

1 The tectonic agenda

A hot, dense body in a cold, sparse Universe.

We live on a dynamic planet. Earthquakes, volcanoes, floods, but mostly benign! This dynamism is a reflection of the fact that the Earth is a hot, dense body in a cold, sparse Universe. In particular, heat transfer operates to disperse the thermal energy² while self-gravitation serves to hold the mass-anomaly together. In order to understand why the Earth is the way it is, and how it evolves in time, it is necessary to understand the competition between these two physical processes. The intricate structure of the Earth, at all scales, is a direct consequence of this competition, as well as the constraints imposed by the behaviour of its constituent materials. Moreover, these processes are responsible for the great diversity and beauty of our planet that provides the basic motivation for much of the Earth Science community – *a motivation that should not be forgotten.*

1.1 Descriptions and utility

Dynamicists are concerned with changes (equivalently, motions) accompanying the passage of time in dynamical systems. The system of concern to the geodynamicist is the Earth and our geological perspective focuses our interest primarily on the *lithosphere* (on which we reside) and, less directly, the *asthenosphere*. Consequently, geodynamics is primarily concerned with the basic physical processes that modulate the time evolution of the lithosphere; with one of its principal aims being the *description of the behaviour* of the lithosphere in the modern Earth.

In order to develop an appropriate geodynamic description we need to understand what constitutes utility. To be useful, the dynamical description must reduce some aspect (optimistically, all aspects) of the behaviour of a complex system to a few general statements. In geodynamics, in which our concern is primarily with the motion of the lithosphere and the forces that drive the motion, we may distinguish between descriptions that are concerned solely with the motion or *kinematics* without regard to the forces or, alternatively, *mechanical* descriptions concerned with the interaction between forces and motions.

² An important question, to which we return to at the end of this course, concerns the geodynamic consequences of the long-term, secular changes in the thermal state of the Earth due to this dispersal of the thermal energy fluctuation.

The kinematic description is far less formidable than the mechanical description and has received considerably more attention as illustrated by *plate tectonics*. Plate tectonics attempts *nothing more* than a description of the motion of the lithosphere, and as such is purely kinematic. The fundamental tenets of the plate tectonic description are:

- The lithosphere is composed of only a few rigid *plates* that deform only at their boundaries. That is, plate motions can be described in terms of translation and rotation.
- The deforming plate boundaries are very narrow in comparison to the lateral dimensions of the individual plates.

Plate tectonics can only provide a useful description if the number of plates remains small; if large numbers of plates are needed to describe the behaviour of the lithosphere, then the description becomes sufficiently complicated to be rendered useless. Does plate tectonics provide a useful description of the behaviour of the lithosphere? Our prejudice concerning the answer to this question – *only in part* – provides the key to the way in which we present the subject matter. Let us explain! Since every seismic event represents a deformation of the lithosphere, a logical consequence of the plate tectonic description is that a plate boundary should be drawn through the focal point of every seismic event (or, earthquake). In the ocean basins seismicity is restricted to very narrow zones along the mid ocean ridges, subduction zones and transform zones, that are separated by large, essentially aseismic regions. The lack of seismicity over large regions within the ocean basins implies that, to a first approximation, they do behave as rigid, or elastic, *plates*. In contrast, seismicity in the continents is widely distributed, even in relatively inactive continents such as Australia, with very large areas of intense, distributed seismicity. The most notable regions of distributed seismicity in the modern earth are the Basin and Range Province in the western USA, the Himalaya- Tibet region in Asia and in the Aegean Sea (which is floored by thin continental crust) in Europe. In these locations, active deformation is taking place over vast areas, which are equally as large as the surrounding aseismic regions. In order to adequately account for such deformation the plate tectonic description would need to invoke hundreds of thousands of individual plates each with lateral dimensions of only a few kilometers.

Clearly, while plate tectonics may provide a useful description of the ocean basins its usefulness for many continental regions is doubtful. Indeed, an alternative description of the continents as essentially continuous ductile media (rather than elastic plates) and which therefore effectively ignores the existence of any discontinuities in the strain field such as faults and, more importantly, plate boundaries is useful for many purposes and will be the description we will emphasize here.

