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Haakon Fossen
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Chapter 1

Structural geology and structural analysis

Structural geology is about folds, faults and other deformation structures in the lithosphere – how they appear and how and why they formed. Ranging from features hundreds of kilometers long down to microscopic details, structures occur in many different settings and have experienced exciting changes in stress and strain – information that can be ours if we learn how to read the code. The story told by structures in rocks is beautiful, fascinating and interesting, and it can also be very useful to society. Exploration, mapping and exploitation of resources such as slate and schist (building stone), ores, groundwater, and oil and gas depend on structural geologists who understand what they observe so that they can present reasonable interpretations and predictions. In this first chapter we will set the stage for the following chapters by defining and discussing fundamental concepts and some of the different data sets and methods that structural geology and structural analysis rely on. Depending on your background in structural geology, it may be useful to return to this chapter after going through other chapters in this book.

1.1 Approaching structural geology

For us to understand structural geology we need to observe deformed rocks and find an explanation for how and why they ended up in their present state. Our main methods are field observations, laboratory experiments and numerical modeling. All of these methods have advantages and challenges. Field examples portray the final results of deformation processes, while the actual deformation history may be unknown. Progressive deformation can be observed in laboratory experiments, but how representative are such hour- or perhaps week-long observations of geologic histories that span thousands to millions of years in nature? Numerical modeling, where we use computers and mathematical equations to model deformation, is hampered by simplifications necessary for the models to be runable with today's codes and computers. However, by combining different approaches we are able to obtain realistic models of how structures form and what they mean. Field studies will always be important, as any modeling, numerical or physical, must be based directly or indirectly on accurate and objective field observations and descriptions. Objectivity during fieldwork is both important and challenging, and field studies in one form or another are the main reason why many geologists chose to become geoscientists!

1.2 Structural geology and tectonics

The word **structure** is derived from the Latin word *struere*, to build, and we could say:

A geologic structure is a geometric configuration of rocks, and structural geology deals with the geometry, distribution and formation of structures.

It should be added that **structural geology** only deals with structures created during rock deformation, not with primary structures formed by sedimentary or magmatic processes. However, deformation structures can form through the modification of primary structures, such as folding of bedding in a sedimentary rock.

The closely related word **tectonics** comes from the Greek word *tektos*, and both structural geology and tectonics relate to the building and resulting structure of the Earth's lithosphere, and to the motions that change and shape the outer parts of our planet. We could say that tectonics is more closely connected to the underlying processes that cause structures to form:

Tectonics is connected with external and often regional processes that generate a characteristic set of structures in an area or a region.

By external we mean external to the rock volume that we study. External processes or causes are in many cases plate motions, but can also be such things as forceful intrusion of magma, gravity-driven salt or mud diapirs, flowing glaciers and meteor impacts. Each of these "causes" can create characteristic structures that define a **tectonic style**, and the related tectonics can be given special names. **Plate tectonics** is the large-scale part of tectonics that directly involves the movement and interaction of lithospheric plates. Within the realm of plate tectonics, expressions such as subduction tectonics, collision tectonics and rift tectonics are applied for more specific purposes.

Glaciotectonics is the deformation of sediments and bedrock (generally sedimentary rocks) at the toe of an advancing ice sheet. In this case it is the pushing of the ice that creates the deformation, particularly where the base of the glacier is cold (frozen to the substrate).

Salt tectonics deals with the deformation caused by the (mostly) vertical movement of salt through its overburden (see Chapter 19). Both glaciotectonics and salt tectonics are primarily driven by gravity, although salt tectonics can also be closely related to plate tectonics. For example, tectonic strain can create fractures that enable salt to gravitationally penetrate its cover, as discussed in Chapter 19. The term **gravity tectonics** is generally restricted to the downward sliding of large portions of rocks and sediments, notably of continental margin deposits resting on weak salt or overpressured shale layers. Raft tectonics is a type of gravity tectonics occurring in such environments, as mentioned in Chapter 19. Smaller landslides and their structures are also considered examples of gravity tectonics by some, while others regard such surficial processes as **non-tectonic**. Typical non-tectonic deformation is the simple compaction of sediments and sedimentary rocks due to loading by younger sedimentary strata.

Neotectonics is concerned with recent and ongoing crustal motions and the contemporaneous stress field. Neotectonic structures are the surface expression of faults in the form of fault scarps, and important data sets stem from seismic information from earthquakes (such as focal mechanisms, Box 9.1) and changes in elevation of regions detected by repeated satellite measurements.

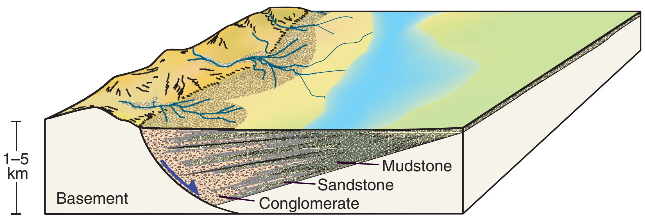

Figure 1.1 Illustration of the close relationship between sedimentary facies, layer thickness variations and syndepositional faulting (growth fault) along the margin of a sedimentary basin.

