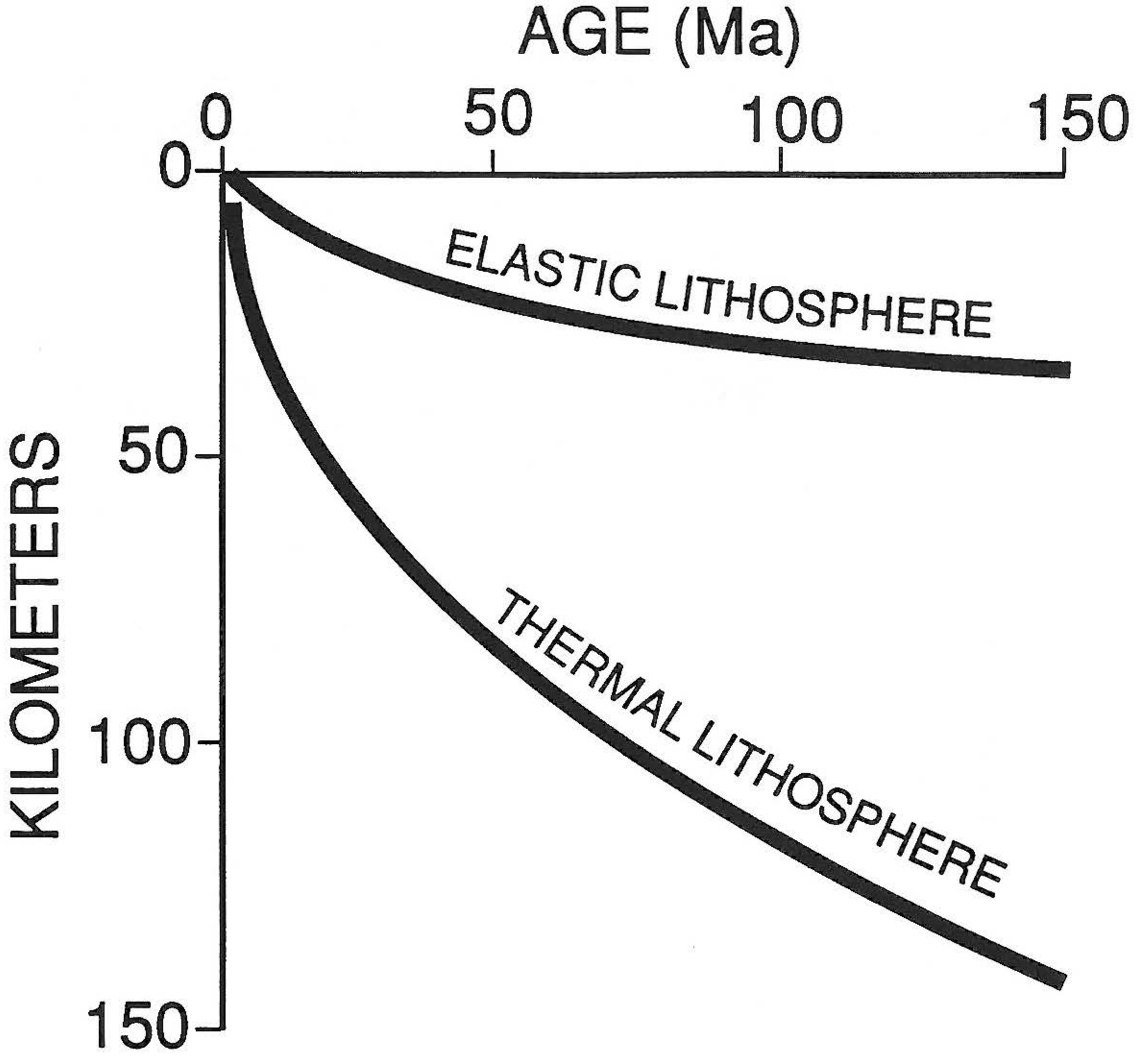

Figure 2.8 Oceanic lithosphere age versus thickness. Data from Turcotte and Schubert (1982) and Watts (1981).