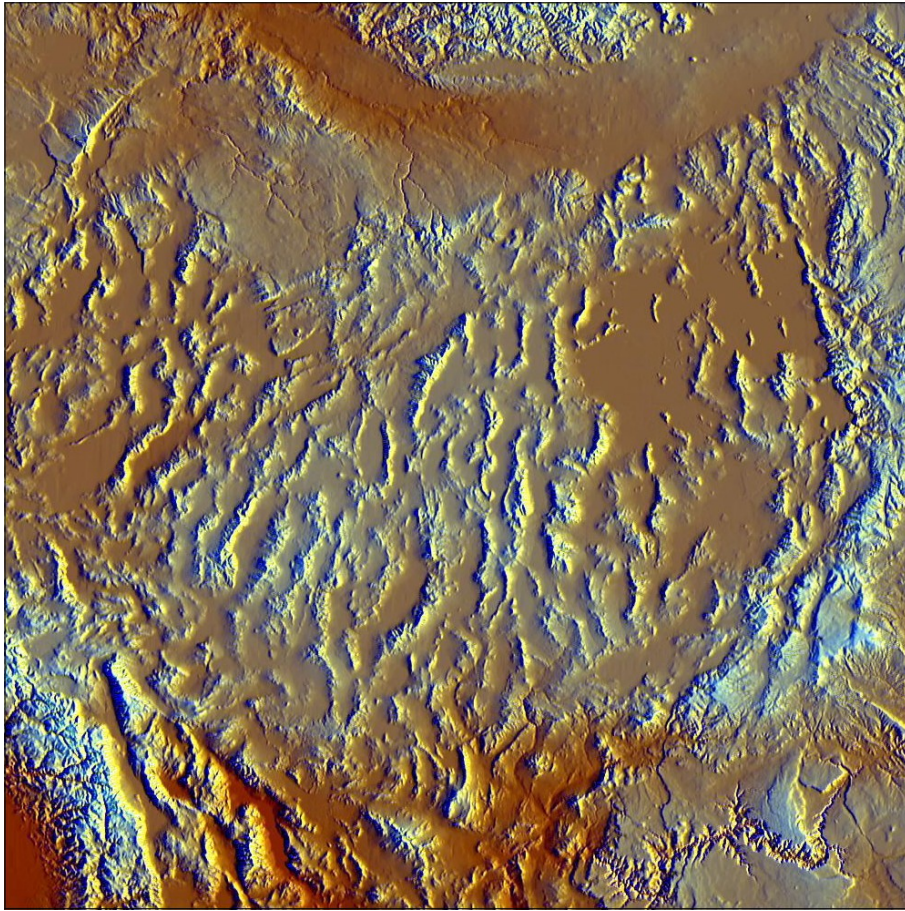


Figure 1.1 Shaded relief image of the Basin and Range province in the western USA, showing N-S trending horst and graben structure indicative of widespread distributed deformation. Derived from the GTOPO30 DEM.

