Chapter 1: Introduction to Structural Geology

A GEOLOGICAL MAP is a medium of communication that uses graphic symbols to represent spatial relationships among geographical and geological feautures. Lines, points, symbols, and texture markings are used to separate various classes of information. But the interpretation of geological maps goes beyond identifying the individual items displayed on the map. A connection must be made between what is perceived on the map and other knowledge. The interpretation of geological maps is basically an attempt to visualize and understand the complex shapes of rock units in the subsurface. A thorough understanding of the variety of geological structures is particularly important, because it helps to determine the nature of subsurface structures from geological maps. Structural geology, therefore, is a major cornerstone of the art of geological map interpretation.

Contents: The aims and nature of structural geology as a discipline are discussed in section 1-1. The practical importance of structural geology is outlined in section 1-2. Avenues for an effective study of the subject are suggested in section 1-3. A guide to the chapters of this book is given in section 1-4.

1-1 What is structural geology?

Structural geology is a practically oriented branch of the earth sciences which aims to study the architecture of the solid Earth and other planets. It studies the geometric variety of *deformation patterns* in rocks and develops techniques and methods to display the results. Structural geology, also, provides guidelines for the production and interpretation of geological maps. The discipline has emerged from the need in the mining and petroleum industry to understand better the structure of rock formations that host mineral and energy resources. Contributions to its development have come, also, from civil engineering studies of large construction projects, from the academic community, and from the geological surveys of many nations.

The structure of rock units beneath the ground surface cannot be seen directly. It needs to be inferred by making skillful use of the data available from surface studies of rock outcrops in road cuts, mountain slopes, and other erosional surfaces. The detailed geometry of the deformation patterns concealed in rocks can be further unravelled using a steadily growing array of field mapping techniques, seismic penetration methods, drilling, and complementary remote sensing of the anomalies in geophysical parameters (albedo, gravity, electrical conductivity, magnetic susceptibility, etc.). Rock formations are presented in structural maps, field sketches, and photographs. Compass measurements are made to determine the inclination and geographical orientation of structural features. Rock samples, carefully indicated on sample location maps, are collected for further study by light microscopy of thin sections or other advanced analyses. This fragmentary information from the surface geology and near-surface structures has to be compiled into a complete synthesis of the geological subsurface structure.

Structural geology is here principally considered as the descriptive study of rock structures. It investigates the detailed structure of rock formations, which formed very slowly in the past and are essentially at rest when exposed. Geologists have developed techniques to map, methods to display, and jargon to describe the geometrical variety of deformation patterns observed in rocks. This book concentrates on the principal terms and techniques employed in the description and map representation of geological structures. The terminology and techniques established for the description of the various classes of deformation structures are outlined.

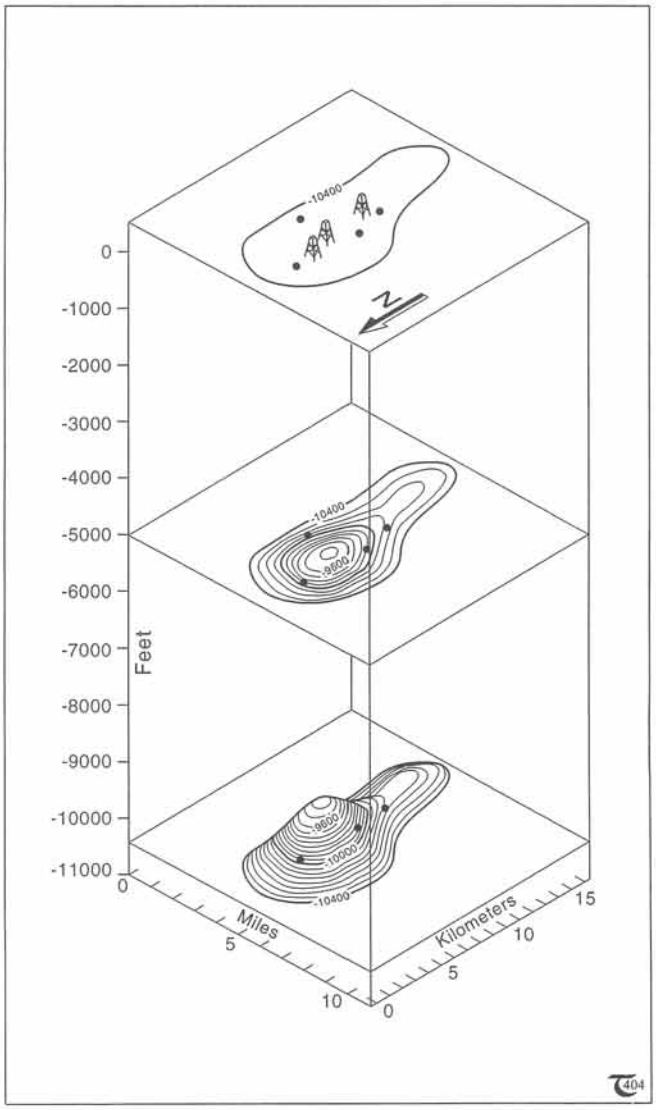


Figure 1-1: *Structure contours (in plan projection and relief view) of the Ekofisk oilfield, North Sea. Outer contour is 10,400 feet below the seabed.*

1-2 Importance of structural geology

Structural geology describes rock structures not only for the sake of academic interest. It has a profound practical value. The understanding of rock deformation structures is of great economic importance. The exploration for and mining of ore bodies and hydrocarbon accumulations is heavily dependent on accurate descriptions of the structures enveloping these natural resources. The construction of dams, tunnels, and road cuts requires detailed knowledge of the structure of the wall rock and subsurface before any planning or stability analysis can be made. Four major application areas of structural geology can be distinguished: (a) exploration for and mining of natural resources, (b) prevention of natural hazards, (c) infrastructure planning and site investigation, and (d) detailed regional mapping. These applications are outlined in turn below.

a) Exploration and mining

The quantity of natural resources needed to sustain the modern industrialized and technocratic world is still growing, and exploration for materials from the Earth continues unabated. The search for fossil fuels, geothermal fields, mineral deposits, building materials, and groundwater reservoirs involves geological exploration and the assessment of the subsurface structure. For example, off-shore drilling for the Ekofisk oilfield, North Sea, was partly planned on the basis of a *structure contour map* of the top of the oil-bearing formation (Fig. 1-1). The oilfield lies three kilometers below sea level, and most of the sub-

Figure 1-2a: Bingham Copper Mine near Salt Lake City, Utah, USA.

