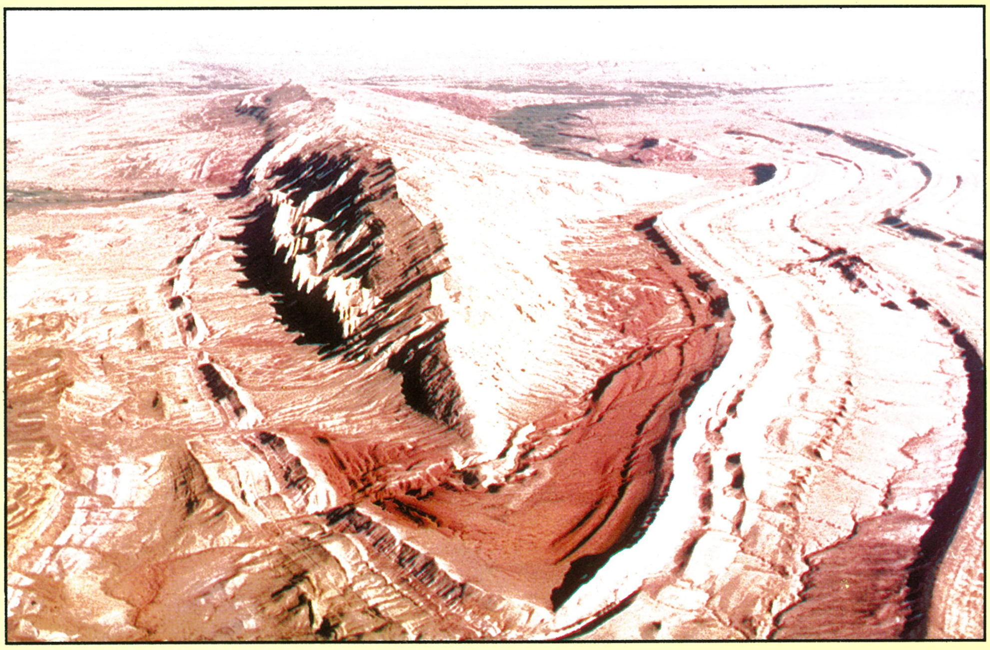
Structural Geology and Map Interpretation



Ruud Weijermars

LECTURES IN GEOSCIENCE

Alboran Science Publishing

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This book is intended for self-study, use in university courses and/or professional training. The inclusion of exercises in each chapter helps the user to quickly grasp the meaning of elementary concepts. Answers to the exercises are given in the back of the book.

Structural Geology & Map Interpretation has been distributed worldwide in hard copy - to over 60 countries – during the first few years after its publication in 1997. Active marketing and distribution ceased in 2001, but bookshops from around the world kept ordering the book for their clients. Users praised the book for its practical approach. Unfortunately, the book was no longer available in hard copy since 2005.

This book, was written in the 1990s, and sponsored by Uppsala University (Sweden) and King Fahd University of Petroleum and Minerals (Saudi Arabia). The intellectual property rights for this book are held by Alboran Science Publishing. Their support for the global distribution of this e-book is kindly acknowledged.

My hope is that this e-book can still serve as a valuable teaching and training aid. This is exactly what the book was written and published for in the first place.

Delft, January 2011

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Structural Geology and Map Interpretation

by Ruud Weijermars

Reviewed by: Dr. Pat James
Dept. of Geology & Geophysics
University of Adelaide, Australia

Not *another* textbook on structural geology and geological map interpretation!? This might be the first response to seeing this book on the bookshelves of the University bookshop (or *via* Amazon.com), or from this review of Dr. Weijermars' text. There have been so many textbooks on structural geology over the last twenty or more years, and on geological mapping, on map interpretation and on structural mapping. Is this just another rerun of what we all know is the fascinating topic of understanding the intricate geometry and map scale distribution of deformed terrains?

No, this *not just* another textbook on structural geology and geological map interpretation! It is an excellently composed resource, a unique view on the subject, and an extremely useful and practical textbook for the first introduction of geological maps of deformed (and other) rocks to basic undergraduate classes.

Where is it different and unique? It is in integration!, in other words, the way that the content, examples, exercises, illustrations have been melded into a curriculum, that makes the product such a potentially useful learning resource.

Its value is in the highly construction of a sequential understanding of structures and their morphology, *i.e.* there is a theoretical underpinning. It is in the large number (more than 300) and proportion compared to text pages, and liberal distribution of line drawing illustrations of structural geometries, maps, sections, block diagrams, cartoons of every conceivable array of structures of all scales. It is in the great variety of half-tone photographs and examples from each type of structural domain; and it is of note that these examples are not singled out from one or two continents (*e.g.* USA or Europe) as in many texts, but are scattered across the globe from Texas to Turkey and from Blinman to Billefjorden. Also many of the examples are taken from the petroleum/hydrocarbon industry and thus for the first time place this geological area on an equal footing with those based on the more traditional structural practical manuals designed around coalfields and metalliferous regions.

But it doesn't end there! Amongst this wonderful array of content and curriculum are more than 100 regularly spaced exercises for students. There are many books where only map exercises occur, but none to my knowledge where they have been so closely integrated into the text to make the book a veritable mine of problem-solving exercises to encourage reflective study. And the answers to all of the exercises are neatly and logically explained at length in Appendix D — Solutions to Exercises.

In commenting on the appendices, there is also an appendix (A) of Auxiliary Reading subdivided into groups of texts dealing with structures, geological maps, remote sensing maps, and structural journals. Appendix B provides detailed credits and information on the origin of all of the (many) figures, which allow ready recourse to the original texts from where they came. Appendix C, again is not usually found in many texts, and is a detailed, alphabetically arranged, glossary of terms (with 16 pages and 444 entries from Active Remote Sensing to Zoned Plutons). These terms are very usefully highlighted in the text by indicating each term in italics. Also finally there is a geographic index, a subject index and a translation of the abstract of the book into six languages.

I said finally, however at the very back of the book is an advertising feature labeled as additional resources or a "new directory of computer and remote sensing resources for geoscience mapping". This lists, again alphabetically (from AAPG Data Systems of Tulsa to Z & S Geologi A.S. of Stavanger), the names, addresses, contact details and some promotional material on the global array of companies currently engaged in the geo-mapping industry — a most useful and necessary finale.

Having lauded the textbook and its complementary appendices, I should perhaps describe the content and layout in more detail, and perhaps finish with a few minor criticisms. The book is entitled "Structural Geology and Map Interpretation", and the close linkage of these two features is followed throughout the text.

The introduction describes the raison d'etre of the subject emphasizing the requirements of a solid grasp of structural geology and map interpretation in the applied fields of land use planning, pollution monitoring, and geological hazard prevention. In other words it links the understanding of structural geology to environmental monitoring as well as resource exploitation and indicates the need for precise understanding of the basic geological form of these features to the continued improvement of today's society.

The contents are then subdivided into 17 approximately evenly sized chapters varying from 8 to 29 pages each, but on average about 12–16 pages. The contents are logically grouped into five or six areas starting with an introduction to the basics concepts of topographic and geological maps, the definition of the structural symbols used on these maps (strike and dip) and the drawing of geological cross sections.

The next group of chapters (5–9) could be described as the geometric underpinning of map scale structures. Here we are introduced to structure contours and their construction (including 3 point problems) and subsequently the illustration of folded rocks, their interaction with complex topography and the development of unconformities.

Chapter 10 is a very useful interlude in this descriptive section and introduces the background and techniques behind the construction of three dimensional block diagrams and the different types of perspective and isometric constructions. This is followed by two chapters (11 and 12) which deal with faulted strata and faulted folds.

The next section may be considered unusual in a text on structural geology, but describes (in Chapters 13–15) the three dimensional geometry and map patterns of intrusive, extrusive, and exogenic (geomorphic) structures. It is followed by two chapters of more modern applications to structural mapping in Remote Sensing Maps (Chapter 16) and finally Computerization of Map Analysis (Chapter 17).

In terms of physical form of the book, I was provided with a softback version, which was printed on high quality gloss paper. Line drawings were excellent, but some of the halftone greyscale photographs appeared under or over exposed, detracting from the total quality of the book. I found only one spelling/typing error in a basically flawless book. In each section and chapter, the introduction, text, illustrations, examples and exercises were carefully interwoven and placed close together to aide simple reading without excess page turning.

I was pleased with the precise and detailed description of the techniques and skills needed to undertake the exercises even down to the frequent suggestions to "color in the unit" or to remember the need to calculate the "apparent" dip. I was less confident in the use of the term aximuth/dip rather than dip direction and I was surprised by the omission of any mention of linked fold/fault – ramp/flat geometries and the use of section balancing techniques — still this is a very introductory text. Overall I found this a potentially very useful teaching and learning resource, and I shall certainly look out for the other offerings to come soon in the Alboran Science Publishing series.

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Structural Geology
and
Map Interpretation

George Bennison, Donal Ragan, and John Shelton each have generously granted permission to reproduce some classical figures and photographs from their respective books (see illustration credits in Appendix B herein). These fundamental books have made lasting contributions to the development of the subject and are recommended for complementary study (see full titles in Appendix A).

Structural Geology and Map Interpretation

Ruud Weijermars

Alboran Science Publishing

Structural Geology and
Map Interpretation

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using eleven point size type
with thirteen point leading.
Headlines in 45 and 20 points.

Cover image: Oblique aerial view
of Sheep Mountain, Wyoming, USA.
Courtesy John Shelton.

Topographical maps have been used to explore first unknown continents, then the submerged ocean floor, and finally our neighboring planets. The more detailed, geological maps have been deployed - and still are - in the search for minerals, energy, and water resources. Urgently, knowledge of geology must now be utilized more widely in order to contribute to the benefit of man in three major fields of application: (1) the planning of land-use, (2) pollution monitoring, and (3) hazard prevention. Knowledge of the subsurface must be taken into account in any serious environmental and urban planning. This applies particularly to large construction projects and the search for appropriate sites for waste disposal. The pollution of many subsurface reservoirs needs better documentation and can be monitored using pollution maps for geological formations. Also, more geological hazard maps need to be made available. These hazards include: seismic zones, landslides, ground subsidence, mudflows, glowing avalanches, ashfalls, and lava flows.

The preparatory work for this book was jointly sponsored by *King Fahd University of Petroleum and Minerals*, Saudi Arabia, and the *Natural Science Research Council (NFR)*, Sweden.

Detailed Contents

Structural Geology and Map Interpretation

Chapter 10: Three-Dimensional Perspective Diagrams

Chapter 11: Maps of Faults in Planar Beds

Chapter 12: Maps of Faulted Folds

Chapter 13: Maps of Intrusive Igneous Structures

Chapter 14: Maps of Volcanogenic Structures

Chapter 15: Maps of Exogenic Structures

Chapter 16: Remote-Sensing Maps

Chapter 17: Computerization of Map Analysis

SCIENCE
Alboran

Preface to the series

Alboran's Lectures in Geoscience **is a textbook series, prepared by experienced earth scientists. The lectures are carefully organized and balanced in approach. Many professionals, students, and instructors have discovered the practical value of these books as user-friendly instruction manuals.**

Alboran's Lectures in Geoscience grew from the relative need for geoscience textbooks, covering topics tailored for university courses of one semester's duration. Many existing textbooks in geoscience tend to include increasingly detailed explanations. Such exhaustive books are very helpful for use in advanced studies and in research programs. But it has become increasingly difficult to cover the material of such books within one semester of teaching. Consequently, instructors have to make difficult choices on what material should be covered and what can be left out. And because most geoscience courses include weekly laboratory sessions, instructors, also, have to find suitable exercises to help students deepen their grasp of the subject.

Alboran's Lectures in Geoscience integrate exercises intimately with explanations of basic principles. This relieves instructors from painstaking compilation work. At present, separate laboratory manuals are sometimes used in combination with textbooks covering the contents of lectures. But, frequently, the material of textbooks and separate laboratory manuals do not easily blend. That is why instructors commonly resort to working through exercises from a variety of sources, and often supplied to students in the form of a collection of photocopies. The need to combine theoretical explanations with practical exercises applies to many subjects within the geosciences.

DR. BLAIR P. BREMBERG *is technical editor for the Alboran Lecture Series. His degrees were obtained from Beloit College (B.S.), University of Puget Sound (J.D.), and University of Utah (LL.M.), USA. He is registered with the Board of Registration for Professional Geologists, State of Wyoming, and serves on the Editorial Advisory Board of the Journal of Natural Resources & Environmental Law. He is a member of several professional organizations, including the Geological Society of America and the State Bar of California. Dr. Bremberg will assist authors in their efforts to contribute to Alboran's Lectures in Geoscience.*

Expansion of Alboran's publications in Geoscience

Join the partnership. *Alboran Science Publishing* welcomes inquiries from experienced geoscientists, who would like to contribute to its program with original titles. Potential contributors are encouraged to submit comprehensive proposals. A provisional outline, sample chapters, and a resume of the principal author(s) should be sent to: *Publications Manager*, Mr. J. Outhuis, Laurierstraat 132A, Amsterdam 1016 PR, the Netherlands. Fax: + 31 20 364 0145.

Each book in this new series targets users of a particular level. The treatment is authoritative, technically sound, and enlightened with excellent illustrations. The text is clear and concise and, therefore, is, also, suitable for refresher courses attended by professional geoscientists. As a comprehensive set of textbooks, this lecture series may contribute to establish a new teaching standard.

Outline of the series

This series starts with the publication of four different textbooks in the field of Structural Geology and Rock Deformation. The principles of structural geology and map interpretation, field analysis, rock mechanics, and the dynamic modeling of rock deformation are comprehensively covered in four up-to-date accounts. Each of the books constitutes an outstanding stand-alone text in its corresponding field. Effective continuity is preserved throughout, and the books may well be used in sequential courses, as follows:

- *Structural Geology and Map Interpretation,* for undergraduate students, published 1997.
- *Principles of Geological Mapping,* preparatory fieldwork training for undergraduates, due 1999.
- *Principles of Rock Mechanics,* for advanced undergraduates and postgraduates, published 1997.
- *Modeling of Rock Deformation,* for advanced undergraduates and postgraduates, due 1999.

> ***"The most ambitious and wide-ranging series of texts on structural geology" - M.P.A. JACKSON, University of Texas.***

Geological map of the central Arabian graben system, explained by Paul Hancock, during a short course by the International Union of Geosciences, 1994.

A brief description of these new titles in the *Alboran Lectures in Geoscience* follows here:

Structural Geology and Map Interpretation

Elementary geological structures and the principles of geological map interpretation are subjects ideally suited for coverage by an introductory course on structural geology. The traditional approach is to treat the principles of structural geology and map interpretation exercises in separate textbooks. The novel approach of this book is that it integrates the description of rock structures with interpretation methods of geological map patterns where possible. The teaching value is achieved not by high-flying theoretical displays, but by practical explanations, excellent illustrations, and detailed exercises, more than in any other contemporary textbook on the subject. This book includes seventeen chapters, four appendices, almost three hundred illustrations, and more than one hundred exercises.

Subjects covered: applications of structural geology, elevation contours, V-rule, true and apparent dip, true and apparent thickness, fold nomenclature and maps, structure contours, insertion of outcrops, three-point problems, cross-sections, perspective diagrams, unconformities, faults, intrusive and extrusive igneous structures, impact structures, landslides, sinkholes, glacial structures, an introduction to remote sensing maps, and methods of computerized map analysis.

Principles of Geological Mapping

Once familiar with the basic meaning of geological maps and the variety of geological structures, students should be given the opportunity to go into the field and individually practice the art of geological mapping. This book teaches geology students how to prepare for field trips and how to observe and document field geology. The special skills and knowledge involved in field surveying are outlined. The emphasis is on those aspects of geology which are best studied in the field with good examples at hand in their natural setting. The main text and exercises explain modern mapping techniques suitable for a range of geological terrains. The material is, also, suitable for theoretical and practical support of advanced field surveys.

> ***"It will be exceedingly difficult for any student following this text diligently to fail his or her terminal exams!"- D. ROBERTS, Geological Survey of Norway.***

Subjects covered: planning and preparation of geological fieldwork, safety and courtesy rules, outcrop location and orientation in the field, distinction of mappable rock units, use of the geological compass, field note compilation, stratigraphic sections, cleavage and foliations, modern terminology and techniques for mapping deformation structures, lineation and foliation terminology, the mapping of major fold closures from the vergence of minor folds and cleavage vergence, fold interference patterns, shear zones and the determination of their sense of movement from kinematic indicators, the mapping of metamorphic isograds, stereographic projection of structural data, practical applications of orientation analysis, compilation of a geological history, and instructions on the writing of geological reports.

Principles of Rock Mechanics

The elementary principles of rock mechanics are introduced. The book is subdivided into two parts: (1) Mechanics and Rheology, which includes eight chapters on classical rock mechanics, and (2) Tensors and Deformation Analysis, devoting eight chapters to the tools and techniques for quantifying patterns and processes of rock deformation. The sixteen chapters include more than one hundred exercises and some three hundred illustrations.

Subjects covered: physical quantities in rock mechanics, force and stress, rock rheology (elasticity, brittle failure, and ductile creep), viscosity and flow laws, stress tensors, strain tensors, deformation tensors, practical strain analysis.

Modeling of Rock Deformation

Techniques for the modeling of rock deformation structures are discussed.

Subjects covered: various modeling methods (analog, analytical, and numerical), section restoration, scaling theory, and applications of advanced stress functions and stream functions.

Preface for this book

● Emergence of this book - Why?

In this textbook, the geometric description of geological structures is deliberately separated from genetic interpretations concerning their formation. However, the wider realm of structural geology includes such genetic interpretations of rock structures, and, also, studies the mechanisms and forces involved in rock deformation. But such references to the dynamics, kinematics, and mechanisms of rock deformation are minimized at this introductory stage. The mechanics of geological structures can be understood properly only if the reader is first introduced to the fundamentals of continuum mechanics, rock rheology, and fluid dynamics. These fundamentals are systematically developed in *Principles of Rock Mechanics*, a more advanced companion text.

Structural Geology and Map Interpretation provides for students a series of exercises on geological maps, integrated with explanations of basic structural geology. To ease the reading, chapters cover only one major theme each, building up from short and simple sentences. The maps of elementary rock structures collected in this book form a valuable resource for students working on map exercises. The inclusion of numerous exercises urges receptive and reflective study of the subject matter.

In this book, the emphasis of the instructive medium is on manual techniques. However, a short introduction to computer programs, aiding the interpretation of geological maps, is given in the final chapter. The present book further differs from other texts through the inclusion of concise chapters on igneous structures (chapters 13 and 14), exogenic structures (chapter 15), and the use of remote-sensing maps (chapter 16). Igneous intrusives are associated with ring dikes, cone sheets, and mantled gneiss-domes, all of which are basic geological structures with intricate map patterns. Similarly, volcanogenic structures include a range of associated fissure patterns and, therefore, deserve some attention in an introductory text of structural geology. Exogenic structures (impact craters, landslides, sinkholes, and glacial structures) are included because such superficial structures may complicate the interpretation of geological maps in many regions.

The author, using geological maps to discuss the geological setting of the Mylonite Zone at Vaermlandsnaes, during a short course for the Geological Survey of Sweden, 1992. Courtesy Thomas Lundqvist.

If only one course is available to cover all elementary aspects of structural geology, then topics on stress and strain have to be included as well. For such condensed courses, selected chapters of this book can be supplemented with material and exercises on stress and strain from the companion text, *Principles of Rock Mechanics*.

● About the author

Dr. Ruud Weijermars is Associate Professor at *King Fahd University of Petroleum and Minerals (KFUPM)*, Dhahran, Saudi Arabia. He received a Ph.D. in geodynamics from the *University of Uppsala* in 1987, and BS and MS degrees in geology and structural geology, respectively, from the *University of Amsterdam.* Dr. Weijermars joined the Department of Earth Sciences at KFUPM in 1992. He has previously worked at the *University of Amsterdam*, Netherlands; *University of Uppsala*, Sweden; *University of Texas* at Austin, USA; and the *Technical Highschool of Zurich*, Switzerland. Dr. Weijermars is the author of numerous research articles. His main publications are in the areas of structural geology, rock mechanics, and the modeling of rock deformation. He is a member of the *American Association for the Advancement of Science*, the *Geological Society of America*, the *American Association of Petroleum Geologists*, and the *New York Academy of Sciences*.

● Course plan

This book is aimed at undergraduate students, already familiar with some of the basic principles of geology as introduced by courses in physical geology or historical geology. The material of *Structural Geology and Map Interpretation* has been designed for a one-semester course, following an American-style course plan. This includes weekly instruction, which is comprised of two lectures (fifty minutes) and one laboratory session (three hours), for fifteen weeks and a fair amount of homework. The seventeen chapters can be covered in thirty lectures, further supported by fourteen laboratory sessions and homework. Each chapter requires about one or two lectures and one laboratory session. Any faster progress makes space for additional activities. These may include field trips, computer demonstrations, and additional reading and exercises.

● Acknowledgements by the author

Each of the chapters in this book has been carefully reviewed by one or more colleagues, who received a first draft in 1994. Their helpful suggestions and comments contributed to establishing a reliable text in a tedious process of writing, rewriting, and editing. I am grateful to the following reviewers for their efforts on the quoted chapters of *Structural Geology and Map Interpretation*: **Richard Lisle**, *University of Wales*, UK (Chapter 1); **Moujahed Husseini**, *Gulf Petrolink*, Bahrain (Chapter 2); **Steve Reynolds**, *Arizona State University*, USA (Chapter 3); **Ben van der Pluijm**, *University of Michigan*, USA (Chapter 4); **David Roberts**, *Geological Survey of Norway* (Chapter 5); **Peter Johnson**, *US Geological Survey Mission*, KSA (Chapter 6); **Peter Hudleston**, *University of Minnesota*, USA (Chapter 7); **Ian Davison**, *University of London*, UK (Chapter 8); **Clive Boulter**, *University of Southampton*, UK (Chapter 9); **Martin Jackson**, *University of Texas*, USA (Chapter 10); **Adrian Pfiffner**, *Univerity of Bern*, Switzerland (Chapter 11); **Steven Wojtal**, *Oberlin College*, USA (Chapter 12); **Jean-Luc Bouchez**, *Université Paul-Sabatier,* France (Chapter 13); **John Roobol**, *Deputy Ministry for Mineral Resources*, KSA (Chapter 14); **David Gee**, *University of Lund*, Sweden (Chapter 15); **Weston Gardner**, *KFUPM Research Institute*, KSA (Chapter 16); **Gabor Korvin**, *King Fahd University of Petroleum and Minerals*, KSA, **Brian Gratto**, *Saudi Aramco*, KSA, and **Paul Williams**, *University of New Brunswick*, Canada (Chapter 17). Translations of the introductory text on the back cover of this book have been provided by: **Abdul-Latif Qahwash**, *King Fahd University of Petroleum and Minerals*, KSA; **Vladislav Alekseev**, *University of Graz*, Austria; **Lu Chia-Yu**, *National Taiwan University*; **Julia Cuevas**, *Universidad del Pais Vasco*, Spain; **Jean Louis Vigneresse**, *CREGU*, France; and **Stefan Schmid**, *University of Basel*, Switzerland.

Partial financial support was provided by *King Fahd University of Petroleum and Minerals*, Saudi Arabia, and the *Natural Science Research Council of Sweden* through research grants ES/-TRANS/154 and ES/ROCK/155 and several NFR-1858 contracts. Guidance on matters of scientific policy was provided by professors Hans Annersten, Abdullah Al-Abdul-Gader, Abdulwahab Abukhodair, Zaki Al-Harari, Ala Al-Rabeh, and Abdullah Al-Zakri.

Many friends and relatives have unknowingly contributed to this book by sharing their trust, warmth, and friendship. Without their support, it would have been impossible to find the peace of mind required to complete this work. I am, also, indebted to my students, who have studied these course materials. Their feedback has helped to test the adequacy of the text and exercises and has resulted in the improvement of this first printing. Technical assistance was provided by many professionals: Jeanette Bergman Weihed, with her efficiency in digital drafting; Bertel Giös and Christer Beck, with their high quality photography; and Nancy Taylor and Blair Bremberg, with their superb editing. Secretarial support was provided by Gulam Khan, Khaled Khan, Azeez Khan, Ahmad Al-Saif, Shahul Hameed, Mohammad Mohammad, and S. Ameeruddin.

> ***"An easy to follow and very well-illustrated book on a difficult subject" - M.I. HUSSEINI, President Gulf Petrolink.***

I feel that it is not appropriate to include exhaustive references in the main text. All of the material discussed is well-established among experts. It has been quoted time and again and, thereby, has become common intellectual property. It is simply impossible to trace the genuine origin of the concepts discussed, because each of them has evolved slowly by incremental contributions of numerous scientists. Perhaps, any room for originality remains only in the way these concepts are explained and illustrated.

Suggestions for auxiliary reading are given in *Appendix A*. Illustration credits are rightfully included in *Appendix B*. A glossary of basic terms is given in *Appendix C*. Solutions to the exercises are outlined in *Appendix D*. American English spelling has been used throughout the text.

I encourage readers to bring any suggestions for further improvement of any aspect of this work to my attention. These suggestions will be taken into account and will help to prepare any updated version of this book.

Dhahran, 23 June 1996

Structural Geology
and
Map Interpretation

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.

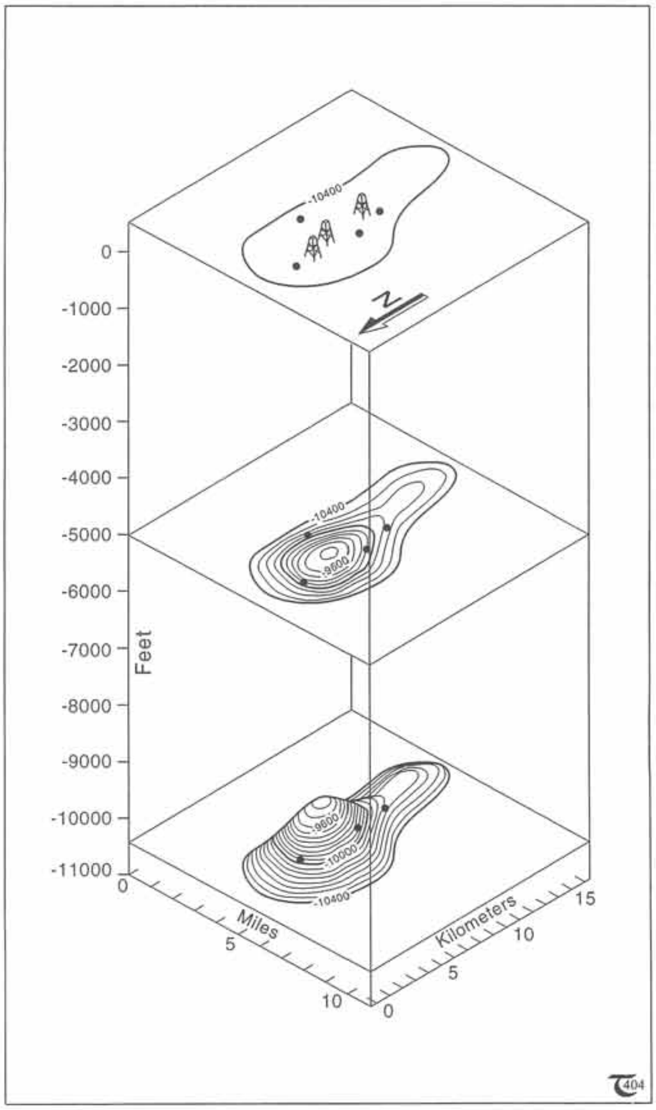


Figure 1-1: Structure contours (in plan projection and relief view) of the Ekofisk oilfield, North Sea. Outer contour is 10,400 feet below the seabed.

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.*

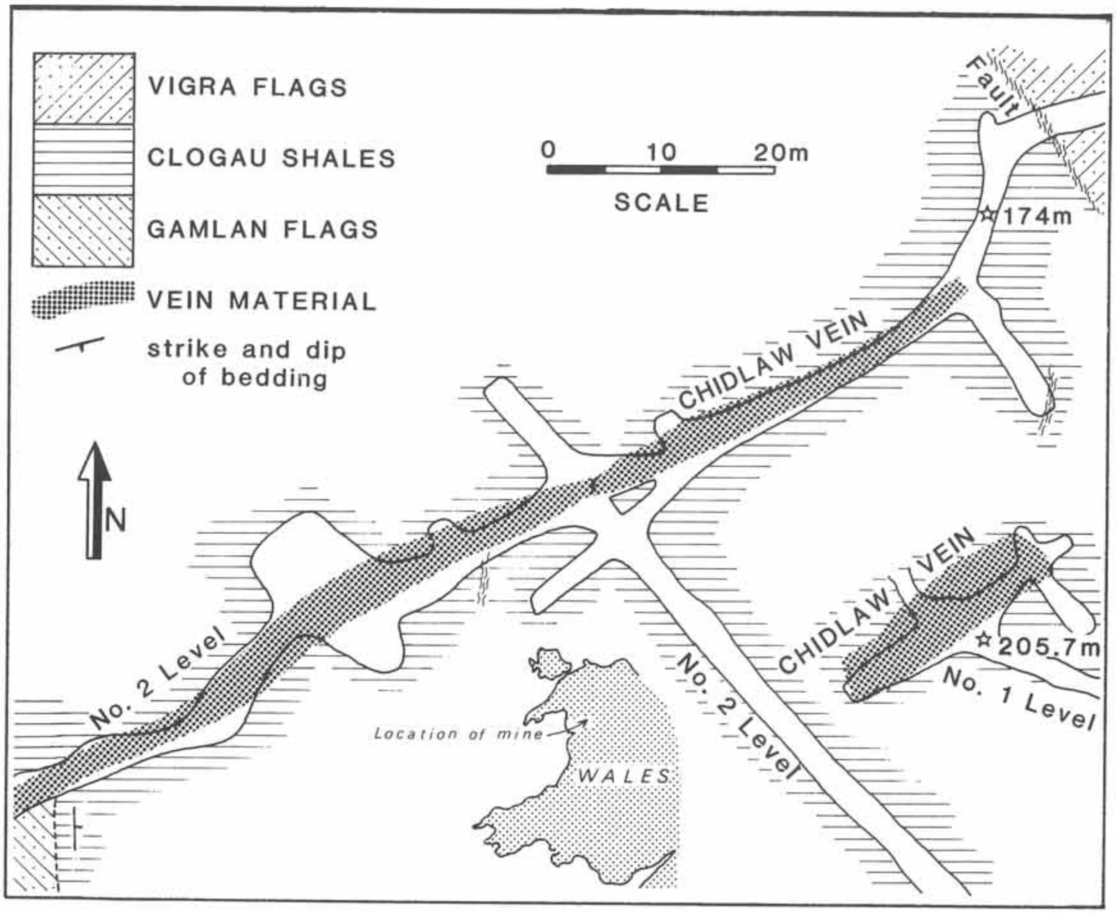
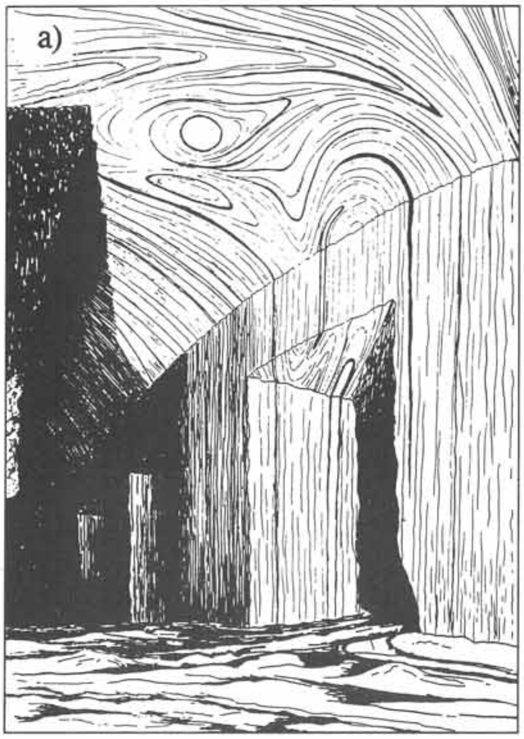


***Figure 1-2b:** Gwynnfynnid Gold Mine, Wales.*



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

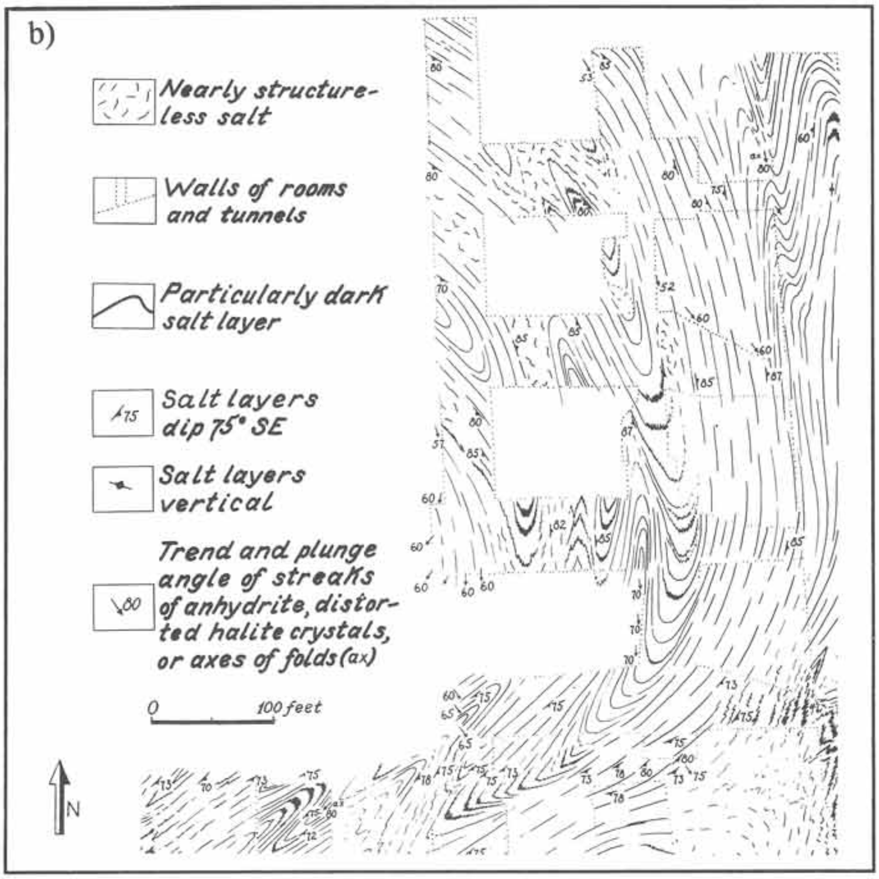


Figure 1-3: a) Sketch outlining the traces of darker layers in folded salt beds inside Jefferson Island salt dome, Louisiana. Portals are about ten meters high. b) Map projection of folded salt beds in the Gran Saline Mine of the Morton Salt Company, Texas.

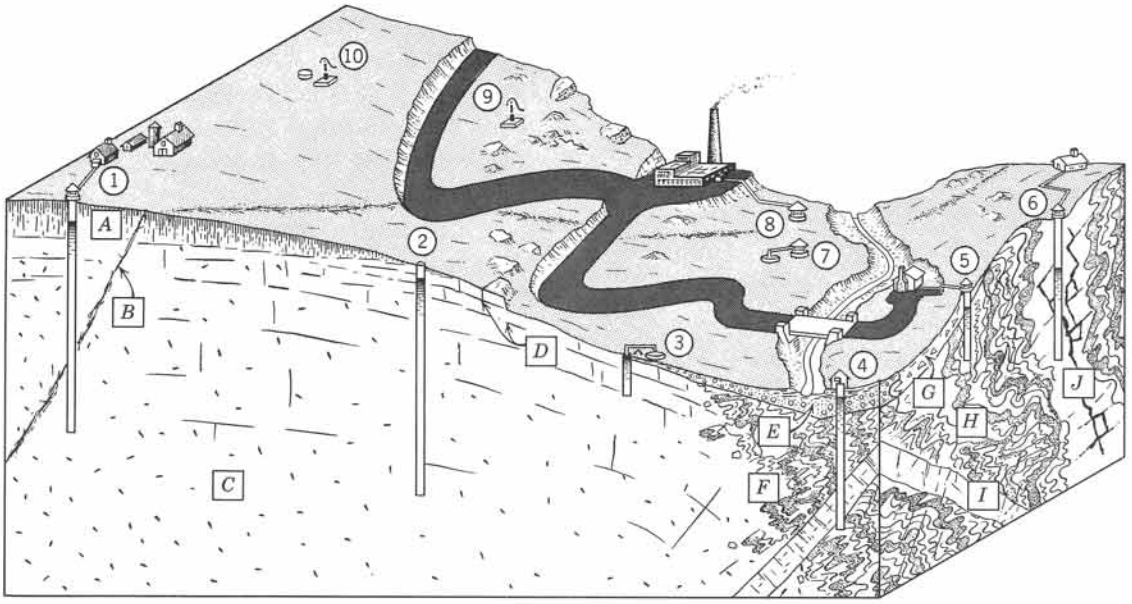


Figure 1-4: Geological structures in a hypothetical region and potential locations for water wells. The well-yields depend upon the hydrogeological subsurface structures (Table 1-1).

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.