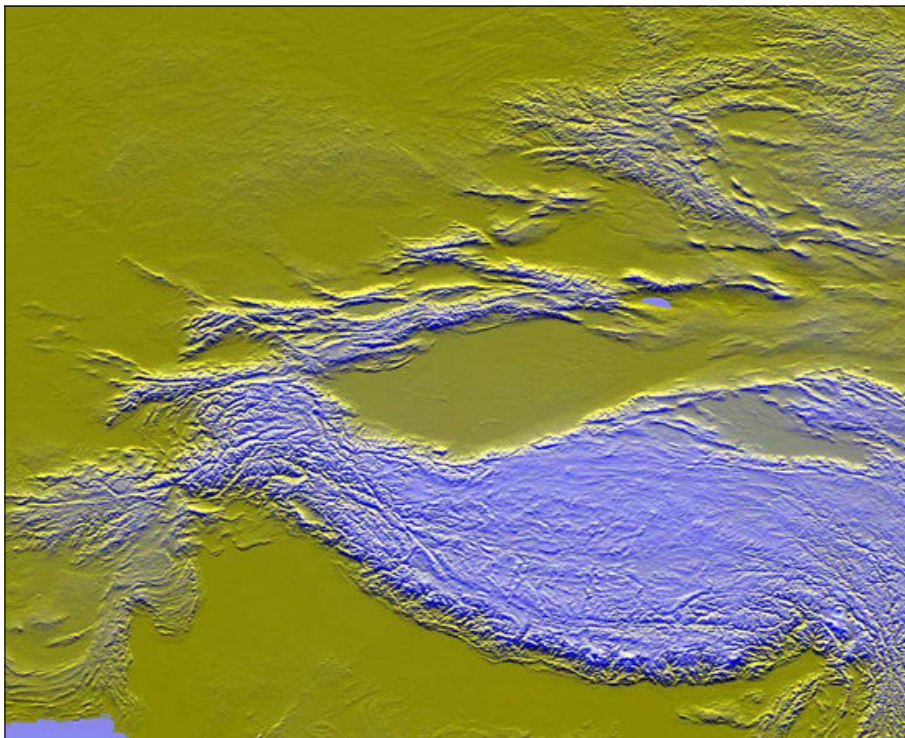


Figure 1.2 Shaded relief image of the Tibetan plateau, central Asia. Derived from

1.2 The tectonic agenda

At the very outset it is useful to establish our agenda in relation to other Earth science studies, such as structural geology, petrology, sedimentology, geomorphology and seismology. The overlap with these fields is substantial, but significant differences remain. We will be concerned primarily with those processes that give rise to the large-scale, regular (or so-called first-order) features that characterize the modern Earth. For example, we will be explicitly interested in understanding the controls on

- the average elevation of the surface of the earth,
- the length-scales of deformation in active mountain belts,
- the gross chemical composition of the continental crust, and
- the normal thermal regime in the lithosphere.

We give *due warning* that we will not generally be concerning ourselves with the small-scale, higher-order variations in topography, strain, composition, and thermal regimes that are very much the stuff of geomorphology, structural geology and petrology, respectively. For example, we will ignore such things as the detailed lithostratigraphic record of individual sedimentary basins, but we will expend considerable effort in trying to understand the controls on subsidence within basins in general. Similarly, the role of assimilation, fractionation and crystallisation that leads to the great variation of magma types that so *excite igneous petrologists* will be overlooked in favour of the general nature of the processes that lead to large-scale melting events and the way in which these processes naturally give rise to the characteristic chemical signature of the average melt product.

The *great challenge and fun* of the geological enterprise lies in deciphering the effects of the first-order processes from the higher-frequency geological *noise* that make the geological record so complex (and, let it be said, at the same time so rich). From the geodynamic point of view the distinction between the first-order processes and the high-frequency noise is readily appreciated once the significance of the lithosphere as the fundamental tectonic entity is acknowledged. This implies for first-order features a natural length scale of the order of 100 km (or greater), as dictated by the thickness of the lithosphere, and natural timescales of the order of 10-100 Ma (at least), as dictated by the thermal response time of the lithosphere.

Where from comes the noise? At least a large part of the rich and diverse geological noise is modulated by exogenic processes.³ Foreexample, whereas landscapes

³ In fact, at the $10^{-1} - 10^5$ m-scale landscapes are fractal with a dimension typically between 2.0 and 2.2 – as discussed in Mandelbrot's idiosyncratic tome *The fractal geometry of nature*.

are very regular when viewed at the $10^5 - 10^6$ m-scale (ie., at lithospheric scales), erosion and gullying have natural length-scales that produce very fragmented landscapes on the $10^1 - 10^4$ m-scale. Similarly, exogenic forcing, as for example associated with Milankovitch cycles, with natural time scales ($10^2 - 10^6$ a) that are very short compared to the thermal time constant of the lithosphere (10^7 a), influence the third- to fifth-order sequence boundaries that are so obvious in the lithostratigraphic record at the $10^{-1} - 10^2$ m-scale. It is the *rheological anisotropy*⁴ caused by this short-wavelength lithological variation which is responsible for the structural chaos of orogenic zones when viewed at the map scale, and is the detail which we seek *quite deliberately* to avoid.