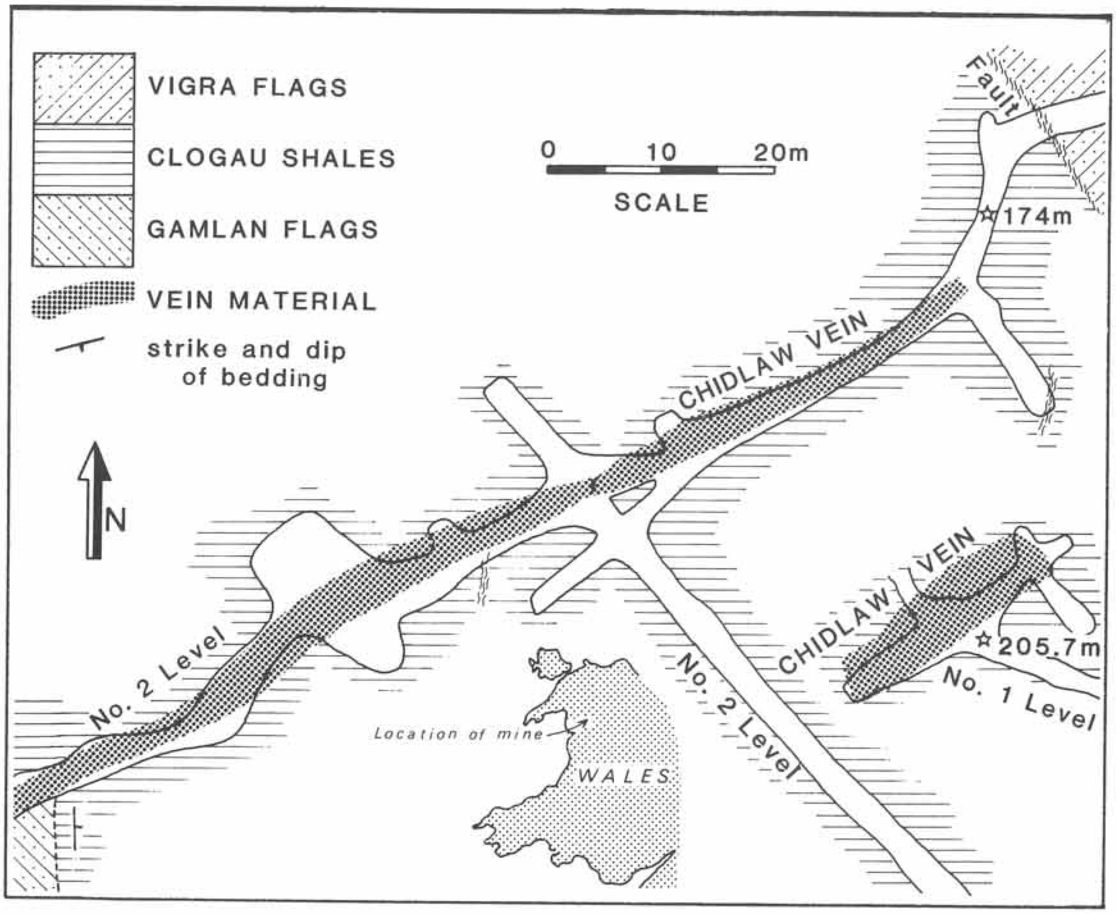
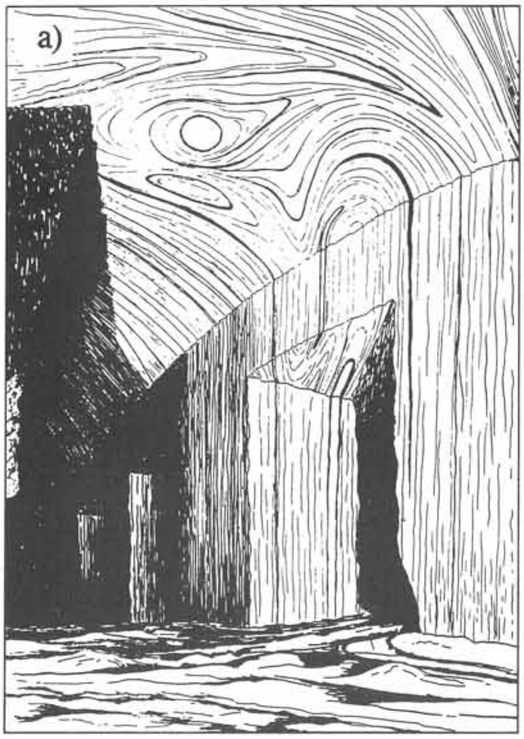


Figure 1-2b: Gwynnfynnid Gold Mine, Wales.



surface information comes from seismic reflection profiling and a few exploration drillings. Production from such an oilfield cannot begin until the shape and extent of the reservoir have been established by an investigation of the geological structure. Hydrocarbon exploration focuses on demarcating the subsurface structural and sedimentary traps formed in sedimentary sequences, and structure contours provide a practical tool to visualize these traps.

Deformation structures may play an important role in the formation of ore deposits. Many hydrothermal ore deposits are localized in fractures, fissures, faults, shear zones, and folds. Figure 1-2a shows an oblique aerial view of the Bingham Canyon Copper Mine near Salt Lake City, Utah. The extraction of about 200,000 tons of raw rock daily requires careful examination of the rock formations that host the copper ore. Evidently, knowledge of the natural fracture patterns and the shape of the ore-bearing rock units is essential for the smooth operation of such mining activities. Figure 1-2b illustrates the geological map of the subsurface, outlining the shape of a gold-bearing quartz vein hosted in the Cambrian shales of the Gwynnfynnid Mine, Wales. The map of the goldworkings shows the Chidlaw vein and the tunnel system at levels one (+205 m) and two (+174 m). The planning of

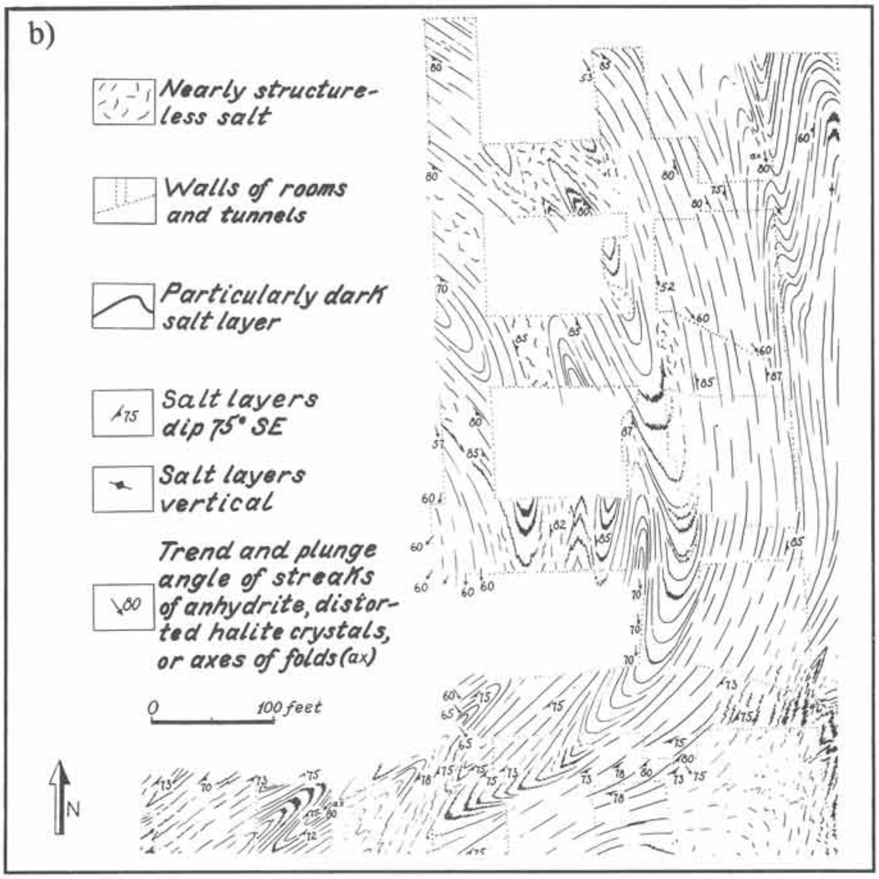


Figure 1-3: a) Sketch outlining the traces of darker layers in folded salt beds inside Jefferson Island salt dome, Louisiana. Portals are about ten meters high. b) Map projection of folded salt beds in the Gran Saline Mine of the Morton Salt Company, Texas.