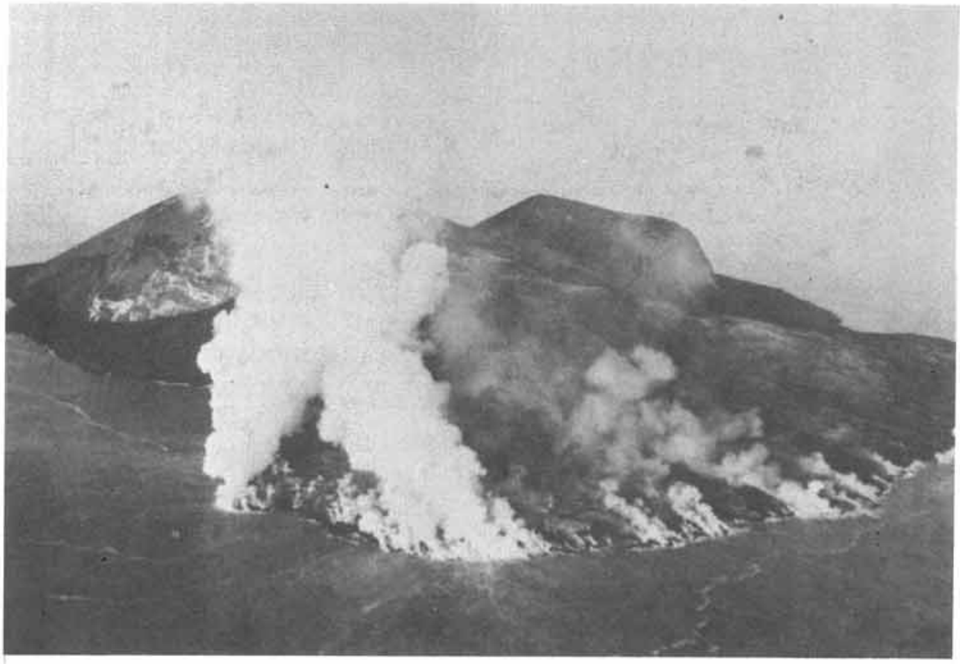


***Figure 1-6a:** Steam escapes, where the advancing lava meets the sea water, during the emergence of the volcanic island of Surtsey in 1963, off-shore Iceland.*

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

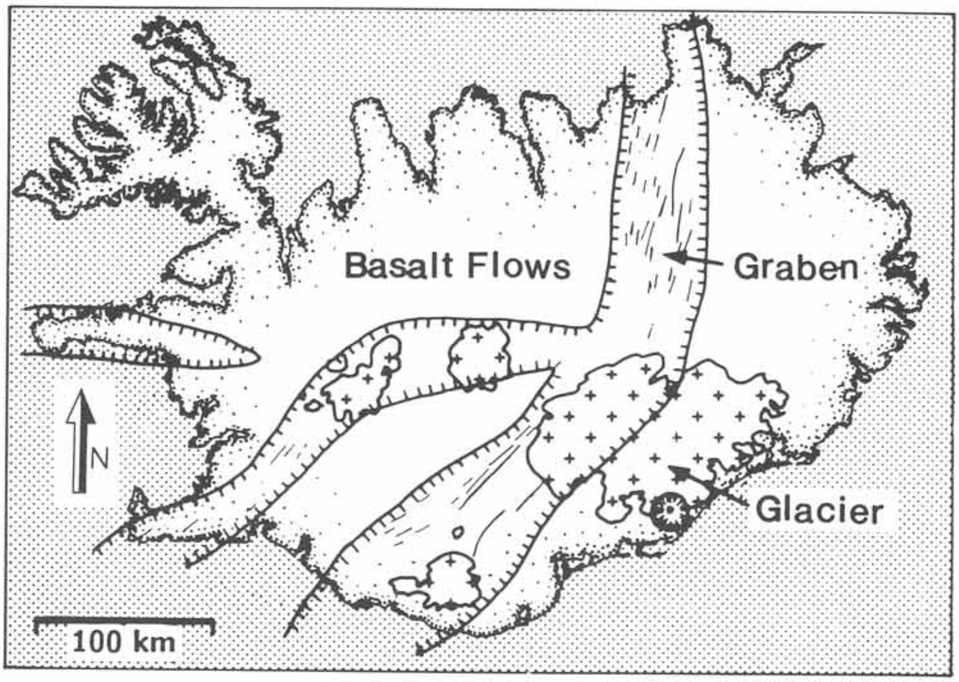


***Figure 1-6b:** Iceland is split between two worlds. The Eurasian and North American plates meet in Iceland and continue to separate by spreading, rifting, and volcanism.*

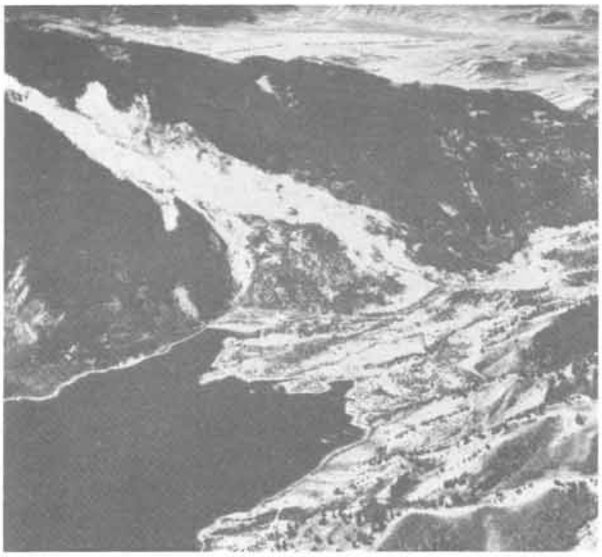


Figure 1-7a: A scar in the landscape marks the site of the Lower Gros Ventre slide, Wyoming, which took place June 23, 1925. View is facing southwest.

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

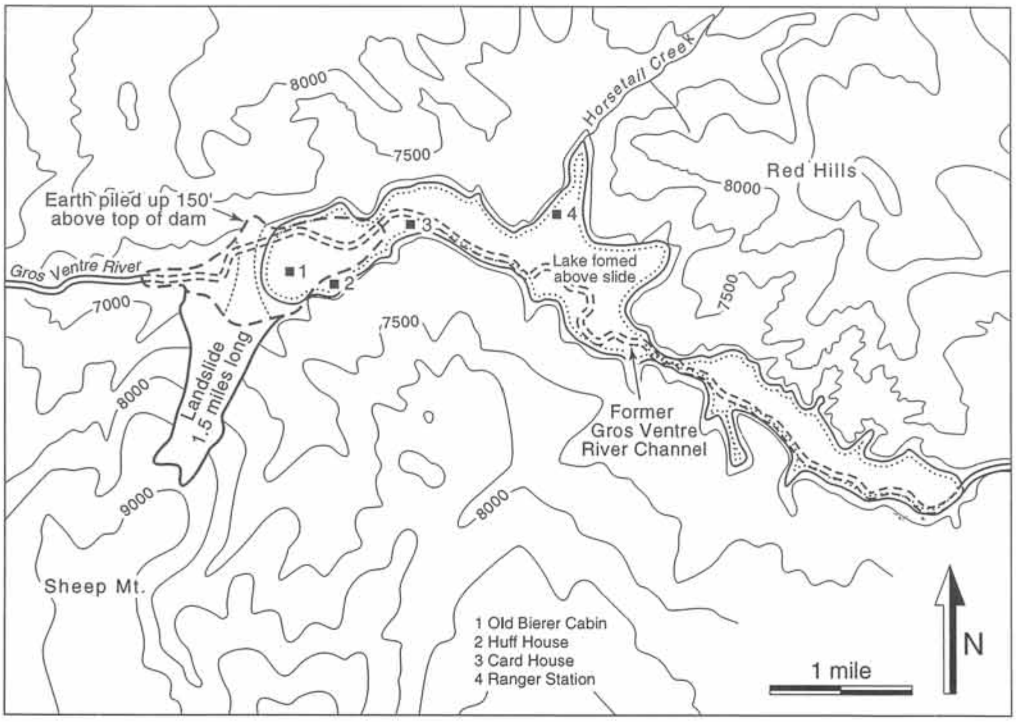


Figure 1-7b: Sketch map of the landslide scar and the dam of the slide mass blocking the Gros Ventre River, which led to the formation of Gros Ventre Lake.

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.*

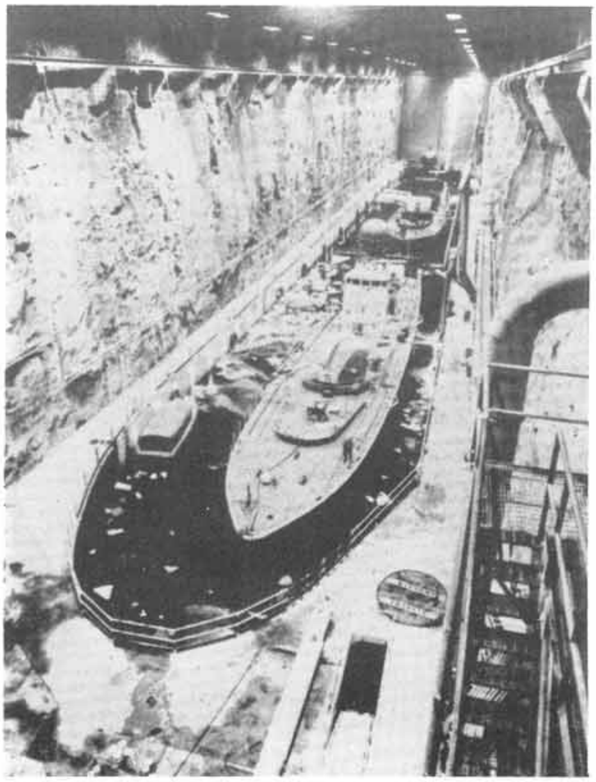


Figure 1-9b: *Underground marine dock, excavated in the Precambrian rocks of the Baltic shield, Sweden. Man at the bow of the destroyer for scale.*

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

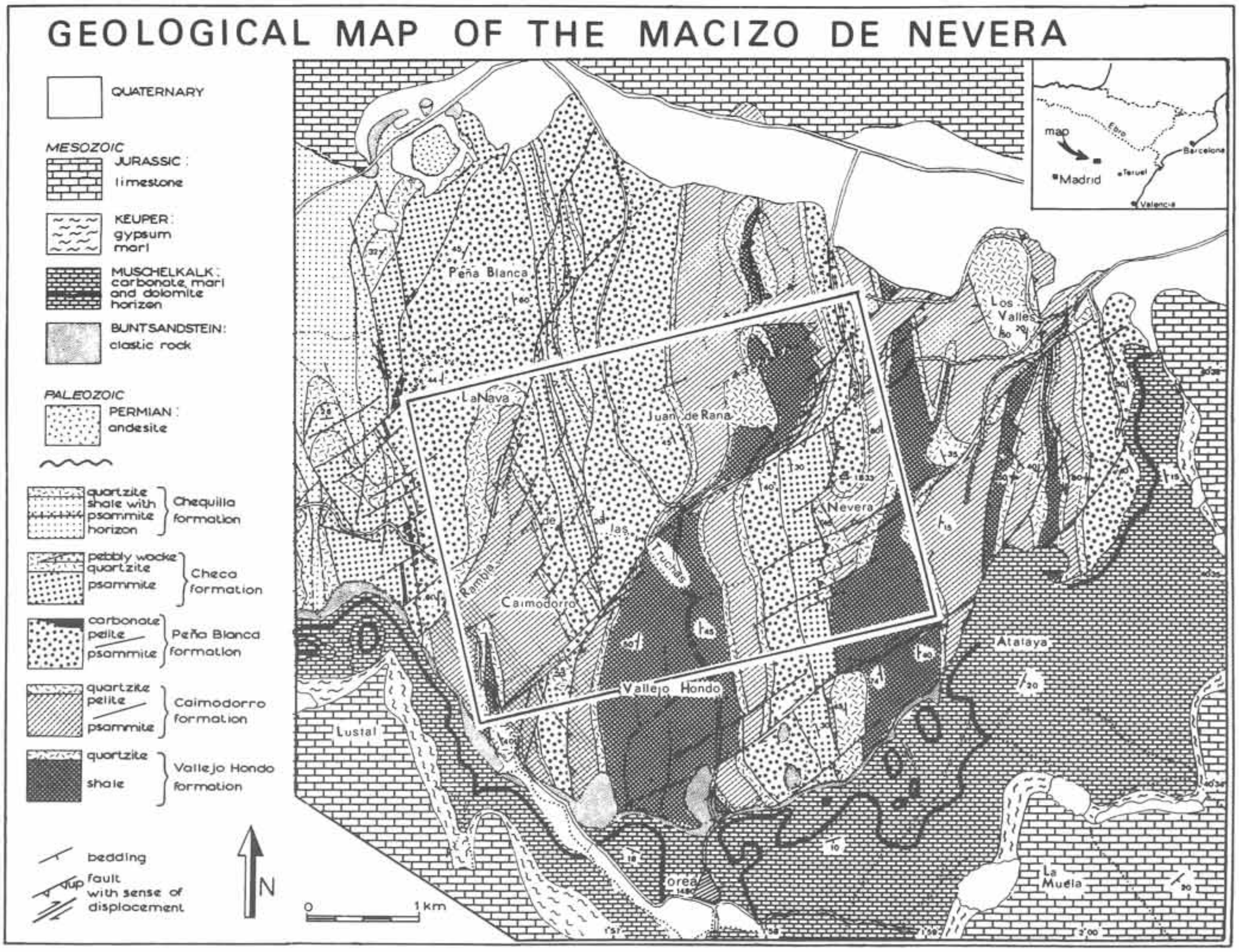


Figure 1-11a: Geological map of the Macizo de Nevera, Sierra de Albarraccin, central Spain. Inset shows location.

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.

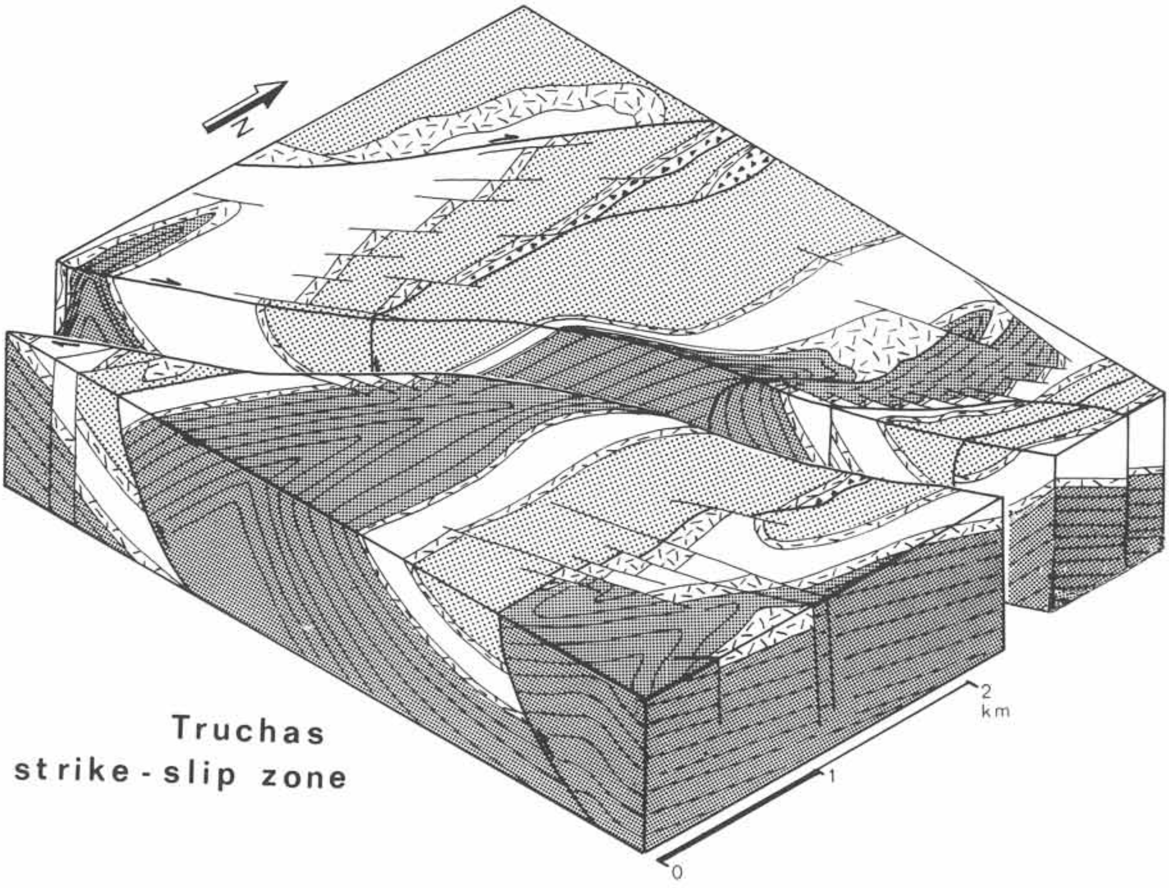


Figure 1-11b: Isometric block diagram of the Truchas shear zone, Macizo de Nevera.

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.

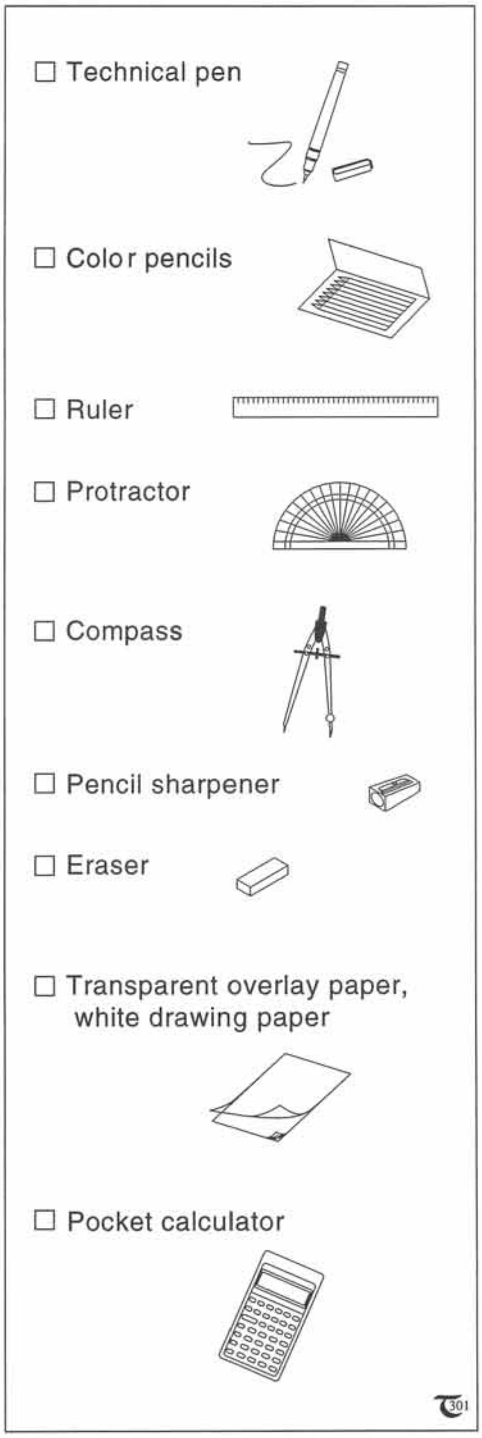


Figure 1-12: Visual of supplies necessary to work on simple map interpretation exercises.

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 manual 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

Chapter 2: Topographic and Geological Maps

MUCH OF structural geology is concerned with the representation and production of geological maps. Such maps are prepared using base maps for the particular area covered. Base maps of various scales are usually available from national geographic surveys or may be prepared from field surveys and remote sensing data. The base map contains a scale bar, geographical north arrow, geographical gridlines, and location names. For detailed geological maps, a good basemap includes the morphology or shape of the landscape as represented by topographic elevation contours. On such geological maps, local irregularities in the terrain greatly affect the map pattern of rock formations.

Contents: The basic principles of elevation contours are explained in section 2-1. Any pronounced relief in the ground surface affects the shape of the outcrop pattern, as explained in section 2-2. Geological cross-sections and columnar sections are briefly introduced in sections 2-3 and 2-4, respectively.

2-1 Elevation contours

The Earth's surface displays a variety of landforms, including mountainous terrains incised by steep valleys, flat plains, meandering river channels, and monolithic mesas, remaining after extensive erosion of an uplifted formerly planar area. The topographic relief of the landscape can be represented by a series of smoothly curved lines, called *contour lines*. The great value of topographic maps is that these show the shape and elevation of the ground surface, using contour lines. A contour line connects points which are all at the same elevation. The coastline of an oceanic island outlines the contour line at sea level (Fig. 2-1a). Contour lines were originally constructed by measuring the elevation at a number of locations in the field. The contour lines were then sketched by extrapolating between the measured points. Modern topographic maps

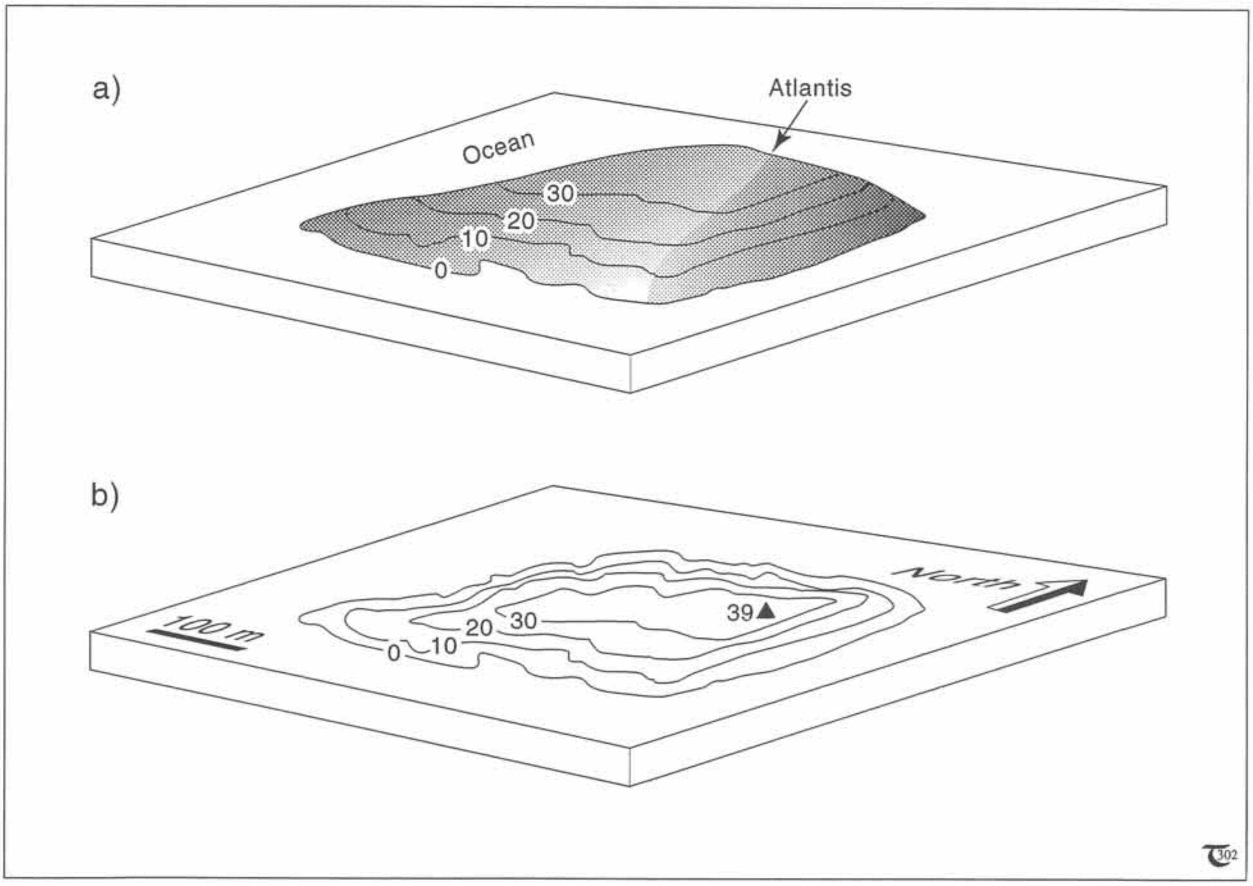
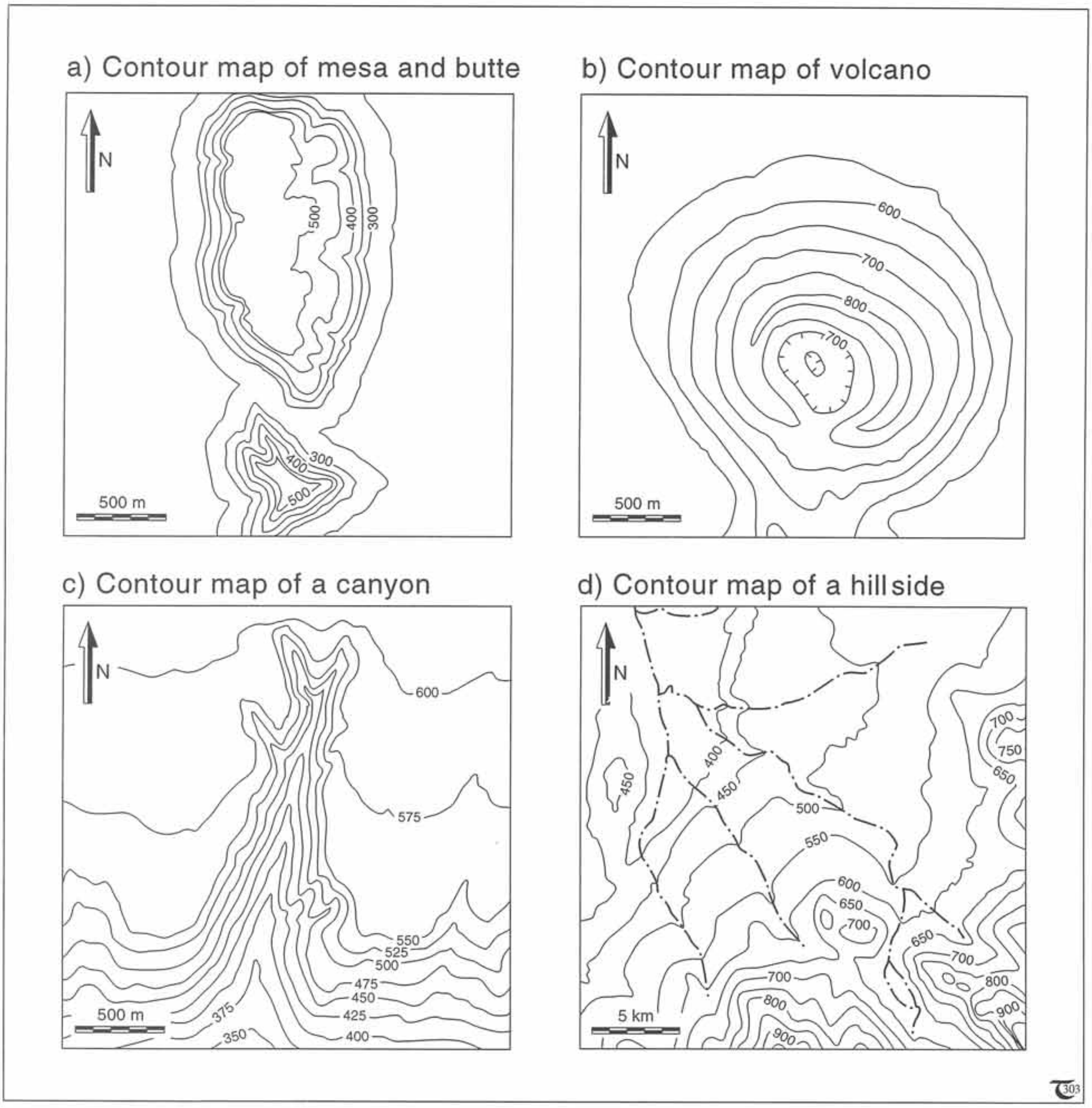


Figure 2-1: *a) Perspective view of a hypothetical island with topographic elevation contours (in m). b) Topographic contour map of the island is obtained by projecting the contours on a plan map.*

are prepared in digital format from stereoscopic pairs of aerial photographs.

Figure 2-1a shows topographic contours sketched on the slopes of an oceanic island. The topographic map is constructed by orthogonal projection of the contour lines onto a horizontal surface (Fig. 2-1b). The spacing of the elevation contours in this example is ten meters. This means that the elevation is indicated only at points of zero, ten, twenty, and thirty meters altitude above sea level. This number of contour lines is sufficient to define the shape of the island. The summit of the island may be an important landmark, and its exact height can be separately indicated and marked by a dot or triangle. The representation of most landscapes is by an orthogonal topographic map.

Although the principle of topographic maps resulting from the orthogonal projection of contour lines is simple, reading of contour maps requires some ability and experience to imagine the three-dimensional shape of the terrain represented. The following rules help us to understand better the concept of topographic contours: (1) Contour lines never cross or divide. They form a set of smooth and subparallel curves (Fig. 2-1b). (2) The spacing of the contour lines reflects the gradient of the slope. The closer the contours, the steeper the terrain. Contours which appear to overlap express a steep cliff. Widely spaced contours imply gently inclined slopes. (3) The difference in elevation between adjacent contour lines is constant on any given map. However, the contour interval on different maps may be different and is determined by what is convenient for



a) Contour map of mesa and butte

b) Contour map of volcano

c) Contour map of a canyon

d) Contour map of a hill side

Figure 2-2: Topographic contour maps of: (a) mesa and butte, (b) volcano, (c) canyon, and (d) hillside.

the particular landform displayed. The elevation of the contours will be indicated along them at regular intervals.

Some basic contour patterns are outlined in Figure 2-2. The closed contours of Figure 2-2a are typical for hills. In this case, the top of the hill is relatively flat and the landform is a mesa or high plateau. The smaller isolated hill in the bottom of the map may be called a butte. The circular contour pattern of Figure 2-2b shows a steep-sided cone with a central depression. The depression is conventionally indicated by closed contours with hachures, short tick marks, pointing downslope. This landform typically is displayed by young, large stratovolcanoes and

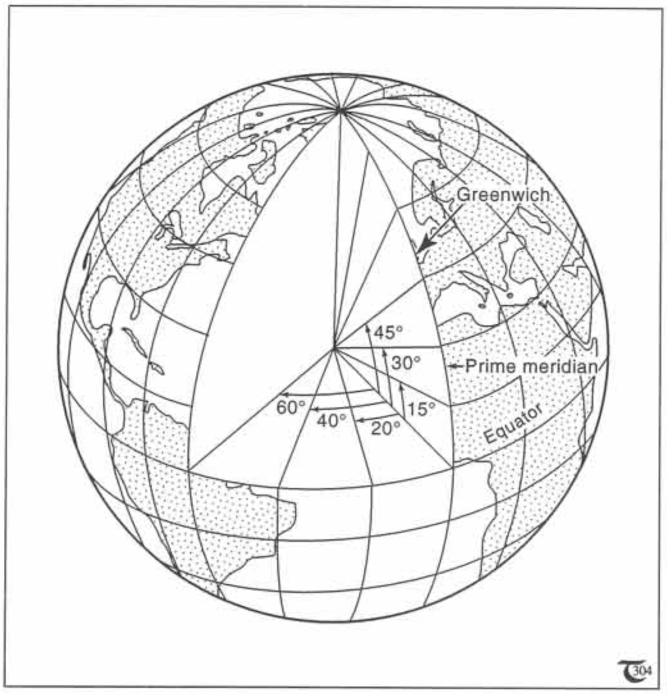


Figure 2-3: *The global longitude and latitude grid; zero degree longitude is at a polar meridian passing over Greenwich, UK.*

smaller cinder cones. Figure 2-2c is a contour map of a steep-sided canyon. Contour lines trend up the valley, cross the stream, and extend down the valley on the opposite side. The contours form a V-shape, pointing upstream and uphill near the stream origin. Figure 2-2d shows the margin of a mountainous area in the southeast with a drainage pattern running off toward the more gently sloping terrain in the northwest.

Figures 2-1 and 2-2 do not have the geographical location marked on them, because they are imaginary examples of elevation contour maps. Professional topographic maps are framed in an outline with tick marks indicating latitude and longitude in degrees and minutes. Most commonly used is the global longitude and latitude grid, which places the Royal Observatory of Greenwich, United Kingdom, at the meridian of 0° longitude and the equator at 0° latitude (Fig. 2-3). The northern hemisphere is subdivided into 90 degrees of northern latitude and places the North Pole at latitude 90° N. The southern hemisphere is similarly divided into 90 degrees of southern latitude. The western hemisphere is subdivided into 180 degrees western latitude and the eastern hemisphere likewise. The longitude lines of 180° E and 180° W coincide in a meridian which, theoretically, defines the international date line. But, in reality, the date line wanders far from the meridian of 180° longitude.

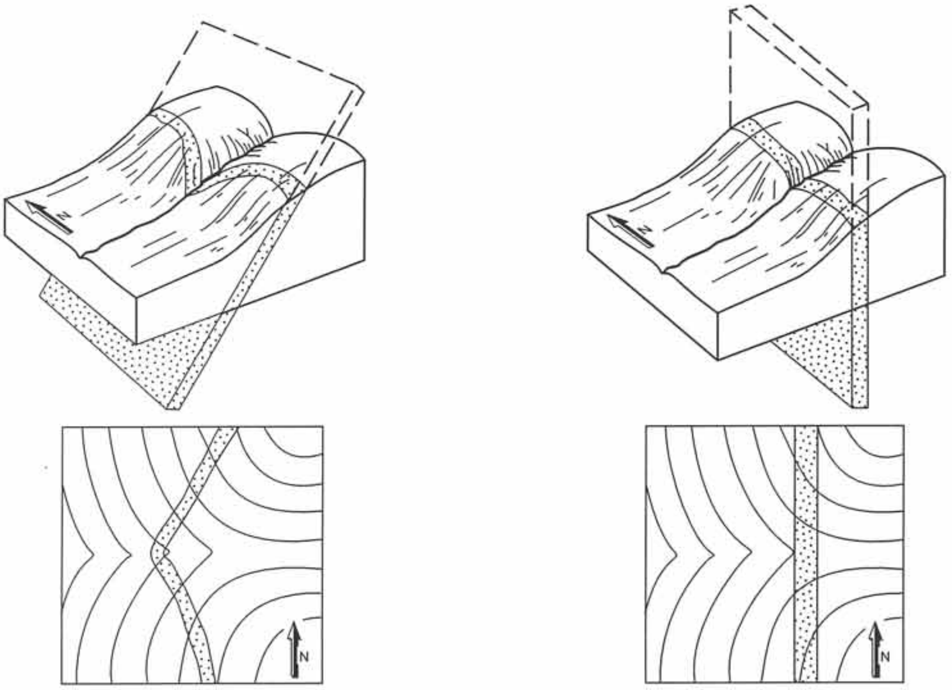
☐Exercise 2-1: What is the average slope of the northern flank of the volcano in Figure 2-2b? Contours are in meters.

☐Exercise 2-2: Determine the geographical coordinates of your own location using a geographical atlas or maps available to you.

2-2 Geological outcrop patterns and V-rule

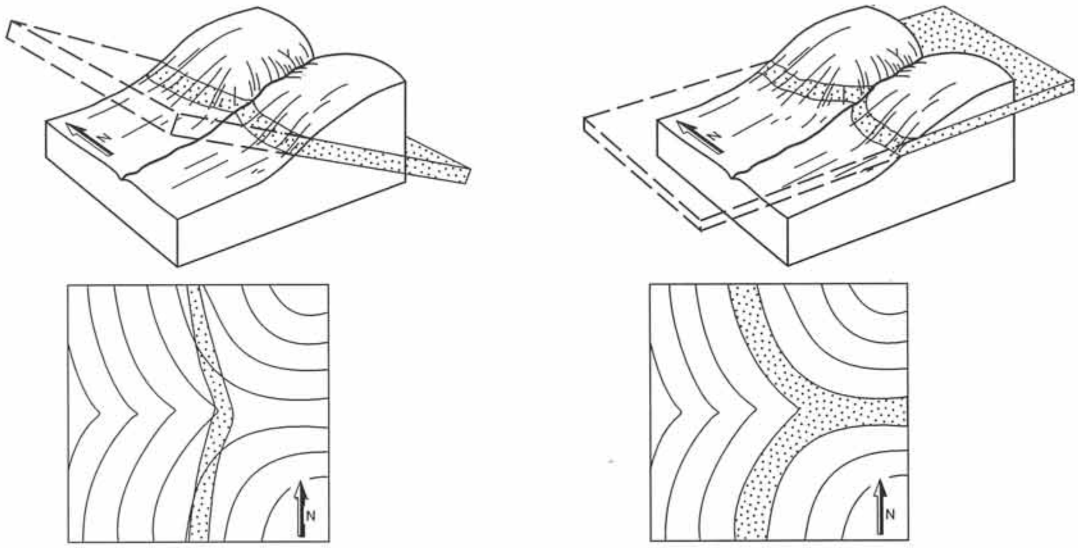
The simplest geological structures are planar unfolded and continuous beds of sedimentary rocks. Such strata may either be horizontal or dip uniformly in a particular direction. Even if the contact between lithological boundaries is straight, these contacts are unlikely to appear as straight lines on the ground surface. The irregular topographic surface intersects the lithological contact, which is then outlined on the ground surface by a smooth, irregular *outcrop pattern*.