At smaller scales, **microtectonics** describes microscale deformation and deformation structures visible under the microscope.

Structural geology typically pertains to the observation, description and interpretation of structures that can be mapped in the field. How do we recognize deformation or **strain** in a rock? "Strained" means that something primary or preexisting has been geometrically modified, be it cross stratification, pebble shape, a primary magmatic texture or a preexisting deformation structure. Hence strain can be defined as a change in length or shape, and recognizing strain and deformation structures actually requires solid knowledge of undeformed rocks and their primary structures.

Being able to recognize tectonic deformation depends on our knowledge of primary structures.

The resulting deformation structure also depends on the initial material and its texture and structure. Deforming sandstone, clay, limestone or granite results in significantly different structures because they respond differently. Furthermore, there is often a close relationship between tectonics and the formation of rocks and their primary structures. Sedimentologists experience this as they study variations in thickness and grain size in the hanging wall (down-thrown side) of syndepositional faults. This is illustrated in Figure 1.1, where the gradual rotation and subsidence of the down-faulted block gives space for thicker strata near the fault than farther away, resulting in wedge-shaped strata and progressively steeper dips down section. There is also a facies variation, with the coarsest-grained deposits forming near the fault, which can be attributed to the fault-induced topography seen in Figure 1.1.

Another close relationship between tectonics and rock forming processes is shown in Figure 1.2, where forceful rising and perhaps inflating of magma deforms the outer and oldest part of the pluton and its country rock.

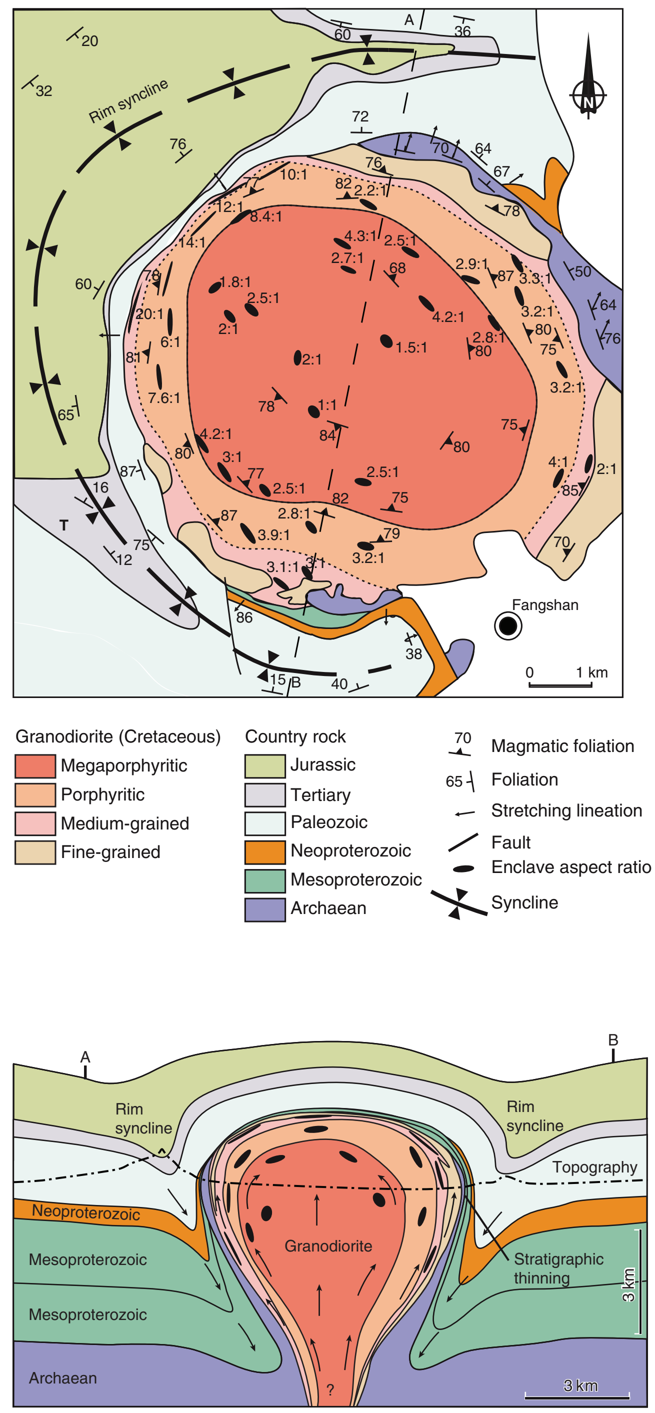

Figure 1.2 Structural geology can be linked to processes and mechanisms other than plate stresses. This map and profile from a granodioritic pluton southwest of Beijing, China, portray close connection between forceful intrusion of magma, strain and folds in the country rock. Black ellipses indicate strain, as discussed in Chapters 2 and 3. The strain (deformation) pattern within and around the pluton can be explained in terms of diapirism, where the intrusion ascends and squeezes and shears its outer part and the surrounding country rock to create space. Based on He *et al.* (2009).