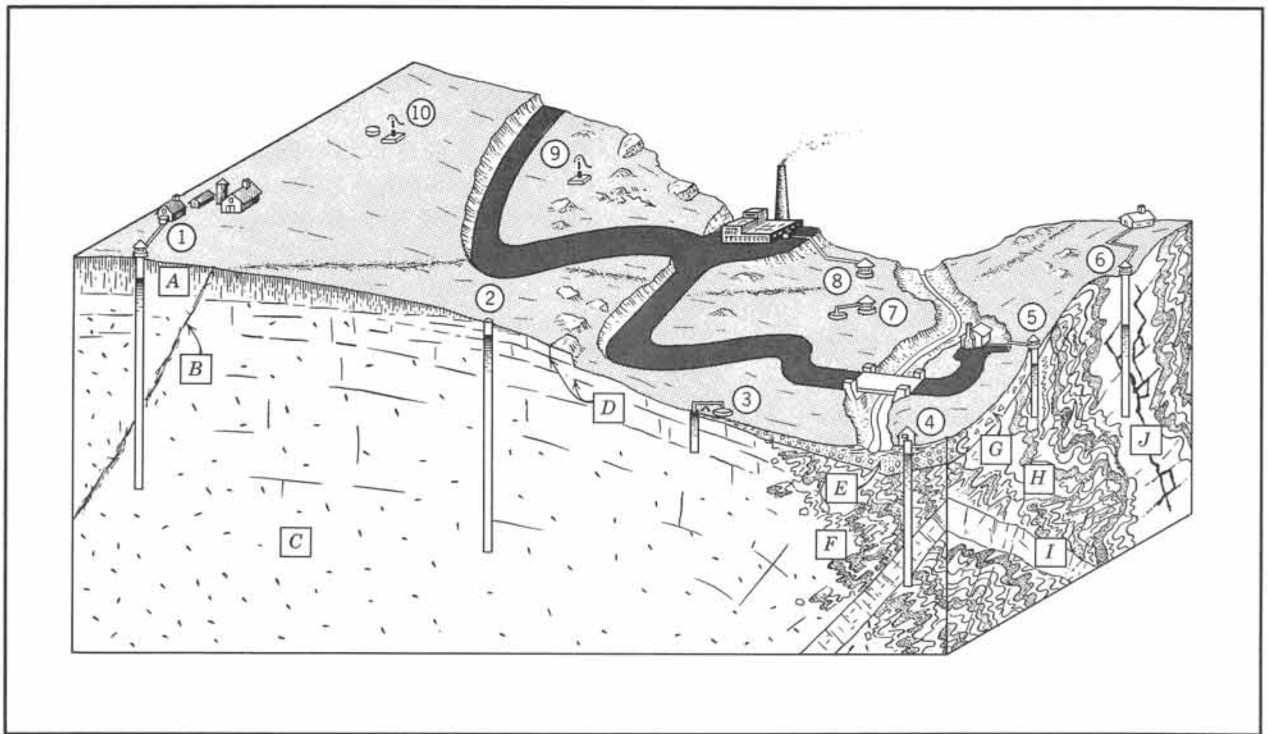


Figure 1-4: *Geological structures in a hypothetical region and potential locations for water wells. The well-yields depend upon the hydrogeological subsurface structures (Table 1-1).*

new tunnels and shafts is heavily dependent on a proper understanding of the three-dimensional structure and extent of the vein network. Ore deposits wrapped in deformation structures, also, are carefully mapped by mining companies to allow estimates of economic reserves.

Figure 1-3a shows a view inside the Jefferson Island Salt Mine, Louisiana. The intricate *fold patterns* of the individual salt layers is carefully mapped from exposures on the walls and ceiling of the tunnels, the only surfaces available to the geologist (Fig. 1-3b). The salt is mechanically excavated, rather than dissolved - a common technique for salt extraction elsewhere - and is used as a raw substrate for industrial processes.

Underground mapping, albeit handicapped by water, mud, and dust covering the floor and walls of the tunnels, helps to determine in which fashion exploitation may proceed.

Groundwater, excluding the amount of water trapped in ice sheets and glaciers, accounts for about ninety percent of the available freshwater. The movement of groundwater is largely controlled by the nature and structure of the geological formations. Figure 1-4 shows how groundwater availability and its use, in a hypothetical region, relate to the geological features in the

Table 1-1: *Well data for Figure 1-4.*

Well no.	Use	Depth (feet)	Production (gal./min.)	Source of Water
1. Drilled	Farm	210	25.0	Weathered granite and fault zone.
2. Drilled	None	200	0.1	Very small amount from joints.
3. Drilled	Stock	630	0.5	Small amount, artesian, from joints.
4. Drilled	Observation	125	15.0	Alluvium and fractures near dike.
5. Drilled	Domestic	80	1.5	Colluvium and joints in schist.
6. Drilled	Domestic	130	45.0	Cavernous zone in marble.
7. Dug	Stock	20	4.5	Alluvium.
8. Drilled	Industry	160	35.0	Alluvium and fault zone.
9. Dug	None	15	0.2	Small amount from joints.
10. Dug	Stock	25	0.7	Weathered granite.

A-residual soil on granite; B-fault; C-granite; D-joints; E-alluvium; F-contact between granite and schist; G-colluvium; H-schist; I-aplite dike; J-marble.