For example, consider a simple valley intersected by a straight rock layer (Fig. 2-4). Each of the four cases shown includes a single straight rock formation, sloping (or dipping): (a) westward, (b) vertically, (c) eastward, and (d) horizontally. Correspondingly, four basic map inter-



a) Downstream dip

b) Vertical dip



c) Upstream dip

d) Horizontal dip

Figure 2-4: *a) to d) Perspective views and map patterns of a simple valley, cutting into a single straight bed in various orientations.*

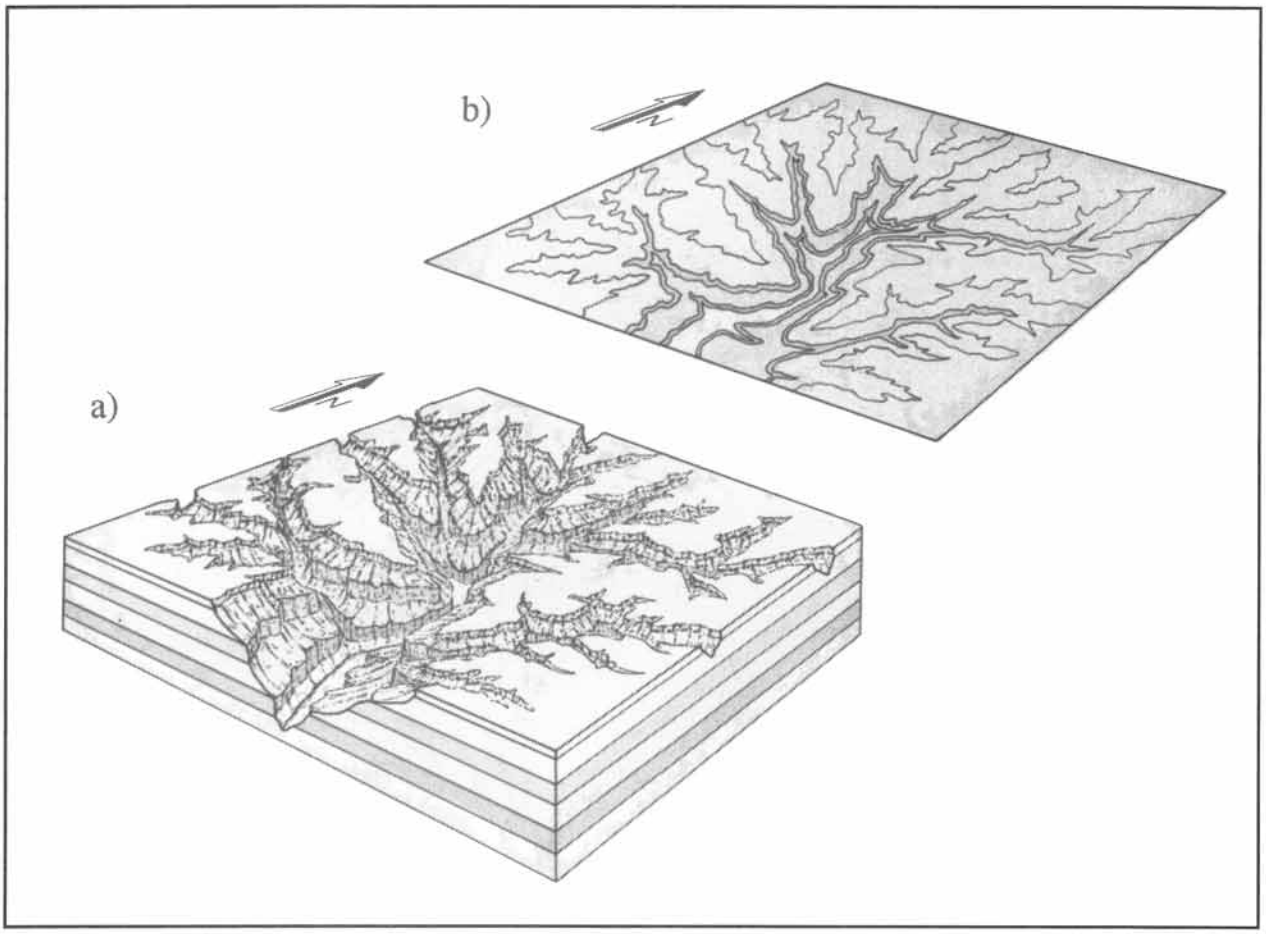


__Figure 2-5:__ a) Perspective diagram of a terrain, comprised of horizontally stratified rock formations incised by a dendritic pattern of deeply eroded channels. b) Geological map view of the same area.

section patterns can be distinguished. If the layer dips downstream, a V-shaped intersection occurs on the topographic map projection and the V points *down dip* (Fig. 2-4a). If the layer is exactly vertical, the intersection of its boundaries with the topography will map as straight lines (Fig. 2-4b). If the layer dips upstream, a V-shaped intersection reappears on the topographic map and the V points *down dip* (Fig. 2-4c). Boundaries of horizontal layers remain entirely parallel to topographic contour lines and appear as V-shaped stream intersections on the topographic

__Figure 2-6:__ Orthographic aerial photograph of a terrain, exposing horizontal beds in the walls of the valleys and on the hillsides.

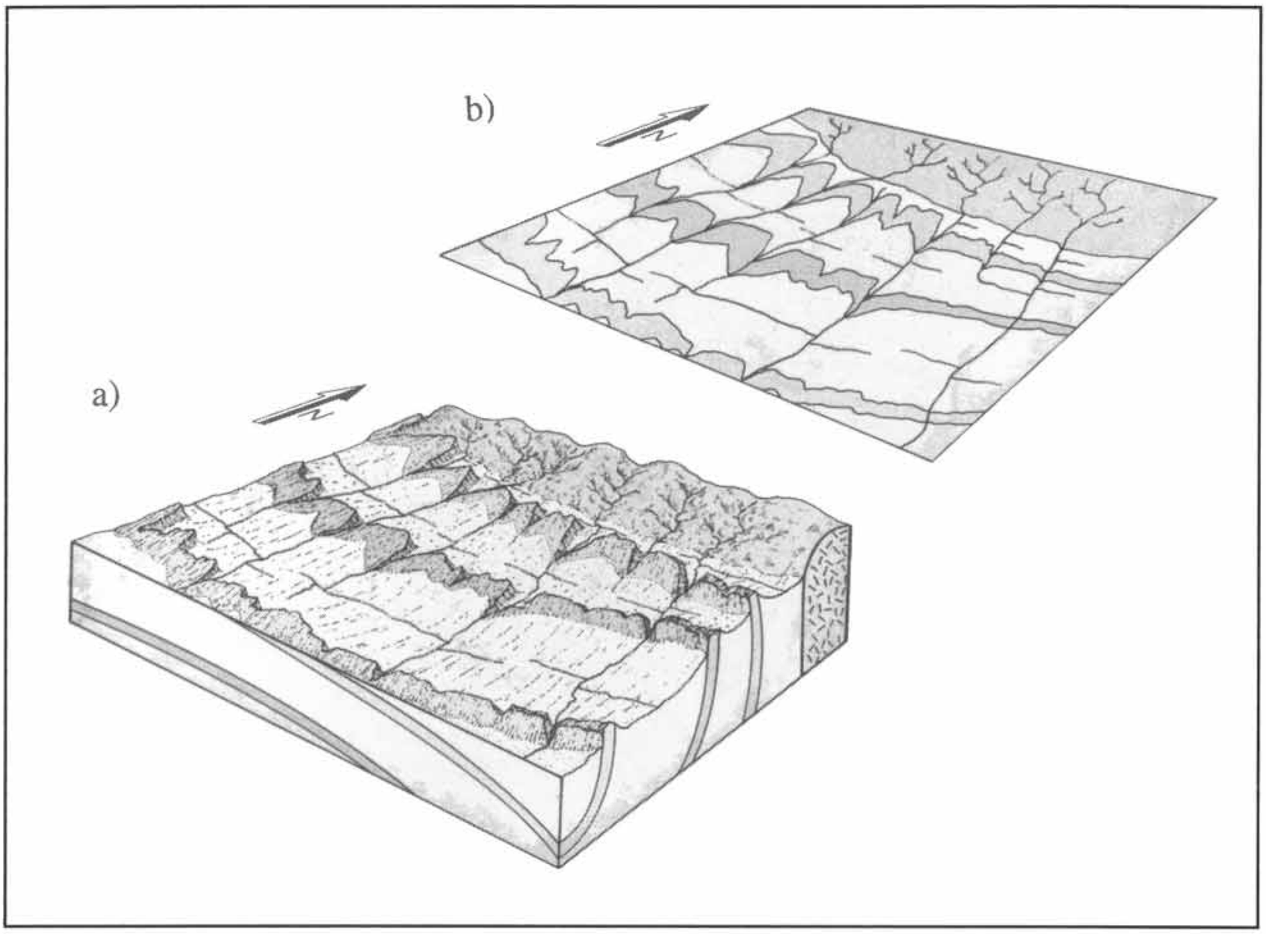


Figure 2-7: a) Perspective diagram of steeply southward dipping rock strata, leaning against a granitic basement in the north. b) Geological map view displays V-shapes, where beds cross stream channels.

map (Fig. 2-4d). All map patterns are different, but the V-pattern outlined by the geological boundaries in the valley floor consistently points toward the down-slope direction of the geological bed. None of the V's in the map views corresponds to folded rock layers; all rock strata are perfectly planar and straight.

The topography shown in Figure 2-4 is extremely simple, and, therefore, the intersection pattern of the sedimentary layer with the ground surface has a simple geometry. However, if the

***Figure 2-8:** Orthographic aerial photograph of rock strata intersected by erosion valleys. The direction of dip is indicated by the V-pattern.*

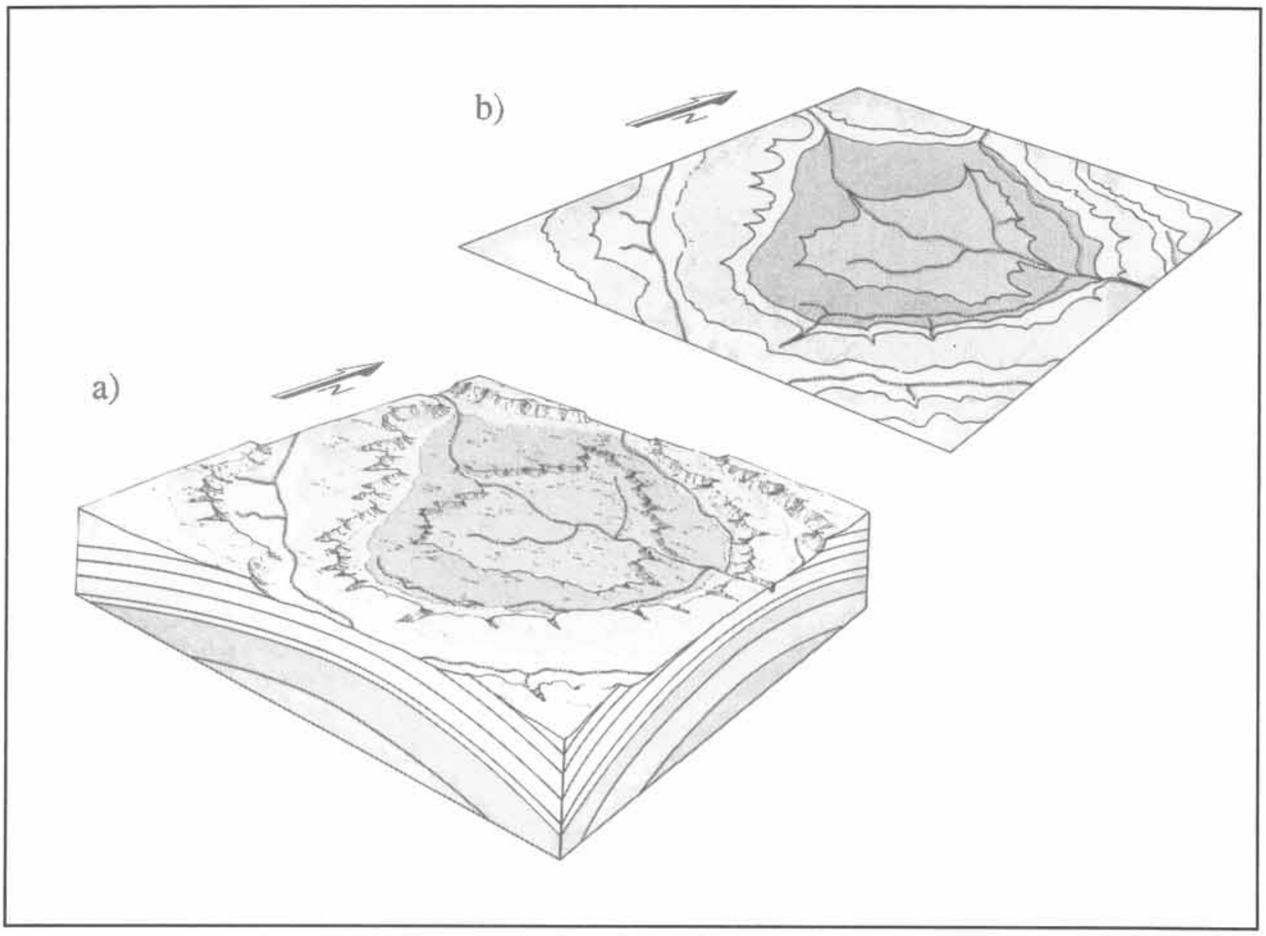


Figure 2-9: a) Perspective diagram of a subcircular dome with strata dipping outward from the center of the dome. b) Geological map of the same area.

topography is complex, the boundaries of geological strata may appear as complex outcrop patterns. Figure 2-5a shows a dendritic canyon system, incising a peneplain underlaid by a succession of subhorizontal sedimentary strata. The geological map projection of the outcrop pattern mimics the dendritic pattern of the canyon system. Even though the topographic contours are not indicated in the map, it can be concluded from the map pattern alone that the layers are subhorizontal. The V's are everywhere pointing *upstream*, but toward inconsistent directions, and,

Figure 2-10: High-altitude aerial photograph of the Richat dome, Mauritania. Image shows an area about fifty kilometers in width.

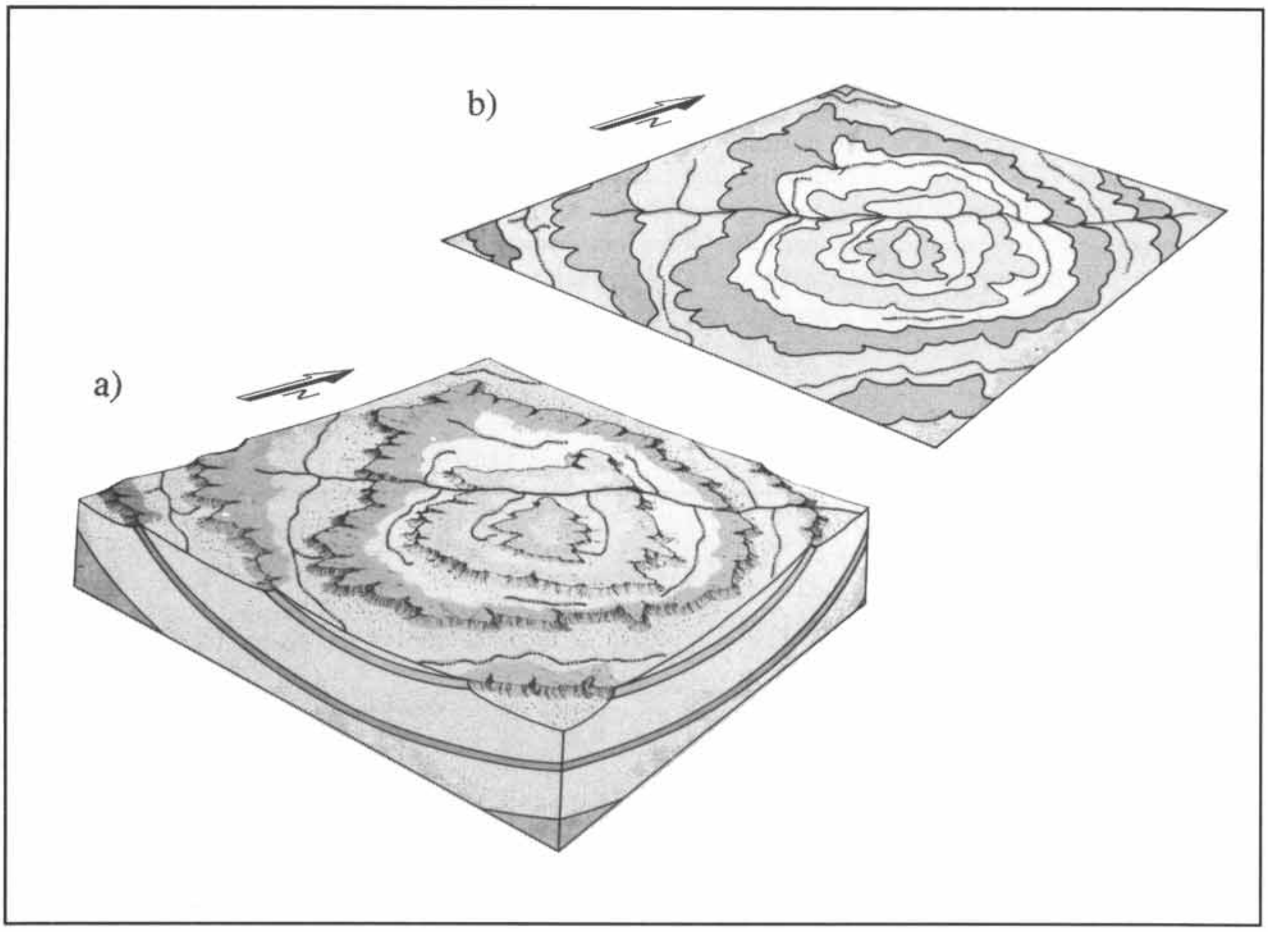


Figure 2-11: a) Perspective diagram of a subcircular basin with strata dipping toward the center of the basin. b) Geological map of the same area.

therefore, do not correspond to any non-horizontal slope of the beds. Once it is realized that the lithological contacts are, in fact, outlining the topographic contours themselves, albeit at an uneven spacing, it becomes simple to understand the structure of an area with horizontal beds. Assuming a normal stratigraphic succession, older strata are exposed in the valleys and younger rocks occur at the higher elevations. Figure 2-6 is an aerial photograph of horizontal rock strata intersected by a southward-running drainage pattern.

***Figure 2-12:** Vertical aerial photograph of the Paredon basin, Mexico. Image shows an area about ten kilometers in width.*

□Exercise 2-3: Figure 2-13 shows a geological outcrop pattern of horizontal strata in an area eroded by a dendritic drainage pattern. Color the various outcrops of the same strata in the same color, and answer the following questions: a) Which letter code represents the oldest formation? b) What is the youngest deposit? c) Are there any unconformable stratigraphic relationships? d) Topographic contours have not been drawn separately on the map, but indicate all contour elevations, given that the contact between bed O and S is at 1000 meters above sea level and all other beds are 100 meters thick. e) Where is the highest peak of the area? f) Which formation occurs at the highest point and why?

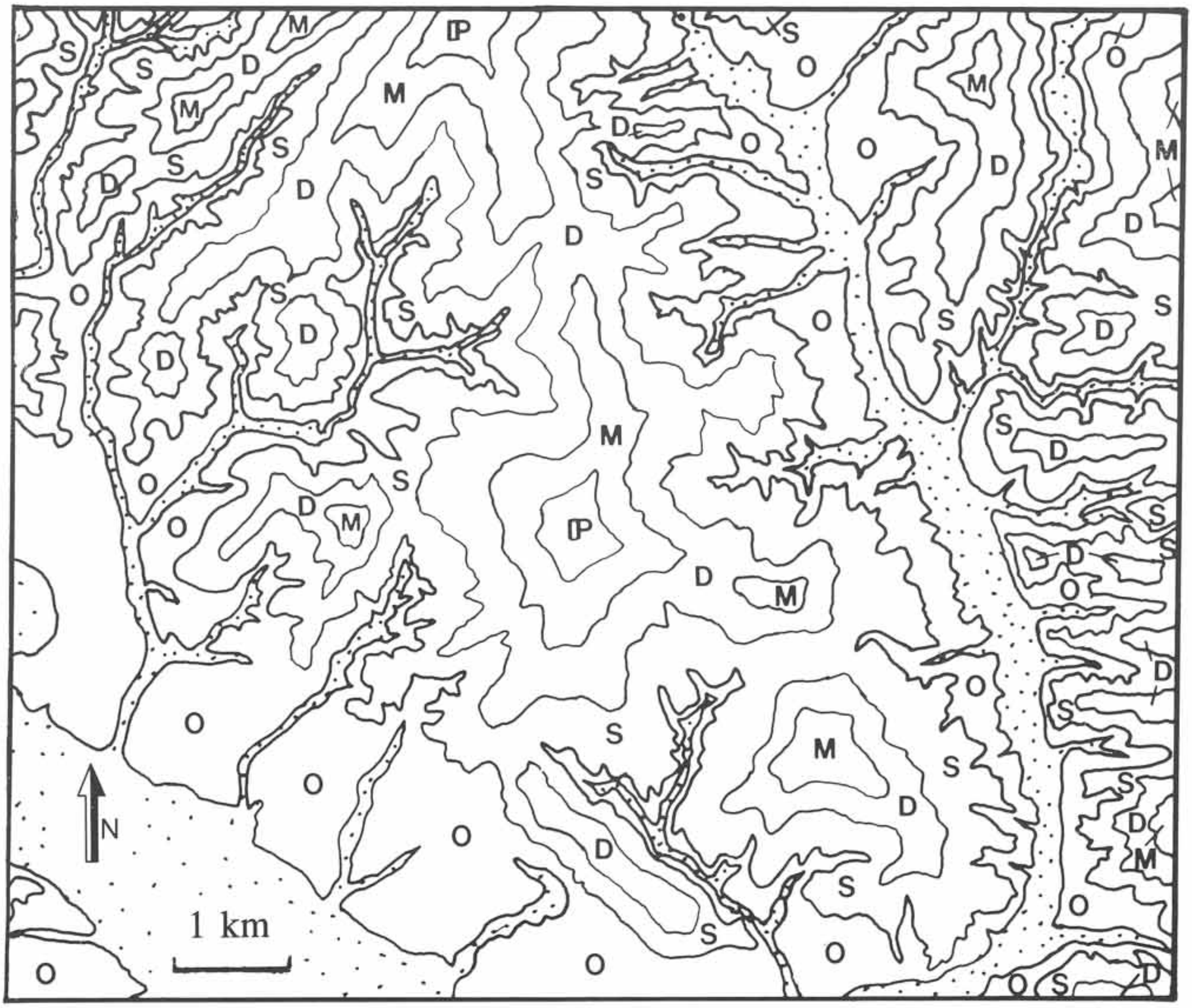


Figure 2-13: Geological map studied in exercise 2-3.

If layers dip uniformly, their direction of dip can commonly be inferred from aerial photographs and geological maps. Such layers form geological boundaries with V-shapes where incised by river valleys (Fig. 2-7a & b). The V's on map patterns of Figures 2-5b and 2-7b differ in the sense that the V's point more or less randomly in the dendritic erosion pattern of Figure 2-5b but point in uniform direction for the dipping layers of Figure 2-7b. Figure 2-8 is an aerial view of uniformly inclined or homoclinal rock strata. The variations in width of the various lithological units is only apparent and arises from the way in which the ground surface intersects the southward-dipping beds.

The use of the V-cusps, outlining the lithological boundaries where transected by drainage patterns, to estimate the dip direction of the rock contact is known as the *V-rule* for dipping strata. Originally horizontal strata, which have been warped into domes by tectonic processes, will display eroded outcrop patterns with V-cusps pointing outward from the core of the dome (Figs. 2-9a & b; 2-10).

☐Exercise 2-4: Figure 2-14 shows an incomplete geological map. The formations in the northwest have been mapped from an aerial photograph and were transferred to a topographic map of the same scale. Study the map pattern and proceed as follows: a) What is the orientation of the strata? b) Complete the outcrop pattern of the entire map, assuming that no faults transect the unmapped area. Use the same symbols as on the map. c) Which area can be mapped only with some uncertainty? d) The thickness of most units can be determined; but which two units are of unknown thickness?

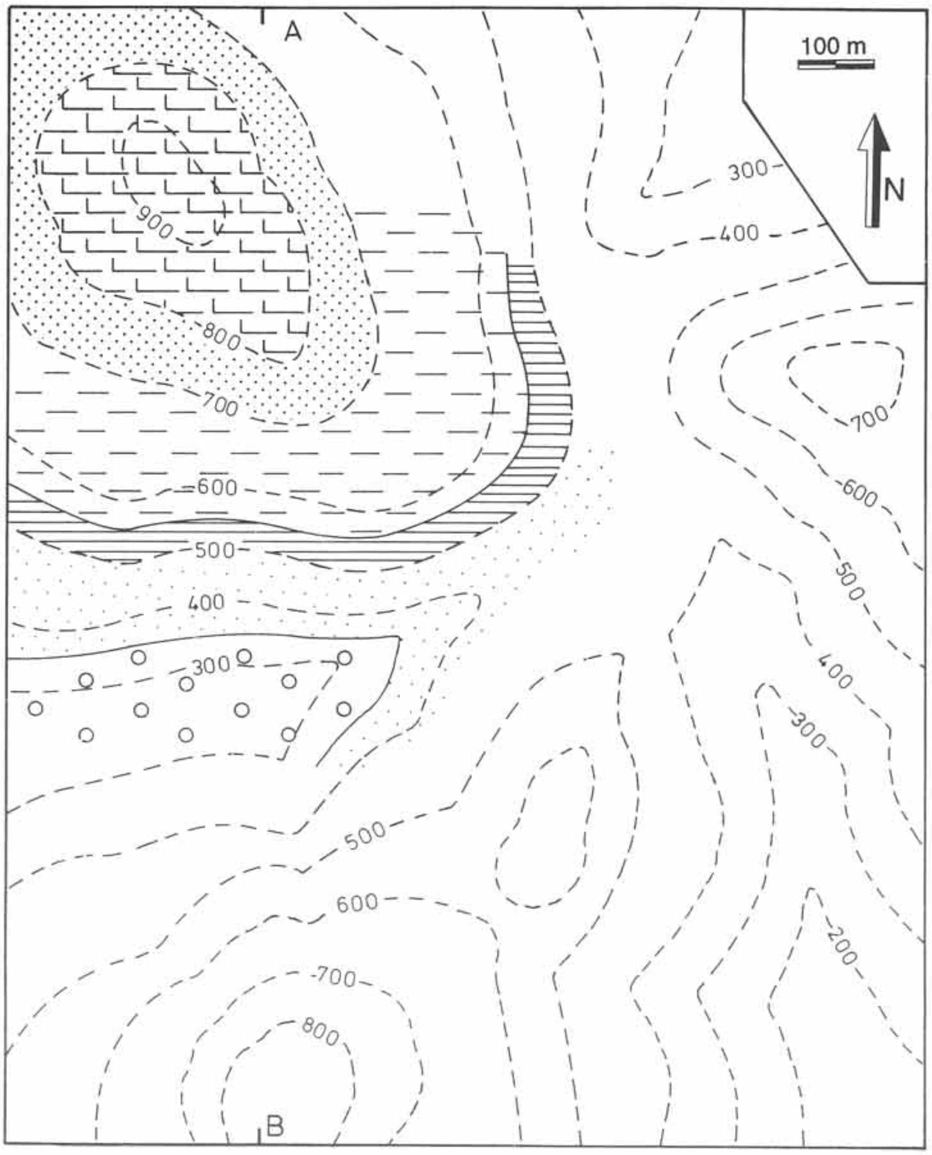


Figure 2-14: Topographic map with incomplete geology to be analyzed in exercise 2-4. Contours are in meters.

Conversely, basin structures are revealed by outcrop patterns with V-cusps consistently pointing towards the center of the basin (Figs. 2-11a & b; 2-12). The V-shape of the outcrop pattern points in the direction in which the rock unit dips below the ground surface. This principle is distinct from the V-shape for topographic contours, where V-patterned contours always point upstream.

2-3 Cross-sections of homoclinal layers

Vertical cross-sections provide a tool to display the internal geological structure of a terrain, and thus these are complementary to the geological map. A cross-section shows the positions of the contacts between strata and other rock bodies that one would see if it were possible to make a vertical cut through the ground. For example, the sides of the block diagrams of Figures 2-4a to d show the orientation of uniformly dipping or *homoclinal* layers in cross-section. Detailed techniques for cross-section construction will be discussed later (see chapter four), but it is useful to introduce a few of the basic principles at this stage.

Consider the map of Figure 2-15a, which is a combined geological and topographic map. First, a *section line* must be selected. For this area, the most complete subsurface view is provided by an east-west section line, transecting the three topographic highs outlined by the topographic contours. Second, the vertical profile or section scale must be selected. If vertical exaggeration is to be avoided, the vertical scale of the profile should be equal to the horizontal scale. Third, the topography of the ground surface is transferred pointwise to the profile box. Elevations are plotted in the cross-section using contours that intersect the section line on the map (Fig. 2-15b). The surface profile is completed on the cross-section by extrapolating between the plotted elevation points. Fourth, the geological boundaries are transferred from the map to the cross-section using only their intersection points with the section line on the

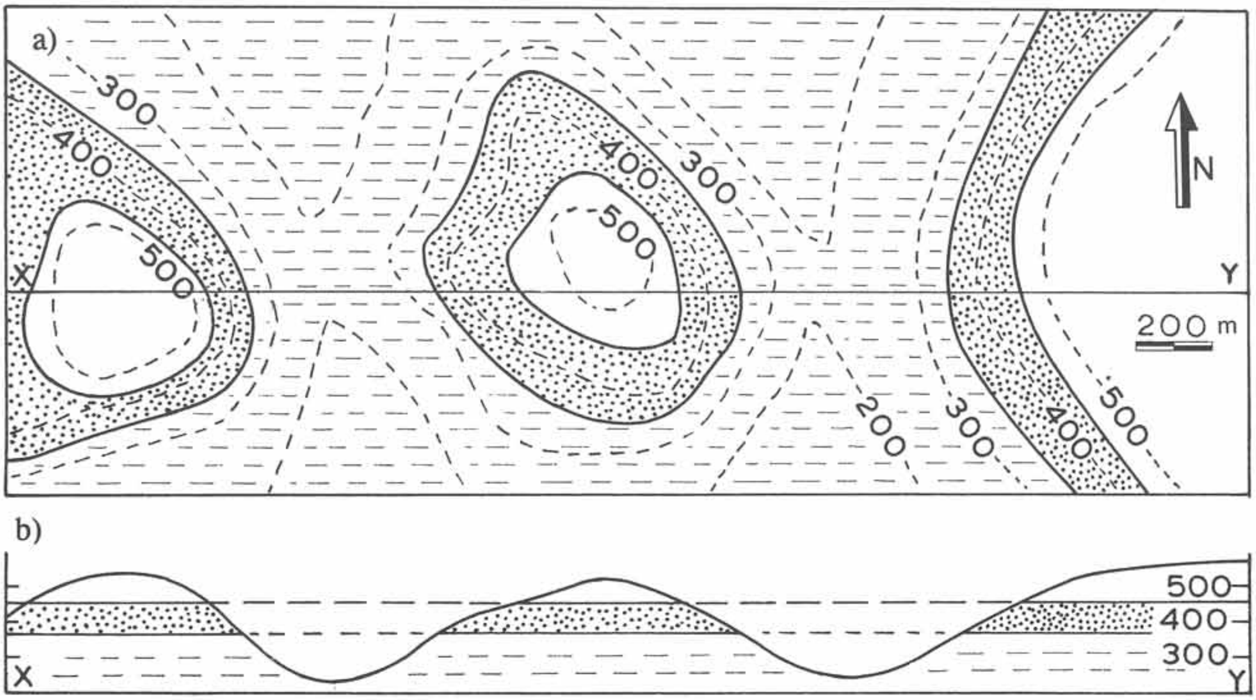


Figure 2-15: *a) Geological map with elevation contours (in m). b) Cross-section along line X-Y. Shown are the topographic relief of the ground surface and the detailed position of the rock strata.*

map. These geological check points are plotted along the ground surface in the cross-section. Subsequently, all corresponding stratigraphic contacts are connected in the subsurface. The completed subsurface section is shown in Figure 2-15b. The cross-section illustrates the simplicity

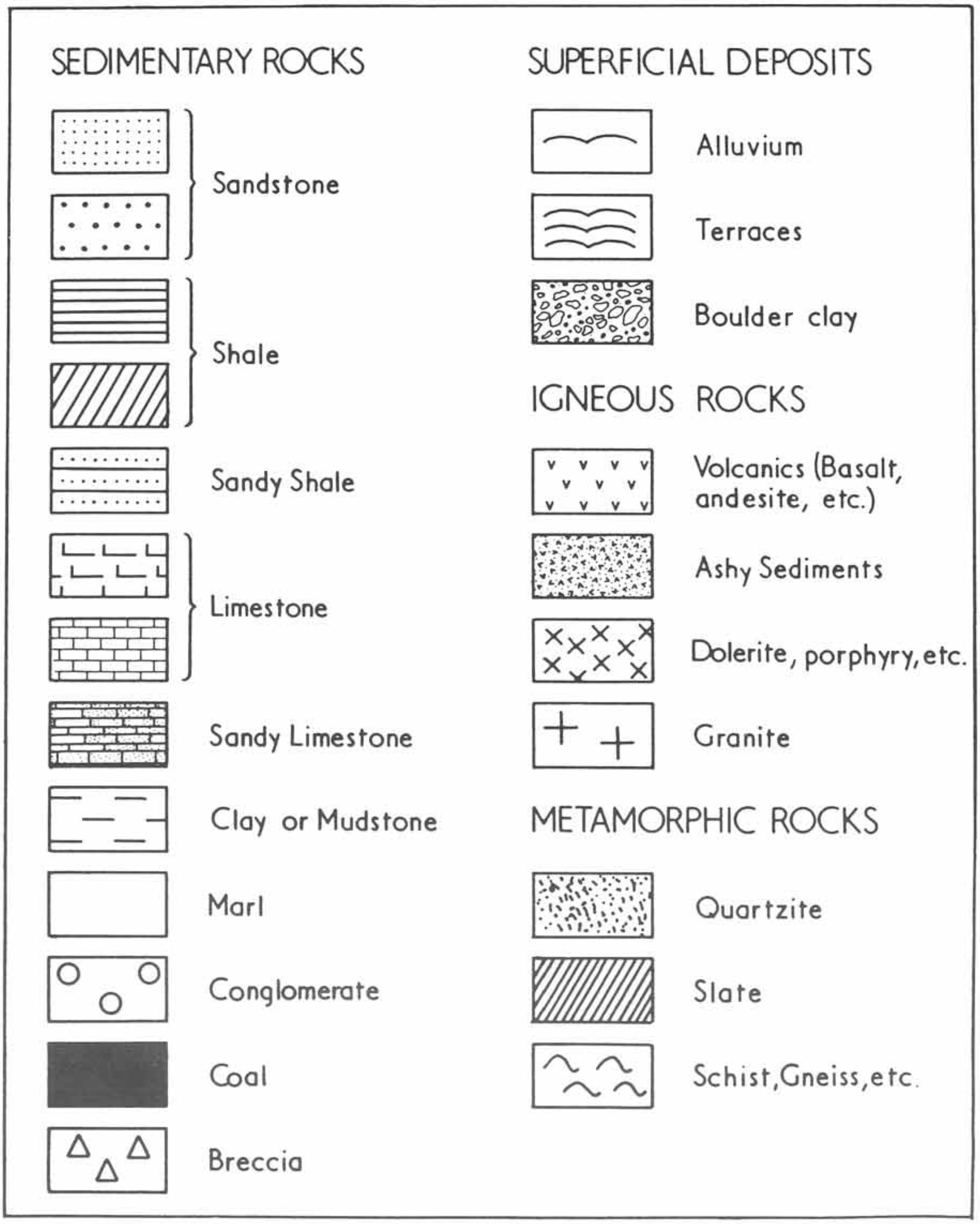


Figure 2-16: *Elementary symbols used to indicate rock types on geological maps and sections.*

of the area's geologic structure, shown to comprise of nearly horizontal rock strata only. Cross-sections provide a powerful means to demonstrate the geological structure of an area. The rock types in such sections are indicated by conventional symbols. Figure 2-16 shows examples of commonly used lithological symbols. However, lithological notation is not standardized and many different symbols are in use throughout the world.

☐Exercise 2-5: Construct a N-S vertical cross-section along trace A-B across the map of Figure 2-14. The cross-section must show both the topography of the ground surface and the geology of the layers beneath. Use the appropriate symbols for the layers in the cross-section (Fig. 2-16).

2-4 Columnar sections

Geologists divide sedimentary rocks into formations. A formation is a mappable rock unit, consisting of uniform or uniformly alternating rocks. Formations are defined on the basis of lithology and fossil-content, and comprise a continuous sequence of beds without any interruption by unconformities (for details on unconformities, see chapter nine). Formations have well-defined, either definite or gradational boundaries. The extent of a formation must be large enough to be mappable at the surface or traceable in the subsurface. The name of each formation consists of two parts. The first part refers to a locality where the formation is clearly exposed; the second part of the name indicates the dominant rock type. Both terms are capitalized, as in, for example, the Kaibab Limestone, Navajo Sandstone, and Burgess Shale. If no single rock type dominates the formation, it is simply referred to as the Rus formation, Dammam formation, and so forth. A formation may be subdivided into members, which in turn may include distinctive beds. Several formations with some stratigraphic unity may be combined to form groups, and groups can be combined into supergroups. The terms formation (lower case f) and Formation (upper case F) are used to distinguish between informal and formal use of a stratigraphic unit. Formal acceptance of stratigraphic subdivisions is a process of accreditation by peers, endorsed at meetings of professional societies.

Columnar sections show the sequence of rocks and their characteristics and include the subdivision into formations and members (Fig. 2-17). Each unit is shown with the stratigraphic thickness scaled vertically, so that the relative thickness of units and the contact relationship between them become clear at a glance. The lithology of each unit is indicated by conventional symbols, denoting the dominant rock type. Accessory features, also, may be indicated by special symbols, and their meaning is explained in a legend to the columnar section. The relative resistance to weathering and erosion of the beds is indicated by relief in the horizontal length of the layers in the column. Many details can be included, but attempts to illustrate too many features usually result in confusing and illegible columns. However, properly organized columnar sections show the most significant stratigraphic data at a glance.