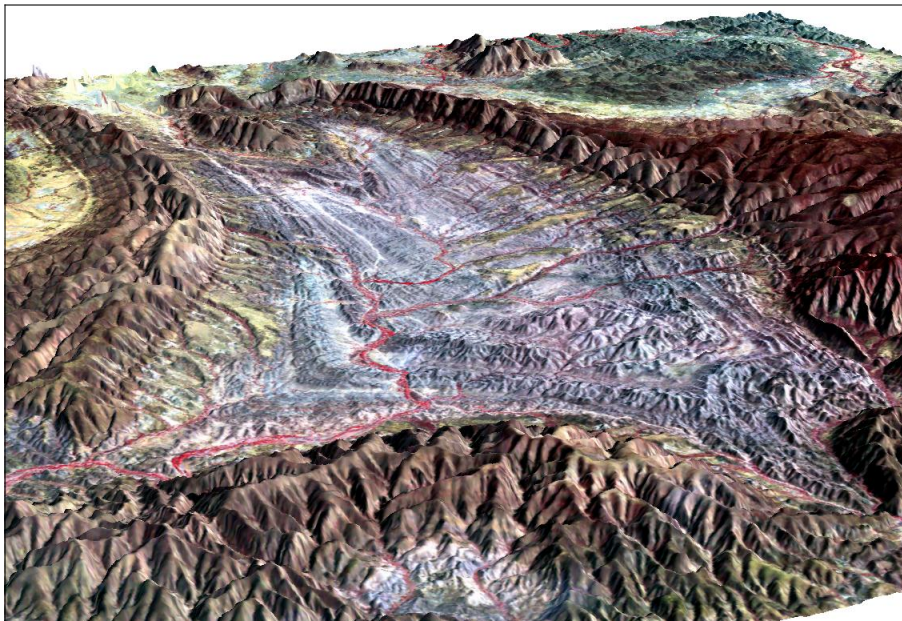


Figure 1.3 Detail of ASTER satellite imagery of the northern Flinders Ranges showing complex landform patterns so characteristic of our planet.

1.3 What is the lithosphere?

As we have emphasized one of our primary concerns is to provide an insight into the nature and behaviour of lithosphere and, particularly, the processes that contribute to its formation. To begin with we need some common idea of what constitutes the lithosphere. We provide two working definitions (Fig. 1.4):

⁴ See Chapter 20 (specifically figure 20.10, p. 399) in Brown, Hawkesworth and Wilson for a discussion of sequence stratigraphy.

- The *thermal lithosphere* is that part of the earth where the dominant mode of heat transfer is conduction (Fig. 1.4a).⁵
- The *kinematic (or mechanical) lithosphere* is that part of the earth where there are no substantial vertical gradients in the horizontal component of the velocity field (Fig. 1.4b). Of course, large horizontal gradients in the horizontal component of the lithospheric velocity field occur because rotation of the lithosphere around vertical poles may occur without appreciable internal deformation.

Both definitions allow the distinction of the lithosphere from the underlying asthenosphere, where heat transfer is primarily by convection, and which is, as a consequence, characterized by large vertical gradients in the horizontal component of the velocity field.

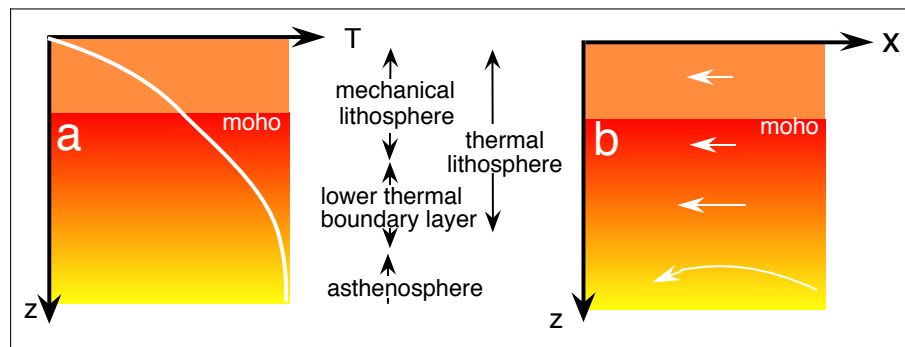


Figure 1.4 The outer part of the earth can be divided into two distinct zones, the kinematic or mechanical lithosphere (heavy stipple) and the asthenosphere (light stipple) separated by a boundary layer (intermediate stipple) which shows transitional properties. In the lithosphere heat is transported by conduction and thus the geotherm, shown in Fig. 1.4a, is a strong function of depth, whereas in the underlying asthenosphere heat is transferred by convection and the geotherm is an adiabat. In the lithosphere there are no significant vertical gradients in the horizontal component of the velocity field (represented by the arrows Fig. 1.4b). Formally the thermal boundary layer is included with the mechanical lithosphere as part of the thermal lithosphere. The Moho, or crust-mantle boundary, lies within the mechanical lithosphere as indicated by the dashed line.

