TEXTBOOK

A.R. Bhattacharya

Structural Geology

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A. R. Bhattacharya

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A. R. Bhattacharya
Department of Geology (Retired)
University of Lucknow
Lucknow, India

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Dedicated to my parents, in heaven,
and to my wife, Krishna.

Preface

In the course of a long career in teaching and research in structural geology, I felt the need of writing a textbook on this subject mainly to incorporate many things that are as yet not seen in many textbooks. Also, the need to cover the entire updated spectrum of the subject in a balanced way and in simple language was in my mind.

The book is primarily written for undergraduate students who want to take up structural geology at higher levels. It emphasizes basics and fundamental concepts with special reference to field and practical aspects such that there is a balance between theory and practice. This would help students grow their own thinking faculty and to learn the art and science of developing models from their own observations and interpretations. At relevant junctures, the relation of structural geology with allied branches has been discussed, and as such several topics have implications for engineering projects and exploration of minerals, petroleum and groundwater. The book should thus develop excitement and interest in students and readers to explore more on the subject. With all these features, plus many more, the book should be of use to students, academicians, practitioners and professionals.

To read the book, two different lettering styles have been adopted. Words in italic are those that are primarily meant for students for understanding and learning. Those in bold are mainly for headings and subheadings and for highlighting or emphasizing a particular aspect for all categories of readers. Most of the words in all these three styles also appear in Glossary as a refresher to the readers.

The real trigger to write the book came from my students who made me competent enough to write a book of this level. I feel lucky that my teachers at the Department of Geology, University of Lucknow, had enhanced my interest in geology with their excellent teachings. I express my deep sense of gratitude to my former teacher and mentor, the late Professor R.C. Misra, for his erudite guidance and benevolent attitude. I gratefully thank my former teacher, the late Professor S.N. Singh, for laying down a strong foundation of basics in structural geology. I emotionally remember, and owe much to, my former colleague, the late Professor A.K. Jauhri, as it was he who provided me the inner courage and energy to take up this work.

The manuscript of the book has been reviewed (wholly or partly in the form of one or more chapters) by several experts. I am especially grateful to Professor J.P. Burg for reviewing all the chapters of the manuscript and to Professor R.H. Groshong, Jr. for reviewing chapters covering half of the manuscript. Their reviews greatly enhanced the quality of the manuscript and brought it up to this level. At the same time, I am highly grateful to Professors R.D. Hatcher, Jr., Terry Engelder, Peter Hudleston, Reinhard Greiling, Chris Hilgers, R.S. Sharma and D.C. Srivastava for reviewing one or more selected chapters. Their erudite reviews have made high-quality improvements in the manuscript. On behalf of Springer Nature, the manuscript has been reviewed by Professor Soumyajit Mukherjee and two unknown reviewers. Their critical comments and excellent suggestions have significantly enhanced the quality of the manuscript and brought it up to this stage. I express my sincere gratitude to all of them. Professor Dhruba Mukhopadhyay helped me during the initial laying out of the structure of the book, for which I am highly grateful to him. I am especially grateful to Professor

R.D. Hatcher, Jr. for his constant encouragement and help in several ways during the preparation of the manuscript. The revised version of the manuscript has been meticulously read by Mr. D.D. Bhattacharya and Dr. Amit K. Verma; they pointed out several overlooks and inconsistencies. I thank both of them for this work.

Professors Terry Engelder, Cees Passchier, Reinhard Greiling, Stefan Schmid and T.K. Biswal have been kind enough to provide me a few technically high-quality photographs of structures, some of which are used in the book. I express my sincere thanks to all of them for this help. Several friends helped me procure relevant study material and reprints, for which special mention may be made of Professors D.C. Srivastava, Soumyajit Mukherjee, T.K. Biswal and Dr. Amit K. Verma. I sincerely thank all of them.

I have benefited much through discussions with several structural geologists during field visits to a number of geological terrains. Special mention may be made of Professors R.D. Hatcher, Jr. (Appalachians of the USA), Klaus Weber (south Germany and the Himalaya), J.L. Urai (Belgium), Chris Hilgers (NW Germany, Belgium and Holland), S.P. Singh (central India), the late Dr. Hans Ahrendt (Alps of Italy, Jura of Switzerland and the Himalaya) and Dr. Axel Vollbrecht (Alps of Italy and Jura of Switzerland). Some relevant field photographs from most of these terrains are also included in this book at suitable places. I express my sincere thanks to all of them.