Columnar sections are based either on original measurements of rock strata across cliffs and benches in the field or can be reconstructed from geological maps. In the latter case, the stratigraphic thickness of the mapped units is estimated from the map and compiled in a columnar section to illustrate their relative thickness. If the layers are horizontal, topographic contours can be utilized to obtain the vertical thickness of the rock units. If the layers are tilted, their true, stratigraphic thickness can be obtained, using methods discussed in the next chapter. If not observed in the field, the relative resistance to erosion, indicated in the relief of the stratigraphic column, can be tentatively inferred from the rock type. Limestone and sandstone commonly form steep cliffs, while shale and marl are much softer and erode more rapidly into gentle slopes. More commonly columnar sections are based on detailed strati-

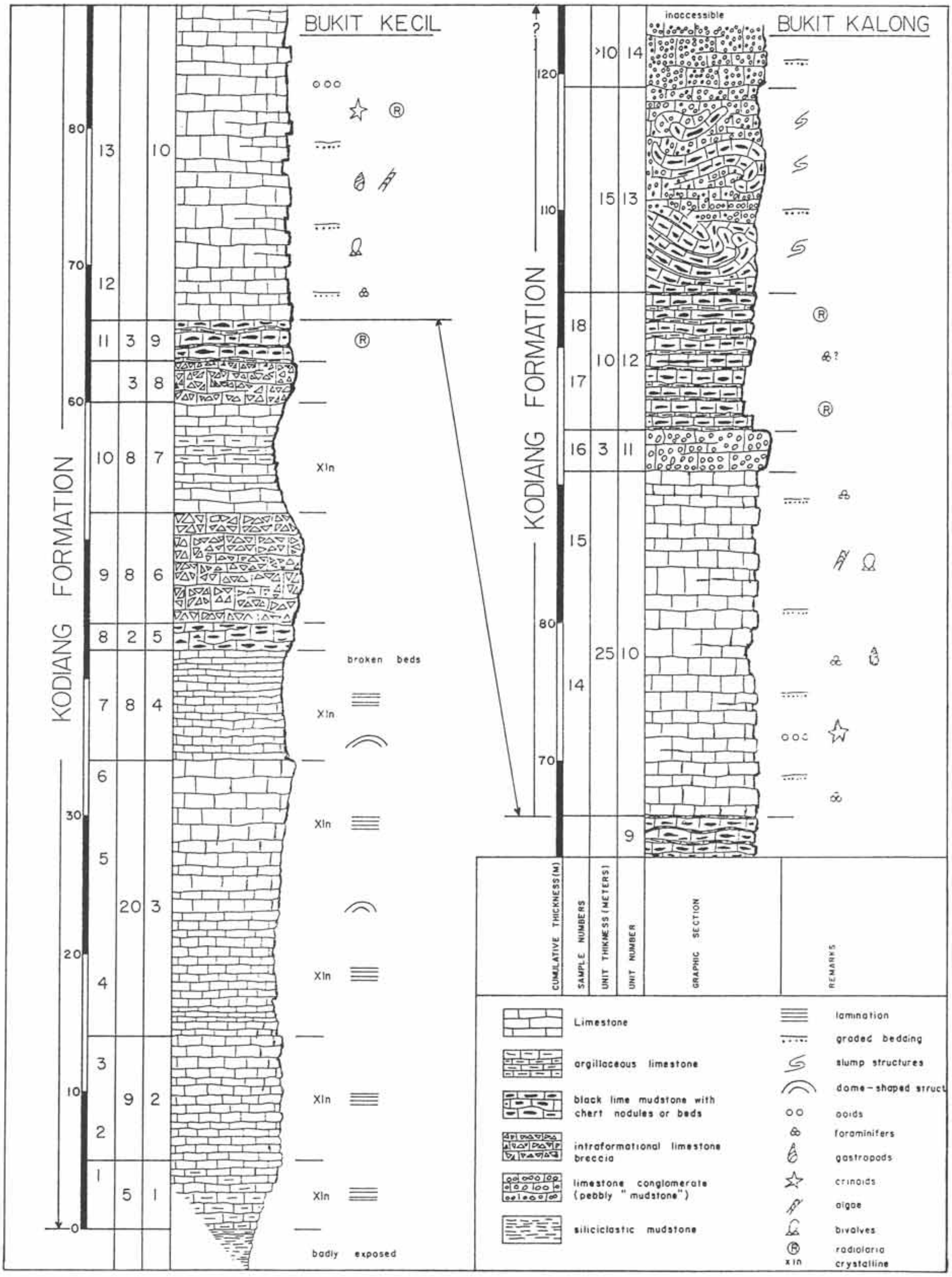


Figure 2-17: Columnar section of the Kodiang Formation.

graphic data measured in the field. Such measured columnar sections usually are cleaned-up compilations of a number of overlapping partial sections taken at different locations, as continuous exposure of a complete succession in a single location is a rarity.

☐Exercise 2-6: Construct a columnar section scaled for the stratigraphic units of the area mapped in Figure 2-14.

Chapter 3:
Strike, Dip, and Map Notation

ABOUT THREE-QUARTERS of the continental surface area is covered with rocks of sedimentary origin. Although the sedimentary succession was originally deposited as horizontal beds, deformation processes may have translated, rotated, and distorted these beds over the course of tectonic history. Consequently, many tectonized sedimentary layers are no longer horizontal. The orientation of planar features, such as tilted layers, can be measured and expressed in terms of azimuth, strike, and dip, introduced in this chapter. The width of inclined layers in horizontal map view decreases with increasing dip. Even in vertical cuts, the dip and thickness of strata seen on such vertical surfaces, perhaps surprisingly, vary with the angle between the line of section and the strike line. In vertical cuts oblique to their strike line, layers appear thicker and with dips shallower than in sections normal to strike. Consequently, the dip and thickness of strata may be either true or only apparent.

Contents: True dip, plunge, strike and azimuth are introduced in section 3-1. The difference between true and apparent dip in oblique sections is explained in section 3-2. True and apparent thickness are discussed in section 3-3.

3-1 Dip, strike, and azimuth of strata

Dip and strike are two measures to describe the orientation of rock layers in the field. The *dip* is the inclination of the layer, measured as the angle between the horizontal plane and the layer itself (Fig. 3-1a & b). The *strike* of a layer is the geographical direction of a horizontal line or surface trace of that layer. The orientation of both the strike line and dip can be measured directly in the field, using a geological compass. The use of the compass for structural measurement itself can be best explained during the preparation for field mapping (see *Principles of Geological Mapping*). Alternatively, strike and dip can be inferred by graphical construction, using the intersection of an outcrop pattern with the topographic contours (see chapter five).

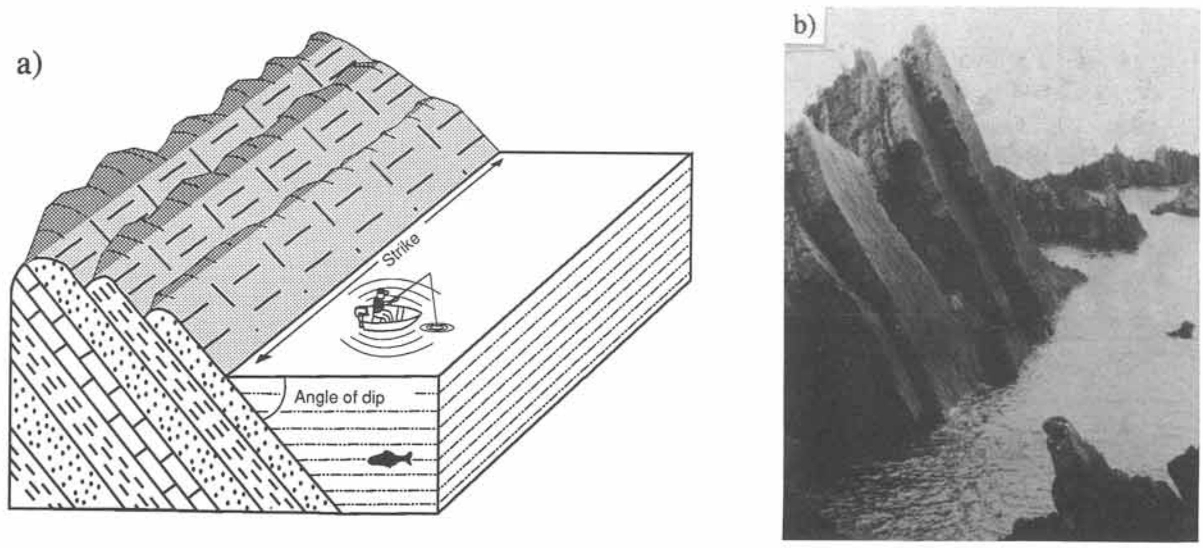


Figure 3-1: a) Sketch showing the strike and angle of dip for uniformly inclined beds. b) Sandstone beds, dipping into the sea, viewed nearly along their strike line due west.

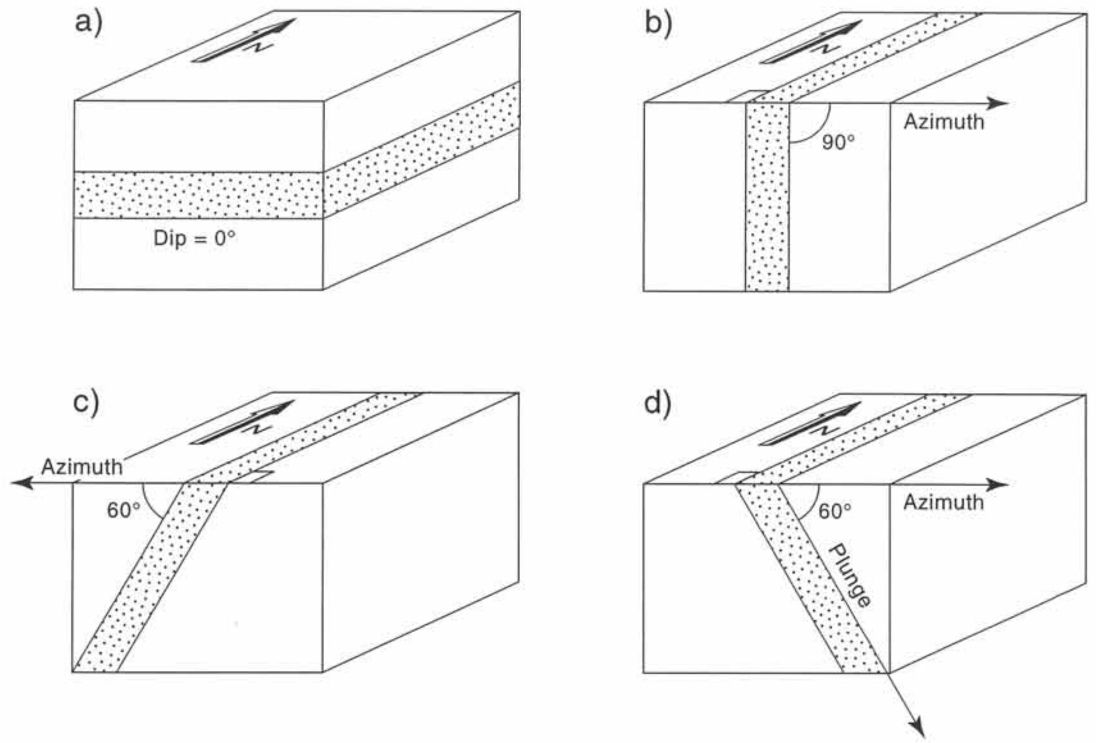


Figure 3-2: *The layer dip is measured in an imaginary vertical plane normal to the strike line of a bed. Orientations shown are: (a) horizontal, (b) vertical, (c) dipping 60°west, and (d) dipping 60°east.*

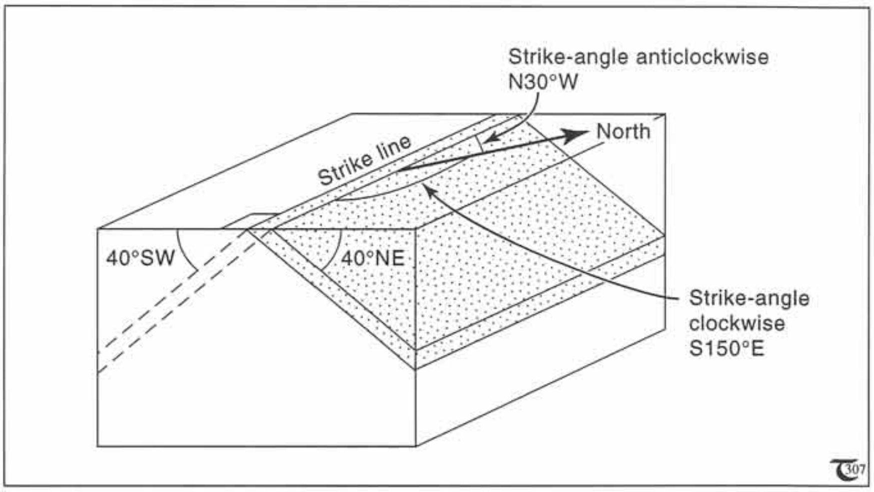


Figure 3-3: *The geographical orientation of the strike line is measured as an angle away from the north, but may be measured either clockwise or anti-clockwise.*

True dip: The true dip of a layer is measured within an imaginary vertical plane, *normal* to its strike line (Fig. 3-2). The vertical plane of measurement intersects the dipping layer along an intersection line or *plunge line*. The vertical plane, also, transects the horizontal surface as a line perpendicular to the strike: the azimuth line. The true dip of any layer will be obtained only if measured between the azimuth and plunge lines (Fig. 3-2). If measured in sections oblique to the strike line, the dip is termed *apparent*, because, in such cuts, the layer appears to slope less than the true dip (see section 3-2). The true dip is an angle varying between 0° and 90°. A layer which dips 0° is effectively horizontal. If small local deviations in dip of several degrees occur, the sheet is termed subhorizontal, which means the layer is more or less horizontal. A layer which dips 90° is vertical. If a layer dips close to (but not exactly) 90°, it is said to be subvertical (meaning more or less vertical). The term *plunge* is usually reserved for the angle between lines (e.g. fold axes) and the horizontal surface, whereas the term *dip* is preferred to indicate the inclination of layers and other planar fabric elements in rocks.

Strike: To characterize the orientation of the layers in Figure 3-2, in addition to the dip, the geographical orientation of the strike line needs to be expressed according to some system. Physically, the strike line is outlined by the trace of inclined layers at the horizontal ground surface. The orientation of strike lines should not be confused by ways of measurement, and it is, therefore, useful to agree upon which convention you follow when exchanging data on strike angles. The strike of a strike line is always expressed as an angle, but there are several ways to express the compass direction of this angle. The geographical orientation of strike lines is measured as an angle away from the north but may be measured either clockwise or anti-clockwise. For example, one possible notation for the strike of the plane in Figure 3-3 is N30°W, measuring 30° in anti-clockwise direction away from N toward the W, so that the strike line trends NW. The angle can, also, be measured in clockwise direction away from the N and represents the same strike line by N150°E. The usual convention (USA) is that the first letter denotes the direction from which to measure the angle and the last letter denotes the direction to measure in. Other notations write NW30°, instead of N30°W. In strike/dip notation of a plane, it is important to add the geographical direction of dip, in order to eliminate one of the two opposite directions of dip possible (Fig. 3-3). Consequently, the orientation of the layer of Figure 3-3 can be written as: N30°W/40°NE or NW30°/40°NE or N150°E/40°NE. It is worth noting that, although the strike is strictly speaking a geographical angle, it is common practice to refer to "strike lines" as "strikes".

Azimuth: Perhaps more practical and straightforward is to represent a plane not by strike/dip notation, but by its azimuth/dip. The azimuth line is normal to the strike line and lies within the horizontal plane; it is, also, part of a vertical plane, containing the line of greatest plunge on the bed. Conventionally measured clockwise, azimuth may vary between 0° and 360°. The representation of the plane in Figure 3-4 by the azimuth and dip of the unique line of greatest dip within that plane is 240°/60°. The latter method for representation of planar features is strongly recommended and will be adopted throughout this book. The azimuth/dip notation is shortest and, also, most practical for later manipulation of the directional data in stereonets (treated in *Principles of Geological Mapping*). However, the various strike/dip notations are employed by many geologists, and, therefore, one must be able to understand all systems used.

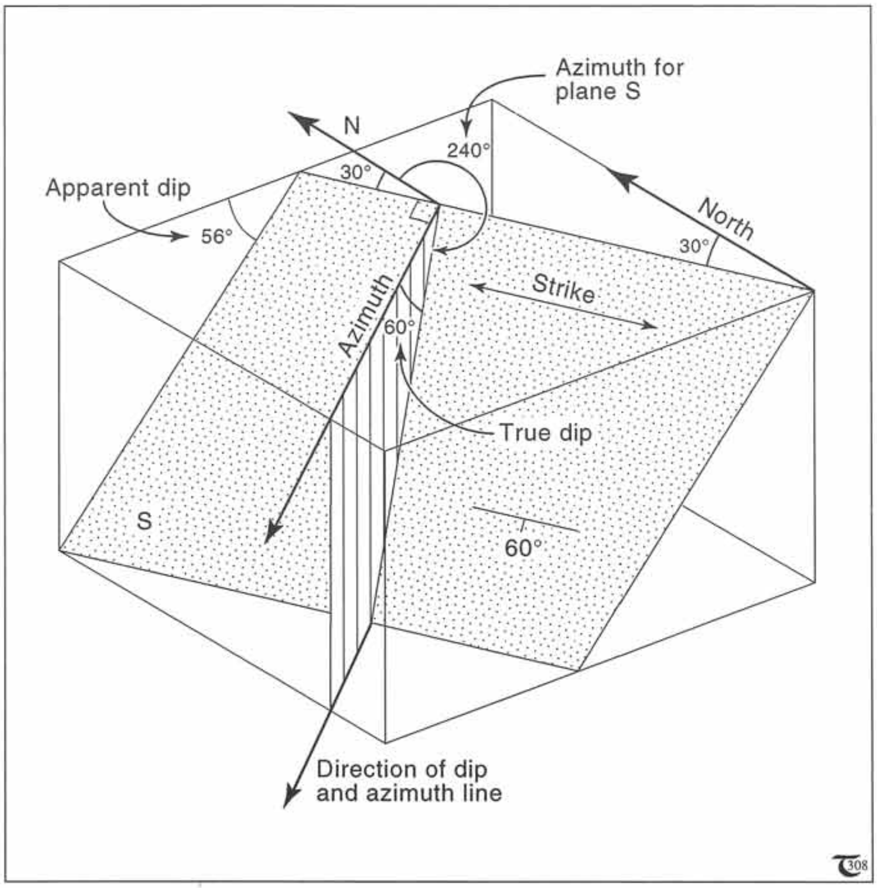


Figure 3-4: *The azimuth line is always horizontal and normal to the strike line. The azimuth is always measured clockwise away from the north.*

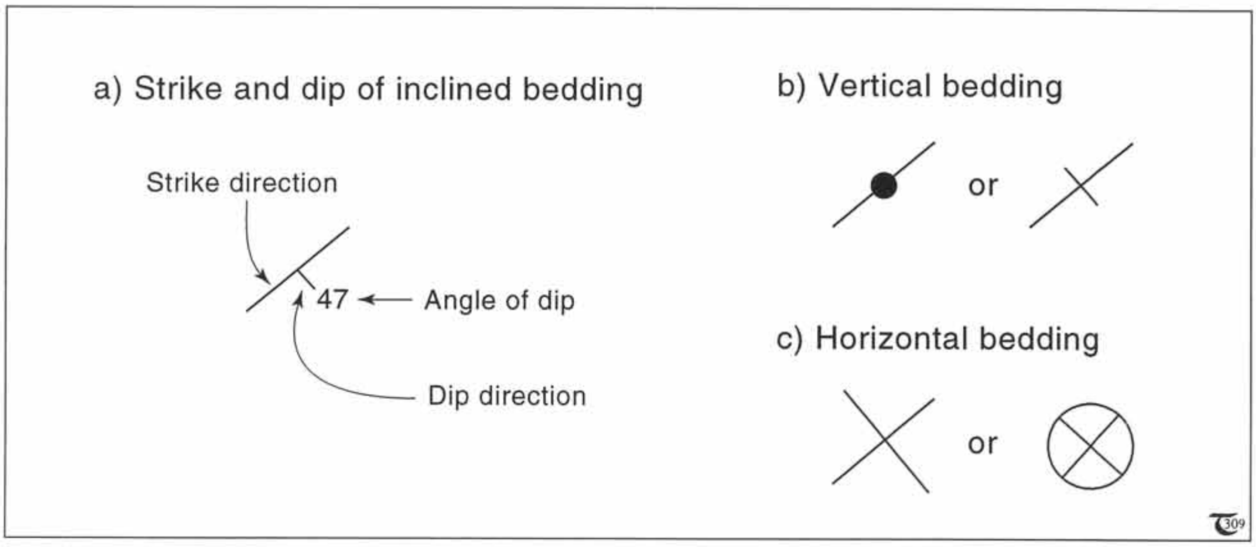


Figure 3-5: *Conventional symbols used to indicate the orientation of strata on geological maps.*

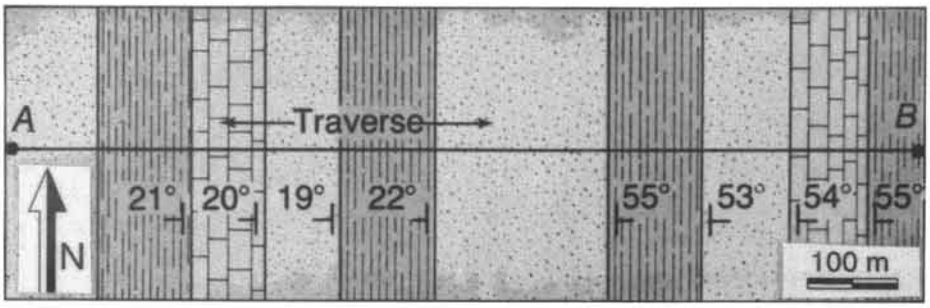
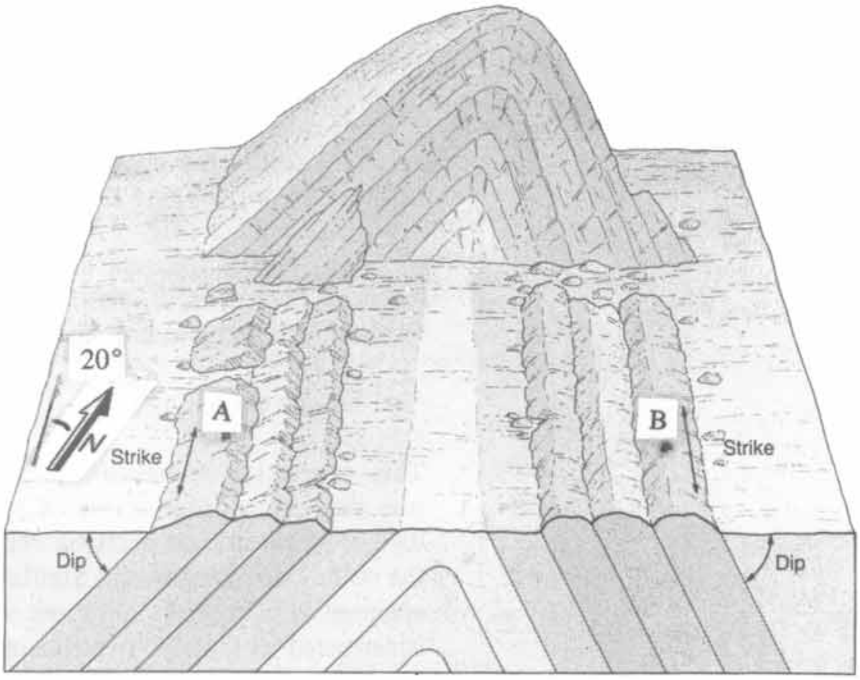


Figure 3-6: Geological map with lithologic and strike-dip symbols. Amount of dip is indicated.

Map symbols: The strike line and dip direction of a layer are represented on the geological map by structural symbols, as indicated in Figure 3-5. The strike-dip symbol for bedding is a long line along strike with a shorter, normal tick mark pointing down the direction of dip. The number near the symbol represents the angle of dip. The strike line orientation need not be written separately on the map, because its orientation is fixed by its angle with the north arrow. It, therefore, is absolutely essential that the geographical north arrow be included in the geological map. Figure 3-6 illustrates a geological map which allows geologists to infer the structure of the subsurface.

☐Exercise 3-1: Refer to Figure 3-7, and consider the layer attitude in the locations marked A and B. Give for both locations: (a) clockwise strike/dip, (b) anticlockwise strike/dip, and (c) azimuth/dip.



☐Exercise 3-2: Sketch a geological map of the area displayed in Figure 3-7. Indicate the orientation of the strata with structural symbols.

Figure 3-7: Perspective view of upright horizontal antiform. See exercises 3-1 & 3-2.

3-2 True and apparent dip of strata

The relevant or true dip of the layer in Figure 3-8 is 45°. If the dip angle were to be measured on a vertical surface that is not normal to the strike line, the dip angle would appear to be less than 45°. The difference between the true and any apparent dip is the consequence of simple goniometric principles. The apparent dip can vary anywhere between 45° and 0° for the example shown in Figure 3-8. The dip of a planar layer in cross-section may vary from an apparent dip of 0° to its true or real dip, depending upon whether the profile line is parallel, oblique, or perpendicular to the strike of that layer (Fig. 3-8).

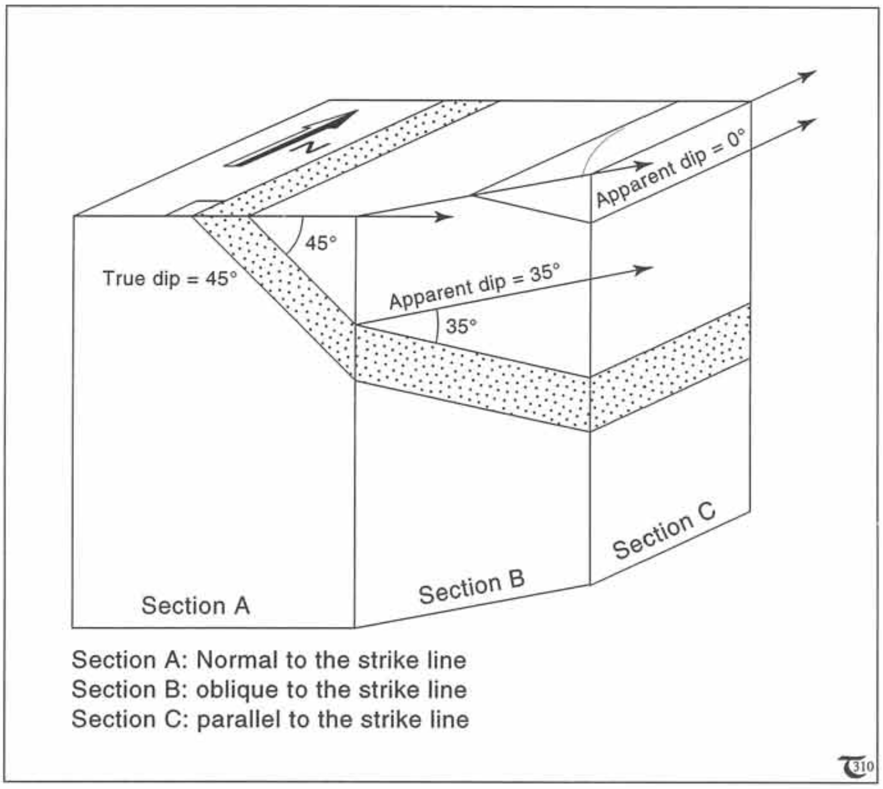


Figure 3-8: *The true dip of a layer dipping 45° eastward is seen in a section normal to the strike line. Any oblique sections give apparent dips, less than the true dip angle.*

True and apparent dips are simply related through the angle, δ, measured between the section line and the strike of the strata studied (Fig. 3-9). If the true dip is α and the apparent dip is β, then the three angles, α, β, and δ are related by the following goniometric expression:

$$\tan \beta = \tan \alpha \sin \delta \qquad (3\text{-}1)$$

This expression is useful to determine true dips from observations of apparent dips of strata in road sections oblique to the strike line of the strata. Similarly, the apparent dip as seen on cross-sections constructed obliquely to strike may be calculated from the true dip measured on field outcrops.

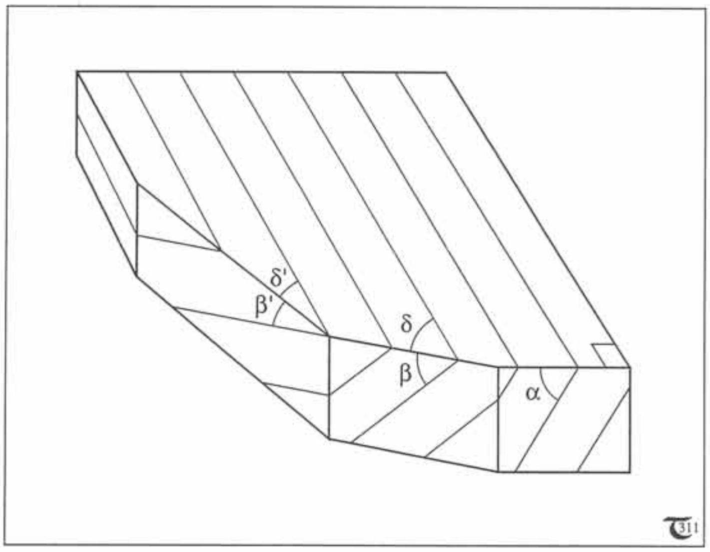


Figure 3-9: *Definition of the three angles, α, β, and δ, used to relate the true dip, α, apparent dip, β, and the angle, δ, between the strike and section of apparent dip. See equation (3-1).*

Instead of calculating equation (3-1), it may be faster to use a nomogram to obtain one of the unknown angles from the other two. Such nomograms aim to transform true dips from maps to apparent dips in oblique profiles and vice versa. Figure 3-10 shows an example of such a nomogram, as used by the United States Geological Survey. Many different conversion tables are available to find the true dip from the apparent dip and vice versa. Such tables are all based on equation (3-1) and give the same answer to your particular problem if properly used. To use the nomogram of Figure 3-10, draw a straight line between any two of the known angles. The third, unknown angle is found at the intersection of the straight line with the corresponding vertical scale. In the example shown, the apparent dip seen in a vertical section is 8°, and the angle between the strike line and the line of section is 15°. It follows that the true dip of the layers must be 30°. Table 3-1 gives the angles in table format.

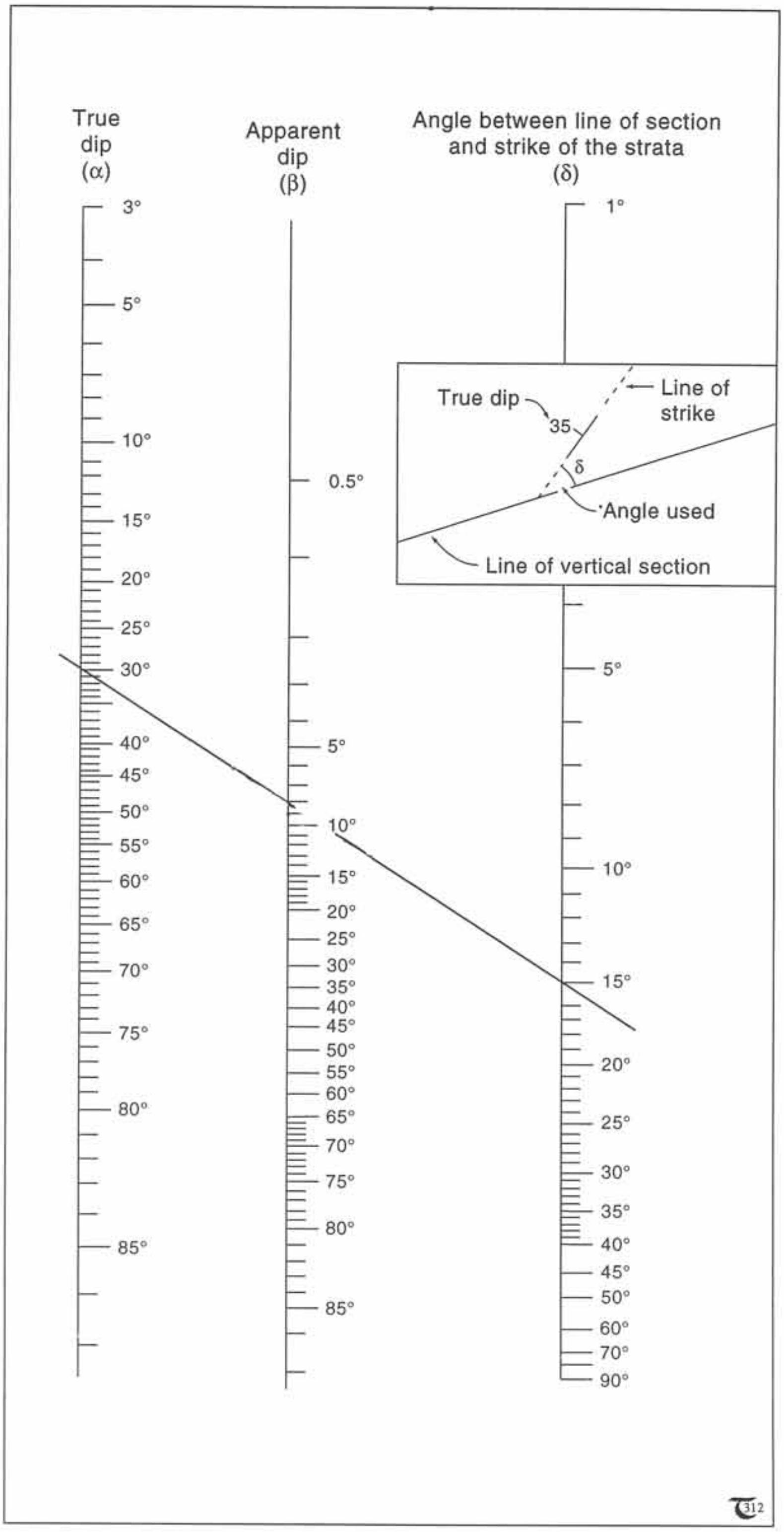


Figure 3-10: Nomogram relating true dip, α, apparent dip, β, and section orientation, δ (see inset for definition of angles). Any straight line connects solutions of equation (3-1).

Cross-sections should preferably be drawn normal to the regional trend of geological structures for the following reasons. If the section is constructed obliquely through the map strike of such structures, all dips in the cross-sections are apparent and may give a misleading view of the subsurface structure. The conversion from the map data to the line of section is, also, more elaborate than in normal profiles. However, there are situations where oblique sections are needed for engineering purposes. For example, sometimes trenches have to be dug for sinking pipelines or a tunnel has to be constructed obliquely to the strike of geological structures.

Table 3-1: Conversion of true dip, α, and apparent dip, β, rounded to the nearest 0.5°.

True dip, α	Acute angle between strike and line of section, δ																	
	0	2.5	5	10	15	20	25	30	35	40	45	50	55	60	65	70	80	90
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0.0	0.5	1.0	1.5	2.0	2.0	2.5	3.0	3.0	3.5	4.0	4.0	4.5	4.5	5.0	5.0	5
10	0	0.5	1.0	2.0	2.5	3.5	4.0	5.0	6.0	6.5	7.0	8.0	8.0	8.5	9.0	9.5	10.0	10
15	0	1.0	1.5	3.0	4.0	5.0	6.5	8.0	9.0	10.0	11.0	11.5	12.5	13.0	13.5	14.0	15.0	15
20	0	1.0	2.0	3.5	5.5	7.0	9.0	10.0	12.0	13.0	14.5	15.5	16.5	17.5	18.0	19.0	20.0	20
25	0	1.0	2.0	4.5	7.0	9.0	11.0	13.0	15.0	17.0	18.0	20.0	21.0	22.0	23.0	24.0	25.0	25
30	0	1.5	3.0	6.0	8.0	11.0	14.0	16.0	18.5	20.5	22.0	24.0	25.0	26.5	27.5	28.5	29.5	30
35	0	2.0	3.5	7.0	10.5	13.5	16.5	19.5	22.0	24.0	26.5	28.0	30.0	31.0	32.5	33.5	35.5	35
40	0	2.0	4.0	8.0	12.0	16.0	19.5	23.0	26.0	28.5	30.5	33.0	34.0	36.0	37.0	38.5	39.5	40
45	0	2.5	5.0	10.0	14.5	19.0	23.0	26.5	30.0	33.0	35.0	37.0	39.0	41.0	42.0	43.0	44.5	45
50	0	3.0	6.0	11.5	17.0	22.0	27.0	31.0	34.5	37.5	40.0	42.5	44.0	46.0	47.0	48.0	49.5	50
55	0	4.0	7.0	14.0	20.0	26.0	31.0	35.5	39.5	42.5	45.0	47.5	49.5	51.0	52.5	53.5	54.5	55
60	0	4.5	8.5	16.5	24.0	30.5	36.0	41.0	45.0	48.0	51.0	53.0	55.0	56.0	57.5	58.5	59.5	60
65	0	5.5	10.5	20.5	29.0	36.0	42.0	47.0	51.0	54.0	56.5	58.5	60.0	62.0	63.0	63.5	64.5	65
70	0	6.5	13.0	25.5	35.0	43.0	49.0	54.0	57.5	60.5	63.0	64.5	66.0	67.0	68.0	69.0	69.5	70
75	0	9.0	18.0	33.0	44.0	52.0	57.5	62.0	65.5	67.5	69.0	70.5	72.0	73.0	73.5	74.0	75.0	75
80	0	13.5	26.5	44.5	56.0	63.0	67.5	70.5	73.0	74.5	76.0	77.0	78.0	78.5	79.0	79.5	80.0	80
85	0	26.0	45.0	63.5	71.5	75.5	78.0	80.0	81.5	82.0	83.0	83.5	84.0	84.0	84.5	84.5	85.0	85
90	-	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90

☐Exercise 3-3: Figure 3-11a shows a map, and the true dip of the layer is constructed in a section normal to its line of strike. Figure 3-11b shows a map of a layer of similar thickness and dip but striking obliquely to the required section line. The dip of this unit in cross-section will not be the same as the true dip. Use the nomogram in Figure 3-10 to infer the apparent dip, and complete the cross-section of Figure 3-11b.