Figure 1-5a: Structural devastation causes loss of life and capital. This house in the Marina district, San Francisco, collapsed during the October 17, 1989, Loma Prieta earthquake.

subsurface. Carbonate rocks, such as limestone, dolomite, and marble are commonly porous and permeable, therefore providing good water-bearing reservoirs. Any deformed rocks, also, classify favorably for water exploration, because the faults and joints thus formed may be water-bearing. Weathered rock zones and alluvium usually provide extremely good well-sites, especially if hydrologically connected to streams and lakes. Obviously, knowledge of the rock strata, their orientation, and the extent of fracture systems is essential in assessing the potential of groundwater reservoirs.

b) Hazard control

Natural hazards involving rock movement include earthquakes, volcanic eruptions, mass wasting, sinkholes, and meteoritic impacts. A better understanding of each of these hazards comes from careful investigations of the geological structures associated with these phenomena. Figure 1-5a is a snapshot of the destruction caused in the Marina district, San Francisco, by the Loma Prieta earthquake of October 17, 1989. The episodic series of earthquakes in California is caused by horizontal slip over segments of the San Andreas fault system. A dense network of monitoring devices provides continuous information on the movement and stress levels along the major faults of the splay system (Fig. 1-5b). Part of the problem of accurate forecasting of any future earthquakes is that newly formed faults may emerge anytime and generate new earthquakes. Additional ambiguity in forecasting is introduced by the presence of existing faults, which remain as yet undetected due to temporary seismic silence. These dormant faults may

Figure 1-5b: Sketch map showing the surface traces of the major faults of the San Andreas system, California.

suddenly reactivate with particularly high seismicity. However, faults can be traced in the field by carefully mapping of the abrupt displacements of otherwise smooth geological boundaries, even in the absence of any seismic noise. Structural field mapping, therefore, is an important means of gaining understanding of seismic hazard zones. Earthquake hazard prevention benefits from the movement history recorded by deformation structures in the wall rock of seismically active faults.

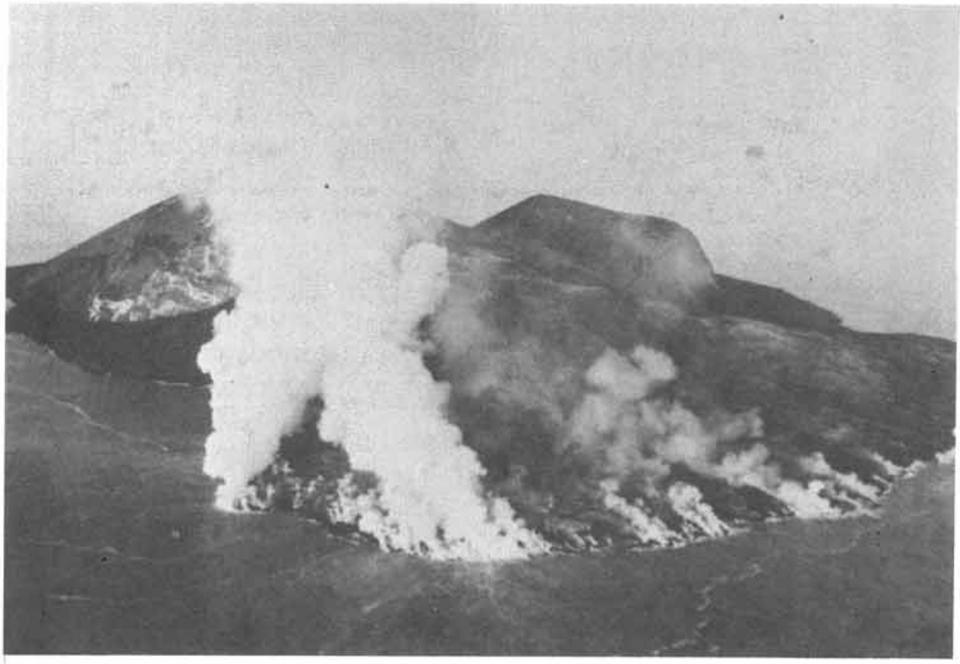


Figure 1-6a: Steam escapes, where the advancing lava meets the sea water, during the emergence of the volcanic island of Surtsey in 1963, off-shore Iceland.

Monitoring the activity of volcanoes is another important field of geological studies. The eruption of hot magma from the Earth's interior is often localized in zones of structural weakness. Figure 1-6a illustrates the eruption of hot lava from the Surtsey volcano, off the coast of Iceland, which first emerged above the sea in 1963. The people of Iceland are extremely familiar with recurrent volcanicity in their country - and much

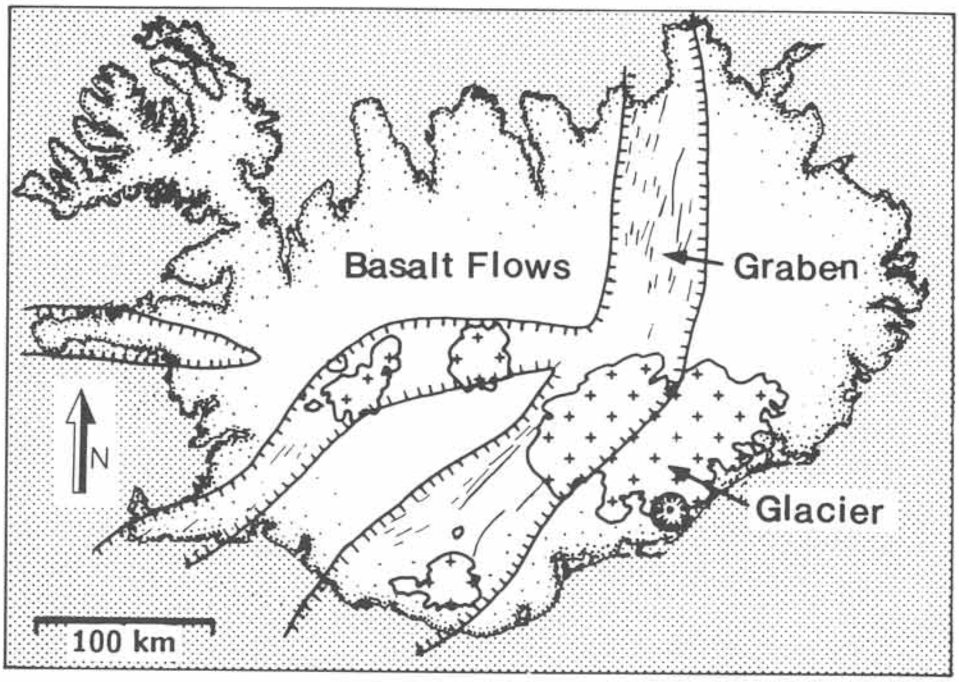


Figure 1-6b: Iceland is split between two worlds. The Eurasian and North American plates meet in Iceland and continue to separate by spreading, rifting, and volcanism.