Forceful intrusion of magma into the crust is characterized by deformation near the margin of the pluton, manifested by folding and shearing of the layers in Figure 1.2. Ellipses in this figure illustrate the shape of enclaves (inclusions), and it is clear that they become more and more elongated as we approach the margin of the pluton. Hence, the outer part of the pluton has been flattened during a forceful intrusion history.

Metamorphic growth of minerals before, during, and after deformation may also provide important information about the pressure–temperature conditions during deformation, and may contain textures and structures reflecting kinematics and deformation history. Hence, sedimentary, magmatic and metamorphic processes may all be closely associated with the structural geology of a locality or region.

These examples relate to strain, but structural geologists, especially those dealing with brittle structures of the upper crust, are also concerned with **stress**. Stress is a somewhat diffuse and abstract concept to most of us, since it is invisible. Nevertheless, there will be no strain without a stress field that exceeds the rock's resistance against deformation. We can create a stress by applying a force on a surface, but at a point in the lithosphere stress is felt from all directions, and a full description of such a state of stress considers stress from all directions and is therefore three-dimensional. There is always a relationship between stress and strain, and while it may be easy to establish from controlled laboratory experiments it may be difficult to extract from naturally formed deformation structures.

Structural geology covers deformation structures formed at or near the Earth's surface, in the cool, upper part of the crust where rocks have a tendency to fracture, in the hotter, lower crust where the deformation tends to be ductile, and in the underlying mantle. It embraces structures at the scale of hundreds of kilometers down to micro- or atomic-scale structures, structures that form almost instantaneously, and structures that form over tens of millions of years.

A large number of subdisciplines, approaches and methods therefore exist within the field of structural geology. The oil exploration geologist may be considering trap-forming structures formed during rifting or salt tectonics, while the production geologist worries about subseismic sealing faults (faults that stop fluid flow in porous reservoirs; Section 8.7). The engineering geologist may consider fracture orientations and densities in relation to a tunnel project, while the university professor uses structural mapping, physical modeling or computer modeling to understand mountain-building processes. The methods and approaches are many, but they serve to understand the structural or tectonic development of a region or to predict the structural pattern in an area. In most cases structural geology is founded on data and observations that must be analyzed and interpreted. Structural analysis is therefore an important part of the field of structural geology.

Structural data are analyzed in ways that lead to a tectonic model for an area. By **tectonic model** we mean a model that explains the structural observations and puts them into context with respect to a larger-scale process, such as rifting or salt movements. For example, if we map out a series of normal faults indicating E–W extension in an orogenic belt, we have to look for a model that can explain this extension. This could be a rift model, or it could be extensional collapse during the orogeny, or gravity-driven collapse after the orogeny. Age relations between structures and additional information (radiometric dating, evidence for magmatism, relative age relations and more) would be important to select a model that best fits the data. It may be that several models can explain a given data set, and we should always look for and critically evaluate alternative models. In general, a simple model is more attractive than a complicated one.

1.3 Structural data sets

Planet Earth represents an incredibly complex physical system, and the structures that result from natural deformation reflect this fact through their multitude of expressions and histories. There is thus a need to simplify and identify the one or few most important factors that describe or lead to the recognition of deformation structures that can be seen or mapped in naturally deformed rocks. **Field observations** of deformed rocks and their structures represent the most direct and important source of information on how rocks deform, and objective observations and careful descriptions of naturally deformed rocks are the key to understanding natural deformation. Indirect observations of geologic structures by means of various **remote sensing methods**, including satellite data and seismic surveying, are becoming increasingly important in our mapping and description of structures and tectonic deformation. **Experiments** performed in the laboratory give us valuable knowledge of how various physical conditions, including stress field, boundary condition, temperature or the physical properties of the deforming material, relate to deformation. **Numerical models**, where rock deformation is simulated on a computer, are also useful as they allow us to control the various parameters and properties that influence deformation.

Experiments and numerical models not only help us understand how external and internal physical conditions control or predict the deformation structures that form, but also give information on how deformation structures evolve, i.e. they provide insights into the deformation history. In contrast, naturally deformed rocks represent end-results of natural deformation histories, and the history may be difficult to read out of the rocks themselves. Numerical and experimental models allow one to control rock properties and boundary conditions and explore their effect on deformation and deformation history. Nevertheless, any deformed rock contains some information about the history of deformation. The challenge is to know what to look for and to interpret this information. Numerical and experimental work aids in completing this task, together with objective and accurate field observations.

Numerical, experimental and remotely acquired data sets are important, but should always be based on field observations.

1.4 Field data

It is hard to overemphasize the importance of traditional field observations of deformed rocks and their structures. Rocks contain more information than we will ever be able to extract from them, and the success of any physical or numerical model relies on the accuracy of observation of rock structures in the field. Direct contact with rocks and structures that have not been filtered or interpreted by people or computers is invaluable.

