CAMBRIDGE

Cambridge University Press
978-1-107-05764-7 — Structural Geology
Haakon Fossen
Excerpt
More Information

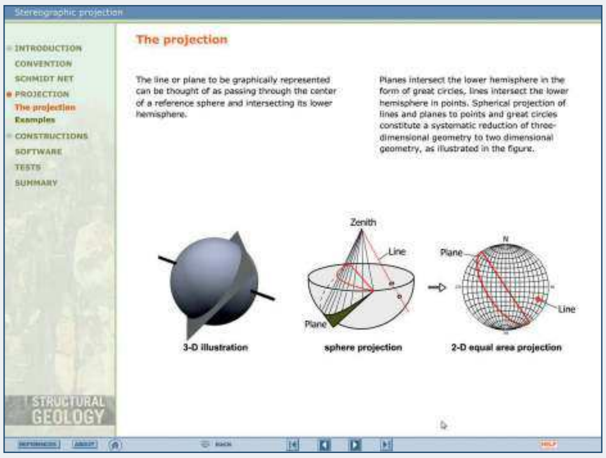
1

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 well-founded 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.

The e-modules for this chapter, *Introduction* and *Spherical projections*, provide further support on the following topics:

- Stress and strain
- Rheology
- Structures
- Tectonic regimes
- Schmidt net
- Projection
- Constructions
- Software
- Convention



1.1 Approaching structural geology

What can today be defined as modern structural geology was born out of field observations. Today indirect observations can also be made from remote data such as seismic data and satellite data, but the fact that observations trigger questions in the mind of the open-minded student remains the same. Answers can be sought through more careful and systematic observations, which commonly involve field measurements, thin section studies, plotting and analyzing structural data, utilize more advanced methods such as radiometric dating, and so on. In addition, we can set up physical experiments in the lab or use numerical modeling to further explore and test our hypotheses.

Each of the different methods that structural geologists use in their pursuit of a satisfactory answer has its advantages and limitations. Observations of structures, be it in the field or from remote sensing imagery, portray the final results of deformation processes, while the actual deformation history is, in most cases, unknown. The evolution of structures through progressive deformation can be observed in laboratory experiments, but how representative are such minute-, hour- or perhaps week-long observations of geologic histories that span thousands to millions of years in nature? And how well do meter-scale models reproduce kilometer-scale natural examples? Numerical modeling, where we use computers, physics and mathematical equations to model deformation, is hampered by simplifications required for the models to be runable with today's codes and computers. Besides, input parameters such as material properties or preexisting heterogeneities may be uncertain. Nevertheless, by combining different approaches we are able to obtain realistic models of how structures can 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 choose 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 20). 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 20. 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 20. 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 10.1) and changes in elevation of regions detected by repeated satellite measurements.

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 more 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. 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.

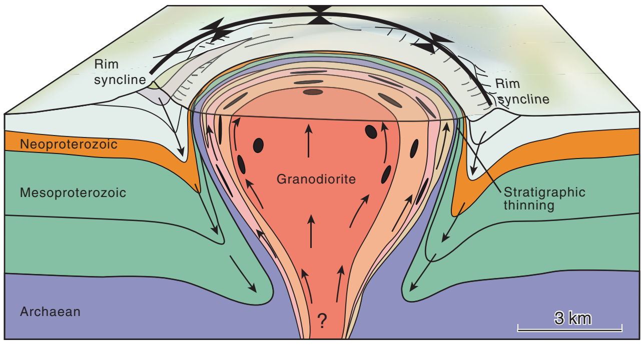


Figure 1.2 Structural geology can be linked to processes and mechanisms other than plate stresses. This illustration of a granodioritic pluton southwest of Beijing, China, portrays the close connection between forceful intrusion of magma, strain and folds in the country rock. Black ellipses indicate 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).