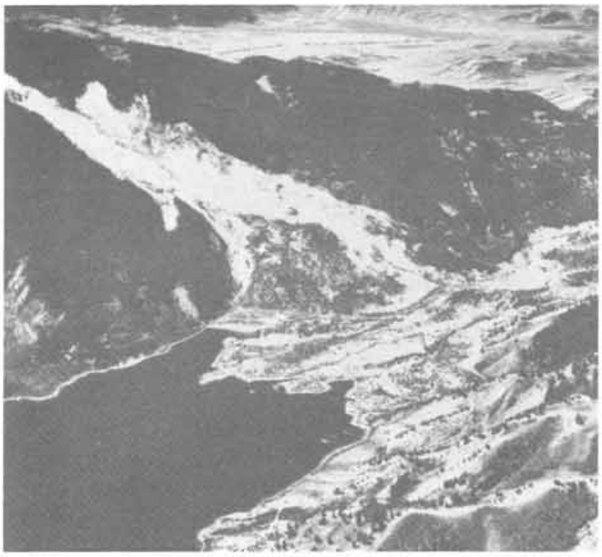


Figure 1-7a: A scar in the landscape marks the site of the Lower Gros Ventre slide, Wyoming, which took place June 23, 1925. View is facing southwest.

of the geothermal heat is used as an energy resource. Many of the eruption sites scattered over the interior of Iceland are *fissure eruptions*, and careful mapping has revealed an *en-echelon* system of fractures in the central graben system (Fig. 1-6b). After establishment of the global framework of the tectonic plates, in the 1960's, it was recognized that western Iceland is part of the North American plate and eastern Iceland rests on the Eurasian plate. These plates are slowly drifting apart, and, consequently, the size of Iceland is growing every year by the episodic crustal accretion in the widening rift zone. Active monitoring of the fracture patterns and the associated geological structures is essential for a detailed understanding of both the present and future eruption patterns in Iceland and elsewhere.

The Earth's surface is full of steep slopes, deep valleys, and overhanging cliffs. The pull of gravity may sometimes destabilize rock and earth masses and causes them to collapse, followed by

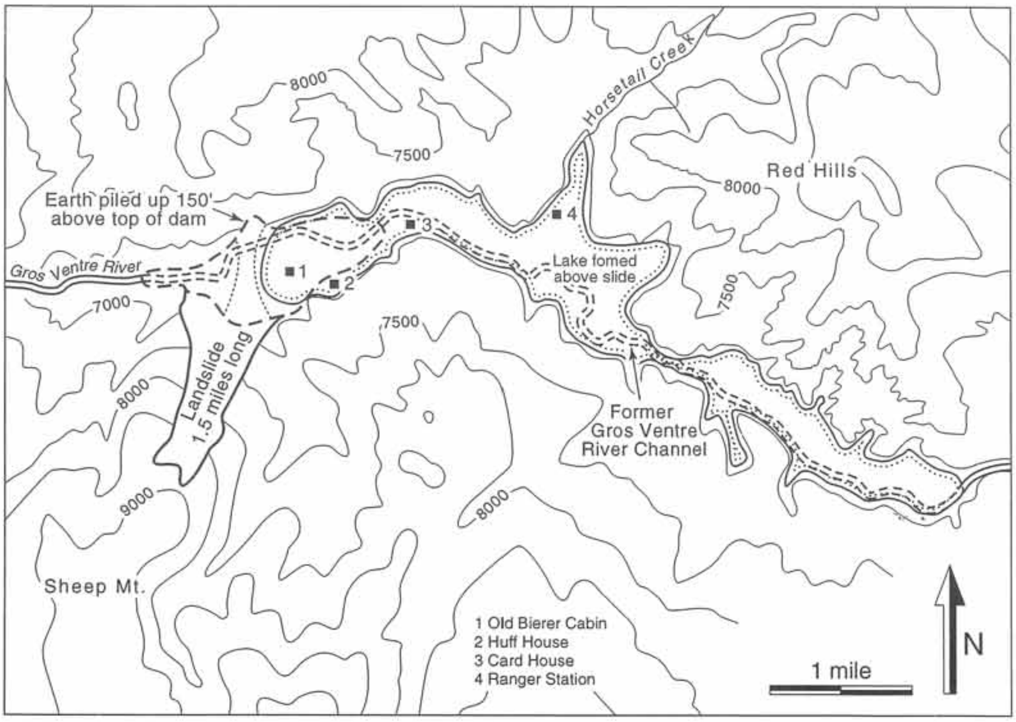


Figure 1-7b: Sketch map of the landslide scar and the dam of the slide mass blocking the Gros Ventre River, which led to the formation of Gros Ventre Lake.

rapid movement of rubble down the topographical slopes - a process termed *mass wasting*. Major destruction is frequently caused by the collapse of rock slopes, mudflows, rock avalanches, slumps, debris slides, rockfall, earth flow, solifluction, and creep. These hazards occur throughout the world and pose a continuous threat to man and his construction. Figure 1-7a shows a southwest view of the scar in the landscape left by the Lower Gros Ventre slide, Wyoming, which took place June 23, 1925. In about three minutes, approximately one hundred million tons of rock-rubble and clay-rich, water-saturated debris moved across the valley floor, thus blocking the Gros Ventre River. Figure 1-7b shows the situation map and the lake which formed behind the slide in the Gros Ventre Valley. Water began to seep through the natural dam soon after the slide. On May 18, 1927, a dam breach and sudden flood lowered the lake by fifteen meters and caused six deaths. Many rockslides and avalanches are not unique but are recurrent features

Figure 1-8a: *Sinkhole of Winter Park, Florida, formed May 7, 1981.*

Figure 1-8b: *Meteor Crater seen in an oblique aerial view from 1.5 kilometers height, looking towards the northwest. Meteor Crater is located 18 miles west of Winslow, Arizona, USA.*

Figure 1-9a: The structure of the rock formations greatly affects the strategy and final shape of tunnel construction. View inside the City Tunnel, Boston, during its construction.

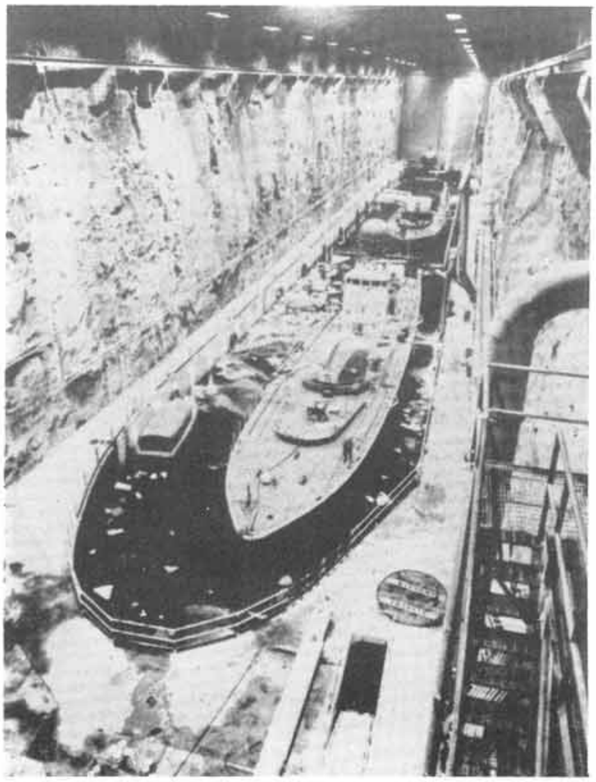


Figure 1-9b: Underground marine dock, excavated in the Precambrian rocks of the Baltic shield, Sweden. Man at the bow of the destroyer for scale.

Figure 1-9c: Geological site investigations ensured the stability of the walls and floor of the Colorado River, supporting the Hoover Dam, Nevada.

in those particular regions where conditions of slope instability occur. Careful mapping of the geological structures outlines both the extent of previous mass wasting and may help to identify potential future slide masses.

