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Richard H. Groshong, Jr.

**3-D Structural Geology**

A Practical Guide to Quantitative Surface  
and Subsurface Map Interpretation

Second Edition



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and Subsurface Map Interpretation**

**Second Edition**

With 453 Figures and a CD-ROM

 **Springer**

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## Preface

Geological structures are three dimensional, yet are typically represented by, and interpreted from, outcrop maps and structure contour maps, both of which are curved two-dimensional surfaces. Maps plus serial sections, called 2½-D, provide a closer approach to three dimensionality. Computer technology now makes it possible for geological interpretations to be developed from the beginning in a fully three dimensional environment. Fully 3-D geological models allow significantly better interpretations and interpretations that are much easier to share with other geologists and with the general public. This book provides an overview of techniques for constructing structural interpretations in 2-D, 2½-D and 3-D environments; for interpolating between and extrapolating beyond the control points; and for validating the final interpretation. The underlying philosophy is that structures are three-dimensional solid bodies and that data from throughout the structure, whether in 2-D or 3-D format, should be integrated into an internally consistent 3-D interpretation.

It is assumed that most users of this book will do their work on a computer. Consequently, the book provides quantitative structural methods and techniques that are designed for use with spreadsheets, mapping software, and three-dimensional computer-graphics programs. The book is also intended to provide the background for understanding what interpretive software, for example, a computer contouring program, does automatically. Most techniques are presented in both a traditional format appropriate for paper, pencil, and a pocket calculator, and in quantitative format for use with spreadsheets and computer-graphics or computer-aided-design programs.

The methods are designed for interpretations based on outcrop measurements and subsurface information of the type derived primarily from well logs and two-dimensional seismic reflection profiles. These data sets all present a similar interpretive problem, which is to define the complete geometry from isolated and discontinuous observations. The techniques are drawn from the methods of both surface and subsurface geology and provide a single methodology appropriate for both. The focus is on the interpretation of layered sediments and rocks for which bedding surfaces provide reference horizons.

The presentation is directed toward geoscience professionals and advanced students who require practical and efficient techniques for the quantitative interpretation of real-world structural geometries at the map scale. The techniques are designed to help identify and develop the best interpretation from incomplete data and to provide unbiased quality control techniques for recognizing and correcting erroneous data and

erroneous interpretations. The second edition has been reorganized to more nearly follow the typical interpretation workflow. Several topics that were previously distributed across several chapters now have their own chapters. A significant amount of new material has been added, in particular numerous examples of 3-D models and techniques for using kinematic models to predict fault and ramp-anticline geometry.

Recognizing that not all users of this book will have had a recent course in structural geology, Chap. 1 provides a short review of the elements of structural geology, including the basic definitions and concepts needed for interpretation. The mechanical interpretation of folds and faults and the relationships between the geometry and mechanics are emphasized. Even with abundant data, structural interpretation requires inferences, and the best inferences are based on both the hard data and on mechanical principles.

Chapter 2 covers the fundamental building blocks of structural interpretation: the locations of observation points in 3-D and the orientations of lines and planes. Both analytical solutions and graphical representations of lines and planes on stereograms and tangent diagrams are provided.

Structure contours form the primary means for representing the geometry of surfaces in three dimensions. In Chap. 3, techniques for effective hand and computer contouring are described and discussed. This chapter also contains discussions of building structure contour maps from cross sections and for improving the maps by using the additional information obtained from dip measurements, fluid-flow barriers, and multiple marker surfaces.

Accurate thickness information is as important to structural interpretation as it is to stratigraphic interpretation. Chapter 4 covers the multiple definitions of thickness, thickness measurements, and the interpretation of isopach and isocore maps.

Chapter 5 covers the geometry of folds, including finding the fold trend and the recognition of cylindrical and conical folds on tangent diagrams; using the fold trend in mapping; dip-domain fold geometry and the importance of axial surfaces; the recognition and use of minor folds; and growth folding.

Cross sections are used both to illustrate map interpretations and to predict the geometry from sparse data by interpolation and extrapolation. Construction techniques for both illustrative and predictive cross sections are given in Chap. 6, including techniques for the projection of data onto the line of section. Also in this chapter is a discussion of constructing maps from serial cross sections.

Chapter 7 discusses the recognition of faults and unconformities; calculating heave and throw from stratigraphic separation; and the geometric properties of faults, including associated growth stratigraphy. The correlation of separate observations into mappable faults is treated here.