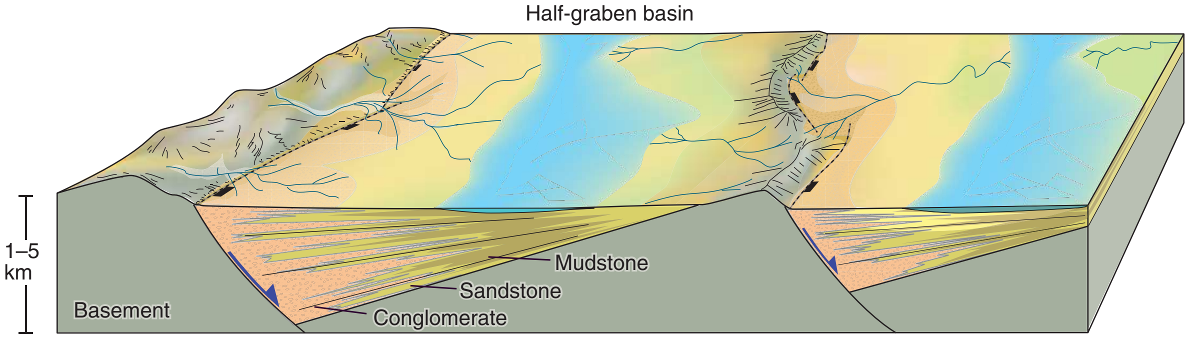


Figure 1.1 Illustration of the close relationship between sedimentary facies, layer thickness variations and syndepositional faulting (growth faults) in an area of active crustal extension.

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 subsurface 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 this relationship 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 may use 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. Any kind of relevant data, such as relative age relations, radiometric dates, evidence for magmatism, and stratigraphic thickness and facies variations, are used as we search for the 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 quality of observation of real rock structures. Direct contact with rocks and structures that have not been filtered or interpreted by other people's minds or computers is invaluable (Figure 1.3).

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. Structures can be overlooked until the day that someone points out their existence and meaning, upon which they all of a sudden start to appear "everywhere". Shear bands in strongly deformed ductile rocks (mylonites) are one such example (Figure 16.25). 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.

Figure 1.3 Direct contact with rocks is important. Make sure you enjoy many days in the field every year where you allow for open discussions and new ideas. Here Donna Whitney and Christian Teyssier are discussing gneissic structures in the Scandinavian Caledonides.

Fieldwork starts with visual observations and sketching (Figures 1.3 and 1.4). It then involves the use of basic tools such as a hammer, measuring device, topomaps, a hand lens and a compass, a camera, and the data collected are mainly structural orientations and samples for thin section studies. Global positioning system (GPS) units and high-resolution aerial and satellite photos are important tools, and 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.

Mapping

A topographic map onto which geologic contacts, locality numbers and orientation measurements can be added has always been essential to the field geologist. The modern field geologist is more likely to take advantage of digital maps and high-resolution digital satellite images and aerial photos that let you map structures and collect, plot and evaluate data more effectively by means of smartphones, tablets and more specialized digital devices with GPS capabilities. This makes for accurate positioning and more efficient data collection. However, the basic concepts remain the same.

Sketching and photographing

In many cases, the most important way of recording field data is by making 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