Sinkholes, or sudden collapse features, occur in limestone strata due to subsurface solution by carbondioxide-charged acidic groundwater. Figure 1-8a illustrates an oblique aerial view of the Winter Park sinkhole, Florida, which collapsed on May 7, 1981, creating a crater of two hundred meters width and fifty meters depth. It swallowed half the communal swimming pool, six cars, and a three-bedroom bungalow. Careful mapping of existing sinkholes may reveal the movement path of major subsurface flows and, thereby, delineate areas threatened by future sinkhole formation. Circular depressions in the landscape are not only caused by the collapse of subsurface cavities, but they, also, may be due to meteoritic impact (Fig. 1-8b). Structural geology investigates the crustal distortions associated with impact craters and provides useful information on the age and extent of such events.

c) Planning and site investigation

Every new construction operation is likely to cause changes in the existing condition of the ground surface. Civil engineering works involving ground movement include open excavations; drainage networks; trenches; tunnels; underground repositories; foundations of dams; bridges; and buildings; road cuts; railways; airfields; harbors; land reclamation; and docks (Fig. 1-9a to c). The chief aim of preliminary geological investigation is to provide accurate information about the subsurface conditions at the site of the proposed work and sometimes to identify possible locations for opening quarries suitable for extracting some of the required construction materials. The geological conditions at the site of construction will determine the cost of the operation. They, also, may reveal the necessity of specific measures needed to stabilize the foundations of the work and other rock faces nearby.

"... and we can save 700 lira by not tak ing soil tests."

Figure 1-10: *Geological site investigations detect unstable ground conditions, which, if undetected, might generate grave problems for the safety and longevity of overlying construction.*

The geological information may further influence the engineering operation in that it may require possible alterations in design of the construction work due to variations encountered in subsurface conditions. It usually, also, determines to some extent the method of construction to be adopted. It is, therefore, necessary to make a thorough geological survey of the area in which the works are to be situated. Before undertaking any design work for a project, a civil engineer must have full information on the foundation conditions. This will necessitate examination of the site of the work. The site study must always be considered in conjunction with, and is conditioned by, information available from previous geological studies of the area. Detailed study of the site itself, including full-scale tests of the rock *in situ*, is a desirable means of further eliminating some of the uncertainties arising from the preparatory studies in major rock stability investigations. The geological structures of interest may

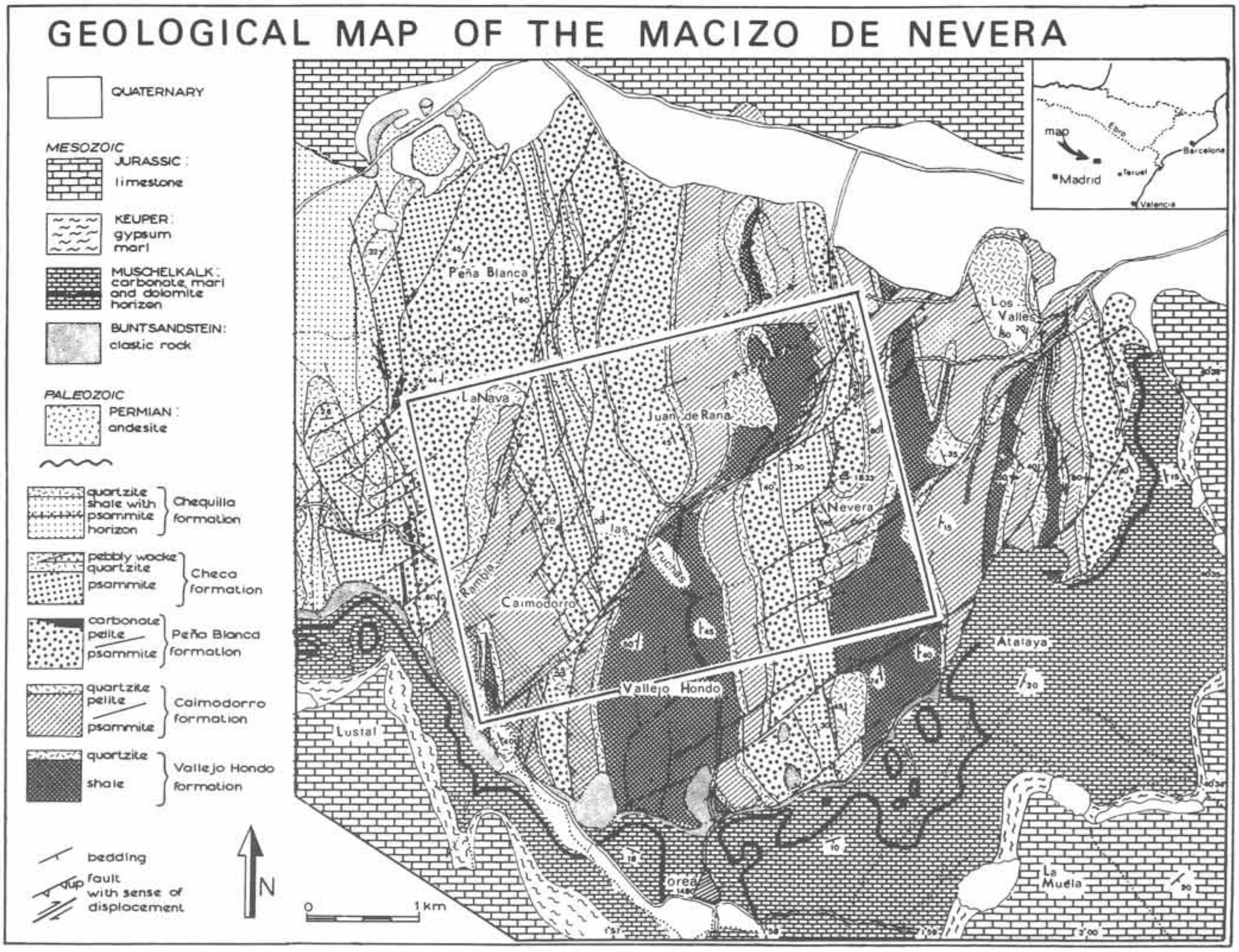


Figure 1-11a: Geological map of the Macizo de Nevera, Sierra de Albarraccin, central Spain. Inset shows location.

include folds, uniformly tilted strata, unconformities, faults, fractures, intrusions, and collapse features, all of which are outlined in this book.

A considerable number of engineering disasters could have been averted by careful geological *site investigation*. The geological conditions are best considered before any design or construction starts - in order to avoid major trouble and cost escalation that may otherwise develop during or subsequent to the construction project (Fig. 1-10). The engineering of large constructions carved into or anchored in solid rock requires detailed knowledge of the subsurface geologic structure. Site investigations will help avoid upward spiralling of costs during construction and minimize the risk of an unexpected geological hazard damaging the work.

d) Regional mapping

The geological survey teams of all modern nations are continually engaged in the preparation of detailed geological maps of their countries.