The lithosphere comprises the crust as well as a significant part of the upper mantle, down to a depth of 100 - 150 km. The exact thickness of the lithosphere is not easily determined by conventional geophysical methods such as seismology since the lower boundary of the lithosphere, the lithosphere - asthenosphere boundary, is not

⁵ This definition of the kinematic or mechanical lithosphere admits the precise form $\frac{\partial v_{x,y}}{\partial z} = 0$ where $v_{x,y}$ is the horizontal component of the velocity field, and z is depth.

defined by a prominent compositional discontinuity. Rather it is defined by changes in the rheology of the mantle-forming rock, peridotite.⁶ Since the composition of the mantle is essentially constant throughout, mantle density, ρ_m , is dependent primarily on the temperature (through the volumetric coefficient of thermal expansion, α) and the confining pressure (through the coefficient of compressibility, β). An increase in the temperature causes a decrease in density, while an increase in pressure causes an increase in density. At a constant depth and hence at constant pressure small lateral changes in temperature result in variations in the density. The strength of all materials, including peridotite, is a function of temperature; at asthenospheric temperatures (approximately 1300°C) peridotite (for peridotite α is about $10^{-5} \text{ }^\circ\text{K}^{-1}$) is sufficiently weak that it will convect in response to stresses resulting from the density variations associated with small lateral temperature gradients whereas in the lithosphere peridotite is sufficiently strong that it does not undergo convection (although it may subduct as an essentially rigid slab). Since the rheological properties of peridotite are likely to be a continuous function of temperature in the range appropriate to the base of the lithosphere there must be a transition zone separating the lithosphere and asthenosphere. This zone is termed the *lower thermal boundary layer* and is formally included in the thermal lithosphere, but excluded from the mechanical lithosphere (Figure 1.1).

It is important to realise that these definitions make no direct correspondence between the lithosphere and the compositional structure of the earth. The compositional structure of the earth is constrained in a number of ways, most notably by the seismic velocity structure determined by the way in which seismic energy is radiated following large earthquakes. This approach leads to the distinction of three compositionally distinct shells within the earth bounded by prominent discontinuities in the seismic velocity structure, namely *the crust, the mantle and the core*. The crust is typically about 6-7 km thick beneath the oceans and 30-50 km thick in the continents with maximum thicknesses of about 70 km beneath the great mountain belts. The detailed velocity structure of the continental crust is complex reflecting a complex compositional structure and history. In comparison the velocity structure of the mantle is more regular with weak discontinuities at about 450 and 650 km, consistent with phase transitions in material with the composition of peridotite. The 650 km discontinuity, corresponding to the maximum pressure stability limit of the silicate spinel structure, is commonly taken as the boundary between the upper and lower mantle. A low seismic velocity region is sometimes present in the upper mantle at depths between 100-200 km. In this scheme, the lower boundary of the lithosphere occurs within the upper mantle probably at depths appropriate to the

⁶ The coefficient of thermal expansion, α , and the coefficient of compressibility, β , are defined as: $\alpha = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P, \beta = -\frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T$ where V is volume.

low velocity zone at around 100-200 km. However, it should be noted that the low velocity zone is not universally present and therefore cannot be used to define the base of the lithosphere.

1.4 About these notes

Already we have suggested that we may need two descriptions to encompass the dynamics of the outer part of the earth; one for the oceans and one for the continents. While this is undoubtedly a simplification, it does suggest a natural subdivision of the subject. In Part 2 we discuss the oceans, about which we have a deeper understanding than the continents (Part 3). Our main aim will be to develop a description of the mechanics of the lithosphere, and so we will be concerned with the nature of the forces driving the motion of the lithosphere (which are reviewed in part 4). To do this we will need to incorporate constraints on the mechanism of formation of the lithosphere which requires an understanding of the geochemical relationships between the crust and mantle as well as lithosphere and asthenosphere. Before we do so it is important to review some fundamental principles which are essential to understanding the dynamics of both the oceanic and the continental lithosphere (Part 1).

A vexing question in the preparation of the notes concerns the level of mathematics that accompnies the text. Many of the important physical processes in tectonics admit very concise mathematical definitions, and therefore mathematics provides a natural way to describe the processes. However, we will try to describe the basic physics and have only included the most important of the mathematical definitions in the main body of the text. Peripheral mathematical definitions are included either as marginal notes or in the appendices. For those of you who struggle with the language of mathematics we hope that a qualitative appreciation of the nature of the physical process will provide a new avenue to understanding the mathematical description; certainly this is how we have learned to tackle the mathematics.