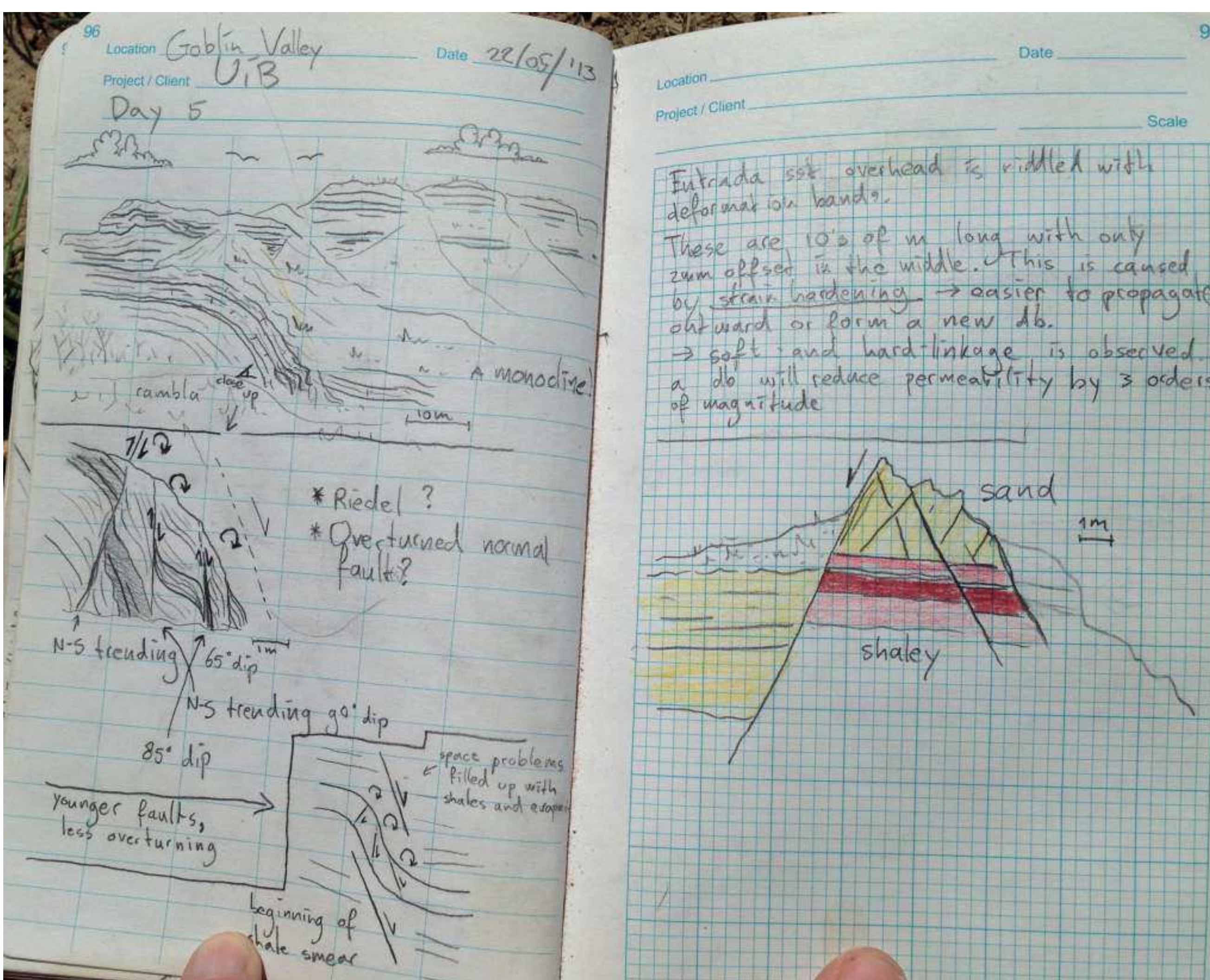


Figure 1.4 Sketching is an important field activity that serves several purposes. It makes you a better observer, gives you ideas, and helps you remember the outcrop. A sketch can be a reproduction of an outcrop where geologic structures are emphasized over uninteresting features (such as vegetation), or more of a principle sketch that illustrates concepts and models. This student sketch (by Gijs Henstra) is an example from a field trip to southern Utah.

that may otherwise be overlooked. Even making a drawing from a good field photograph can reveal features that would otherwise have gone unnoticed. Another use of sketches is to emphasize relevant information and tone down or neglect irrelevant details. Many of us find it useful to make an overview field sketch in order to get the overview of an outcrop. A more detailed drawing of particularly interesting structures or parts of the outcrop can then be made. It is always a good idea to back up sketches with pictures, most conveniently with a camera with a built-in or external GPS unit. Field sketching is, largely, a matter of practice.

Taking measurements

There are a variety of manual compasses available to measure planar and linear structures, and we will not go through the details of how to use them here. In addition, there are several apps for smartphones that can be very useful (see online resources for more information). These apps allow you to easily measure, plot and directly or indirectly present measurements on maps or images, but they have their own shortcomings with respect to accuracy, battery power, etc. that must be taken into account. Unfortunately, different notations are being used for orientation measurements. In particular, planes can be represented by their strike/dip values, or by dip and dip direction (dip azimuth), and although conversion is simple, unambiguous field notes are important to avoid confusion.