I am thankful to the Humboldt Foundation of Germany for awarding me an Alexander von Humboldt Fellowship, under which I visited Germany a few times for research work. Some of the results of my research work carried out under Humboldt Fellowship are reflected in the book. A few fabric diagrams appearing in this book were prepared at Göttingen University, while some of the photomicrographs, also appearing in this book, were prepared at RWTH (Aachen University of Technology), for which I express my grateful thanks to Professors Klaus Weber and J.L. Urai, respectively.

I owe much to the Department of Geology, University of Lucknow, that provided me a platform for teaching and research in structural geology. And this book is a reflection of what I gained from this department. Although the book has been written after my retirement, the department continued to extend me all facilities as and when I needed. The faculty members, research workers and members of the non-teaching staff always cooperated with me in this respect. I sincerely thank all of them. I am especially thankful to Professors Vibhuti Rai and Rameshwar Bali for their help and cooperation in several ways.

For 1 year (2014–2015), I got a book writing grant from the Department of Science and Technology (DST), Government of India, New Delhi, under its USERS programme. I express my grateful thanks to the DST for this grant. This programme was carried out at Sri Jai Narain Post Graduate College, Lucknow, for which I express my cordial thanks to the college authorities.

Dr. Amit K. Verma has very sincerely helped me at all stages of preparation of the manuscript. He especially helped me in procuring reprints and preparing most of the line diagrams and coordinated with me at several critical junctures. I sincerely thank him very much for all this. Mr. A.K. Gupta prepared a number of line diagrams for which I thank him very much. Drs. Narendra K. Verma and Gautam K. Dinkar helped me in several ways; they, as well as Dr. Prabhas Pande, provided me a few relevant photographs, some of which are used in the book. I sincerely thank all of them. Profs./Drs./Messrs. Talat Ahmad, Rajesh Kumar Srivastava, S.C. Tripathi, J.S. Mehta, Anshumali Sharma and N.K. Tewari are especially thanked for their help in several ways. Omission of any name in this list is merely by mistake, not by intention. Lastly, but not the least, my family, especially my lovely grand-daughter Noyonika, persistently provided me the motive force and created the congenial environment for writing the book.

With great pleasure, I convey my grateful thanks to Springer Nature, USA, for publishing my book. At the same time, I am happy to place on record my very nice experience with the Springer Nature team, mainly headed by Drs./Messrs. Zachary Romano, Aaron Schiller,

Herbert Moses, Zoe Kennedy and Nirmal Selvaraj. They meticulously guided me through all the stages of manuscript preparation, and it is because of them and their team members that the manuscript could be brought to the final stage so easily. I understand that occasionally I had put them on vexing points, but they were so patient and helpful that I always found the ball in my court. I express my very sincere thanks to all of them.

Lucknow, Uttar Pradesh, India A. R. Bhattacharya

About the Book

This textbook is a complete, up-to-date and highly illustrated account of structural geology for students and professionals and includes fundamentals of the subject with field and practical aspects. The book aims to be highly reader friendly, containing simple language and brief introductions and summaries for each topic presented, and can be used both to refresh overall knowledge of the subject and to develop models for engineering projects in any area or region. The book is presented in 20 chapters and divided into 3 parts: (A) Fundamental Concepts; (B) Structures: Geometry and Genesis; and (C) Wider Perspectives. For the first time as full chapters in a textbook, the book discusses several modern field-related applications in structural geology, including shear-sense indicators, and deformation and metamorphism. Also uniquely included are coloured photographs, side by side with line diagrams, of key deformation structures not seen in other books before now. Boxes in each chapter expand the horizons of the reader on the subject matter of the chapter. Detailed significance of the key structures, not to be seen in any textbook so far, provides a better grasp to students. Questions at the end of each chapter provide a self-test for students. Glossary at the end of the book is a refreshing aspect for readers. Though written primarily for undergraduate and graduate students, the text will also be of use to specialists and practitioners in engineering geology, petrology (igneous, sedimentary and metamorphic), economic geology, groundwater geology, petroleum geology and geophysics and will appeal to beginners with no preliminary knowledge of the subject.