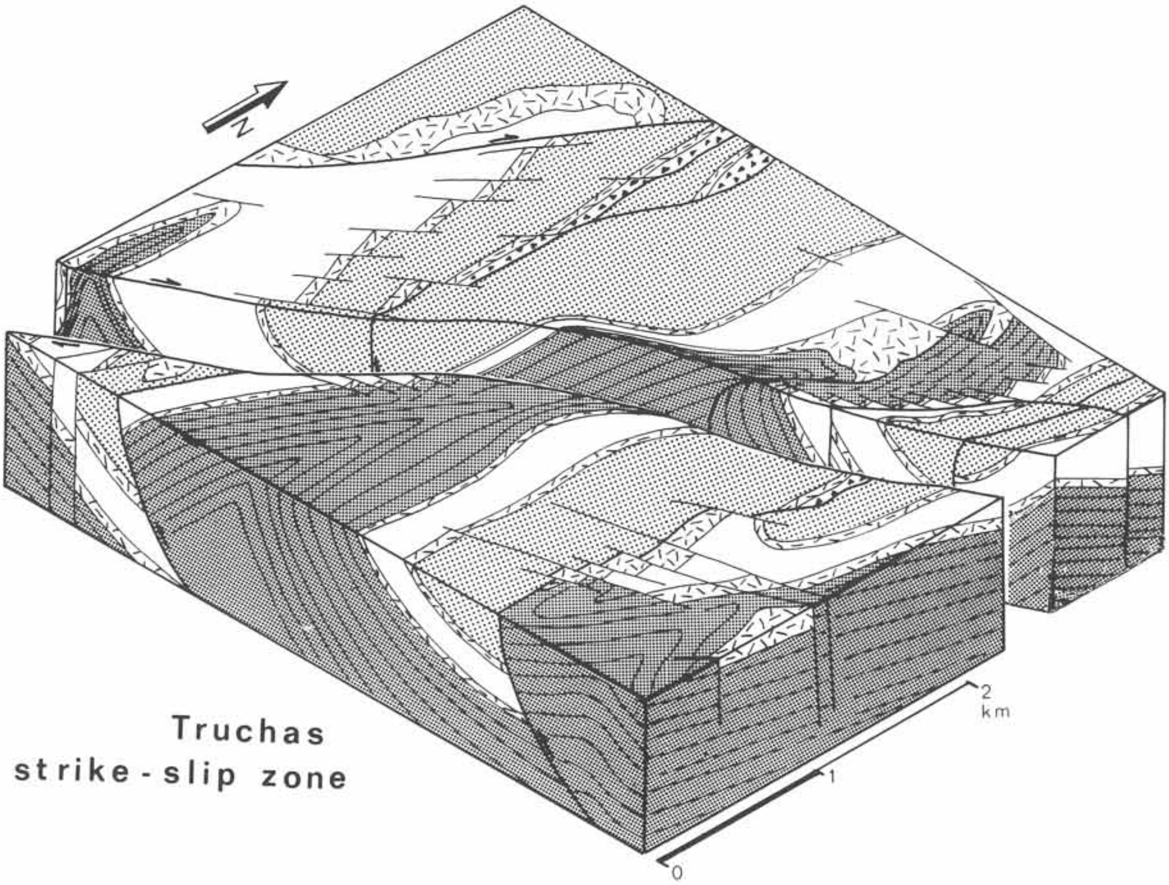


Figure 1-11b: *Isometric block diagram of the Truchas shear zone, Macizo de Nevera.*

These maps show the spatial distribution of the various rock formations and their structures at ground surface. Geological base maps are necessary for targeted mineral exploration, to support land management directives, and to facilitate engineering and construction projects. Extremely detailed maps are, also, produced by academic groups with a long-term presence in regions of particular interest to them. Useful geological maps include detailed information on the variety of deformation structures encountered. Studying the deformation patterns in the Earth's crust is, further, important for developing a better understanding of the way in which continents break apart, grow, and remold.

Figure 1-11a shows a geological map of the Macizo de Nevera, central Spain. The map area includes folded sedimentary rocks of Paleozoic age, covered by flat-lying strata of Mesozoic age. Although the pattern of the rock formations seems extremely complex to the untrained eye, this map represents relatively simple geological structures. The folds in the basement rocks are transected and displaced by dextral strike-slip movement on the Truchas *shear zone*. An isometric block diagram of the Truchas shear zone visualizes the three-dimensional structure of the subsurface (Fig. 1-11b). One of the aims of this book is to make users familiar with the reading and interpretation of the data conveyed in geological maps, cross-sections, and perspective diagrams.

1-3 Study of structural geology

Structural geology is closely related to somewhat younger branches of the earth sciences, such as tectonics and rock mechanics. Tectonics is the discipline describing the kinematic history of deformation patterns in rocks, and the dynamic forces that deform rocks are studied by rock mechanics. In summary, structural geology, tectonics, and rock mechanics investigate, respectively, (1) the geometry of *WHAT* we study, (2) *HOW* that geometry changed with time, and (3) *WHY* that geometry changed with time. Each of these disciplines concentrates on the nature of either the (1) geometry, (2) kinematics, or (3) mechanics of rock deformation patterns.

The variety of rock structures in nature, combined with their intriguing regularity, provides a fantastic playground for breath-taking geometric puzzles. These puzzles can be completed successfully by students only if professional techniques are properly explained, understood, and made familiar ground by way of practice. Most students are rapidly converted into enthusiastic participants, prompted by the ingenious methods available to interpret the information collected on geological maps. Their efforts need to be matched by an accurate and lucid textbook, which convinces them of the soundness of concepts and techniques. This book provides a series of exercises on geological maps for students, with explanations of basic structural geology. Figure 1-12 illustrates some of the basic supplies recommended to complete the exercises.

The emphasis of the instructive medium in this book is on manual techniques. The simple principles of map interpretation introduced here can be practiced rapidly even without the aid of modern technology. However, a short introduction to computer programs, aiding the interpretation of geological maps, is given in chapter seventeen. Data manipulation has become more versatile by digitally storing geological base maps, and students need to be familiarized with a selection of the presently available fine software at an early stage. Obviously, digital technology may, in many instances of routine operations, remove time-consuming tedium. Nonetheless, it is important that students master the man-