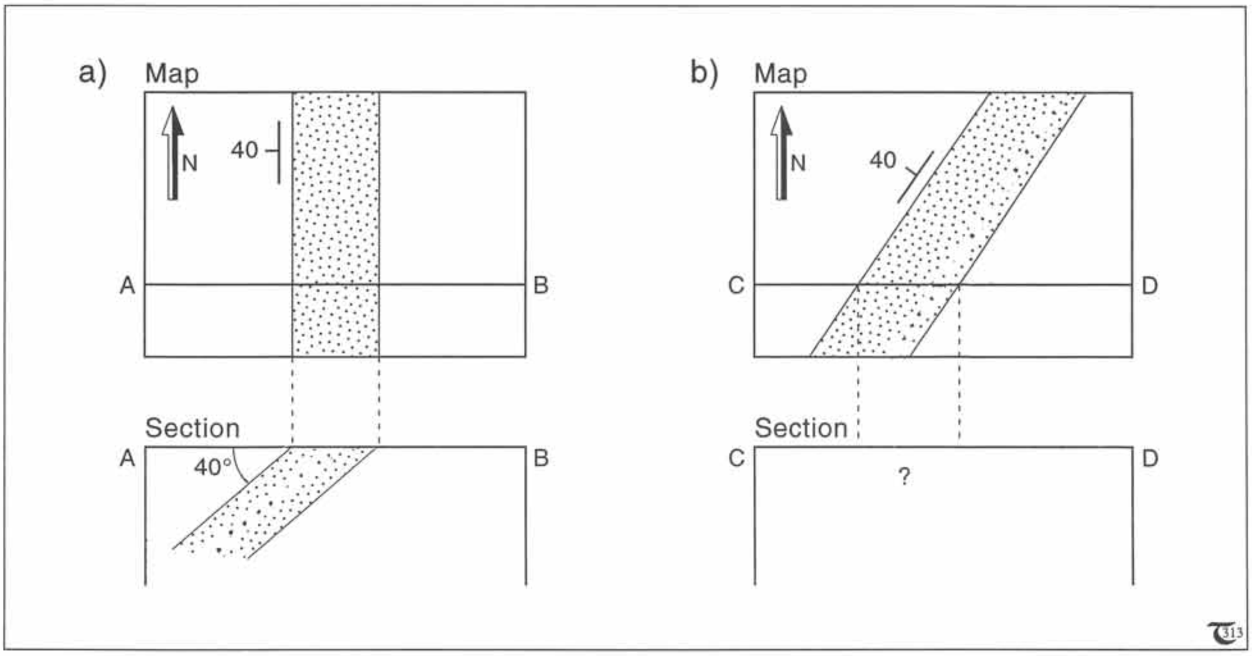


Figure 3-11: a) Map view and section of a bed dipping westward. b) Map view and section oblique to the strike of the bed. See exercise 3-3.

☐**Exercise 3-4: Figure 3-12 is a geological map with stratigraphic units labelled A to D. a) Construct five different cross-sections: along lines P-Q, P-R, P-S, P-T, and P-U. Use the nomogram of Figure 3-10 to find apparent dips where necessary. Arrange all five sections on one sheet, such that their left-hand scales are vertically aligned. b) Which section gives the best view of the subsurface structure? c) Which is the least representative?**

☐**Exercise 3-5: Assume a contractor asks you to plan the cheapest way to construct a narrow, five-meter-deep trench between locations P and S. The cost per horizontal meter is $100 for trench-cuts through the soft units A, B, and D, but the cost of cutting through unit C is three times higher. a) Sketch in red pencil, on the map of Figure 3-12, the cheapest pathway of the trench. b) Calculate how much is saved by the cheaper transection as compared to a straight ditch from P to S.**

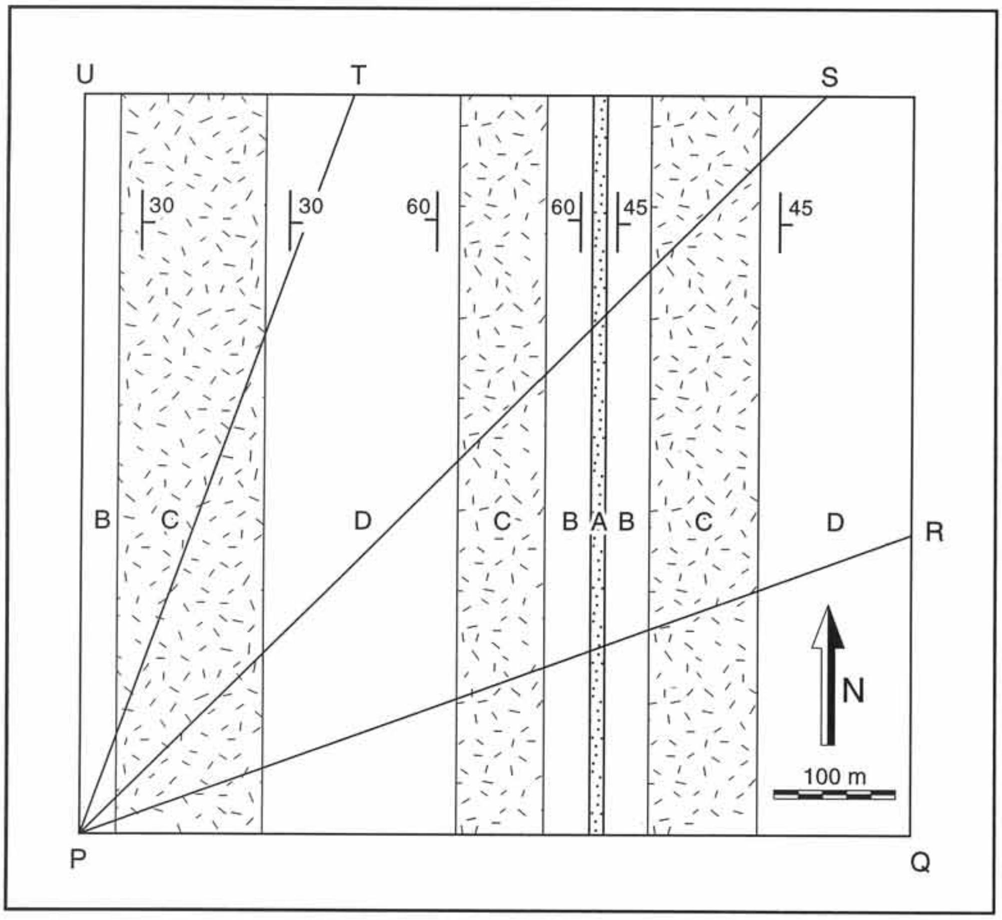


Figure 3-12: Geological map of a stratigraphic sequence with units A to D. Exercises 3-4 and 3-5 call for five different sections to be completed along the traverses P-Q, P-R, etc.

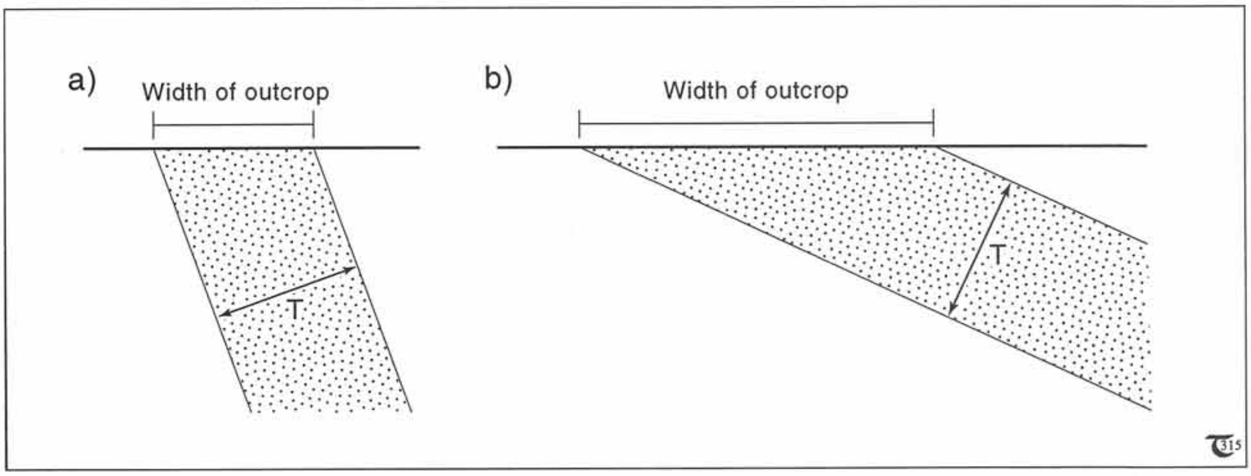


***Figure 3-13:** a) & b) The width of an outcrop seen at the ground surface in flat terrains always overestimates the true thickness of the beds, unless the dip is vertical so that the true width is exposed.*

Only sections oblique to the regional structures and parallel to the trace of the planned trenches and tunnels can show what rock units will be encountered and where (see exercises 3-4 & 3-5). Moreover, strikes of all units are not always parallel. For example, straight sections through plunging folds cannot show all true dips (see, also, exercise 4-10).

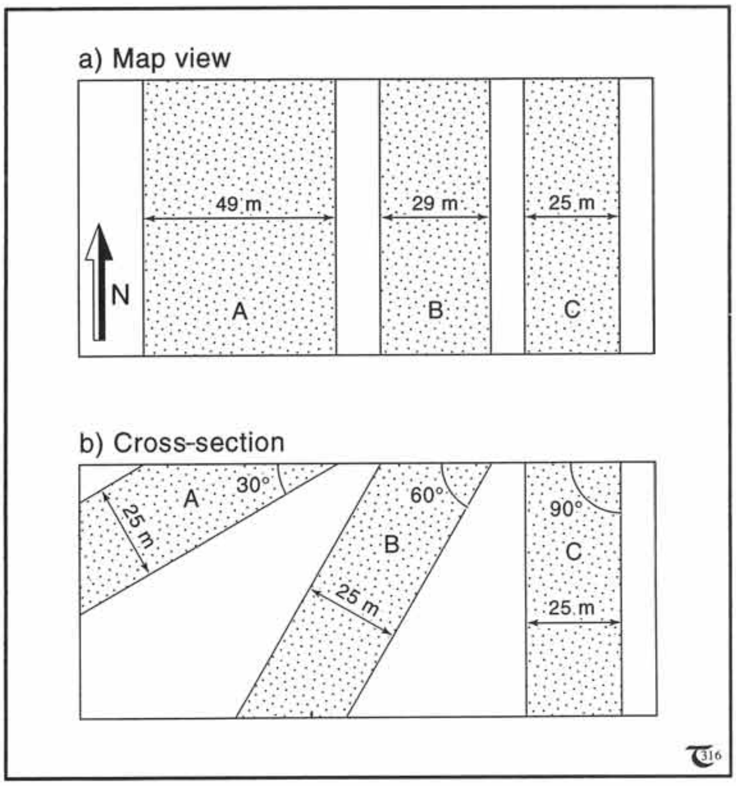


***Figure 3-14:** Map view (a) and cross-section (b) of three igneous dikes of identical thickness (A, B, and C). The steepest dike appears with an outcrop-width smaller than that of dikes with shallower dips.*

3-3 True and apparent thickness of strata

The thickness of inclined strata as seen on maps may appear much thicker than on sections orthogonal to the bedding (Fig. 3-13a & b). The true or normal thickness, T, is seen on a map only if the layers are exactly vertical (Fig. 3-14a & b, dike C). The smaller the dip of such inclined layers, the greater their apparent thickness or width, W, as seen on maps cutting obliquely through them (Fig. 3-14a).

The true thickness (T) and the outcrop width (W) in relatively flat areas are simply related by the true dip, α (Fig. 3-15a):

$$T = W \sin \alpha \qquad (3\text{-}2)$$

The true thickness of horizontal layers seen with width, W, in road cuts, mine pits, or canyon walls of slope, γ, is given by (Fig. 3-15b):

$$T=W \sin \gamma \qquad (3\text{-}3)$$

The true thickness of inclined layers cut parallel to their strike by inclined walls is given by (Fig. 3-15c):

$$T=W \sin (\gamma-\alpha) \qquad (3\text{-}4)$$

In vertical drill holes, the true thickness, T, can be inferred from the vertical thickness, T_V, and the layer dip, α:

$$T=T_V \cos \alpha \qquad (3\text{-}5)$$

In terrains of rugged relief, the width of inclined layers may vary greatly, according to the rock unit's resistance to erosion. Less resistant rocks erode with outcrop patterns wider than those of rock units more resistant to erosion (Figs. 3-16a & b). Field evidence indicates that units of limestone and sandstone are commonly very resistant to erosion and, therefore, form steeper outcrops. In contrast, shales, marls, and claystones are less resistant to erosion. These form gently sloping outcrops, and even very thin layers may appear on geological maps as bands of broad width, falsely suggesting a large thickness for such soft units. For example, in Figure 3-16b, the shale of true thickness T_4 is thinner than the underlying sandstone unit of true thickness T_3, but their outcrop width suggests the opposite.

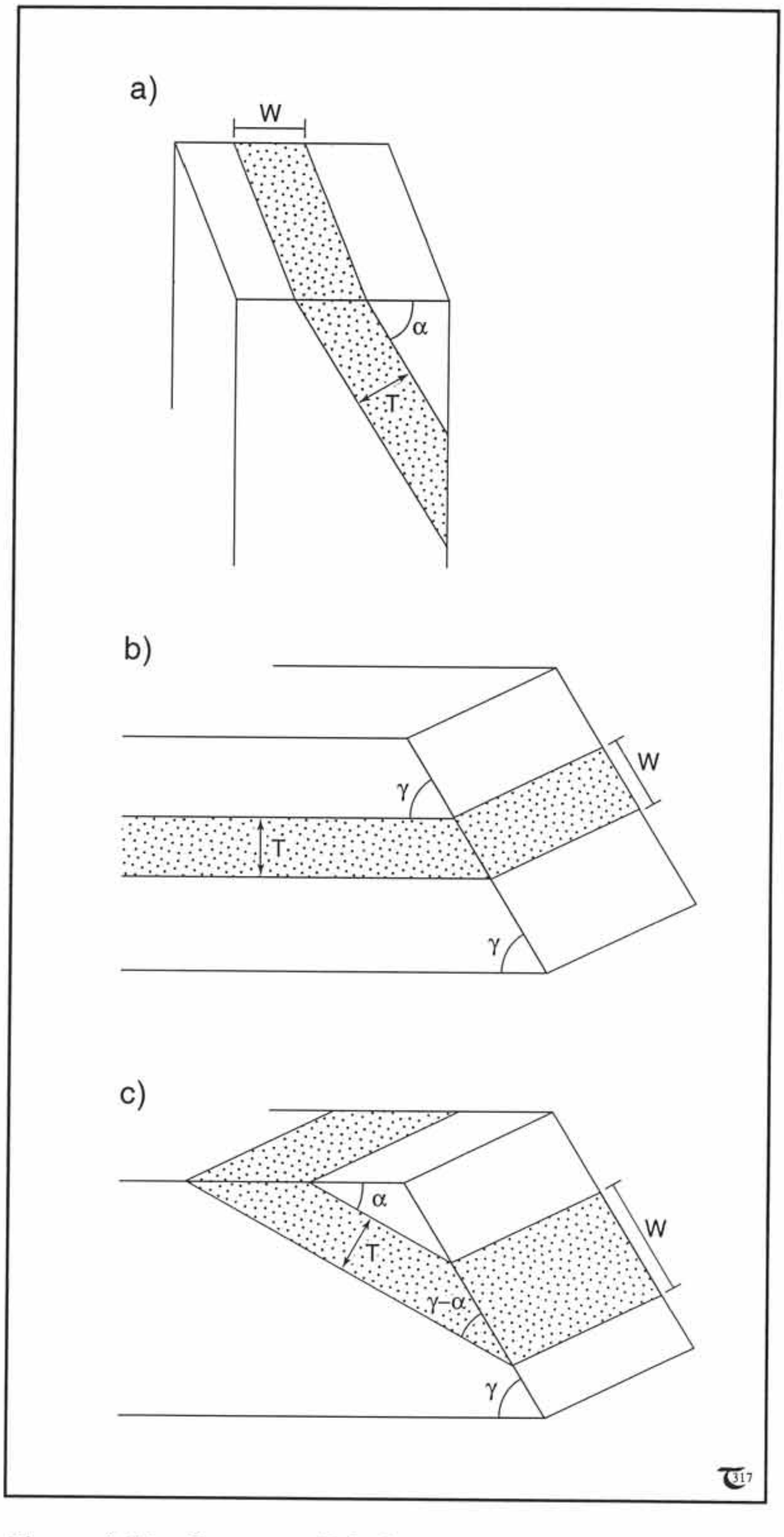


Figure 3-15: Outcrop width for: (a) inclined layers in flat terrain, (b) horizontal beds in the walls of road cuts and trenches, and (c) inclined beds in the walls of trenches.

The previous section emphasized that geological cross-sections, aiming to show the subsurface structure accurately, should be oriented normal

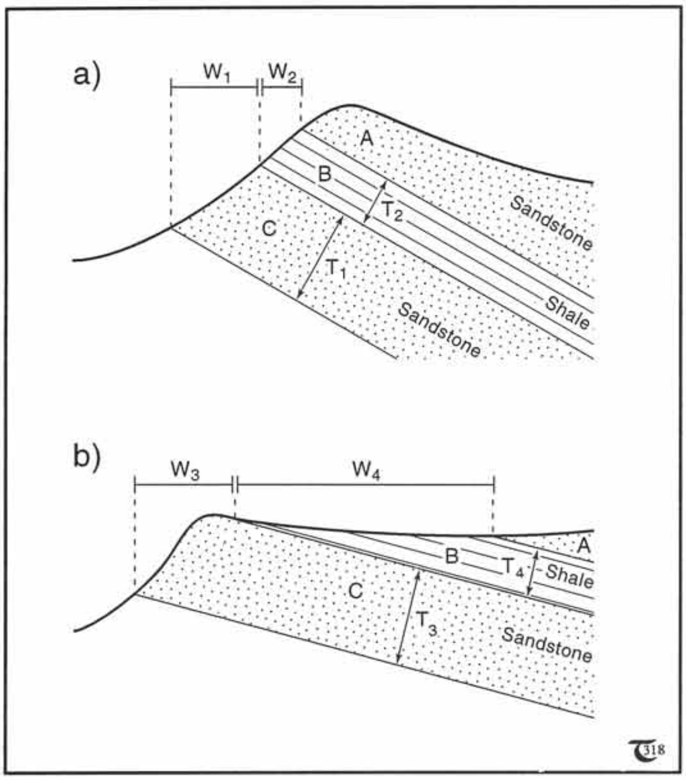


Figure 3-16: a) & b) The width, W, of beds as seen on orthographic map projections is dependent on the topographic relief of the terrain. The topography itself is partly controlled by the erosional resistance of each rock unit.

☐Exercise 3-6: The map of Figure 3-17a shows the outcrop pattern of a uniformly inclined layer in a flat terrain. The cross-section of Figure 3-17b shows that the same map pattern (W=100 m) may arise for layers of different thickness if their dip angle is fixed correspondingly. a) Calculate the true thickness of each layer, using equation (3-2). b) Construct a vertical cross-section at 45° to the strike of the layers A, B, and C.

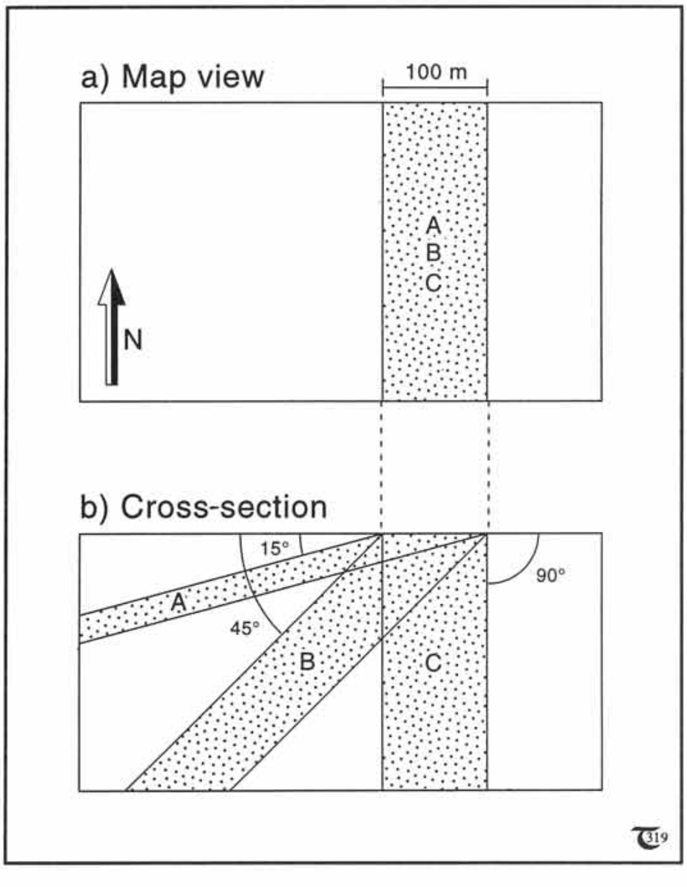


Figure 3-17: a) & b) Similar outcrop patterns arise for beds A, B, and C, shown in the carefully scaled cross-section (b). See exercise 3-6.

☐Exercise 3-7: Construct a cross-section along line A-B on the map of Figure 3-18a. The topography along the line of section has been constructed for convenience in Figure 3-18b. a) Complete the cross-section of Figure 3-18b by showing the geological strata. Use the symbols of Figure 2-16. b) Make a stratigraphic column showing the true thicknesses of each layer. c) Compare the true thickness of the rock units seen in the column with the apparent thickness seen in the map. Explain the difference.

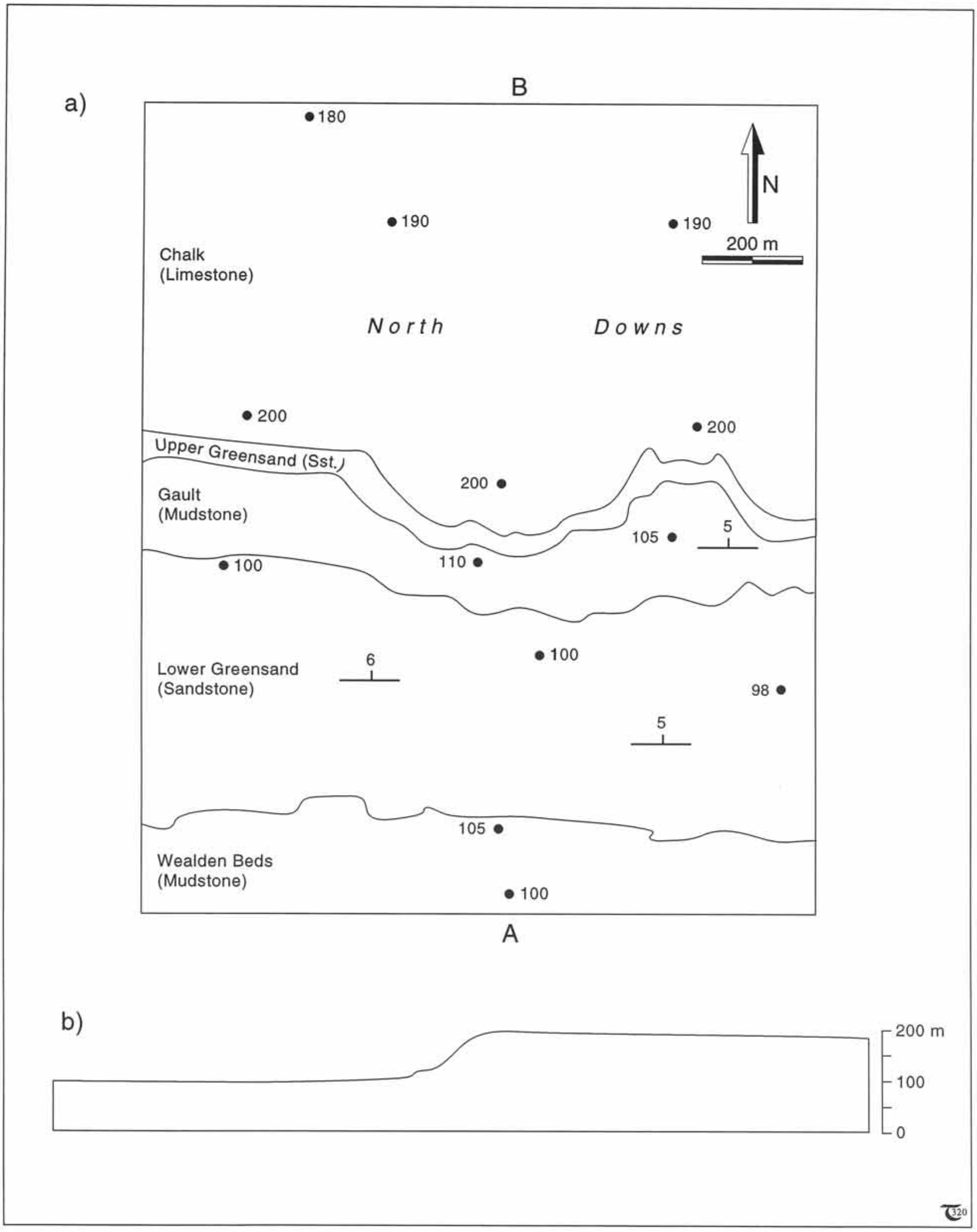


Figure 3-18: *a) Geological map of part of the English basin. Spot elevations (dots) are in meters. b) Complete the cross-section along traverse A-B, as in exercise 3-7.*

to the strike of rock strata. If the section is oblique to the strike, the true dip is obscured by an apparent dip. Another important reason for orienting profile lines normal to the regional strike of sedimentary layers is that their thicknesses appear as true thicknesses, unlike those in oblique sections. This assumes equal horizontal and vertical scales. If these two scales are unequal, both the dip and thickness of layers will be only apparent and not true, as explained in detail in the next chapter.

☐Exercise 3-8: A sandstone aquifer strikes N90°E and dips 42°S. The width of its outcrop, measured due north, is 425 meters. There is no topographic relief in the region. Determine the true thickness of the aquifer: (a) by construction of a sketch map and a cross-section, and (b) by using equation (3-2).

Chapter 4: Geological Cross-Sections

THE THREE-DIMENSIONAL structure of an area may be effectively illustrated by the combination of a geological map and one or more cross-sections. Cross-sections serve to clarify the subsurface structure, usually as seen in a vertical plane. The construction of cross-sections across any geological structure involves the risk of several geometric distortions. This chapter outlines the nature of these distortions, and provides guidelines for selecting section lines that show the most appropriate view of the subsurface. A technique related to cross-section construction, representing the subsurface structure in block diagrams, is addressed in chapter ten. The vertical sides of such block diagrams effectively show cross-sectional views of the subsurface.

Contents: Criteria for the selection of section lines are discussed in section 4-1. Further instructions for profile construction are given in section 4-2. Visual distortions occurring in differentially scaled cross-sections are outlined in section 4-3. The effects of apparent thickness and dip are resumed in section 4-4.

4-1 Location of sections

Geological maps are commonly accompanied by cross-sections, illustrating the geological structure of the region. Cross-sections intend to show the form and orientation of geological structures in the subsurface. However, various kinds of distortion of the form and orientation of rock structures may arise in such cross-sections. These distortions depend on: (1) the relative scaling of the horizontal and vertical axes in the section, and (2) the way in which the section cuts the actual structure. These two sources of distortions are discussed in some detail in sections 4-3 and 4-4, respectively.

The previous chapter explained that cross-sections should, preferably, be constructed, as close as possible, normal to the regional trend of structures. If the surface trace of the profile is oblique to the structural trend, an apparent thickness of layers would be seen rather than the true thickness. Likewise, dips of layers in such oblique sections are apparent rather than true.

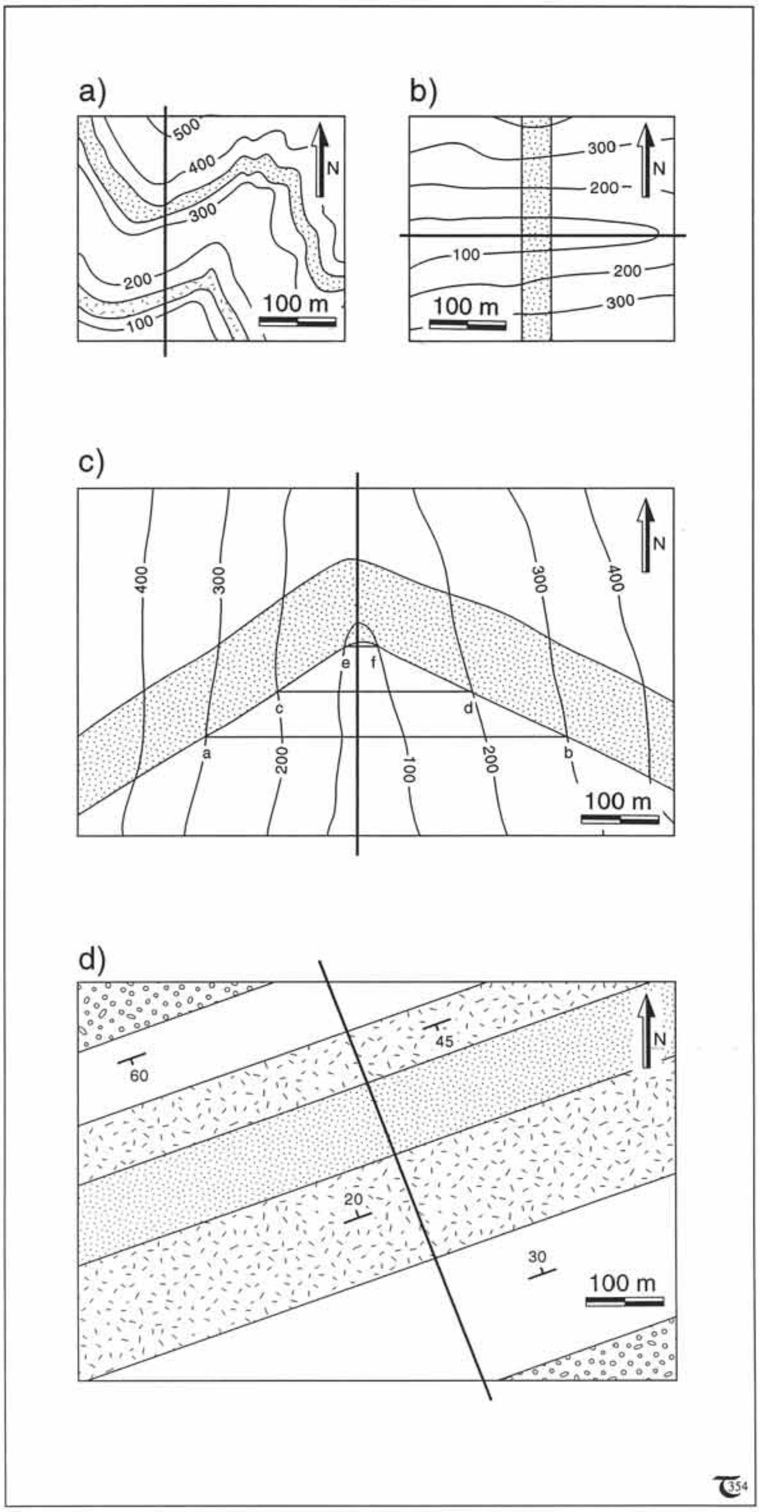


Figure 4-1: a) to d) Four geological maps, each representing a different structure, but the best section line is consistently normal to the strike of the strata.

Figure 4-1 illustrates four geological maps of terrains with stratified rocks. When constructing cross-sections across these terrains, the criteria to keep in mind are as follows: The line of section should be perpendicular to the strike of the beds and close to any field measurements of strike and dip indicated on the maps. But the layers in the map of Figure 4-1a are subhorizontal, and, in that case, the only criterion used is that the section should show the most complete view of the stratigraphy. This is achieved by choosing the line of section so that it crosses the points of lowest and highest elevation within the area.

If a layer is vertical, its outcrop pattern will not be distorted by the topography, and the section is chosen conveniently normal to its strike so that the true thickness will be preserved in the section (Fig. 4-1b). If a layer is dipping moderately, the outcrop pattern in rugged terrains may be complex (Fig. 4-1c). The direction of dip is indicated by the V-pattern in the valley intersection. The cross-section should be selected normal to the strike of the layers as indicated by structure contours labeled a-b and c-d (for details on structure contours, see chapter five). Folded sequences are, also, sectioned perpendicular to strike (Fig. 4-1d).

4-2 General procedure

If the strike and location of a cross-section have been chosen carefully, the construction of the section itself starts with the transferral of the topography of the terrain to the section (Fig. 4-2a & b). First, mark the topographic elevation along the line of section on a strip of paper. Second,

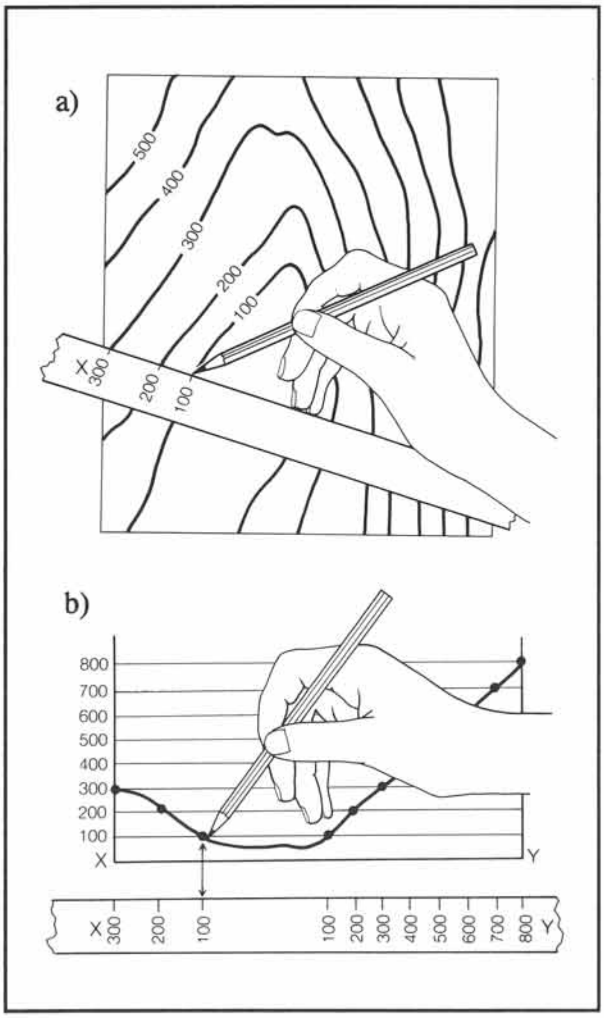


Figure 4-2: *a) & b) Steps involved in construction of a topographic cross-section.*

transfer the elevations from the paper-strip to a cross-section, showing the topography of the ground surface. The scaling of the depth axis of the section preferably should be equal to that of the horizontal scale; otherwise, the slope of the terrain appears different from that in reality. An increased vertical length scale exaggerates the slope of the terrain, whereas a decreased vertical length scale suppresses topography (Fig. 4-3a to c). For convenience of construction, use only a few of the topographic contours if many intersect the line of section, but always take sufficient points to define accurately the distinctive parts of the profile, such as ridge crests and valley floors.

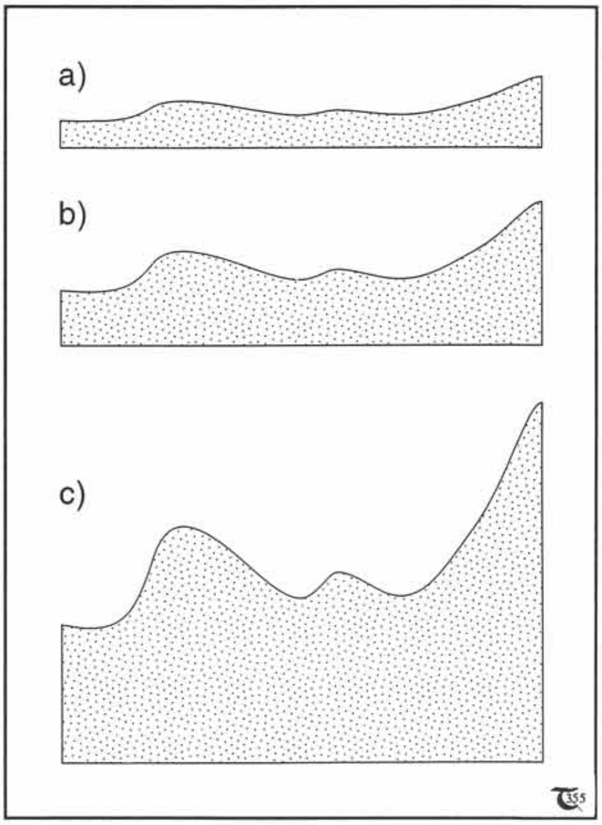
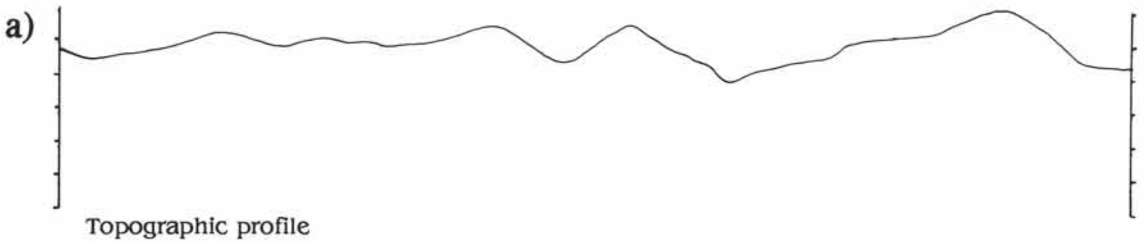


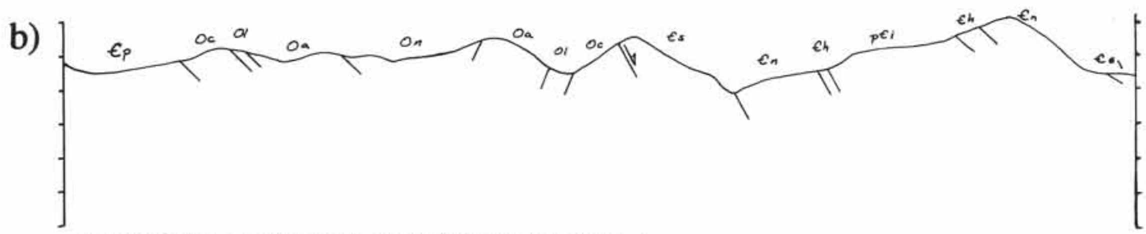
Figure 4-3: *Visual effects of variable horizontal and vertical scaling. a) Vertical scale is half the length of the horizontal scale. b) Isometrically scaled. c) Vertical scale is extended 2.5 times.*

Finally, geographical orientations should always be indicated near the vertical scale bars at either side of the section. It is, also, common and useful to write explicitly under the section "horizontal and vertical scales equal" or "horizontal:vertical=1:1" or "no vertical exaggeration."