Many geologists denote the orientation of a plane by its **strike** and **dip**. Strike is the intersection between our plane and the horizontal plane, and the strike value is the angle between the strike and north. This can be represented by either of two conjugate angles, which in the example shown in Figure 1.5 are 060 and 240, respectively. I use the (American) **right-hand rule**, which says that when you look in the "correct" strike direction, the plane should be dipping to the right. Or, with respect to your right hand; if your right-hand thumb is pointing in the strike direction, your fingers should be pointing in the direction of dip. In our example, the plane dips to the right when looking toward 060, not toward 240. Hence, the orientation of the plane can be denoted 060/30. We always use three digits for strike to avoid confusion with the dip value. It may also be a good idea to denote the direction of dip, in our case to the SE. Now our plane is denoted 060/30 SE. Adding direction (SE) also distinguishes it from a lineation measurement. You may also see this orientation written as N 060 E/30 SW, meaning that the strike direction is 60° E of N. Planar structures are plotted as great circles or as poles to planes in spherical projection diagrams (Appendix B). Strike directions are sometimes represented by means of rose diagrams, particularly for fractures (see Appendix B).

A plane can also be described by its **dip direction**. The dip value is the same as above, but the strike value is now exchanged for dip azimuth, or the horizontal direction in which our plane is dipping. So if our plane is dipping toward 150 (to the SE), its orientation is denoted 150/45 or 45/150. Basically this adds 90° to our strike angle, so it is easy to go between the two, but also easy to confuse if you get data from other geologists. Dip directions are plotted as poles in spherical projections, since they are effectively lines.

Linear structures are represented by their **trend** and **plunge**, where the trend is the projection of the linear structure onto the horizontal plane, and the plunge is the angle

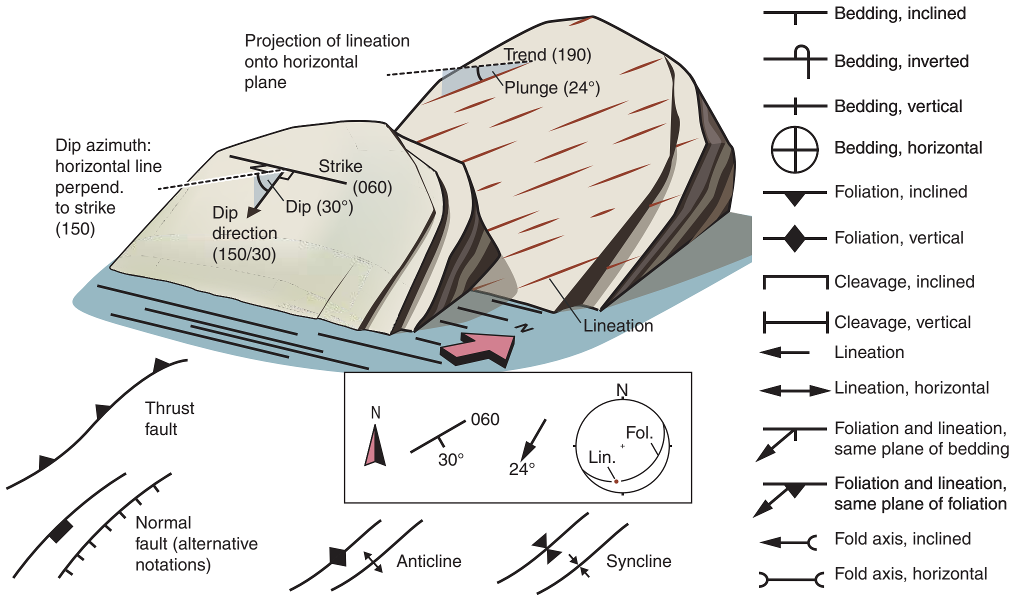


Figure 1.5 Description of foliation and lineation in an outcrop, together with some commonly used map symbols. The box shows how the foliation and lineation in the figure may appear on a map and as equal-area projections.

between this line and the lineation. In some cases pitch is measured, as explained in Appendix B. Linear structures are represented by poles in spherical projections.

Magnetic declination is the difference between true and magnetic north, which can be quite significant in some places and must be accounted for. It can be done by adjusting your manual compass (but remember to readjust when moving to a different area) or the measurements can be adjusted later (in a spreadsheet or by rotating the data in a spherical projection program). If you are using a smartphone app, it may or may not automatically correct for declination.

Spherical projections

Orientation data are plotted on spherical projections (equal angle or area) and rose diagrams, and smartphone compass apps automatically plot data on the screen so that we can immediately evaluate the results and, if necessary, add measurements. Convenient plotting applications are available into which data can be entered or imported from handheld devices. However, it is absolutely necessary to understand spherical projections in order to make full use of the plots that they produce. Hence, review the basics of plotting orientation data on equal angle and area diagrams, as presented in Appendix B and the e-module Spherical projections.