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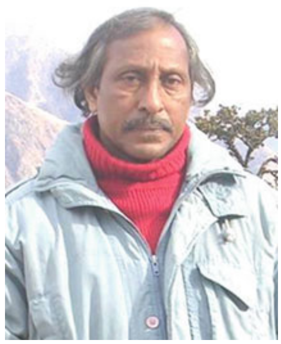
About the Author



A. R. Bhattacharya is a Retired Professor of Geology from the University of Lucknow, India. He had obtained his B.Sc., M.Sc. and Ph.D. degrees from this university, and later he joined the faculty of the Department of Geology where he taught, and carried out research work in, structural geology for about four decades. His research interests include geometry and genesis of structures, shear zones, fabric development and evolution of structural complexes. Some of his notable contributions include a new classification of folds, two new parameters of fold geometry, an empirical equation for natural folds, a mathematical model of fold development, quantitative modelling of shear zones and a graphical method for distinguishing different fold generations. His work on the Himalaya has thrown newer lights on the structure and deformational processes in the Kumaun-Garhwal sectors that have far-reaching implications for understanding the evolution of mountain belts. His researches on the Bundelkhand craton of central India, especially on the identification of crustal scale shear zones, structural elucidation of quartz reefs, mesoscopic fold geometry and deformational processes in the internal domains of rocks, are of pioneering nature for this craton. One of his research papers (published in *Tectonophysics*, vol. 387, 2004) was selected as 'Top 25 Hottest Papers' by Science Digest, and it was ranked 15th. He has co-edited two research-level books. He has been an Alexander von Humboldt Fellow of Germany under which he visited Germany a few times, having worked at Göttingen University and at Aachen University of Technology. In addition, he had also visited the USA, France, England, Italy, Switzerland, Belgium and Holland for academic/research purposes. He has a vast geological field experience of the Himalaya and the peninsular shield of central India, as well as of several structurally important regions of the world, mainly the Appalachians of the USA, Alps of Italy, Jura of Switzerland, Variscan Belt, Rhine Graben and NW Schist Belt of Germany and Palaeozoic-Mesozoic Belts of Belgium and Holland.

Part I

Fundamental Concepts

1 Introduction to Structural Geology

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Abstract

Standing on a rocky terrain, one may occasionally notice beautiful structures in rocks. The variety of geometrical shapes of the structures poses great inquisitiveness to an onlooker. What are these structures, how are these formed and what does their occurrence indicate are some of the questions that haunt his/her mind. Answers to these questions are hidden in a discipline of geology called *structural geology*, which encompasses the study of all aspects of the deformation structures such as their geometry, field relations, geographic distribution, genesis and related aspects. Since the structures in the context of structural geology are formed by deformation, these are also called *deformation structures* or *tectonic structures*. They occur on scales ranging from tens of kilometres to those that can be seen only under a microscope. Faults, folds and joints are some common examples of structures. Structural geology is closely related to another discipline of geology called *tectonics*, which includes deformation on a much larger scale, i.e. from regional to lithospheric. Structural geology and tectonics commonly go together and even overlap when studied on the same scale. Structures are sometimes associated with economic minerals and hydrocarbons. The type and orientation of structures are important in civil engineering work such as dams, tunnels and bridges. Structural geology has implications for academic, economic, societal and environmental aspects.

This chapter presents a panoramic view of the wonderful world of structural geology so that the reader systematically starts gearing up for an in-depth study of this discipline.

Keywords

Structural geology · Tectonics · Deformation structures · Scale of structures · Methodology of structural geology · Remote sensing · Significance of structural geology

1.1 What Is Structural Geology?

Structural geology encompasses the study of all aspects of the deformation structures such as their geometry, field relations, geographic distribution, genesis and related aspects. Rocks after their formation are subjected to stresses inside the earth. When the amount of applied stresses exceeds the strength of a rock, the latter yields to or accommodates the stresses by undergoing deformation that is manifested in some typical structures called *deformation structures*. In structural geology, we commonly mean structures that are formed due to deformation by externally applied stresses. These structures are preserved for millions of years. Common examples of deformation structures are folds, faults, joints and fractures.