Unfortunately, our ability to make objective observations is limited. What we have learned and seen in the past strongly influences our visual impressions of deformed rocks. Any student of deformed rocks should therefore train himself or herself to be objective. Only then can we expect to discover the unexpected and make new interpretations that may contribute to our understanding of the structural development of a region and to the field of structural geology in general. Many structures are overlooked until the day that someone points out their existence and meaning, upon which they all of a sudden appear "everywhere". Shear bands in strongly deformed ductile rocks (mylonites) are one such example (Figure 15.25). They were either overlooked or considered as cleavage until the late 1970s, when they were properly described and interpreted. Since then, they have been described from almost every major shear zone or mylonite zone in the world.

Traditional fieldwork involves the use of simple tools such as a hammer, measuring device, topomaps, a hand lens and a compass, and the data collected are mainly structural orientations and samples for thin section studies. This type of data collection is still important, and is aided by modern global positioning system (GPS) units and high-resolution aerial and satellite photos. More advanced and detailed work may involve the use of a portable laser-scanning unit, where pulses of laser light strike the surface of the Earth and the time of return is recorded. This information can be used to build a detailed topographic or geometrical model of the outcrop, onto which one or more high-resolution field photographs can be draped. An example of such a model is shown in Figure 1.3, although the advantage of virtually moving around in the model cannot be demonstrated by a flat picture. Geologic observations such as the orientation of layering or fold axes can then be made on a computer.

In many cases, the most important way of recording field data is by use of careful field sketches, aided by photographs, orientation measurements and other measurements that can be related to the sketch. Sketching also forces the field geologist to observe features and details that may otherwise be overlooked. At the same time, sketches can be made so as to emphasize relevant information and neglect irrelevant details. Field sketching is, largely, a matter of practice.

1.5 Remote sensing and geodesy

Satellite images, such as those shown in Figure 1.4a, c, are now available at increasingly high resolutions and are a valuable tool for the mapping of map-scale structures. An increasing amount of such data is available on the World Wide Web, and may be combined with digital elevation data to create three-dimensional models. Orthorectified **aerial photos** (orthophotos) may give more or other details (Figure 1.4b), with resolutions down to a few tens of centimeters in some cases. Both ductile structures, such as folds and foliations, and brittle faults and fractures are mappable from satellite images and aerial photos.

In the field of neotectonics, **InSAR** (Interferometric Synthetic Aperture Radar) is a useful remote sensing technique that uses radar satellite images. Beams of radar waves are constantly sent toward the Earth, and an image is generated based on the returned information. The intensity of the reflected information reflects the composition of the ground, but the phase of the wave as it hits and becomes reflected is also recorded. Comparing phases enables us to monitor millimeter-scale changes in elevation and geometry of the surface, which may reflect active tectonic