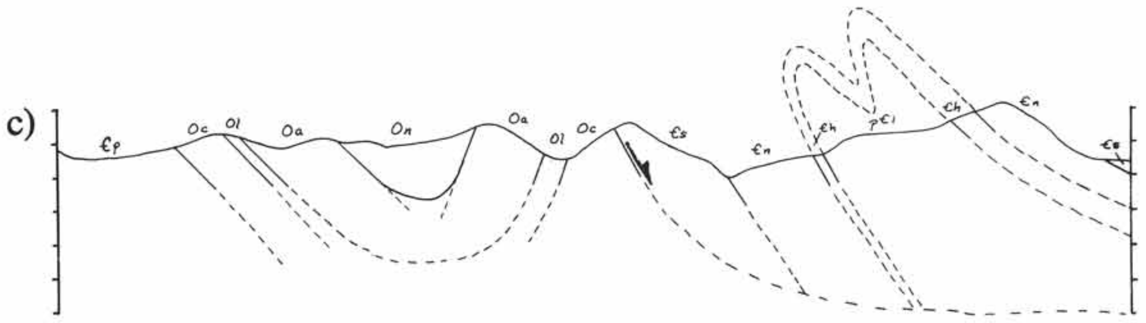
Once the topographic section is completed (Fig. 4-4a), the geological contacts are transferred to the surface of the section (Fig. 4-4b). This can be achieved by marking contacts on a slip of paper placed along the line of section on the geological map. Use colors to distinguish the rock units separated by the contact markings. If available, data from drill cores and seismic reflection profiles could be included in the section. Remember that dip angles may need correction for apparent dip, if necessary. Indicate the



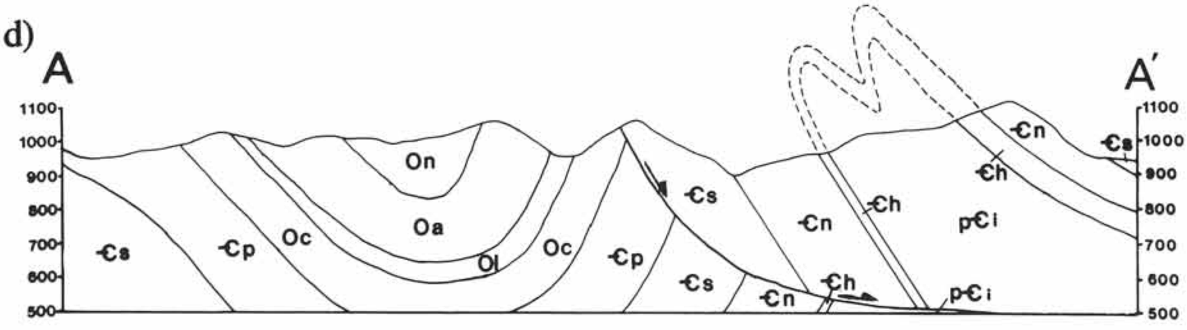
Topographic profile



Contacts (at correct angles) and temporary labels



Partially completed section



Completed, partially labeled section

Figure 4-4: *a) to d) The construction of geological cross-sections: a) Topographic profile, b) Transferral of surface dips from map to section, c) Extrapolation of surface data to depth, d) Completed section.*

direction and amount of dip for all the geological contacts involved (Fig. 4-4b).

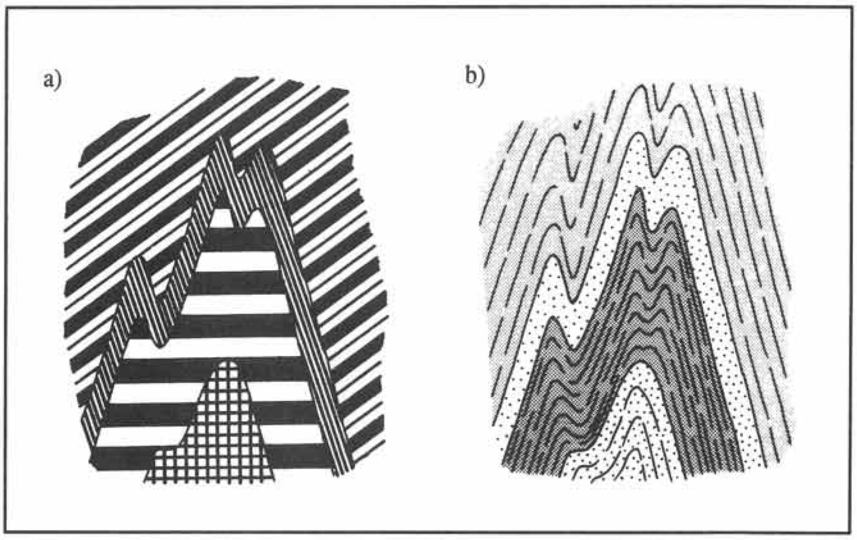


Figure 4-5: a) & b) Symbols in cross-sections: a) Inappropriate use of symbols. b) Properly used symbols follow form lines of the bedding.

The next step, completion of the section, involves a great deal of interpretation. Attempt to be as realistic as possible, and, therefore, use the surface observations close to the line of section as a starting point. The scarcer the subsurface data, the larger the interpretation factor will be. The reliability of the extrapolation of the surface data downwards in the section decreases with depth. It is, therefore, important to consider to what depth the cross-section can be extended with some certainty. The depth of the section should be no more than two to three kilometers in the absence of drill or seismic data. Guidelines for subsurface interpretation are poor, and the extrapolation is largely a matter of personal style and experience. In folded terrains it is common to assume that the stratigraphic thickness of the layers will remain constant within the plane of the cross-section (Fig. 4-4c). Fold limbs may be connected in the section by dashed curves above the ground surface to clarify the geological structure.

Finally, the cross-section will be complete only if the units are clearly labeled and their symbols are explained in a legend of the units. The legend lists the layers with the oldest units below and the youngest units above, maintaining their proper sequence. The labeling of the section may be done either by lettering (Fig. 4-4d) or by using lithological symbols. The symbols used in cross-sections are classically bound to a particular lithology (Fig. 2-16). Limestone, dolomite, and sandstone all have their characteristic symbols. The form surface of the structures (e.g., lines that parallel bedding within formations) should be expressed as clearly as possible when making use of these symbols. Figure 4-5a shows how *not* to use the symbols and Figure 4-5b shows a more appropriate use. The visual image of cross-sections allows us to appreciate the shape and orientation of geological structures. Such sections are complementary to geological maps, and their preparation and proper interpretation deserves careful attention.

☐**Exercise 4-1: Complete the cross-section of Figure 4-4c using arbitrary symbols, and draw up a legend.**

☐**Exercise 4-2: Construct cross-sections along each of the section lines outlined on the maps of Figure 4-1a to d.**

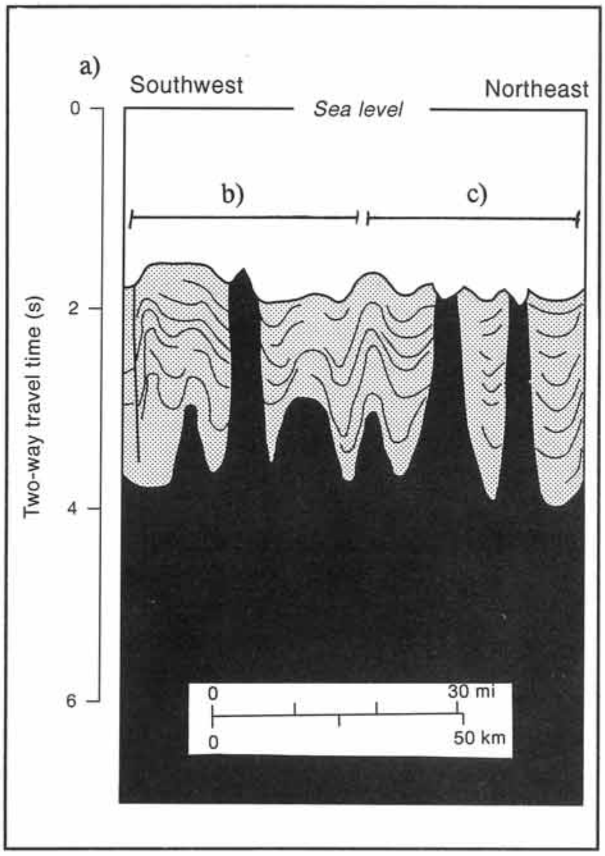


Figure 4-6a: *Seismic section through salt domes (black), piercing a sedimentary sequence (gray shade). The steepness of the domes is entirely artificial, due to exaggeration of the depth scale.*

4-3 Scaling of sections

It is vital to understand the detailed geometric implications of vertical exaggerations in structural profiles. There is a growing trend in the industry to remove such exaggerations where possible, because they introduce problems to structural interpretations. But, in some circumstances, depth scales of cross-sections are deliberately exaggerated with respect to the horizontal scale. Such unequal length scales are sometimes adopted when base lines are extremely long, and this is particularly common for cross-sections based on the interpretation of seismic reflection profiles. Figure 4-6a illustrates a common migrated seismic section through salt domes, piercing a sedimentary sequence. The exaggeration of the layer thickness and their dips is large, as becomes apparent from a representation of the same section with the vertical exaggeration removed (Figs. 4-6b & c). Obviously, the form and orientation of structures is distorted in vertically exaggerated sections, thereby obscuring the very information the structural section seeks to illustrate. It is, therefore, extremely important always to include in any cross-section clear information, concerning the vertical exaggeration factor.

Four visual effects, associated with an increased vertical scale, are: a) any structural planes appear to dip more steeply than their

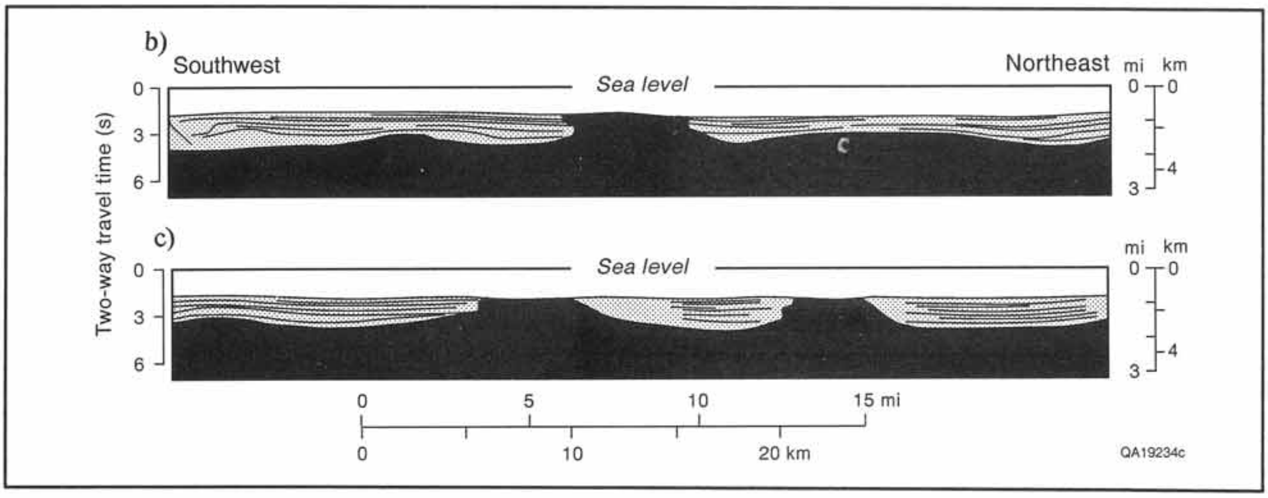


Figure 4-6: *b) & c) Restoration of the same seismic section to equidimensional or isometric scales.*

actual dip in that section plane (remember that the section is not necessarily normal to the strike), (b) the angles between cross-cutting structures are distorted in a complex fashion, (c) the thickness of geological units appears generally much greater than their true thickness, and (d) layer thicknesses may falsely appear to change laterally. Each of these effects will be discussed in detail below as they are particularly common features of seismic profiles used by the oil and gas industry.

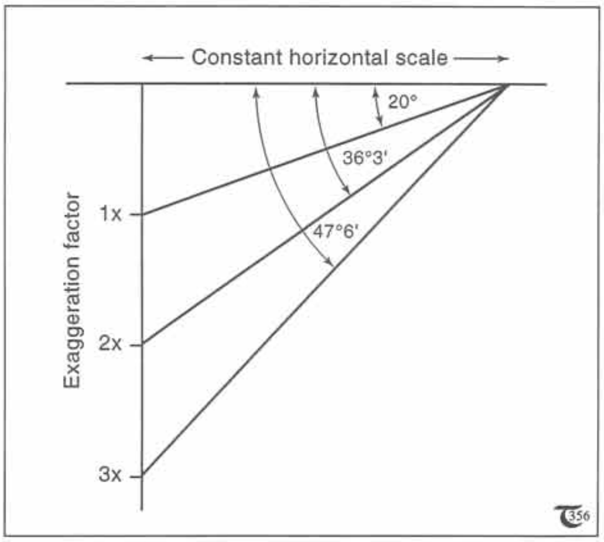


Figure 4-7: *The angle of dip increases if the vertical scale of seismic and other cross-sections is exaggerated. See eq. (4-1).*

a) Exaggerated dip

The dip of any non-horizontal layers will be exaggerated if the vertical scale is increased. The exaggeration factor, V, can be defined as the ratio of the vertical and horizontal length scales. It is easy to see that the true dip, α, will be exaggerated into the apparent dip, α^*, by the exaggeration factor, V:

$\tan \alpha^* = V \tan \alpha$ (4-1)

The dip exaggeration principle is illustrated in Figure 4-7 for a planar surface whose true dip is 20° due west. If the vertical length scale is twice the horizontal length, the exaggeration factor, V, equals 2 and the exaggerated dip will be 36°. If the exaggeration factor, V, equals 3, the exaggerated dip is 48°.

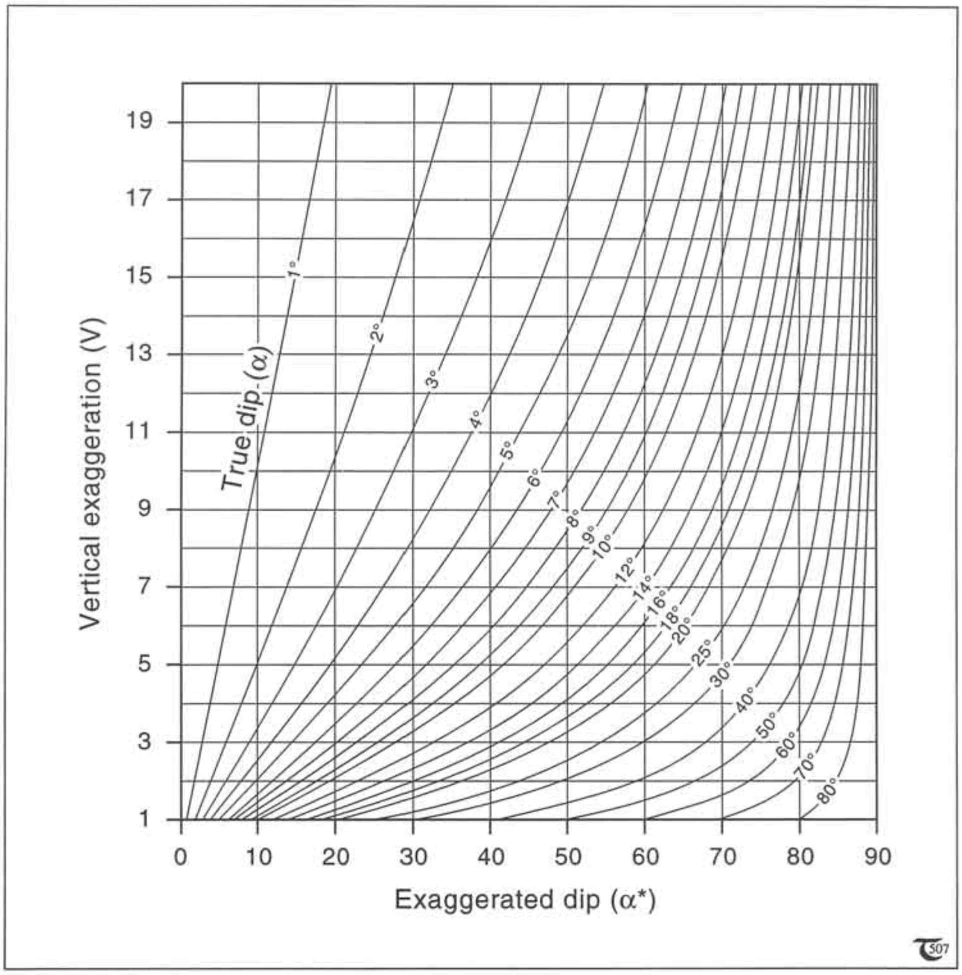


Figure 4-8: Nomogram relating the true dip, α, to the exaggerated dip, α^*, for a range of vertical exaggeration factors [eq. (4-1)].

Instead of calculating equation (4-1), it may be faster to use a nomogram to obtain one of the unknown angles from the vertical exaggeration factor. Figure 4-8 shows an example of a nomogram, used to transform exaggerated dip to true dip and vice versa. Note that the effect of dip exaggeration becomes less profound for layers which have already large true dips. The extreme case is a vertical layer; its dip will not change by vertical exaggeration.

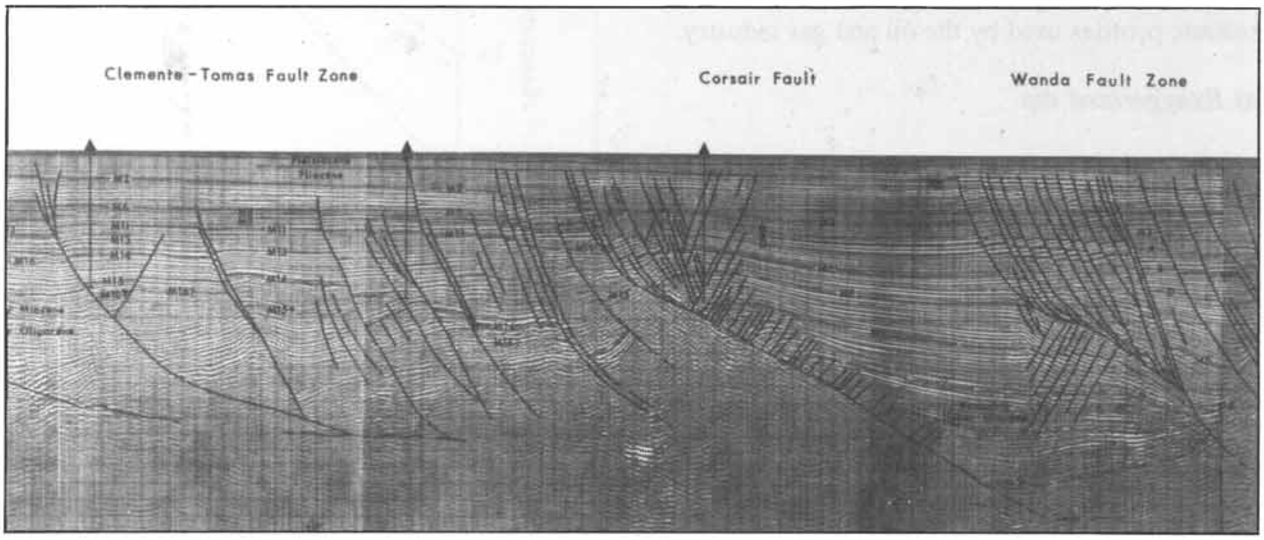


Figure 4-9a: Original seismogram across the Clemente-Tomas, Corsair, and Wanda fault systems in the Gulf of Mexico, off-shore Texas.

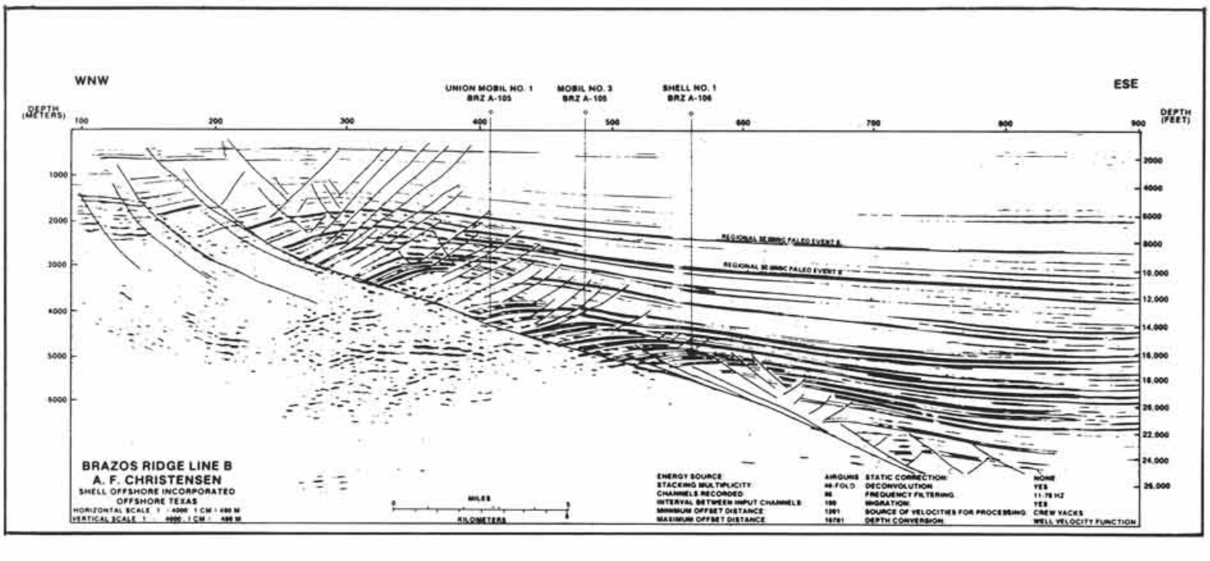


Figure 4-9b: Restored section of the Corsair fault system with the horizontal and vertical scales equal.

☐Exercise 4-3: The Clemente-Tomas and Corsair fault systems are prominent structural features beneath the submerged floor of the Gulf of Mexico. Figure 4-9a illustrates the seismic section with the vertical scale exaggerated, and Figure 4-9b is scaled with no vertical exaggeration. The difference in dip of the main Corsair fault in the two figures can be used to determine the exaggeration factor for the seismic section in Figure 4-9a. Obtain the answer in two different (but similar) ways: (a) applying equation (4-1), and (b) using the nomogram of Figure 4-8. Your answers should converge.

b) Distortion of angles

Figure 4-10a illustrates a cross-section, with horizontal and vertical scales equal, portraying a faulted sequence unconformably overlain by another, onlapping sequence of sedimentary rocks. Figure 4-10b shows the appearance of the same section with a vertical exaggeration factor, V=8. One important aspect is the apparent increase in the dip of both the faults and the layers. Angular differences between shallow dipping contacts are *increased*. For example, the true unconformity angle is 5°, but it appears as 27° in the exaggerated section. Angular differences between steeply dipping surfaces are *reduced*. For example, the acute angle between the two normal faults is 24° in reality but appears as only 5° in the exaggerated section.

c) Exaggerated thickness

Exaggerating the vertical length scale in cross-sections not only exaggerates the dip of geologi-

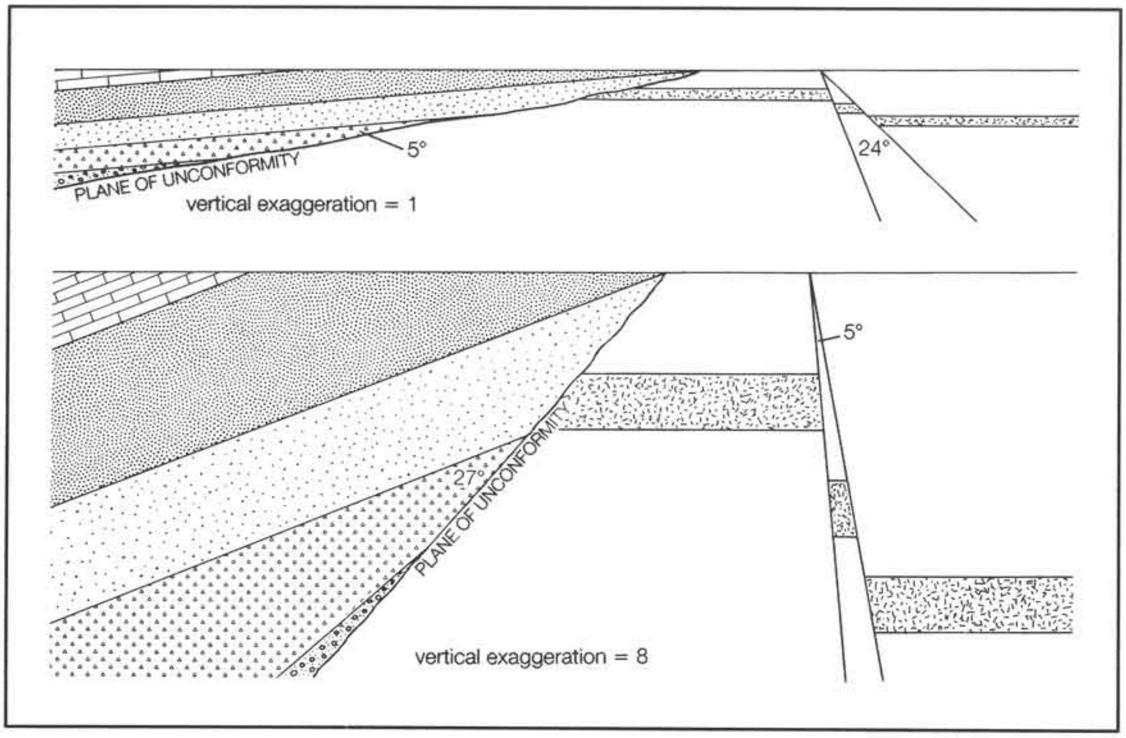


***Figure 4-10:** a) & b) Distortion of angles occurs in non-isometrically scaled sections. a) Original isometric section. b) Same section with vertical exaggeration factor of eight.*

cal contact surfaces, but, in addition, visually distorts the thickness of all layers, except for vertical beds. The length/thickness ratio of the central, horizontal sandstone layer, located between the fault plane and the unconformity in Figure 4-10b, is markedly decreased, as compared to that in the true-to-scale section in Figure 4-10a. The normalized exaggerated thickness, T^*/T, is dependent on the vertical exaggeration factor, V, and the original layer dip, α:

$$T^*/T=[V/\cos\alpha]\cos[\tan^{-1}(V\tan\alpha)] \qquad (4\text{-}2)$$

☐Exercise 4-4: Figure 4-12a is a true-to-scale cross-section, illustrating two vertical igneous dikes separated by a sedimentary sequence tilted at 10°. The same section is redrawn in Figure 4-12b with a vertical exaggeration factor of 8. The sandstone - an important aquifer - has an exaggerated thickness of 100 meters. Estimate the true thickness of the aquifer, using: (a) equation (4-2), and (b) the nomogram of Figure 4-11.

Instead of using equation (4-2), it may be faster to use a nomogram to obtain the normalized exaggerated thickness from the vertical exaggeration factor, V, and the particular original dip of the strata. Figure 4-11 shows an example of a nomogram used to obtain the orthogonal thickness exaggeration from V and the original layer dip. The effect of thickness exaggeration becomes less profound for layers with steep dips. The effect is largest for horizontal layers (i.e., $T^*/T=V$) and is absent for vertical layers. The thickness of vertical layers will not change by vertical exaggeration.

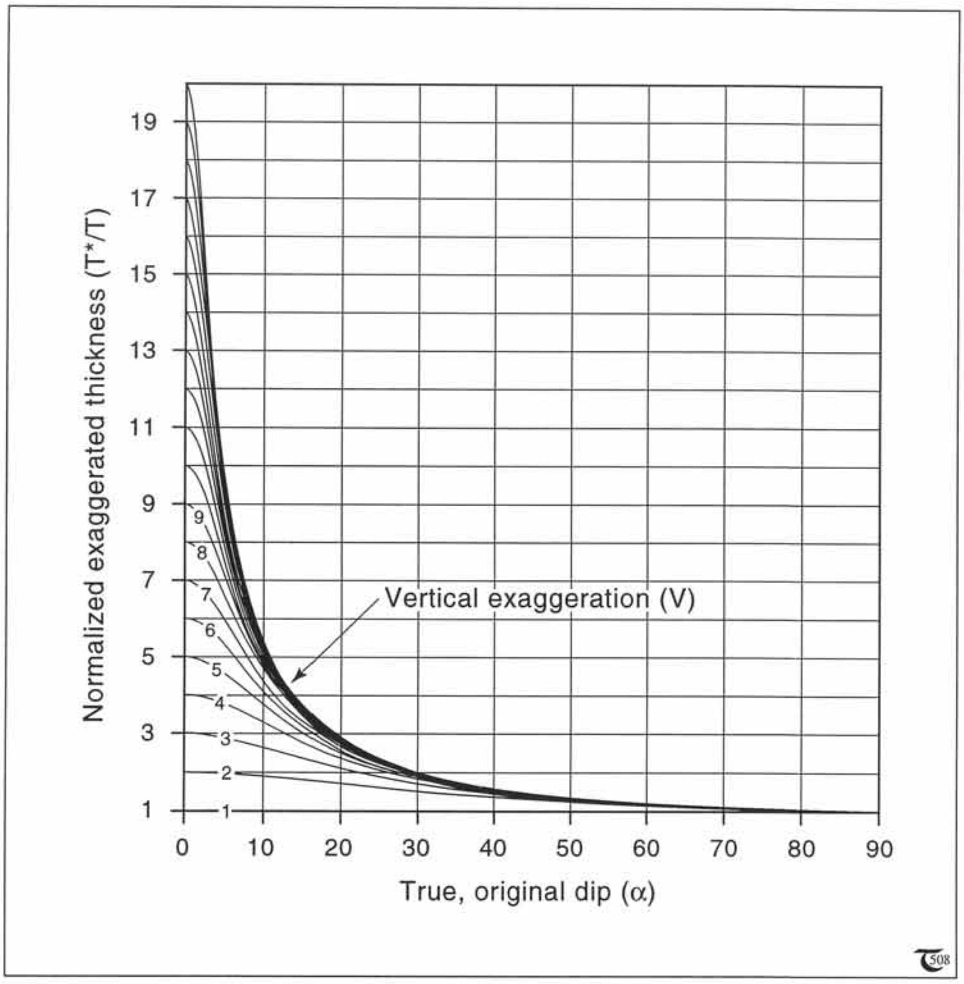


***Figure 4-11:** Nomogram relating the true dip, α, to the normalized exaggerated thickness of a layer, T^*/T, for a range of vertical exaggeration factors, V. See eq. (4-2).*

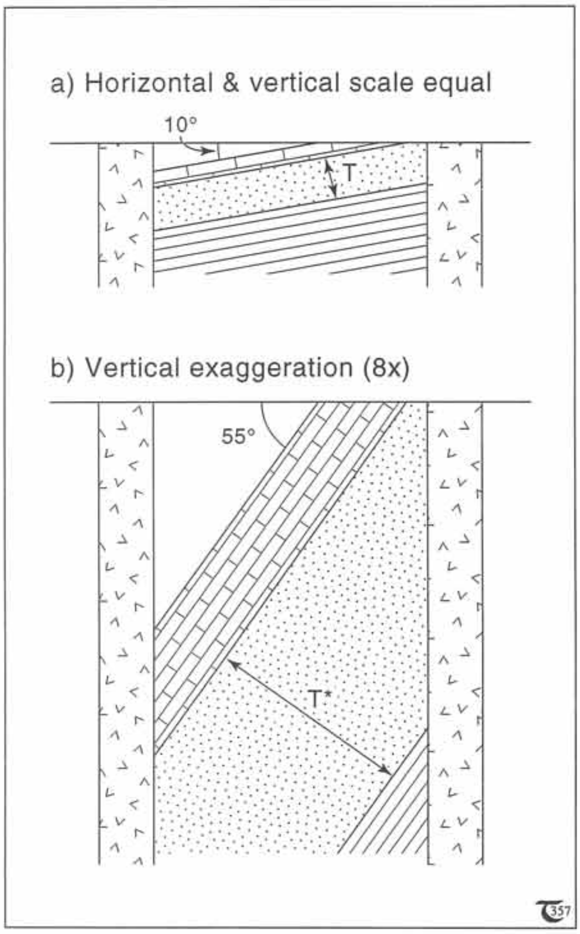


Figure 4-12: *a) & b) Isometric and vertically exaggerated cross-sections (V=8). The layer thickness, T, is artificially enhanced in the exaggerated section to T*. See exercise 4-4.*

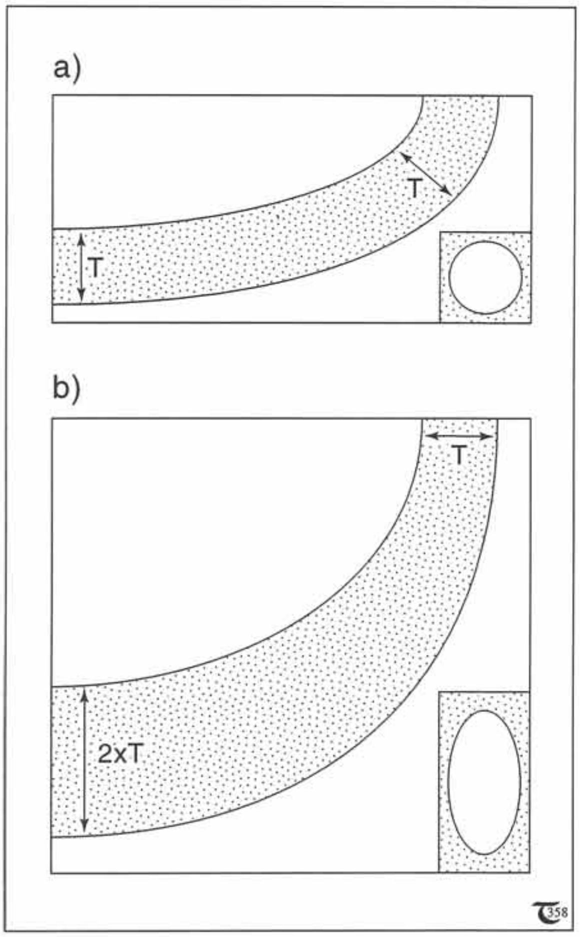


Figure 4-13: *a) & b) Appearance of folded layer of constant thickness in: (a) isometrically scaled, and b) vertically exaggerated cross-section, two-fold (V=2). The strain ellipse scales the exaggeration.*

d) Apparent thickness change

The thickness of dipping layers is affected, either more or less, by exaggerating the vertical length scale, depending upon the initial or true dip of the beds. A very informative example of this effect occurs on layers of *constant thickness*, but with gradual changes in the amount of dip (Fig. 4-13a), which appear on the exaggerated cross-section with *lateral changes in thickness* (Fig. 4-13b). Consequently, the thickness of a folded sequence will be attenuated in seismic sections on the hinge zones. Similarly, the central part of depocenters may appear thickened on vertically exaggerated seismic sections, purely as an apparent visual, rather than a real, feature. An expression linking the normalized exaggerated thickness of beds, T^*/T, directly to the vertical exaggeration factor, V, and the exaggerated dip, α^*, is:

$$T^*/T=[V \cos \alpha^*]/ \cos[\tan^{-1}(\tan \alpha^*/V)] \quad (4\text{-}3)$$

The function is plotted in the nomogram of Figure 4-14 for practical use.