Structural geology is closely related to another branch of geology called *tectonics* that includes the study of lithosphere and deeper mantle rocks also. Considering the earth as a dynamic planet, tectonics includes the study of deformation, bending, rupturing, movements and related processes of the lithosphere including the formation of mountains and ocean basins and evolution of the continents and of the crust.

Structural geology is an important discipline of geology that acts as a tool to specialists and practitioners in engineering geology, petrology (igneous, sedimentary and metamorphic), economic geology, groundwater geology, petroleum geology and geophysics.

1.2 What Are Structures?

1.2.1 Tectonic Structure

In this book, the word **structure** is a password. Structures, in the context of structural geology, are formed by deformation of rocks. As such, these are also called **tectonic structures**. To a layman, or even to a beginner, it may sound unrealistic to note that structures in rocks are formed under hard rock, not soft rock, deformation conditions.

Rocks start their journey as sediments eroded from the continents. These sediments are transported by agencies like rivers, wind and glaciers and are ultimately deposited in a basin in the form of layers (Fig. 1.1). The basin may be a sea, river, desert or glacier. The layers are thereafter buried to deeper levels where they are subjected to pressure and, to some extent, temperature that lead to lithification due to which the layers become hard and compact and are thus converted to layers of rocks. This process is called induration. At depth, the rocks are subjected to stresses mainly due to overburden as well as tectonic stresses that are oriented in some definite directions. Thereafter starts another chapter in the journey of rocks caused mainly by deformation. The rock layers may initially be tilted (Fig. 1.2) and then, depending upon the nature and type of stresses, are followed by formation of different types of structures. The type of structures, mainly their geometrical shapes, depends upon the type and orientation of the externally applied stress on initially flat layers. Some common structures formed in rocks, such as folds, faults, thrusts, joints, lineation and foliation, are briefly described below.

A *fold* is a bend in rock formed due to compressive stresses acting parallel to, or across, the originally flat surfaces of rock. The fold can be an anticline (Fig. 1.3) in which the rock layers are convex upward towards the centre.

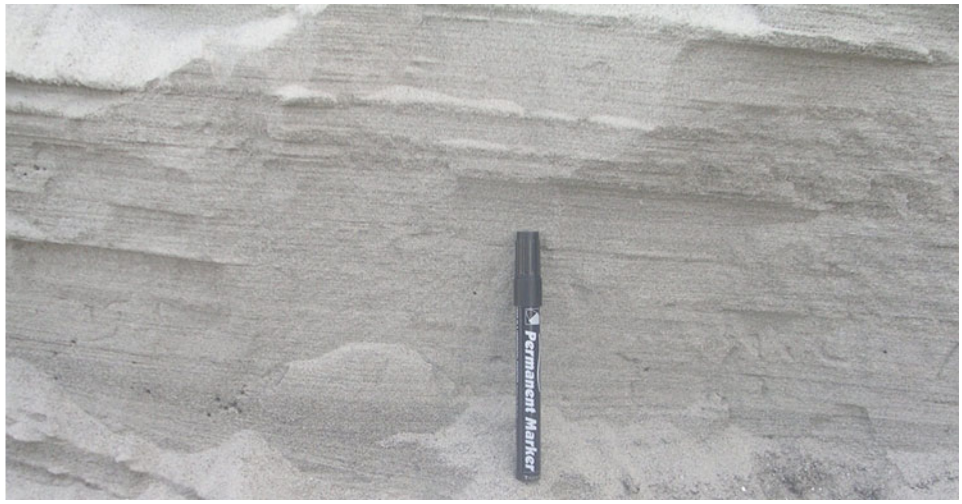

Fig. 1.1 Sedimentary layering in loose, unconsolidated sands on the banks of River Ganga, near Rishikesh, India. The sands are deposited layer by layer by the river during flood times. The layering pattern is visible due to variations in grain size and texture of sands in each layer. (Photograph by the author)

Fig. 1.2 After induration of rocks, they are subjected to stresses inside the earth, thus forming structures in rocks. In this photograph, the rocks are exposed as inclined beds. This inclination, or tilting, is an effect of deformation

There can be a syncline also in which case the rock layers are concave towards the centre. Both anticline and syncline may occur together, i.e. adjoining one another (Fig. 1.4).