Scanlines

Scanlines are lines across structures such as fractures or deformation bands, where the location of each structure or number of structures per meter is recorded. Scanline data can be collected by stretching out a measuring tape across the structures of interest, or from cores or borehole image data. Such data can be plotted in frequency graphs such as that shown in Figure 9.13. Note that it is commonly desirable to measure perpendicular to structures, and where this is not possible, to make a simple geometric correction so that true spacing, for example of a joint set, can be found.

Geologic maps

Geologic maps are important presentations of structures as they are supplied with symbols representing various planar and linear structures. The use of symbols differs, and some common ones are shown in Figure 1.6. Each geological survey seems to have their own set of symbols, in addition to the great variation between individual authors. Hence, the symbols used must be explained in the legend of the map.

While mapping used to involve paper and pencils, many geologists now draw contacts and add measurements digitally on handheld devices in the field. Also, geologic field data are commonly presented on three-dimensional (3-D) models (such as Google Earth), where geologic contacts and orientation data are projected onto elevation models aided with remote sensing images.

Cross-sections

A geologic map is not complete without one or more cross-sections (Figure 1.6), which is constructed by making a topographic profile with surface information from field observations. Usually the section is chosen in the dip direction of important lithologic boundaries or the foliation, or perpendicular to major faults or fold hinges, which in many cases captures the tectonic transport direction. The topographic profile is usually constructed from digital elevation data. Then, with the aid of geophysical data and well information, the surface information is extended downward into the subsurface. The section should be restorable to a reasonable pre-deformational situation, as discussed in Chapter 21.

Collecting oriented samples

It may be important to know the orientation of a sample, for example for kinematic analysis or for oriented thin sections. To collect an oriented sample, put the sample back in place, draw a strike and dip symbol on a dipping surface of the sample while it is in place, and write the strike and dip values on the sample, as shown in Figure 1.7. If there is a lineation it may be useful to also mark it with an arrow and its trend/plunge, but note that a lineation by itself does not contain sufficient information to reorient the sample. Also add sample number and position information, and take a picture of the sample in place before putting it into a well-marked sample bag.

1.5 Remote sensing and geodesy

Satellite images, such as those shown in Figure 1.8a and 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 3-D models. Ortho-rectified **aerial photos** (orthophotos) may give more or other details (Figure 1.8b), 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