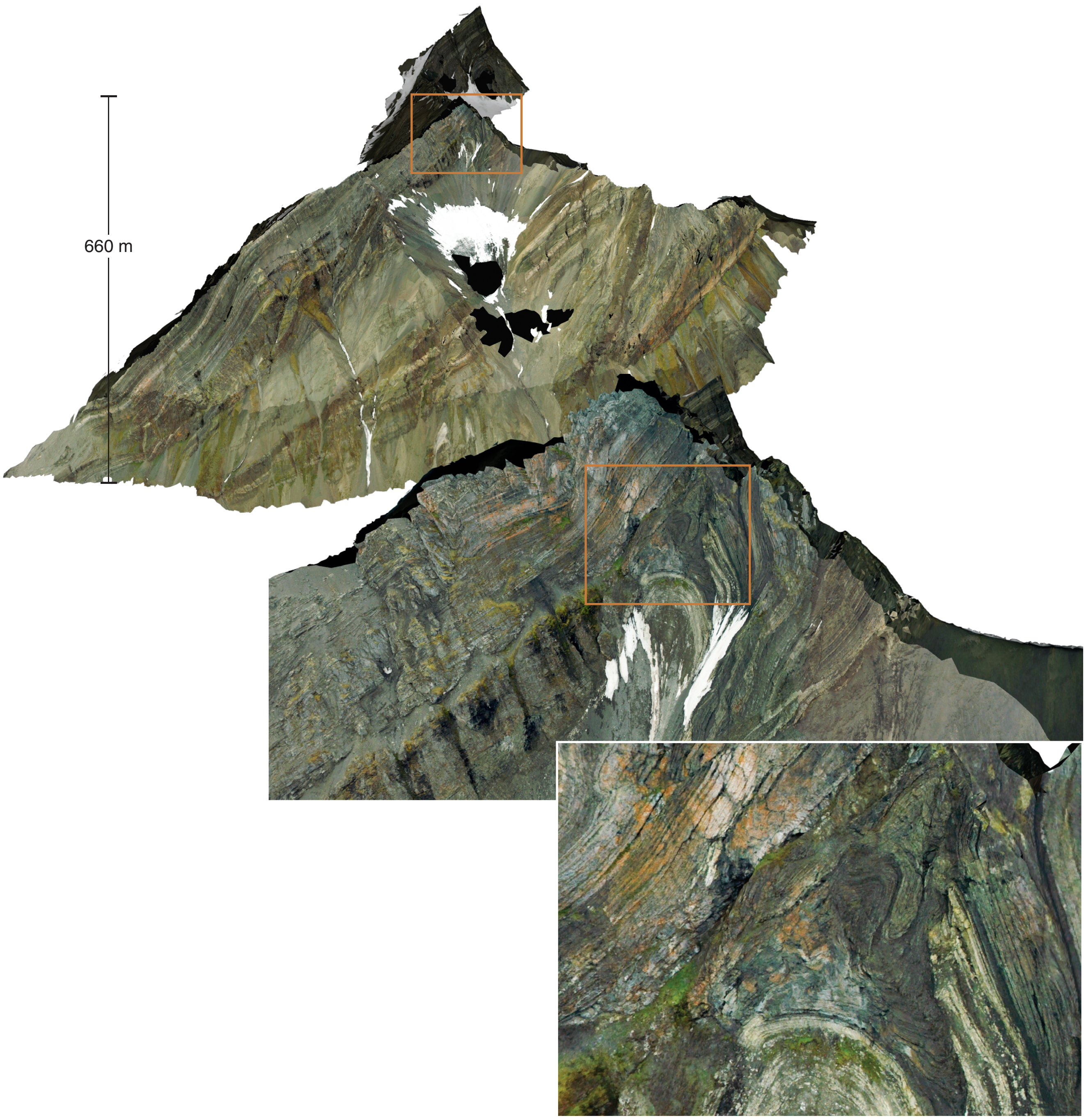

Figure 1.3 Mediumfjellet, Svalbard, based on LIDAR (LIght Detection And Ranging) data (laser scanning from helicopter) and photos. This type of model, which actually is three dimensional, allows for geometric analysis on a computer and provides access to otherwise unreachable exposures. The lower figures are more detailed views. Modeling by Simon Buckley.

movements related to earthquakes. In addition, accurate digital elevation models (see next section) and topographic maps can be constructed from this type of data.

GPS data in general are an important source of data that can be retrieved from GPS satellites to measure plate movements (Figure 1.5). Such data can also be collected on the ground by means of stationary GPS units with down to millimeter-scale accuracy.

1.6 DEM, GIS and Google Earth

Conventional paper maps are still useful for many field mapping purposes, but rugged laptops, tablets and hand-held devices now allow for direct digitizing of structural features on digital maps and images and are becoming more and more important. Field data in digital form can be combined with elevation data and other data by

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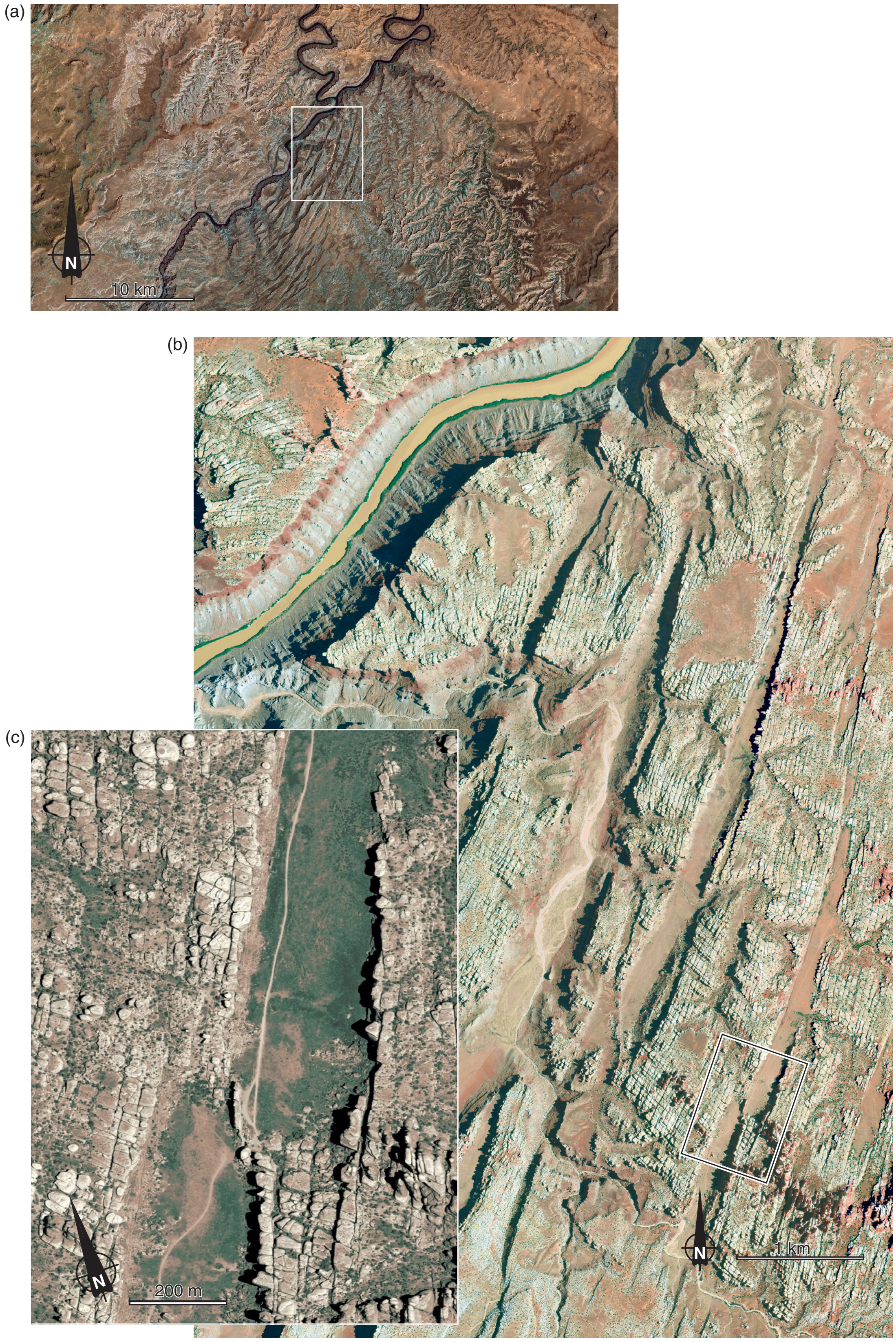