A *fault* is a fracture along which two blocks of rock have moved past each other (Fig. 1.5). A *thrust* is also a fault, called reverse fault, in which the hanging wall has moved up relative to the footwall (Fig. 1.6). A *joint* is a fracture along which there has been little or no transverse displacement of rock (Fig. 1.7). *Lineation* is any fabric or orientation in a rock developed in a linear fashion (Fig. 1.8). *Foliation* is a planar fabric given by the preferred orientation of minerals showing platy or tabular habit. Foliation can be seen with unaided eye in hand specimen and in outcrops in the form of alternating compositional layers (Fig. 1.9). Sometimes, the minerals that constitute compositional layers are too small to be seen only under a microscope (Fig. 1.10).

Structures in rocks occur on varied sizes. Some are visible with naked eyes, while others are either too small or too large to deter proper study with unaided eyes. For structural studies, therefore, a system of scales of geological structures is in practice. *Megascopic structures* are developed on the scale of several kilometres to tens of kilometres. *Mesoscopic* *structures* occur on a small outcrop to hand specimen scale. *Microscopic structures* can be studied only under a microscope.

Fig. 1.3 Field photograph of a fold in limestone. This fold is an anticline in which the rock layers are convex upward towards the centre. Loc. near Hampteau Hotton, Belgium. The author happily stands for scale

During fieldwork, a structural geologist commonly studies structures on outcrop to hand specimen scales, i.e. on mesoscopic and macroscopic scales. He/she may use a hand lens for more clarity of a structure, but still the structure falls in the category of mesoscopic scale; the hand lens in this case has been used only to have a better or clearer look of the structure or parts(s) of it.

1.2.2 Nontectonic Structure

Earth materials can deform without being involved in tectonic processes. Stresses can be imposed upon them by, for example, overburden loading, sedimentary processes, shear from overriding sediment-fluid flows and glaciers. Structures thus formed are called *nontectonic structures*.

Sedimentary processes commonly produce a variety of structures called *sedimentary structures*. A common example is the layering pattern (Fig. 1.1) shown by loose, unconsolidated sediments. This layering pattern is developed after the sediments are deposited in a basin by any agency such as wind or water. By their general look, this layering pattern resembles a layered rock. However, the term **bed** is commonly used for lithified, hard rocks. A bed is a unit of a sedimentary rock, just like the unit of a building is a brick, or the unit of an organism is a cell.

Deep on the ocean floor, occasionally huge mass of unconsolidated sediments flow down the deep interiors of oceans due to gravity. These are called *slump structures*. Of the variety of structures formed by slumping, some look like deformation structures such as folds, faults and thrusts, but these are all nontectonic structures and are sometimes called *soft-sediment deformation*.

Fig. 1.4 Photograph of a syncline (left) in which case the rock layers are concave upward at the centre, together with an anticline (right). The rocks constitute a sedimentary sequence of the fold and thrust belt of the Andes Mountains exposed near Lake Argentino, Patagonia region, Argentina. (Photograph courtesy Narendra K. Verma)

Fig. 1.5 Field photograph of faults developed in pink granite of Bundelkhand craton, central India. One can see that a marker layer (light coloured) is successively displaced along a plane, the fault plane. (Photograph by the author)

Fig. 1.6 Photograph of a thrust fault in the Canadian Rockies near Alberta. In the photograph, one can see that a stack of folded Palaeozoic carbonates and sandstones is being transported by a low-angle thrust. (Photograph courtesy Narendra K. Verma)

Fig. 1.7 Field photograph of joints developed in quartzite of Bundelkhand craton, central India. (Photograph by the author)

Fig. 1.8 Field photograph of lineations in the form of mullion structure developed in sandstone alternating with shale. Loc. North Eifel, Germany. (Photograph by the author)