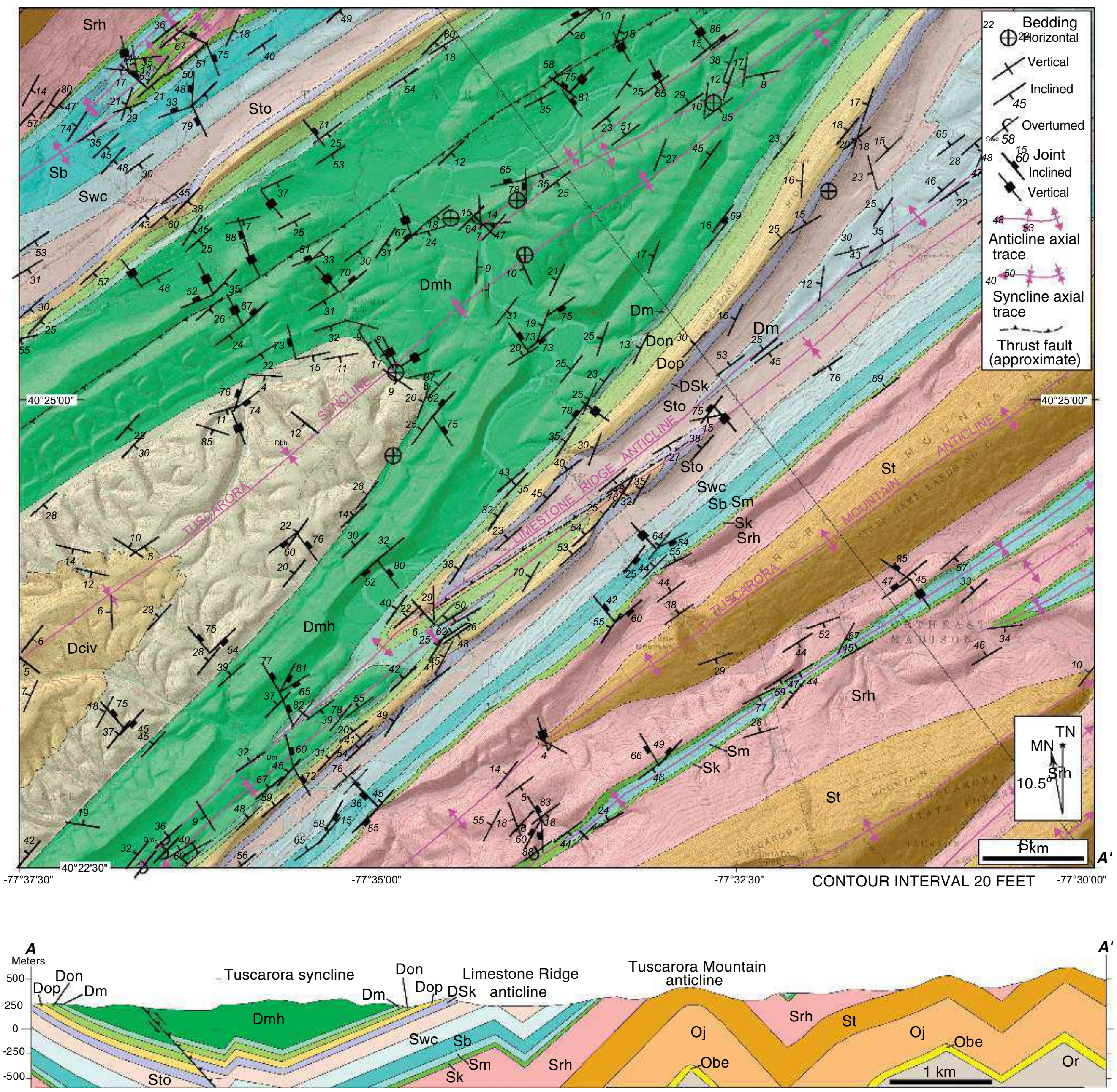


Figure 1.6 Example of a bedrock geologic map from the Ridge and Valley province (Appalachians) of Pennsylvania, with structural data and a cross-section (A–A'). The stratigraphic column of the Ordovician–Devonian sedimentary succession exposed on this map sheet is not shown here. Modified from McElroy and Hoskins (2011).

technique that combines two or more radar satellite images to map variations in ground surface deformation. Beams of radar waves are constantly sent toward the Earth from satellites, 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 movements related to earthquakes or sliding. 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 1.9). Such data can also be collected on the ground by means of stationary GPS units with down to millimeter-scale accuracy.

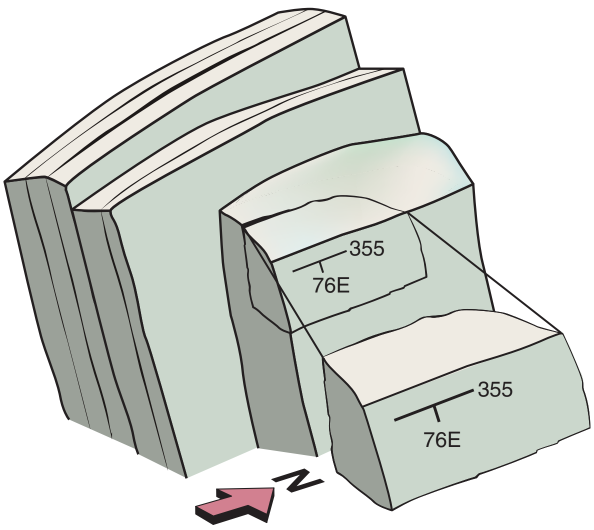


Figure 1.7 Collection of an oriented sample requires that the orientation (strike/dip) of one of the faces is measured and marked on the sample before it is permanently removed from the outcrop.

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 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 colored and shaded 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.

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 1.10 and Box 1.1) are collected by boat, where a sound source (air gun) generates sound waves that penetrate the crustal layers under the sea bottom. Microphones (hydrophones) can also be put on the sea floor (OBS, or ocean bottom seismic). 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 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 create geometrical challenges when interpreting a time-migrated section. The accuracy of the depth-migrated data does however rely on the velocity model.