Figure 1.4 (a) Satellite image of the Canyonlands National Park area, Utah. The image reveals graben systems on the east side of the Colorado River. An orthophoto (b) reveals that the grabens run parallel to fractures, and a high-resolution satellite image (c) shows an example of a graben stepover structure. *Source*: Utah AGRC.

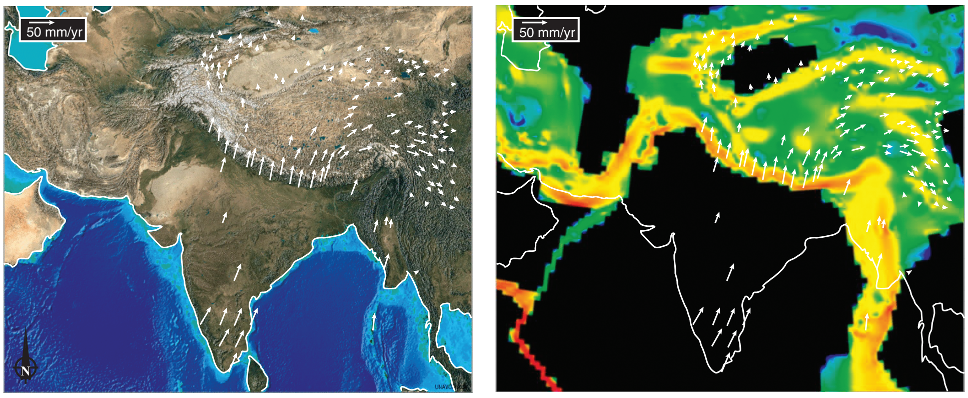


Figure 1.5 Use of GPS data from stationary GPS stations worldwide over time can be used to map relative plate motions and strain rates. (Left) White arrows (velocity vectors) indicating motions relative to Europe. The vectors clearly show how India is moving into Eurasia, causing deformation in the Himalaya–Tibetan Plateau region. (Right) Strain rate map based on GPS data. Calculated strain rates are generally less than 3×10^{-6} y^{-1} or 10^{-13} s^{-1}. Warm colors indicate high strain rates. Similar use of GPS data can be applied to much smaller areas where differential movements occur, for example across fault zones. From the project The Global Strain Rate Map (http://jules.unavco.org). See Kreemer *et al.* (2003) for more information.

means of a Geographical Information System (GIS). By means of GIS we can combine field observations, various geologic maps, aerial photos, satellite images, gravity data, magnetic data, typically together with a digital elevation model, and perform a variety of mathematical and statistical calculations. A **digital elevation model (DEM)** is a digital representation of the topography or shape of a surface, typically the surface of the Earth, but a DEM can be made for any geologic surface or interface that can be mapped in three dimensions. Surfaces mapped from cubes of seismic data are now routinely presented as DEMs and can easily be analyzed in terms of geometry and orientations.

Inexpensive or free access to geographic information exists, and this type of data was revolutionized by the development of Google Earth in the first decade of this century. The detailed data available from Google Earth and related sources of digital data have taken the mapping of faults, lithologic contacts, foliations and more to a new level, both in terms of efficiency and accuracy. Because of the rapid evolution of this field, further information and resources will be posted at the webpage of this book.

1.7 Seismic data

In the mapping of subsurface structures, seismic data are invaluable and since the 1960s have revolutionized our understanding of fault and fold geometry. Some seismic data are collected for purely academic purposes, but the vast majority of seismic data acquisition is motivated by exploration for petroleum and gas. Most seismic data are thus from rift basins and continental margins.