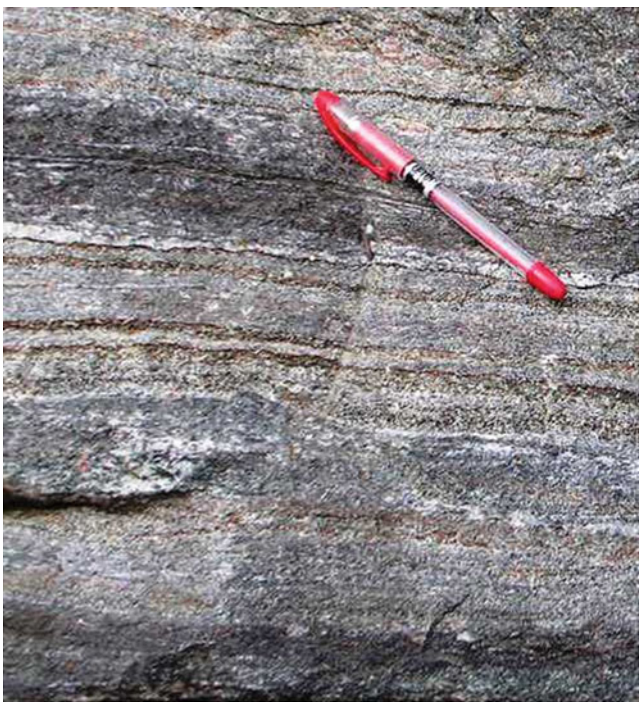

Fig. 1.9 Field photograph showing foliation in crystalline-metamorphic rocks of Southern Appalachians, USA. This is gneissic foliation defined by alternating dark and light-coloured bands (running left-right). (Photograph by the author)

Glaciers are huge bodies of ice that slowly move down the slope due to gravity. Glaciers can produce features that resemble tectonic structures. As such, the toe of a glacier is an area of enormous stress. The accumulated stress is accommodated by the formation of several types of structures that resemble faults (Fig. 1.11), folds, thrusts, etc. Formation of structures by glaciers is called *glaciotectonics*. But these are all nontectonic structures.

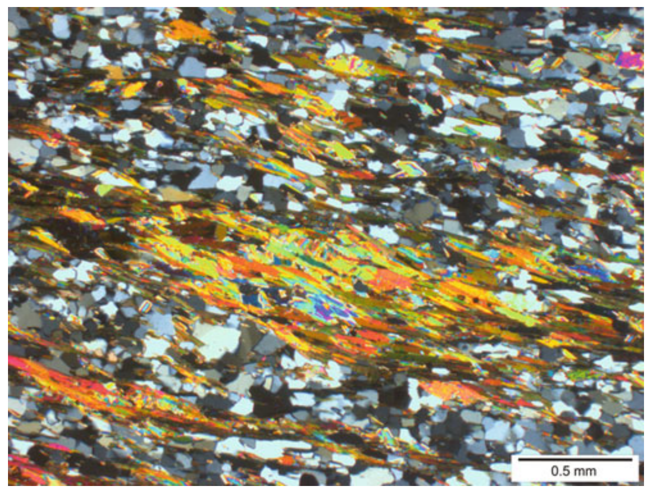

Fig. 1.10 Foliation as seen in thin section under a microscope. The foliation is given by a preferred orientation of micaceous minerals that are seen as different colour bands in the photomicrograph

1.3 The Ultimate Cause of Deformation

Deformation structures, as we have discussed above, are formed by tectonic stresses. Now the question arises as to wherefrom these stresses are generated. It is only in the late 1960s and early 1970s that we got a satisfactory answer to this nagging question in the form of *plate tectonics* that has virtually transformed the concepts of tectonics. Plate tectonics is based on the concept that the earth's outer rigid shell, called *lithosphere*, is broken into several blocks, called *plates*. The plates are of different sizes—seven or eight very large, six or seven medium-sized and a few smaller ones—that move over the molten upper part of the mantle, called *asthenosphere*. The lithosphere is about 100 km thick and includes the crust and the outer mantle of the earth. The plates are constituted of oceanic lithosphere as well as of continental lithosphere; the latter is thicker than the former. The plates