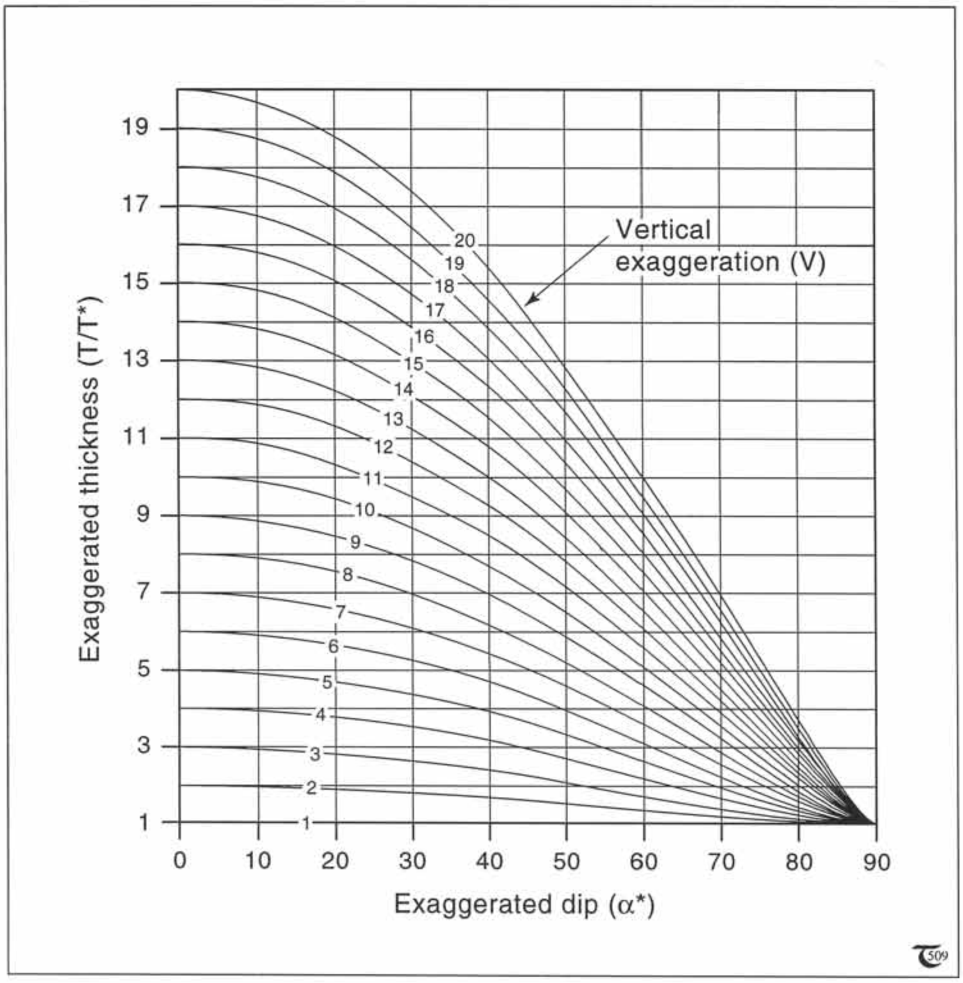


Figure 4-14: Nomogram relating the exaggerated dip, α, to the normalized exaggerated layer thickness, T*/T, for a range of vertical exaggeration factors, V. See eq. (4-3).*

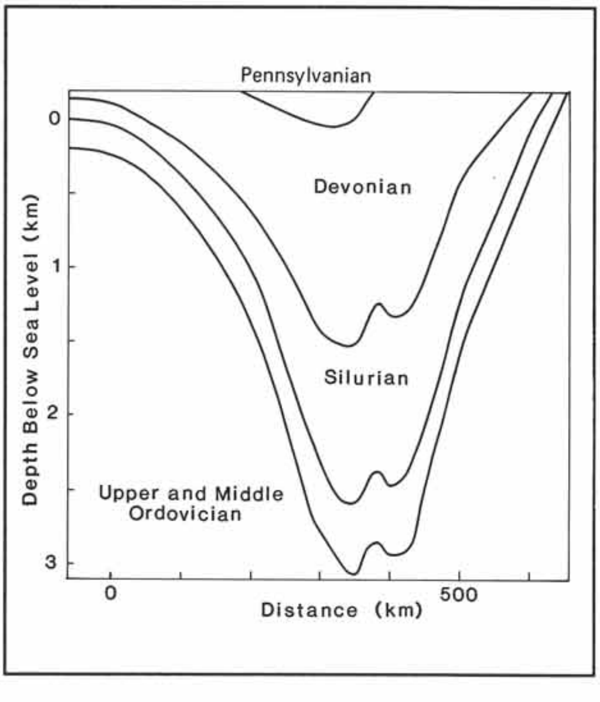


Figure 4-15: Cross-section, two hundred times vertically exaggerated, of the Michigan Basin, North America.

☐Exercise 4-5: Study the cross-section through the Michigan Basin (Fig. 4-15). The true thickness of about one kilometer of the Silurian beds can be read from the vertical scale, where the layers are horizontal, i.e., in the center of the basin. The section suggests that the Silurian thins dramatically towards the margins of the basin. However, this is largely a visual artifact due to the extremely large vertical exaggeration. Although the Michigan basin is just a gentle depression, the section suggests it has the shape of a tight synform. Use equation (4-1) to specify the true dip of the base of the Silurian in the steepest part of the basin.

4-4 Apparent thickness and dip

The distortions outlined in section 4-3 are all artifacts of the difference in horizontal and vertical scales, sometimes used in the construction of cross-sections. Two other distortional effects, associated with the orientation of cross-sections, are (a) apparent dip and (b) apparent thickness of layers (see, also, chapter three). However, these distortions are of a different nature from the purely artificial distortions discussed in section 4-3. Natural surfaces cutting oblique to the strike of geological structures actually display apparent dips, and appear less steep than the true dip.

☐Exercise 4-6: The cross-section of Figure 4-16 shows the hydrocarbon-bearing cover sequence of the Arabian shield. The basement appears at the surface in the extreme left of the section, and the contact with the main fault of the Zagros Mountains is indicated in the right-hand part. The vertical exaggeration of the section is of factor V=80. a) Use equation (4-1), and specify the true dip of the base of the cover sequence in the steepest part of the basin. b) Discuss all the visual effects which are only apparent and thus distort the true geometry of the subsurface structure seen.

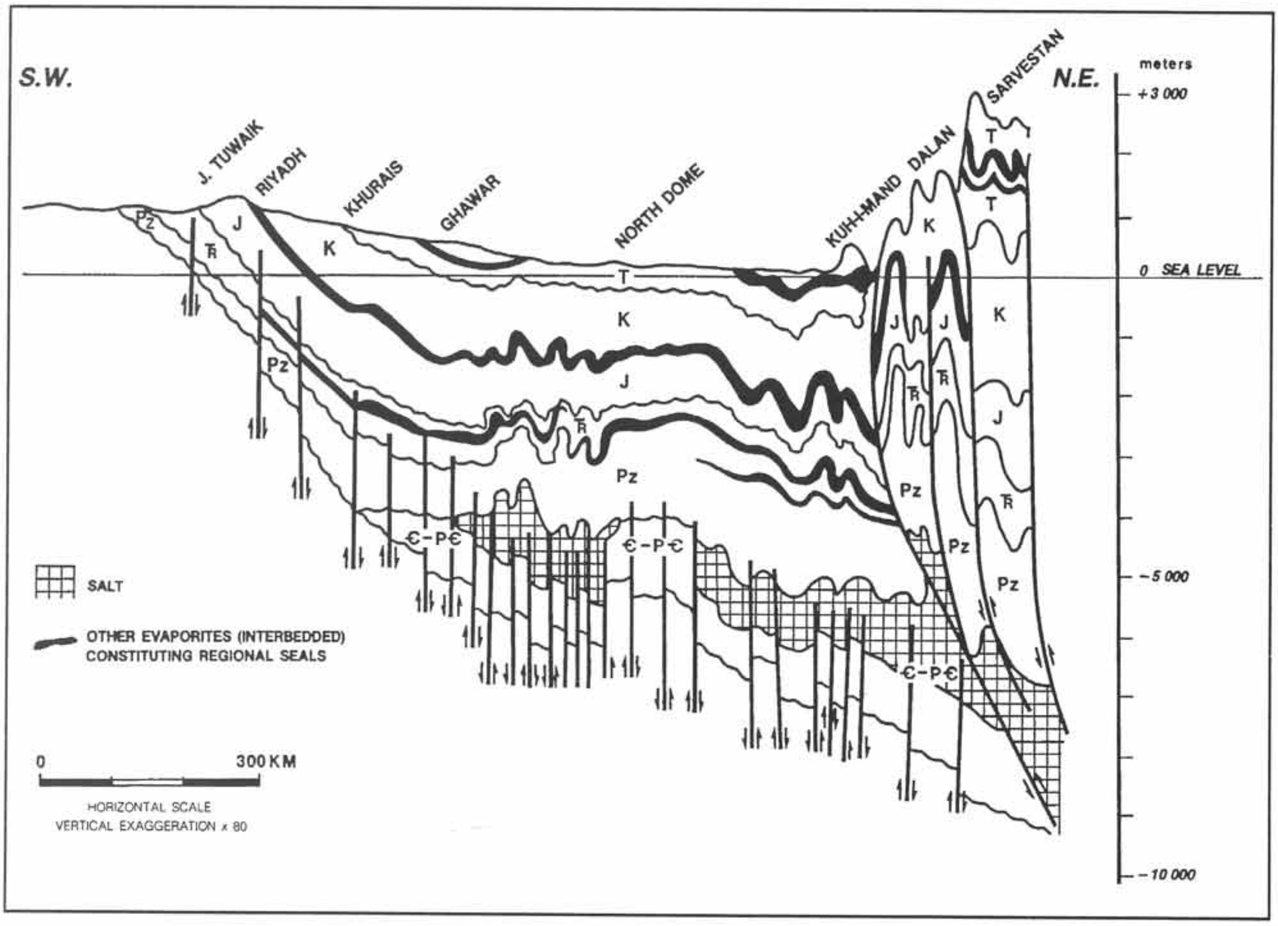


Figure 4-16: Cross-section, eighty times vertically exaggerated, of the Arabian platform sequence, adjacent to the Zagros Mountains in the northeast.

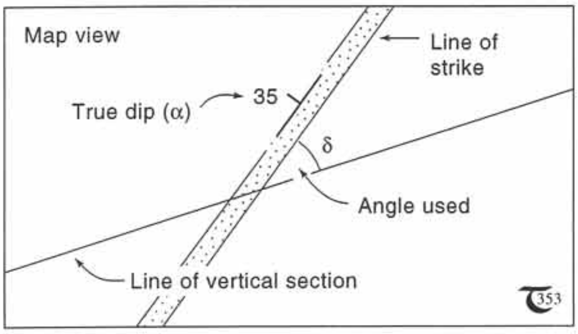


Figure 4-17: The angle, δ, is measured in map views between the strike of a bed and the section line. Thickness exaggeration relates to the true dip, α, through the section angle, δ.

This is because the dip of inclined layers may, in cross-sections without scale exaggeration, vary between zero and the true dip, depending upon whether the profile line is parallel or perpendicular to the strike of that plane. The apparent dips and thicknesses in oblique cross-sections may give misleading views of the structure of a region. Geologists must be aware of these kinds of visual distortions, especially when examining field exposures of rock structures. The walls of natural canyons and man-made road cuts are likely to be oblique to the structural strike. It is often hard to conceive that such sections of real rock surfaces may show misleading, distorted views. One danger associated with the interpretation and study of both constructed and natural cross-sections is that sectional distortions are overlooked. The true thickness and true dip of sedimentary beds are seen only if the cross-section is oriented perpendicular to the strike of the beds. If cross-sections are constructed with apparent thickness and dip of the layers, the transferral of the map data to such oblique sections is more elaborate than in profiles normal to the strike. In such oblique cross-sections, all true dips need to be transformed to apparent dips. For example, at least some beds in areas of gently plunging folds will strike oblique to any vertical plane of section (see chapter seven, exercise 7-10), and the effects of apparent dip and thickness may be different for limbs at either side of the axial plane.

The thickness of inclined layers in vertical cuts oblique to strike is exaggerated and appears with an apparent thickness, T_A. True and apparent thicknesses are partly controlled by the angle, δ, measured between the section line and the strike

***Table 4-1:** Factors of thickness exaggeration for layers of true dip, α, cut oblique at angle δ.*

True dip, α	Acute angle between strike and line of section, δ 0	5	10	15	20	25	30	40	50	60	70	80	90
0	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1
10	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1
15	1.04	1.03	1.04	1.03	1.03	1.03	1.03	1.02	1.01	1.01	1.00	1.00	1
20	1.06	1.06	1.06	1.06	1.06	1.05	1.05	1.04	1.03	1.02	1.01	1.00	1
25	1.10	1.10	1.10	1.10	1.09	1.08	1.08	1.06	1.04	1.02	1.01	1.00	1
30	1.16	1.15	1.15	1.14	1.13	1.12	1.11	1.08	1.06	1.03	1.02	1.00	1
35	1.22	1.22	1.22	1.20	1.19	1.17	1.15	1.11	1.08	1.04	1.02	1.00	1
40	1.31	1.30	1.29	1.28	1.26	1.23	1.20	1.15	1.10	1.06	1.03	1.01	1
45	1.41	1.41	1.39	1.37	1.34	1.30	1.27	1.19	1.12	1.07	1.03	1.01	1
50	1.56	1.55	1.53	1.49	1.44	1.39	1.34	1.24	1.15	1.08	1.04	1.01	1
55	1.74	1.73	1.69	1.64	1.57	1.49	1.42	1.28	1.18	1.10	1.04	1.01	1
60	2	1.98	1.92	1.83	1.72	1.61	1.51	1.34	1.20	1.11	1.05	1.01	1
65	2.37	2.33	2.22	2.07	1.91	1.75	1.61	1.39	1.23	1.12	1.05	1.01	1
70	2.92	2.84	2.64	2.38	2.13	1.91	1.72	1.44	1.26	1.13	1.06	1.01	1
75	3.86	3.64	3.24	2.78	2.38	2.07	1.83	1.49	1.28	1.14	1.06	1.01	1
80	5.76	5.14	4.10	3.24	2.64	2.22	1.92	1.52	1.29	1.15	1.06	1.02	1
85	11.47	8.13	5.16	3.67	2.84	2.33	1.98	1.55	1.30	1.15	1.06	1.02	1
90	∞	11.47	5.76	3.86	2.92	2.37	2	1.56	1.55	1.31	1.06	1.02	1

of the strata studied (Fig. 4-17). Layers of dip, α, and map width, W, have, in vertical cuts at angle δ to their strike, an apparent thickness, T_A:

$$T_A = W \sin[\tan^{-1}(\tan\alpha \sin\delta)]/\sin\delta \qquad (4\text{-}4)$$

The true thickness, T, relates to map width, W, and dip, α, by:

$$T = W \sin\alpha \qquad (4\text{-}5)$$

Consequently, the thickness exaggeration factor, T_A/T, is:

$$T_A/T = \sin[\tan^{-1}(\tan\alpha \sin\delta)]/(\sin\alpha \sin\delta) \qquad (4\text{-}6)$$

Equations (4-4) and (4-6) are invalid if δ equals zero. For such cases, the vertical thickness of layers is given by: $T_A = W/\sin(90°-\alpha)$. The corresponding thickness exaggeration factor then becomes: $T_A/T = 1/\sin(90°-\alpha)$. For α equal to 90°, the thickness exaggeration factor reduces to: $T_A/T = 1/\sin\delta$.

Table 4-1 lists exaggeration factors for the full range of angles possible for α and δ. The thickness of sedimentary beds, visually exaggerated in sections oblique to the strike of the beds, can, also, be inferred using the thickness exaggeration factors, included in the nomogram of Figure 4-18. This nomogram can, also, be used to trans-

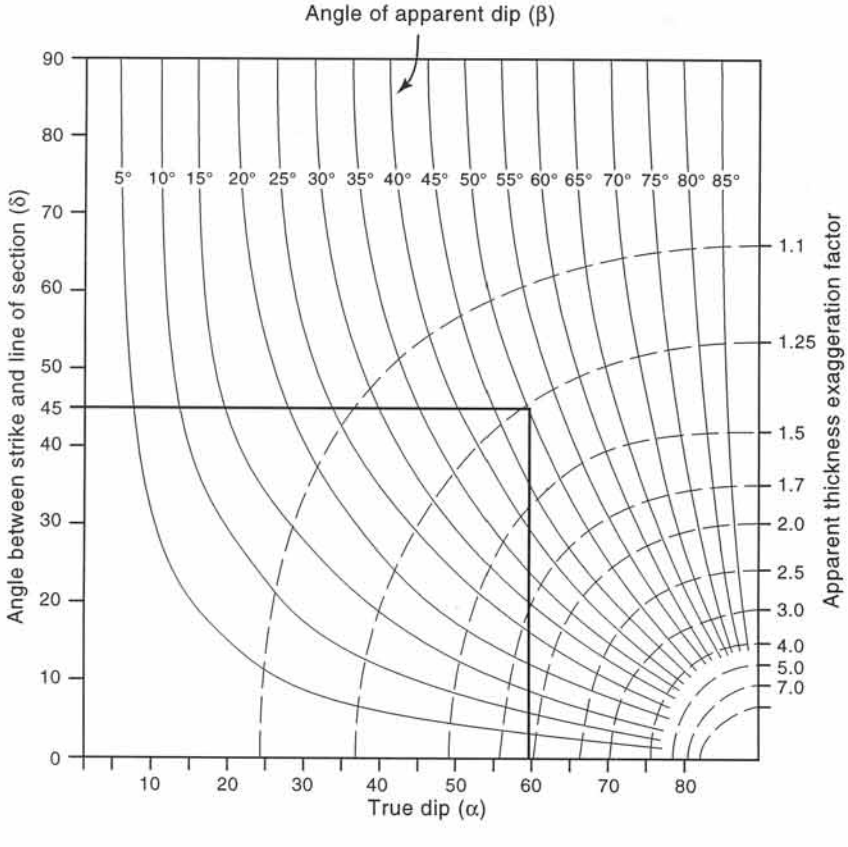


Figure 4-18: Nomogram relating true and apparent dip, including the exaggeration factor for the apparent thickness of beds in sections oblique to the structural strike.

form true dips from geological maps to apparent dips on cross-sections, and vice versa. Similarly, apparent dips, as seen in oblique cross-sections, may be converted to true dips measured in field outcrops. The mathematical expression used to obtain true dips from apparent dips of strata in sections oblique to strike was given in chapter three [eq. (3-1)].

Figure 4-19: *View of the Grand Canyon from Lipan Point, about fifty kilometers east from the visitors' center. See exercise 4-8.*

☐Exercise 4-7: A sandstone bed dips 60° due east. A canyon cuts the bed at 45° to its strike. a) Use the nomogram of Figure 4-18 to predict which dip you will see for the bed in the canyon walls. b) If the bed in the canyon walls appears with a thickness of 128 meters, how much is the true thickness according to the nomogram? c) What is the outcrop width of the bed as seen on the horizontal plateau next to the canyon? d) A limestone bed concordant with the sandstone bed is known to have a true thickness of 200 meters. What will be the thickness as seen in the canyon wall?

☐Exercise 4-8: A subhorizontal Paleozoic top sequence (1.5 kilometers thick) rests unconformably on the Precambrian Grand Canyon Series, which dip gently to the NW (Fig. 4-19). a) Explain why the contact between the Paleozoic and Precambrian beds seems concordant in the right part of the picture, whereas an angular unconformity appears in the left part. b) Explain why the thicknesses of the Precambrian beds in the left and right parts of the picture appear almost similar, despite the different orientations of the canyon slopes.

Chapter 5: Structure Contours for Planar Beds

THE LOCAL orientation of a geological bed or stratum can be represented on geological maps by a strike/dip symbol. A more complete way of representing the shape of complex geological structures is by means of structure contours. Such contours can be constructed using points where topographic contours intersect geological outcrop patterns on the ground surface. The interpretation of structure contours then allows an assessment of the subsurface structure of such areas. Structure contours are used not only to represent the shape of geological surfaces, but also provide a means of inferring the strike and dip of geological formations from maps.

Contents: Structure-contour maps are introduced in section 5-1. The determination of strike and dip from structure-contour maps is outlined in section 5-2. The effect of the topographic relief on the outcrop patterns of planar, inclined layers is illustrated for thin beds in section 5-3 and for thick beds in section 5-4.

5-1 Structure-contour maps

The shape of geological structures can be represented by a set of *structure contours*, which are lines or curves connecting points of equal

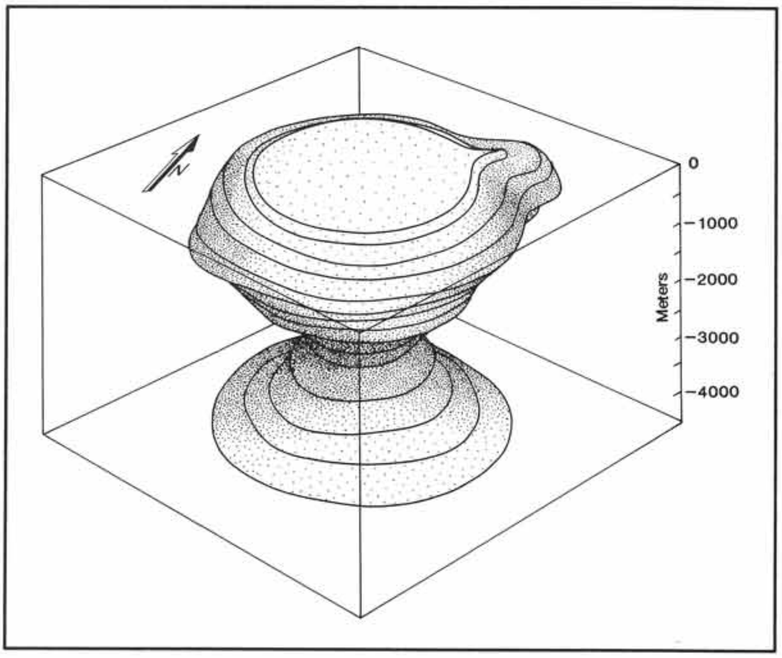


Figure 5-1: *Structure contours on the Hainesville salt stock, USA, in perspective view.*

altitude on a specific horizon. Structure contours have properties similar to those of topographic contours. Both sets of contours are used to represent the shape of a particular surface. However, whereas topographic contours are exclusively used to portray the shape of the ground surface, structure contours are employed to illustrate the shape of geological surfaces. Such surfaces may include: bedding planes, fold shapes, fault planes, salt domes, etc. For example, the mushroom shape of a buried salt body can be outlined by structure contours (Fig. 5-1). Structure contours, like topographic contours, commonly form a set of smooth and subparallel curves or lines. Structure contours are straight lines only when the geological surface resembles a flat plane, like an inclined planar bed or a planar fault.

It is often practical to project structure contours on a horizontal map. The spacing of the contour lines in such *structure-contour maps* reflects the gradient of the slope. The closer the contours, the steeper the inclination of the structural surface. Widely spaced contours imply gentle slopes. The difference in elevation between adjacent contours is constant on any given map. Figure 5-2 illustrates a structure-contour map of the top of the Precambrian *basement* of the Michigan Basin. The maximum depth of the basin is four kilometers (12,000 feet).

The contour spacing on different structure-contour maps may be different and is determined by what is convenient for the particular structure displayed. The height or depth of the contours is indicated along them at regular intervals. Figure 5-3 illustrates a structure-contour map for the top of the Precambrian basement of the Arabian plate. The map suggests that the deepest part of the Arabian basin is fifteen kilometers (45,000 feet) below the ground surface.

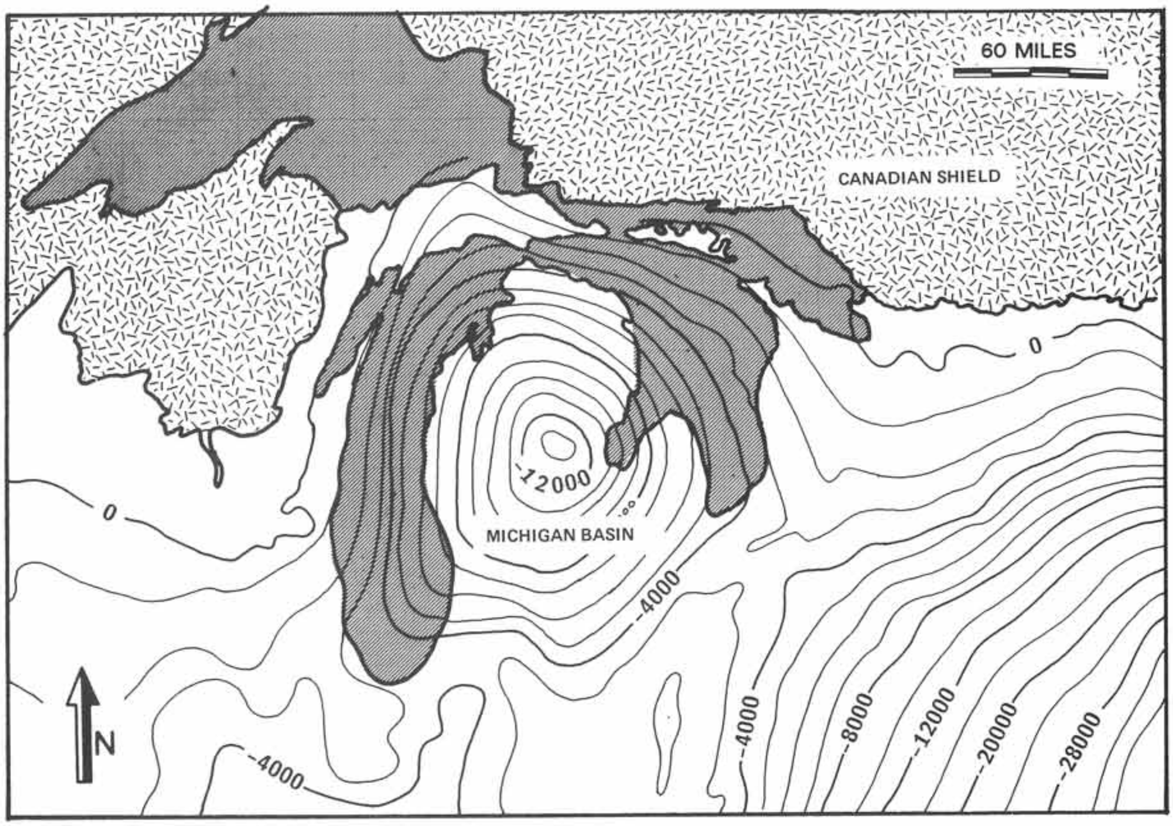


Figure 5-2: *Structure-contour map of the top of the Precambrian basement in the Michigan Basin. Units are in feet.*

☐Exercise 5-1: a) Examine the map of Figure 5-3, and calculate the average slope of the top of the Precambrian. b) Give the azimuth/dip for the top of the Precambrian basement for the area to the east of its surface outcrop.

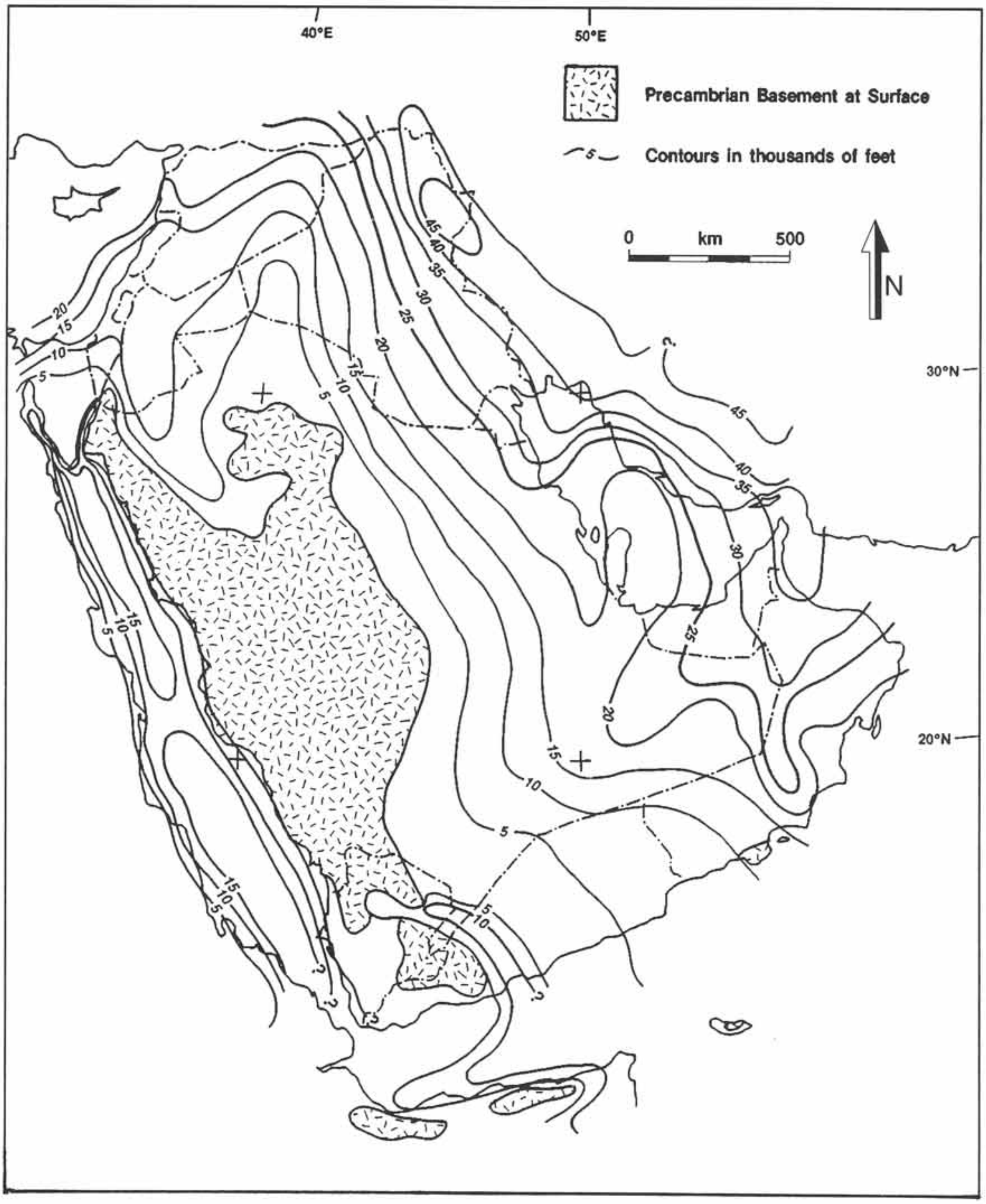


Figure 5-3: Structure-contour map of the top of the Precambrian basement of the Arabian Peninsula. Contours in thousands of feet below sea level.

5-2 Strike and dip determination

The structure contours for planar inclined beds are made up of a series of evenly spaced and parallel strike lines (Fig. 5-4). These can be projected orthogonally on the map surface to obtain a structure-contour map. Conversely, it is simple to infer the strike and dip of the original bed from its structure contours. Figure 5-5a shows a structure-contour map. The strike orientation of the bed immediately follows from the trend of the contours, which is parallel to the strike. The dip of the bed, α, can be inferred from the horizontal spacing between the projected contour lines, d, and the contour interval, x, using (Fig. 5-5b):

$$\alpha = \tan^{-1}(x/d) \qquad (5\text{-}1)$$

The map of Figure 5-5a immediately reveals the azimuth/dip of the contoured layer as 270°/45°.

☐Exercise 5-2: Figures 5-6a and b are structure-contour maps for the top of a limestone bed. a) Give the azimuth/ dip of the limestone for locations 1 to 4. b) Construct cross-sections along lines A-B and C-D. c) Name the structure seen in the map of Figure 5-6b.

5-3 Outcrop patterns of thin beds

The outcrop pattern of a layer, its structure contours, and the elevation contours have a particular relationship. Figure 5-7a illustrates the outcrop pattern of a very thin limestone layer in a terrain of topographic relief. The map includes three types of contours: elevation contours for the surface topography, structure contours with the elevations of the limestone bed, and the outcrop pattern of the limestone at the ground surface.

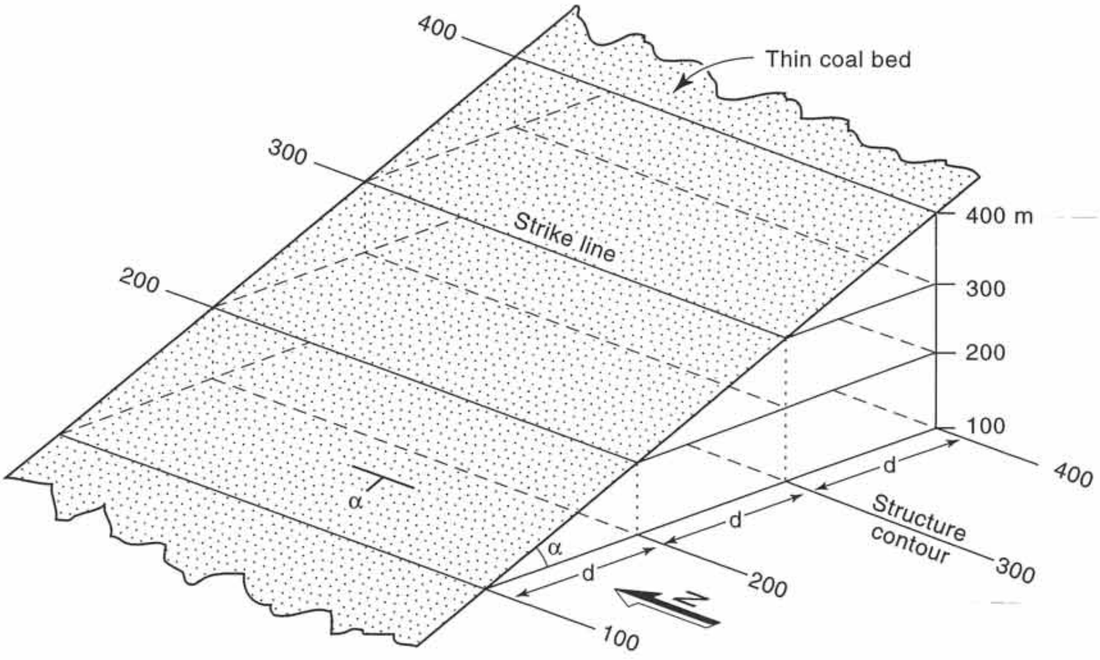


Figure 5-4: Structure contours on homoclinal beds are parallel to the strike lines and mark regularly spaced elevations. Orthographic projection of the contours gives a structure-contour map of the coal bed.

The layer reaches the surface in any location where the topographic contour cuts a structure contour of the same elevation. In other words, the outcrop pattern is the intersection of the structure and the topography as defined by their contours. The implications of this relationship are as follows: (1) Structure contours can be constructed if the outcrop pattern and the topographic contours are known. (2) The outcrop pattern of a geological stratum can be constructed if the structure contours and topographic contours are both known. The concept of point (1) will be practiced in this chapter, and that of point (2) will be examined in more detail in the next chapter.

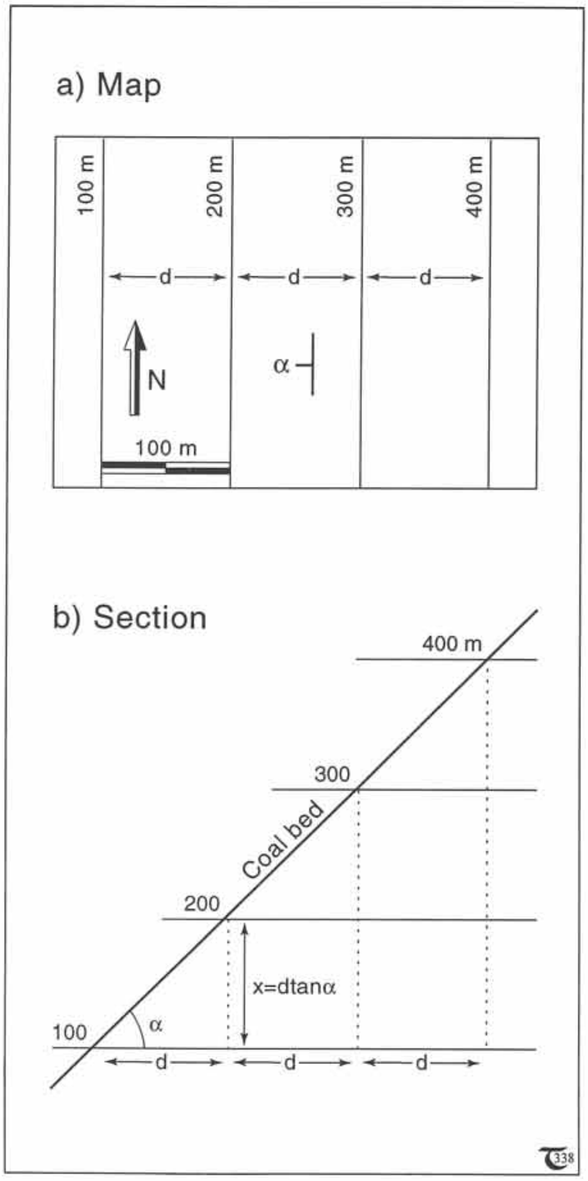


__Figure 5-5:__ a) Structure-contour map of 100 m intervals. The even spacing indicates a homoclinal bed. b) E-W section across the map of (a). The dip of the bed, α, is given by equation (5-1).