Acquisition of seismic data is, by its nature, a special type of remote sensing (acoustic), although always treated separately in the geo-community. Marine seismic reflection data (Figure 1.6) are collected by boat, where a sound source (air gun) generates sound waves that penetrate the crustal layers under the sea bottom. Microphones can also be put on the sea floor. This method is more cumbersome, but enables both seismic S- and P-waves to be recorded (S-waves do not travel through water). Seismic data can also be collected onshore, putting the sound source and microphones (geophones) on the ground. The onshore sound source would usually be an explosive device or a vibrating truck, but even a sledgehammer or specially designed gun can be used for very shallow and local targets.

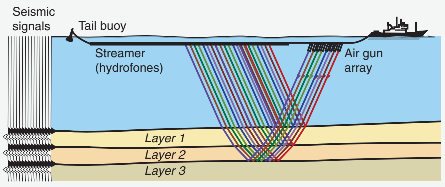
The sound waves are reflected from layer boundaries where there is an increase in acoustic impedance, i.e. where there is an abrupt change in density and/or the velocity with which sound waves travel in the rock. A long line of microphones, onshore called geophones and offshore referred to as hydrophones, record the reflected sound signals and the time they appear at the surface. These data are collected in digital form and processed by computers to generate a seismic image of the underground.

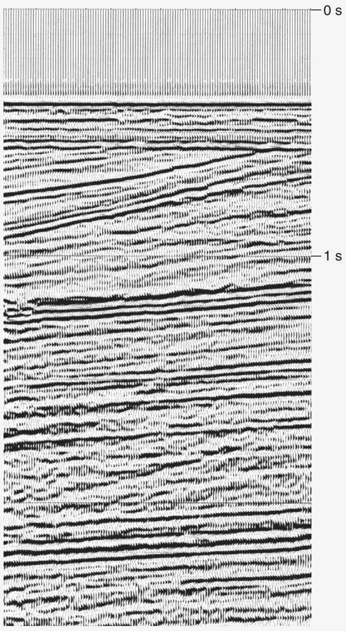
Seismic data can be processed in a number of ways, depending on the focus of the study. Standard reflection seismic lines are displayed with two-way travel time as the vertical axis. Depth conversion is therefore necessary to create an ordinary geologic profile from those data. Depth conversion is done using a velocity model that depends on the lithology (sound moves faster in sandstone than in shale, and yet faster in limestone) and burial depth (lithification

BOX 1.1 | MARINE SEISMIC ACQUISITION

Offshore collection of seismic data is done by a vessel that travels at about 5 knots while towing arrays of air guns and streamers containing hydrophones a few meters below the surface of the water. The tail buoy helps the crew locate the end of the streamers. The air guns are activated periodically, such as every 25 m (about every 10 seconds), and the resulting sound wave that travels into the Earth is reflected back by the underlying rock layers to hydrophones on the streamer and then relayed to the recording vessel for further processing.

The few sound traces shown on the figure indicate how the sound waves are both refracted across and reflected from the interfaces between the water and Layer 1, between Layer 1 and 2, and between Layer 2 and 3. Reflection occurs if there is an increase in the product between velocity and density from one layer to the next. Such interfaces are called reflectors. Reflectors from a seismic line image the upper stratigraphy of the North Sea Basin (right). Note the upper, horizontal sea bed reflector, horizontal Quaternary reflectors and dipping Tertiary layers. Unconformities like this one typically indicate a tectonic event. Note that most seismic sections have seconds (two-way time) as vertical scale.





leads to increased velocity). In general it is the interpretation that is depth converted. However, the seismic data themselves can also be depth migrated, in which case the vertical axis of the seismic sections is depth, not time. This provides more realistic displays of faults and layers, and takes into account lateral changes in rock velocity that may cause visual or geometrical challenges to the interpreter when dealing with a time-migrated section. The accuracy of the depth-migrated data does however rely on the velocity model.

Deep seismic lines can be collected where the energy emitted is sufficiently high to penetrate deep parts of the crust and even the upper mantle. Such lines are useful for exploring the large-scale structure of the lithosphere. While widely spaced deep seismic lines and regional seismic lines are called two-dimensional (2-D) seismic data, more and more commercial (petroleum company) data are collected as a three-dimensional (3-D) cube where line spacing is close enough (*c.* 25 m) that the data can be processed in three dimensions, and where sections through the cube can be made in any direction. The lines parallel to the direction of collection are sometimes called **inlines**, those orthogonal to inlines are referred to as **crosslines**, while other vertical lines are **random lines**. Horizontal sections are called **time slices**, and can be useful during fault interpretation.