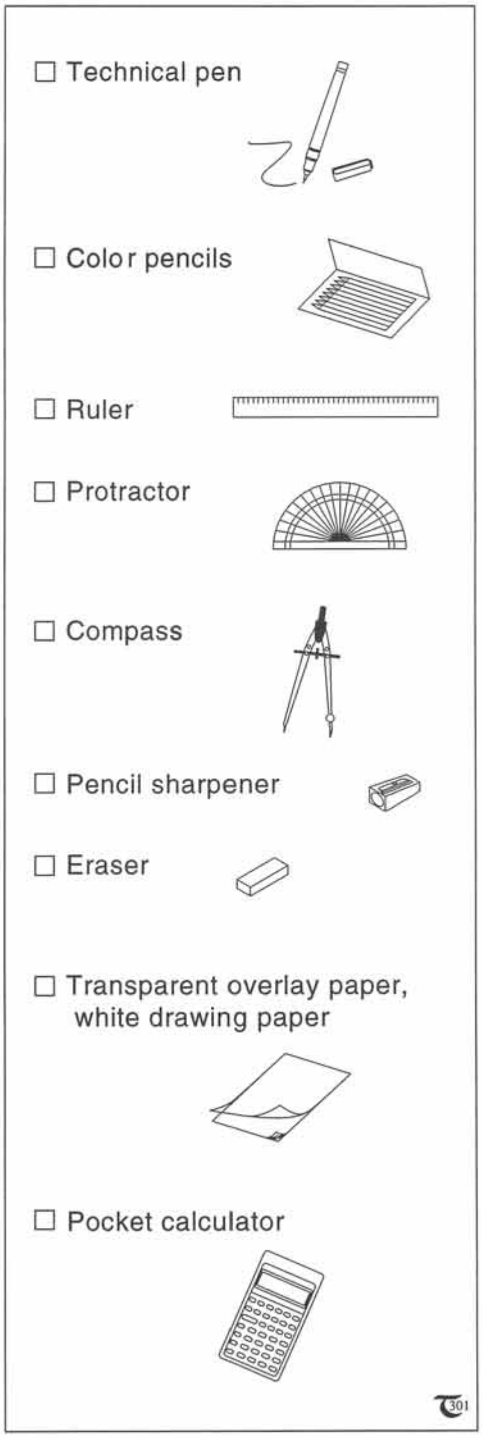


Figure 1-12: *Visual of supplies necessary to work on simple map interpretation exercises.*

ual construction techniques as a means of learning and because continued access to a computer set-up may not always be practical during field operations. A detailed understanding of the fundamental techniques of geological map interpretation is more important than ever, and the many exercises in this book aim to help the user achieve this end.

Because of the course organization adopted here, it may be useful to outline a broader structural geology curriculum considered appropriate in view of modern developments in the science. An effective teaching program covering most aspects of structural geology in a systematic fashion could include the following core courses: (1) structural geology and map interpretation, (2) geological field mapping and report writing, (3) field project, (4) mechanics of rock deformation, (5) tectonics, and (6) modeling of rock deformation. Course no. 2 is recommended as a full-semester course in combination with many short outdoor trips to demonstrate mapping principles. This course is ideally followed by a coordinated field project (no. 3) of several weeks where students can develop their individual mapping skills. An additional course in remote sensing may be considered for inclusion in the curriculum, because aerial photographs and satellite images serve as a base for many geological maps. However, if such a course is not included in the curriculum, chapter sixteen of this book provides a practical introduction to the methods of remote sensing. The following preparatory courses are recommended: (1) physical geology for a broader understanding of geological processes that shape the Earth's interior and exterior and (2) sedimentology, mineralogy, and petrology for a better understanding of the matter of which rocks are built.

1-4 Guide to the chapters

This book outlines basic geological structures and illustrates techniques of map interpretation. The chapters are organized as outlined below.

Chapter one has provided an introduction to the subject of structural geology by explaining the practical situations that led to its development as a scientific discipline and its applications. The relationship between this subject and other disciplines and courses was outlined in the previous section. The main text is further developed as follows.

Chapter two summarizes the principles of elevation contours and discusses how the topography of a terrain influences the outcrop pattern of geological units. The V-rule is introduced, and simple cross-sections are drawn.

Chapter three explains the use of dip, strike, and azimuth of units for characterizing the orientation of geological features. The differences of true and apparent dip and true and apparent thickness are explained.

□Exercise 1-1: Study the block diagram of Figure 1-4 and the associated data of Table 1-1. Answer the following questions: a) Which wells have the largest and smallest yields? b) Where does the water of the fault zone in well number one come from? c) What is the role of the aplite dike in the yield of well number four?

□Exercise 1-2: Refer to the map of Figure 1-7b. a) Color the scar of the 1925 Gros Ventre slide in red, the slide deposit in green, and the Gros Ventre Lake in blue. b) Why did the slide mass move due north, and why did it cease to move in the outlined location? c) What happened to the Old Bierer cabin?

Chapter four outlines the use of geological cross-sections. Such sections serve to clarify the subsurface structure. Criteria for the selection of a section line and the various sources of distortions in sectional views are outlined.

Chapters five and six discuss the many applications of structure contours. Such contours can be used to determine geological strikes and dips. Discussed are: inliers and outliers, three-point problems, and the insertion of outcrops.

Chapter seven introduces elementary terminology for the description of folds. The map patterns of both upright horizontal and plunging folds are explained. Doubly plunging and recumbent folds are, also, briefly outlined.

Chapter eight discusses the use of form lines and explains the principles of structure contours in analyzing map patterns of horizontal and plunging folds.

Chapter nine outlines maps of terrains that include various types of unconformities. Isopach maps are, also, discussed.

Chapter ten summarizes techniques for the 3-D visualization of geological structures, using various types of block diagrams.

Chapters eleven and twelve concentrate on map patterns of faulted rock units. Faulted, homoclinal beds are discussed first, followed by fold patterns displaced by several types of faults.

Chapters thirteen and fourteen outline the map pattern and tectonic aspects of intrusive and extrusive igneous structures. Ring dikes, cone sheets, mantled gneiss-domes, nested granites, and fissure eruptions are some of the structures discussed.

Chapter fifteen summarizes the geological map patterns related to meteoritic impacts, landslides, sinkholes, and glacier movement.

Chapter sixteen highlights the importance of aerial photographs and satellite images for mapping the ground surface. Methods are outlined to aid the interpretation of such remote sensing maps.

Chapter seventeen is the final chapter of this book. The increasing importance of computerized data manipulation, connected to geological maps and other display methods, is outlined.

MOST MAPS AND SECTIONS IN THIS BOOK ARE SCALED METRICALLY BUT SOME ARE SCALED IN NON-METRIC LENGTH UNITS, USING FEET OR MILES. IT IS IMPORTANT TO BE FAMILIAR WITH BOTH SYSTEMS, BECAUSE NON-METRIC UNITS ARE STILL WIDELY USED IN THE PETROLEUM INDUSTRY. CONVERSION FACTORS OF LENGTH SCALES ARE GIVEN IN TABLE 1-2.

***Table 1-2:** Conversion of length scales.*

	centimeters	inches	feet	meters	kilometers	miles
centimeters	1.0	0.3937	0.0328	0.01	10^{-5}	6.215×10^{-6}
inches	2.540	1.0	0.0833	0.0254	2.54×10^{-5}	1.578×10^{-5}
feet	30.48	12.0	1.0	0.3048	3.048×10^{-4}	1.894×10^{-4}
meters	100.0	39.37	3.281	1.0	10^{-3}	6.215×10^{-4}
kilometers	10^{5}	3.94×10^{4}	3281	10^{3}	1.0	0.6215
miles	1.609×10^{5}	63360	5280	1609	1.609	1.0

Example: 1 meter=3.281 feet