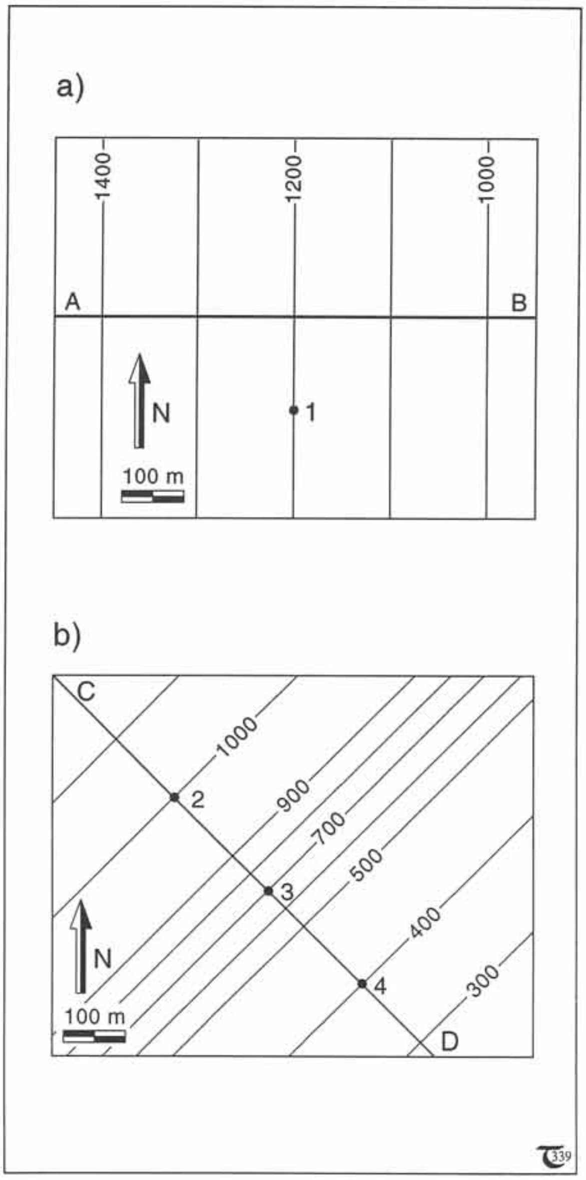


__Figure 5-6:__ a) & b) Two structure-contour maps, studied in exercise 5-2. Contours are in meters.

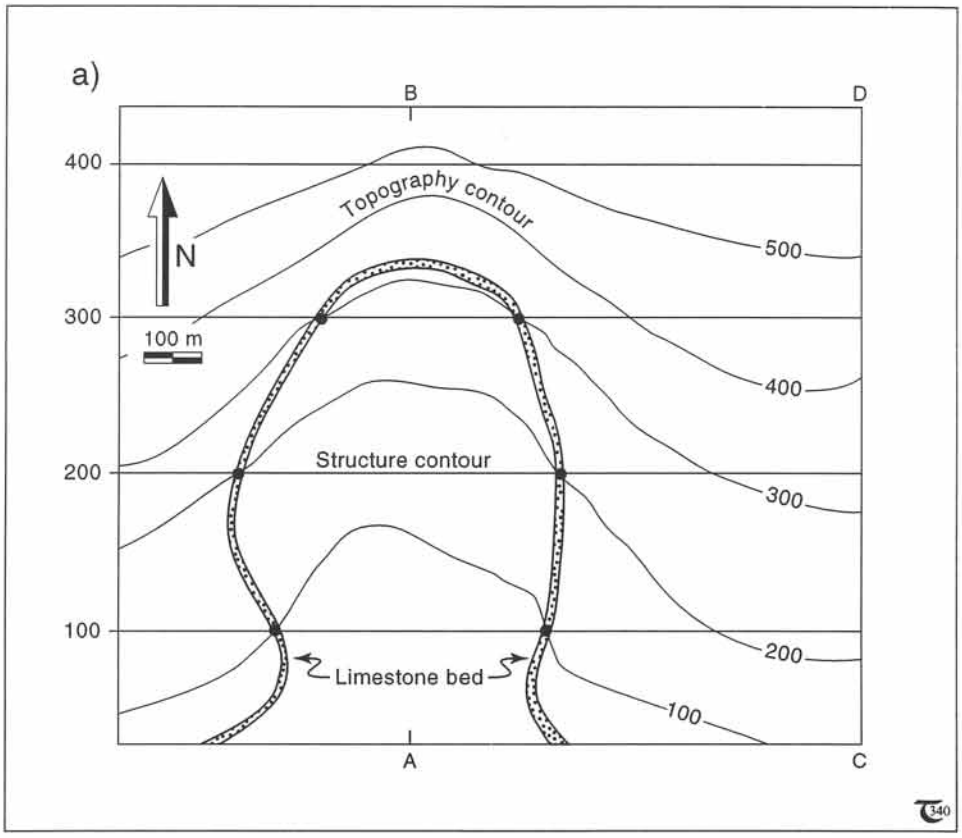


Figure 5-7a: *Geological map, including three types of contours: elevation contours, structure contours, and contours outlining the outcrop pattern of a limestone bed. Contours are in meters.*

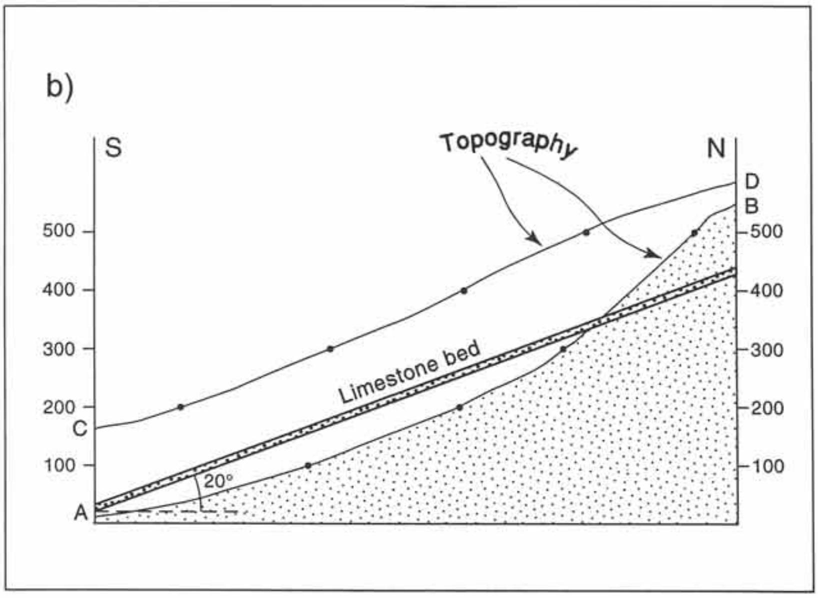
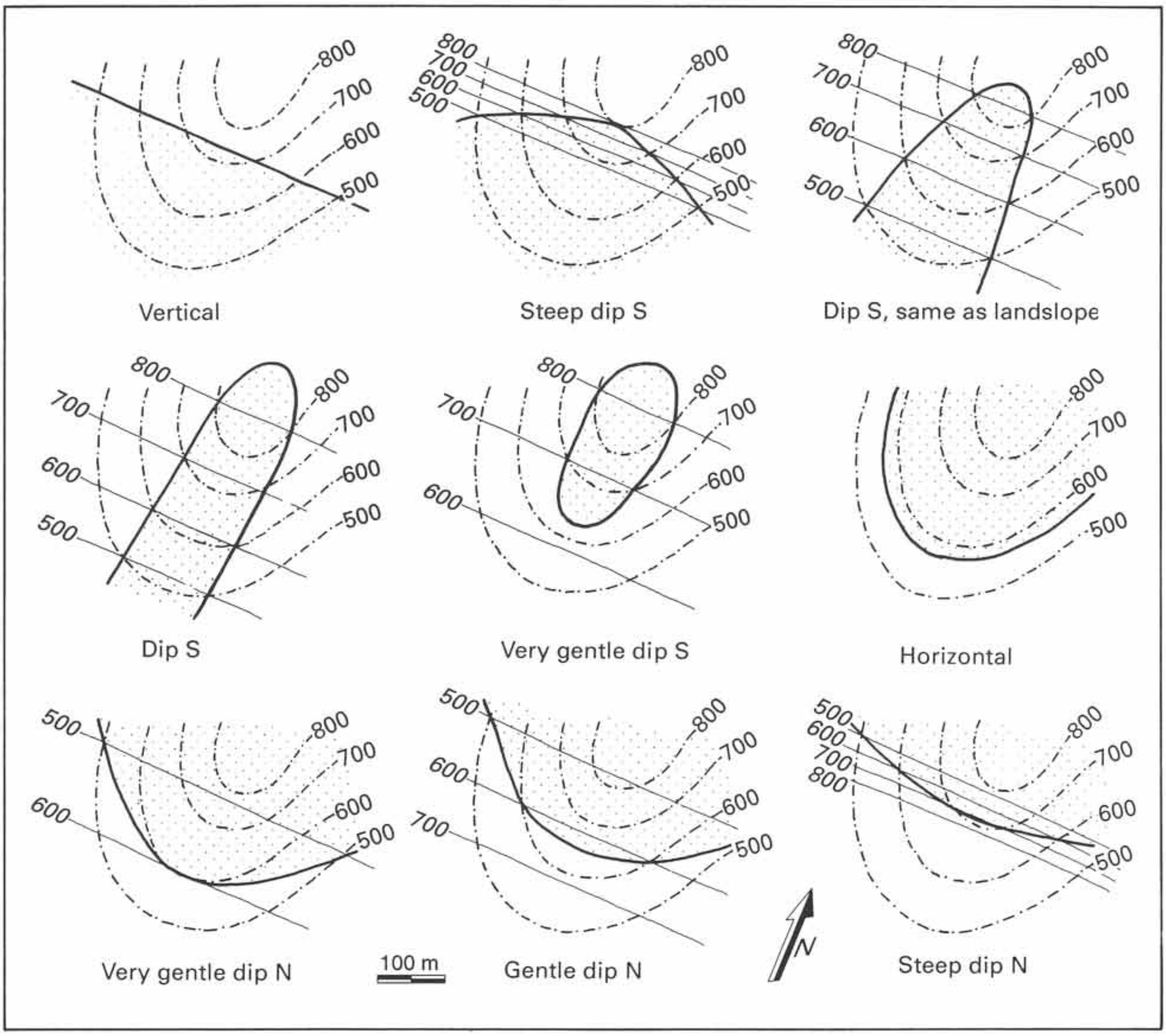


Figure 5-7b: *Two, superposed cross-sections, A-B and C-D, across the map of Figure 5-7a. Contours are in meters.*

Figure 5-7b shows, in one profile, the cross-sections A-B and C-D across the map of Figure 5-7a. The limestone beds of both sections coincide, but the topography is different. The limestone bed is not seen at the surface along section C-D, because the layer is buried by younger deposits. The layer is visible at the surface in one location along section A-B but has been eroded away in the southern part of the map area. The outcrop-pattern of thin beds, even if homoclinal, may take on an endless variety of shapes, depending on the way the ground surface intersects the bedding plane. Figure 5-8 illustrates a variety of map patterns for a thin coal layer, crossing the same rounded hill for a range of layer dips The strike line is consistently oriented in all map views. The patterns follow the intersection of the structure contours and the topographic surface.

☐Exercise 5-3: The rocks on top of the limestone layer of Figure 5-7 contain placer deposits of native gold. Color red the part of the map area where gold can be found. Also, color the gold-bearing rocks in the section.



Vertical

Steep dip S

Dip S, same as landslope

Dip S

Very gentle dip S

Horizontal

Very gentle dip N

Gentle dip N

Steep dip N

Figure 5-8: *Variety of outcrop patterns, resulting from a homoclinal coal bed with a range of inclinations. The shaded portion of each map indicates the rocks on top of the thin coal bed.*

☐**Exercise 5-4: The map of Figure 5-9 shows the outcrop pattern of a thin coal bed traced from an orthogonal aerial photograph and transferred to a topographic contour map of the same scale. The vertical lines on the map are structure contours for the coal bed. a) What is the azimuth/dip for the coal bed? b) Construct one W-E cross-section, passing over the two mountain peaks in the map area. Show both the topography and the position of the coal seam. c) Color the parts of the map where the subsurface does not contain coal.**

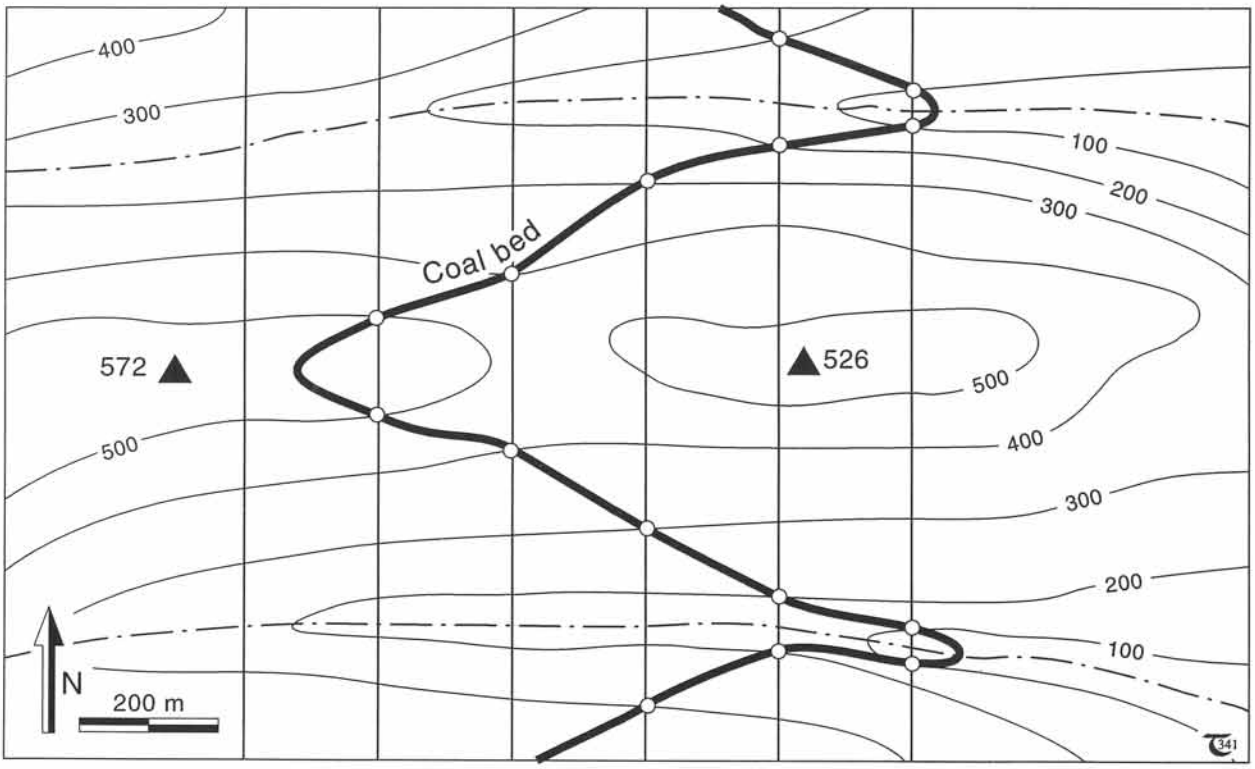


Figure 5-9: Topographic contour map with outcrop pattern of a thin coal bed. See exercise 5-4.

5-4 Outcrop patterns of thick formations

The outcrop patterns of relatively thick beds or entire formations will be affected by the intersection of their top and bottom surfaces with the topography. If the ground surface is flat, the top and bottom planes of a planar, though inclined, bed will appear on the map as a set of parallel lines. Figure 5-10a illustrates a sandstone formation, dipping gently eastward. The structure contours of the top surface and bottom surface of the formation are mapped in Figures 5-10b & c. The outcrop pattern on the flat ground surface is formed by the two traces of the top and bottom surface, which are two lines of constant spacing if topographic relief is negligible (Fig. 5-10d).

Figure 5-10: a) Sandstone formation with structure contours. b) & c) Structure-contour maps for the top and bottom of the sandstone. d) Map pattern of the sandstone.

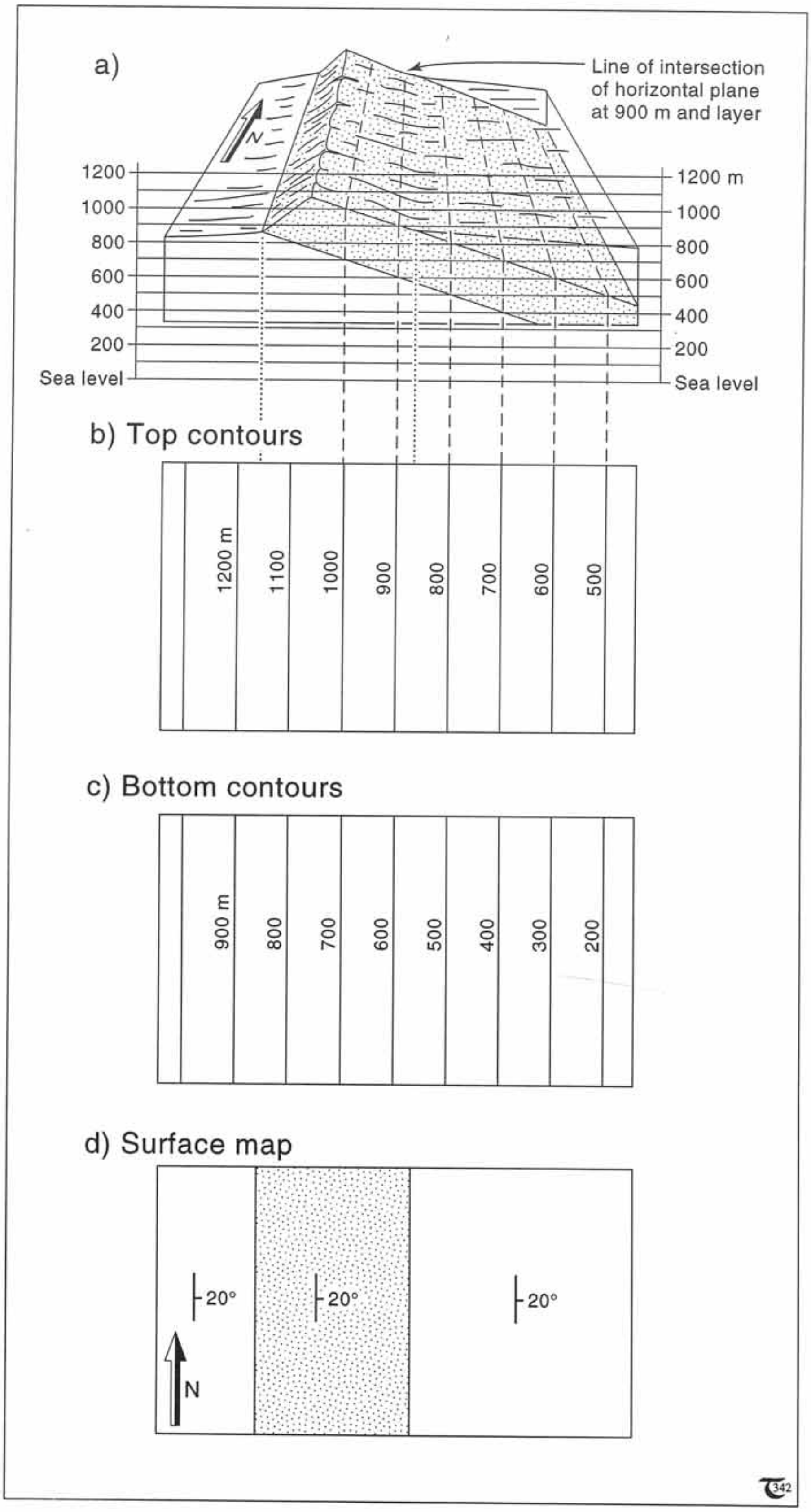


Figure 5-11a shows the outcrop pattern of another sandstone formation, dipping eastward in a terrain of steep topographic relief. The dip of this formation is similar to that occurring in the map of Figure 5-10d. The map pattern of Figure 5-11a is much more complex, solely due to the way in which the eroded topography cuts the bed. The same formation occurs in two different outcrops, disconnected by the erosion surface.

☐**Exercise 5-5: a) Construct structure contours for both the top and bottom of the sandstone formation in the map of Figure 5-11a. Use diffferent colors for each set of contours. b) What is its vertical thickness? c) Give the azimuth/dip of the formation. d) What is the true thickness of the sandstone formation? e) Complete the profile of Figure 5-11b by including the topography. f) Color the parts of the map where the subsurface does not contain the sandstone formation.**

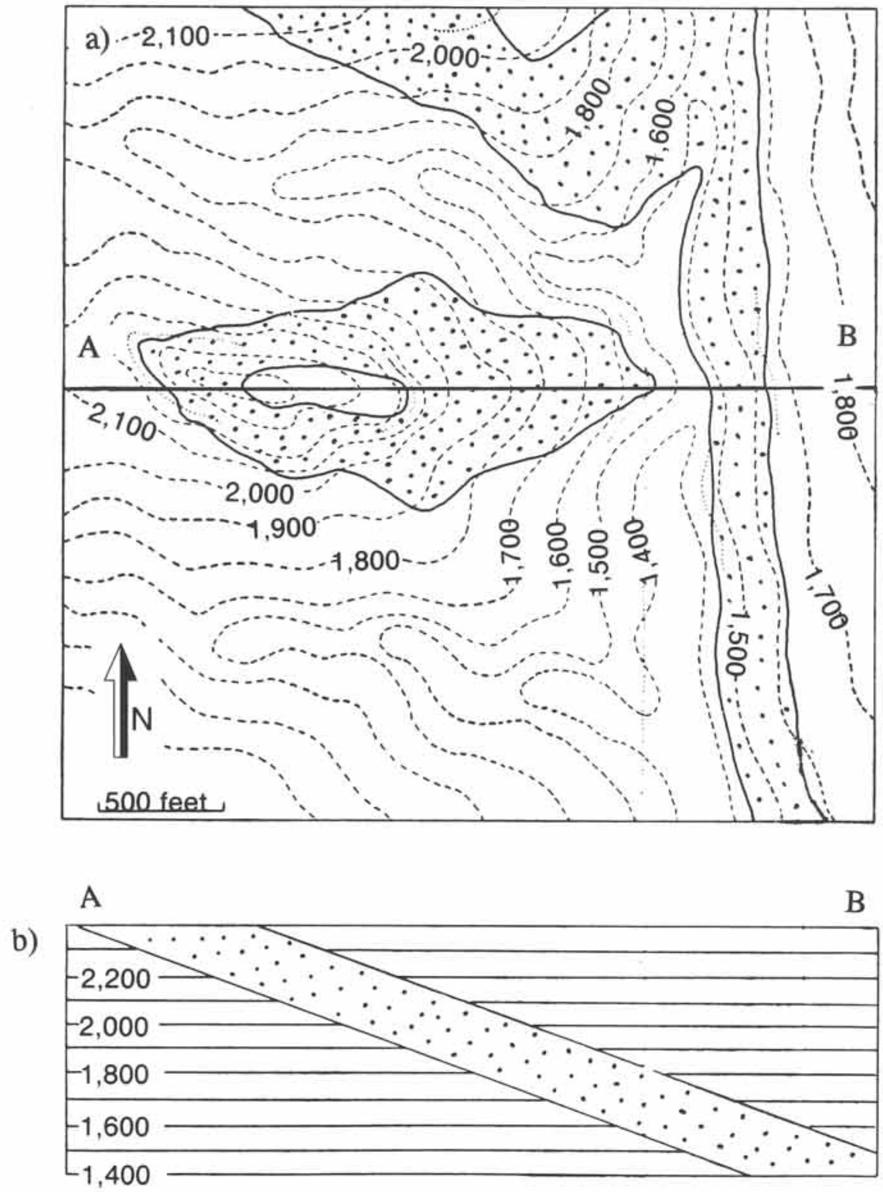


Figure 5-11: a) Topographic map with outcrop pattern of a thick sandstone bed. b) Cross-section A-B across the map of (a) illustrates a single homoclinal bed. Contours are in feet.

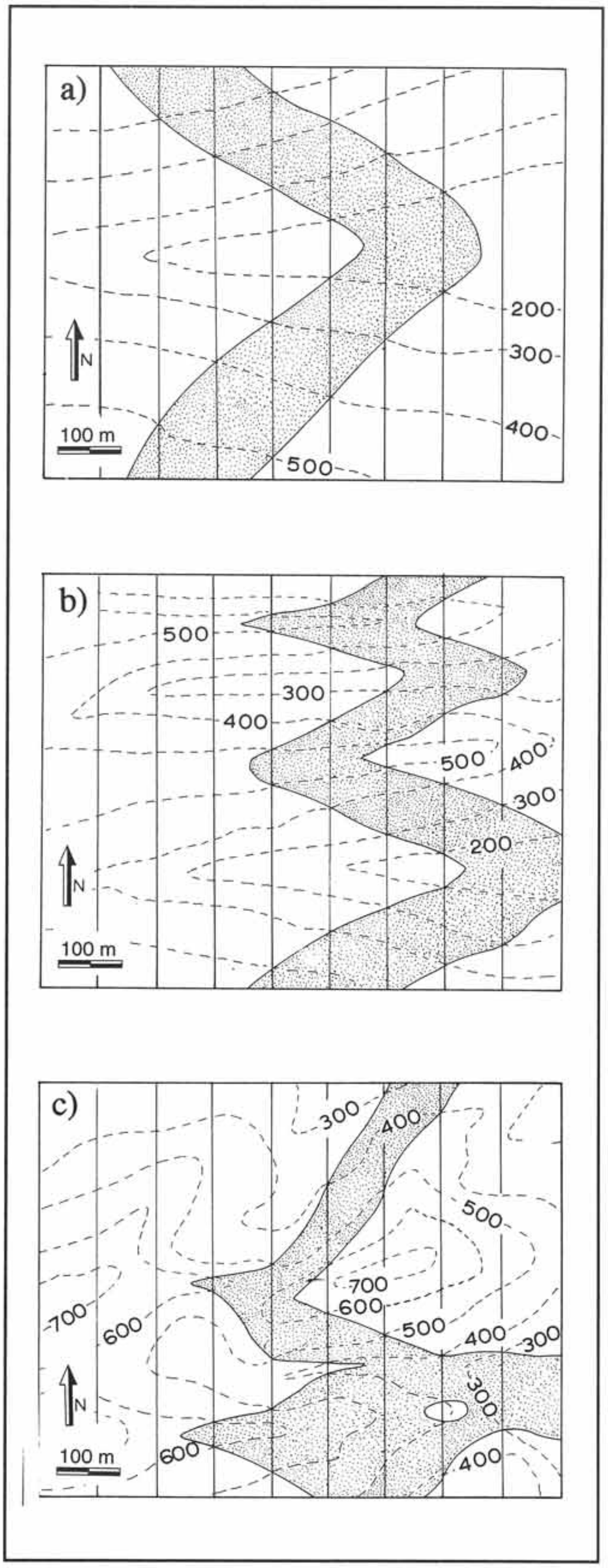


Figure 5-12: *a) to c) Outcrop patterns of the same sandstone bed dipping homoclinally 45° east. The three maps portray the sandstone bed in terrains of different surface topography.*

Figures 5-12a to c compare the outcrop patterns of a thick sandstone bed of the same thickness and orientation in three different terrains. The different outcrop patterns are solely due to the way in which the eroded ground surface cuts the sandstone bed. The sandstone has a uniform 45° dip towards the east and is not folded or contorted in any way, unlike the suggestive map pattern. Exercises 5-6 through 5-8 illustrate the use of structure contours.

☐Exercise 5-6: Refer to the map of Figure 5-13. a) Before constructing structure contours, infer the approximate direction of dip from the V-rule. b) Construct structure contours for both the top and bottom of the sandstone formation. c) Give the azimuth/dip of the formation. d) Construct a profile normal to the strike of the formation across the map area, including the peak in the topography.

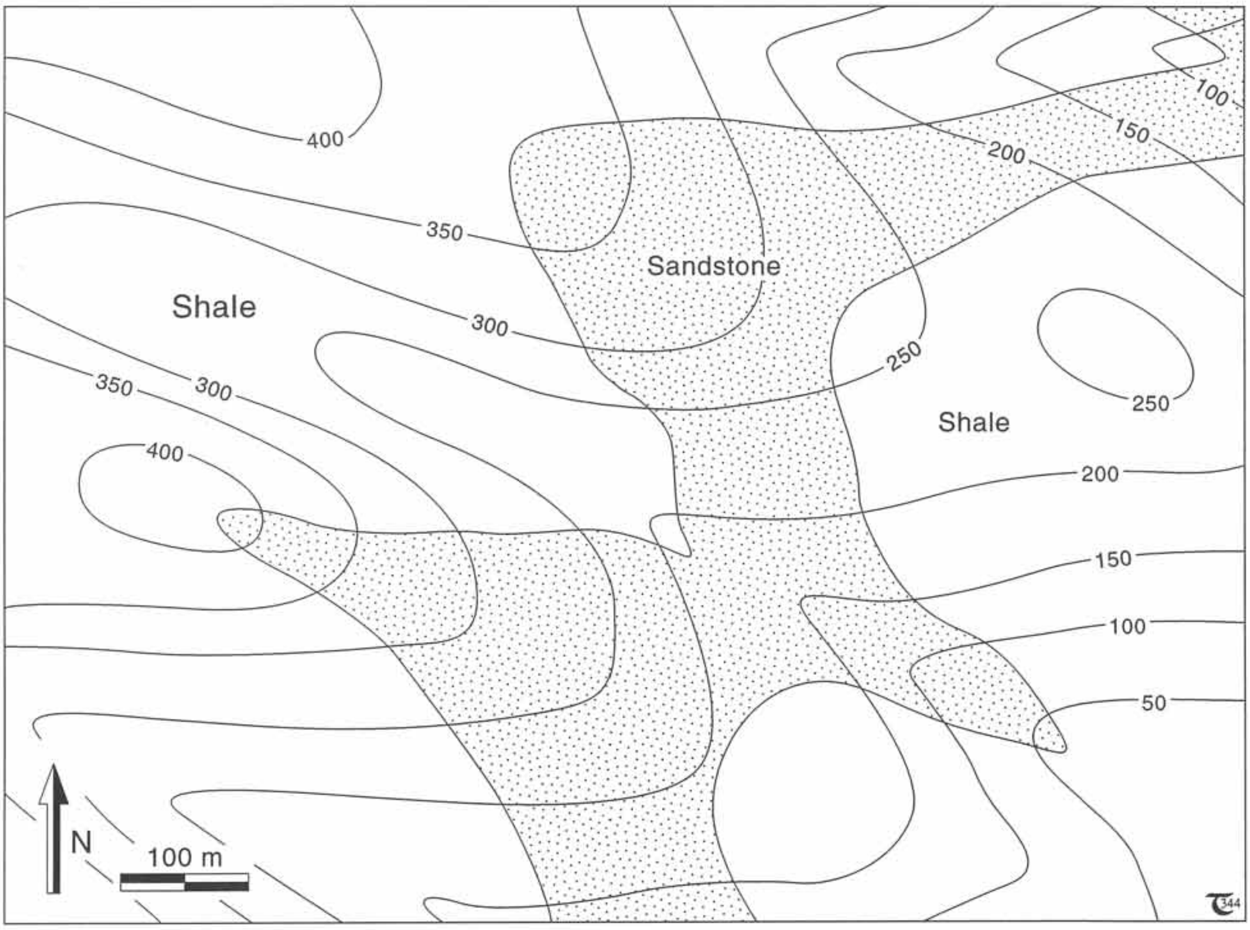


Figure 5-13: Topographic contour map with outcrop pattern of a thick sandstone formation. See exercise 5-6. Contours are in meters.

☐Exercise 5-7: Refer to the geological map of Figure 5-14. a) Use structure contours to construct the exact azimuth/dip of the layers. b) Determine the true or stratigraphic thickness of the indicated sandstone unit. c) Color the part of the map where the subsurface does not contain the sandstone formation.

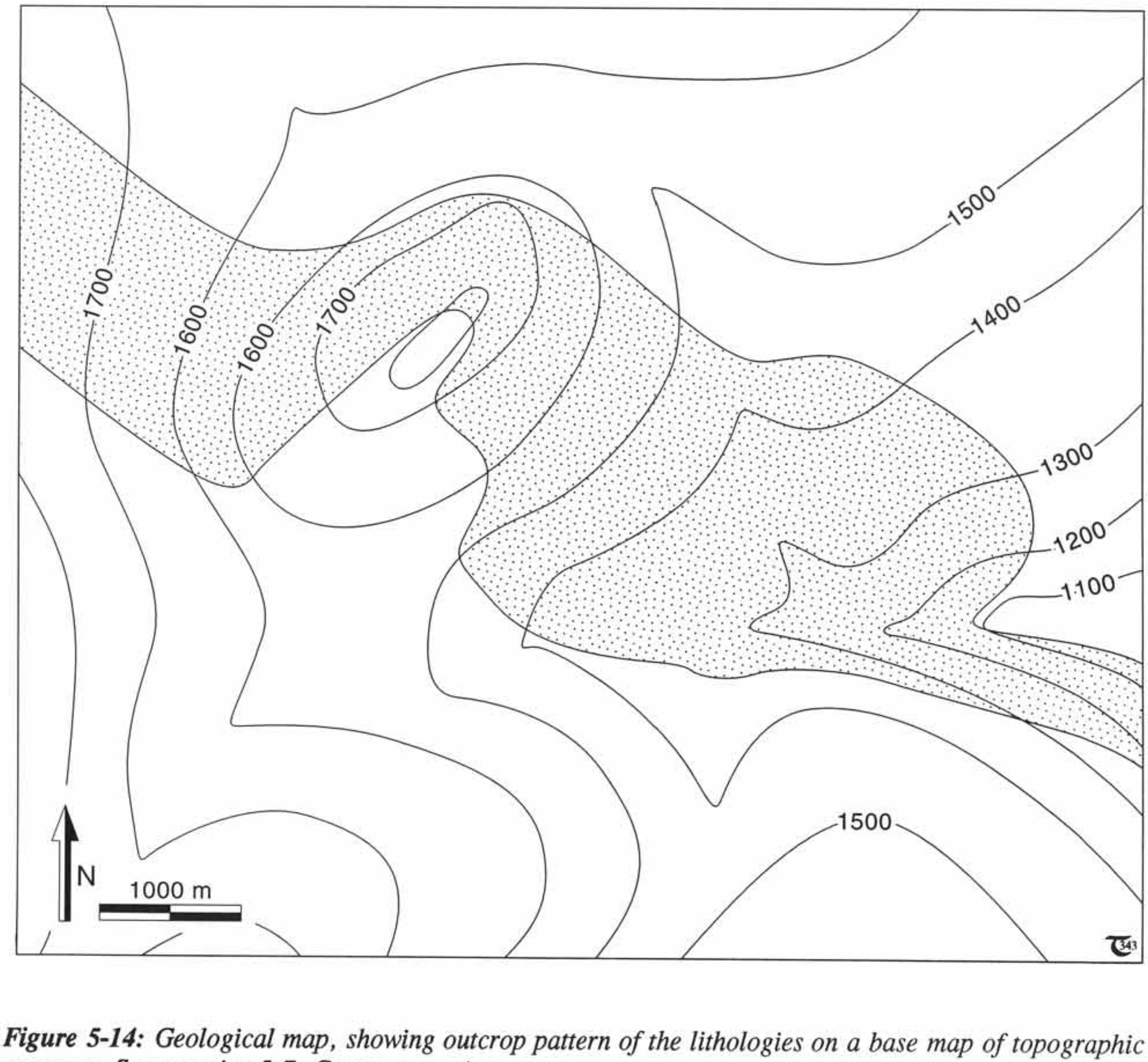


Figure 5-14: Geological map, showing outcrop pattern of the lithologies on a base map of topographic contours. See exercise 5-7. Contours are in meters.

☐Exercise 5-8: Refer to the geological map of Figure 5-15. a) Before constructing structure contours, infer the approximate direction of dip from the V-rule. What is the youngest bed of the outcrop sequence? b) Use structure contours to construct the exact azimuth/dip of the layers. c) Determine the true or stratigraphic thickness of each layer, and represent the result as a columnar section. d) Complete cross-sections A-B and C-D.

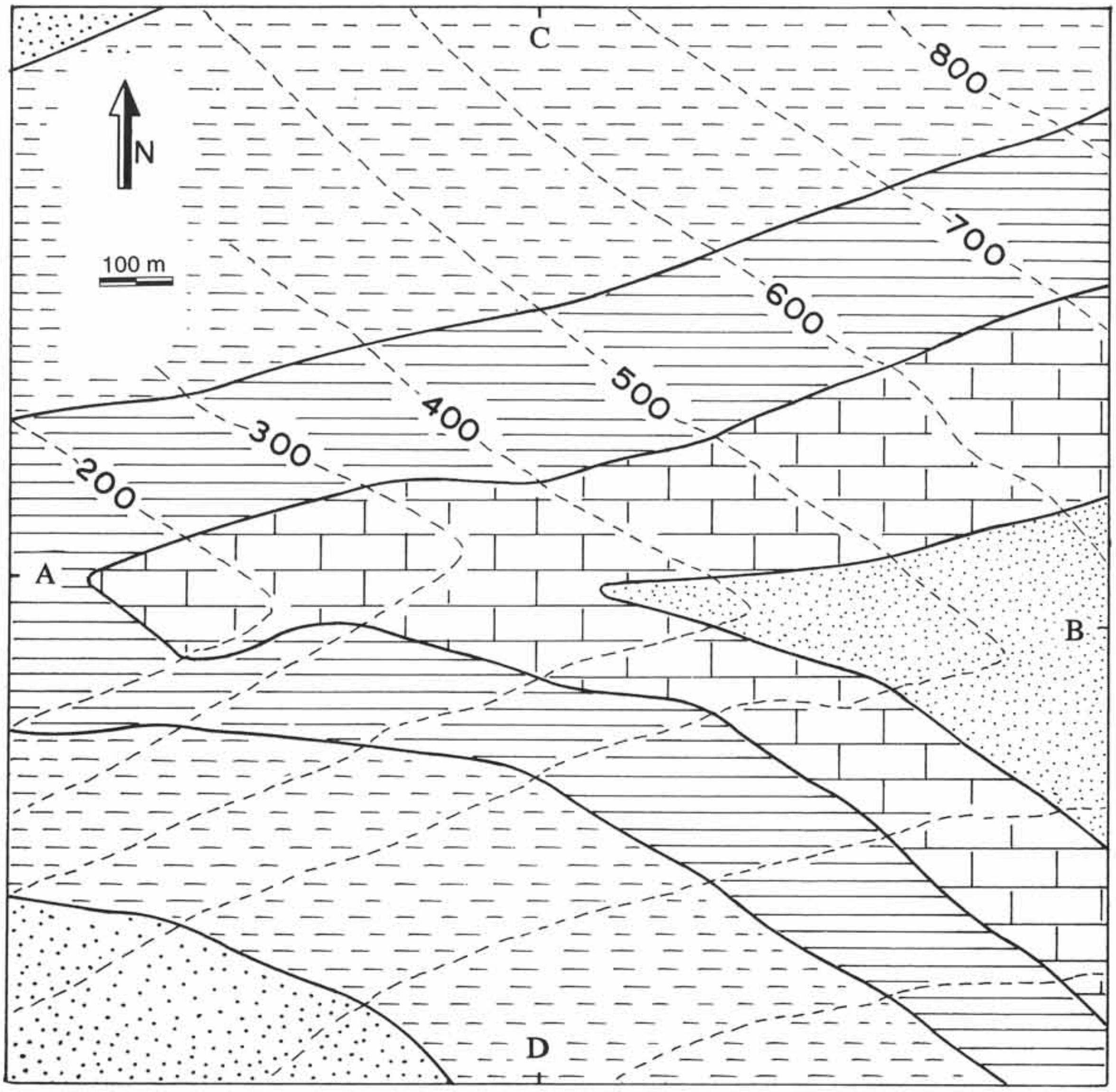


Figure 5-15: Geological map, showing outcrop pattern of the lithologies on a base map of topographic contours. See exercise 5-8. Contours are in meters.