Three-dimensional seismic data provide unique opportunities for 3-D mapping of faults and folds in the subsurface. However, seismic data are restricted by **seismic resolution**, which means that one can only distinguish

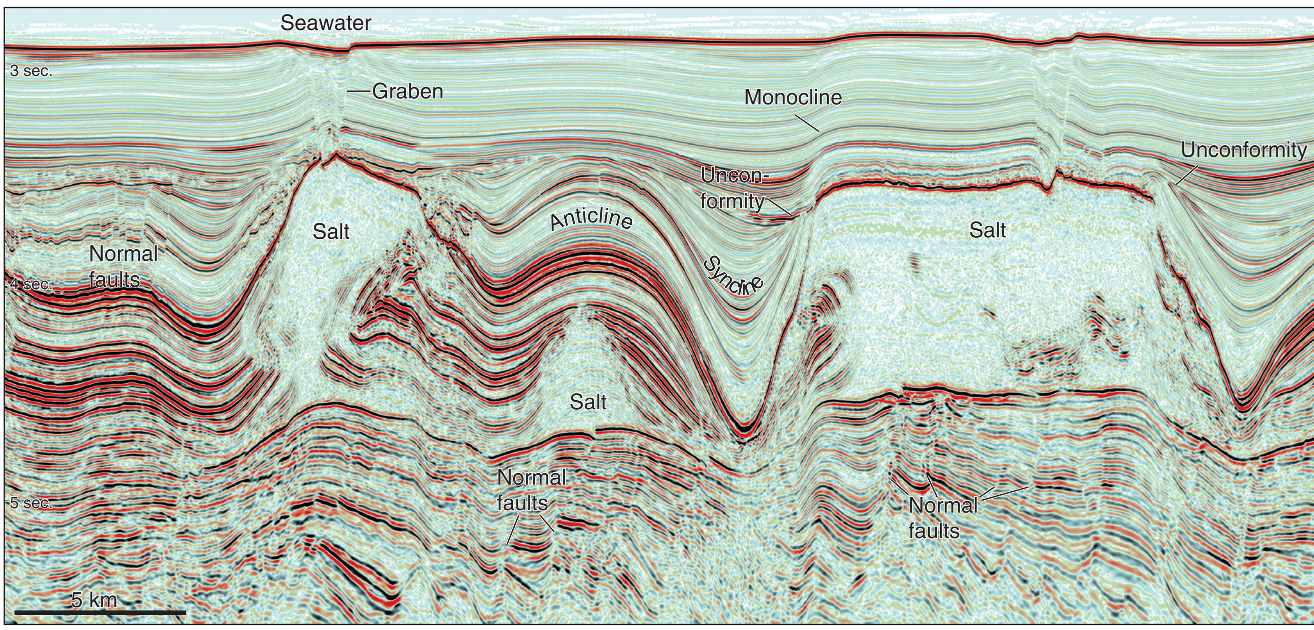


Figure 1.6 Seismic 2-D line from the Santos Basin offshore Brazil, illustrating how important structural aspects of the subsurface geology can be imaged by means of seismic exploration. Note that the vertical scale is in seconds. Some basic structures returned to in later chapters are indicated. Seismic data courtesy of CGGVeritas.

layers that are a certain distance apart (typically around 5–10m), and only faults with a certain minimum offset can be imaged and interpreted. The quality and resolution of 3-D data are generally better than those of 2-D lines because the reflected energy is restored more precisely through 3-D migration. The seismic resolution of high-quality 3-D data depends on depth, acoustic impedance of the layer interfaces, data collection method and noise, but would typically be at around 15–20 m for identification of fault throw.

Sophisticated methods of data analysis and visualization are now available for 3-D seismic data sets, helpful for identifying faults and other structures that are underground. Petroleum exploration and exploitation usually rely on seismic 3-D data sets interpreted on computers by geophysicists and structural geologists. The interpretation makes it possible to generate structural contour maps and geologic cross-sections that can be analyzed structurally in various ways, e.g. by structural restoration (Chapter 20).

3-D seismic data form the foundation of our structural understanding of hydrocarbon fields.

Other types of seismic data are also of interest to structural geologists, particularly seismic information from earthquakes. This information gives us important information about current fault motions and tectonic regime, which in simple terms means whether an area is undergoing shortening, extension or strike-slip deformation.

1.8 Experimental data

Physical modeling of folding and faulting have been performed since the earliest days of structural geology (Figure 1.7), and since the middle part of the twentieth century such modeling has been carried out in a more systematic way. Buckle folding, shear folding, reverse, normal and strike-slip faulting, fault populations, fault reactivation, porphyroclast rotation, diapirism and boudinage are only some of the processes and structures that have been modeled in the laboratory. The traditional way of modeling geologic structures is by filling a box with clay, sand, plaster, silicone putty, honey and other media and applying extension, contraction, simple shear or some other deformation. A ring shear apparatus is used when large amounts of shear are required. In this setup, the outer part of the disk-shaped volume is rotated relative to the inner part. Many models can be filmed and photographed during the deformation history or scanned using computer tomography. Another tool is the centrifuge, where material is deformed under the influence of the centrifugal force. Here the centrifugal force plays the same role in the models as the force of gravity does in geologic processes.

Ideally we wish to construct a **scale model**, where not only the size and geometry of the natural object or structure that it refers to are shrunk, but where also physical properties are scaled proportionally. Hence we