Chapter 8 completes the basic steps required to build internally consistent 3-D structural interpretations. Techniques are provided for constructing structure contour maps of faulted surfaces, for constructing and interpreting fault cutoff maps (Allan diagrams) and for interpreting faults from isopach maps. Also in this chapter are discussions of the geometry of overlapping, intersecting, and cross-cutting faults.

Dip-sequence analysis of both folds and faults is treated in Chap. 9. Also known as SCAT analysis, the methodology provides a systematic approach to interpreting the structure found along dip traverses in the field and from dipmeters in wells.

Chapter 10, quality control, is a discussion of methods for recognizing problem areas or mistakes in completed maps and cross sections. Quality control problems range from simple data-input errors, to contouring artifacts, to geometrically impossible maps. Corrective strategies are suggested for common problems.

Chapter 11 is a discussion of concepts and techniques for structural validation, restoration, and prediction. The area-depth relationship is treated first because it is a validation and prediction technique that does not require a kinematic model or require restoration. A structure that is restorable to the geometry it had before deformation is considered to be valid. Because restoration techniques are based on models for the kinematic evolution of the geometry, they are inherently predictive of both the geometry and the evolution. The generally applicable kinematic models for predicting fault geometry from hangingwall geometry and hangingwall geometry from fault geometry are presented here along with discussions of the best choice of method for a given structural style.

Vector geometry is often the most efficient approach to deriving the equations needed in 3-D structural interpretation. Chapter 12 provides derivations of the basic equations of vector geometry, the results of which are used in several of the previous chapters. In addition this chapter includes suggestions about how other useful relationships can be derived.

Numerous worked examples are presented throughout the text in order to explain and illustrate the techniques being discussed. Exercises are provided at the ends of Chap. 2 through 11. Many of the map interpretation exercises provide just enough information to allow a solution. It is instructive to see what answers may be obtained by deleting a small amount of the information from the well or the map or by deliberately introducing erroneous data of a type commonly encountered, for example by transposing numbers in a measurement, reversing a dip direction, or by mislocating a contact. For additional practice, use the questions provided at the ends of the chapters to interpret other geologic maps and cross sections.

This edition includes a CD which supplements the text in several ways. Color, shading, and transparency all communicate important information in 3-D models. The CD contains a complete copy of the text with the model-based figures in color. The 3-D models presented here were constructed using the software program Tecplot ([www.amtec.com](http://www.amtec.com)). The CD contains representative Tecplot files that can be viewed or modified as desired. For those interested in working exercises in mapping software, xyz input files are provided for many of the map-based exercises. Spreadsheet templates are included for some of the key calculations, the area-depth relationship, and for SCAT analysis, including the tangent diagram. Answers to a number of exercises are also on the CD.

The first edition benefited from the helpful suggestions of a number of University of Alabama graduate students, especially Bryan Cherry, Diahn Johnson, and Saiwei Wang, whose thesis work has been utilized in some of the examples. I am extremely grateful to Denny Bearce, Lucian Platt, John Spang and Hongwei Yin for their reviews and for their suggestions which have led to significant improvements in the presentation. Additional helpful suggestions have been made by Jean-Luc Epard, Gary Hooks, Jack Pashin, George Davis, Jiafu Qi, Jorge Urdaneta, and the University of Alabama Advanced Map Interpretation class of 1997.

The second edition owes a great debt to Richard H. Groshong, III, who redrafted many of the figures and who constructed all the otherwise unreferenced Tecplot models. Without his help this edition would not have been possible. Alabama graduate students Roger Brewer, Baolong Chai, Mike Cox, Guohai Jin, Carrie Maher, and Marcella McIntyre have provided insights and examples for which I thank them. I have benefited from helpful discussions with Jim Morse, Jim Tucker and Bruce Wrightson about the SCAT analysis of dipmeters. I began assembling the material on restoration and prediction in Chap. 11 as a visiting professor at l'Université de Lausanne in Switzerland, and I am extremely grateful to Professor Henri Masson for making it possible. Collaboration with Dr. Jiafu Qi, Director, Key Laboratory for Hydrocarbon Accumulation Mechanism, China Petroleum University, P.R. China, partially funded by the National Natural Science Foundation of China Contract No. 40372072 and the Ministry of Education Contract No. 200303, have helped advance the work on several of the topics presented in Chap. 11. Finally, I would like to thank the numerous students in my OGCI/Petroskills classes for their comments, questions, and suggestions which, I hope, have helped to make this edition clearer and more complete.

Tuscaloosa, Alabama  
January 2006

Richard H. Groshong, Jr.



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