Teaching Structural Geology in Indian Context

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Abstract While updates on the Indian structural geological and tectonic research have been available from time to time (e.g., Bhattacharya et al. in Proc Indian Nat Sci Acad 82:435–443, 2017), teaching strategy and critique on these subjects from India has not come up yet. This chapter emphasizes the urgent need for quantitative structural geology and tectonics teaching in India. In this chapter, I share few personal approaches in teaching structural geology to M.Sc. applied geology students in the Department of Earth Sciences, IIT Bombay: (i) students' evaluation through their peers, (ii) group discussions, (iii) field training, and (iv) going beyond the syllabus. Several papers in the Journal of Geoscience Education discuss mode and motto of tectonic and structural teaching, geological visualization, and field approaches (e.g., Badgley in Structural methods for the exploration geologist. Harper & Row, New York, p. 280, 1959; Libarkin and Brick in J Geosci Educ 50:449–455, 2002; Elkins and Elkins in J Geosci Educ 55:126–132, 2007; Orion et al. in J Geosci Educ 45:129–132, 2018).

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1 Approach in Structural Geology

Structural geology has been described classically as a field-based subject. However, with time the scope of the subject has increased. Presently, geoscientists can think structural geology being practiced by the following principal methods:

(1) Field studies
(2) Microscopy
(3) Modeling: analogue and analytical.

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The aim of structural geology has been chiefly to decipher the geometry and genesis of structures at different scales that are mostly deformation-induced, i.e., the secondary structures. With time, diverse industry-oriented branches have also cropped out. Structural geologists' inputs have been crucial in engineering geology in applied field. Structural geology has also attempted extracting rheological (Talbot 1999; Mukherjee et al. 2010; Mukherjee 2011, 2013; Mukherjee and Mulchrone 2012, 2013; Mulchrone and Mukherjee 2015, 2016) and thermodynamic information (Mukherjee and Khonsari 2018; Mukherjee 2017a; Mukherjee and Mulchrone 2013; Mulchrone and Mukherjee 2015, 2016; Marko and Caddick 2018; Mukherjee and Agarwal 2018) of rocks by a number of indirect methods. Geomechanics is now considered to be an important aspect of structural geology (e.g., Dasgupta et al., in press).

Recently, Geological Society of London published a book on "Industrial Structural Geology" (e.g., Richardson et al. 2015). Fossen (2010, 2016) introduced several issues of hydrocarbon geology, such as the primer for fault seal analysis, for the first time within the structural geology textbook. Possibly because of lack of funds for core/pure research and more importantly current societal/industrial requirements have pushed structural geologists to explore (numerical modeling of) carbon sequestration, radioactive waste disposal and other waste management issues, pore pressure prediction, well bore stability, etc. The modern and the broad range of structural geology is also well reflected in the scope of the Journal of Structural Geology (Internet Reference-1): "*The* Journal of Structural Geology *publishes process-oriented investigations about structural geology using appropriate combinations of analog and digital field data, seismic reflection data, satellite-derived data, geometric analysis, kinematic analysis, laboratory experiments, computer visualizations, and analogue or numerical modelling on all scales. Contributions are encouraged to draw perspectives from rheology, rock mechanics, geophysics, metamorphism, sedimentology, petroleum geology, economic geology, geodynamics, planetary geology, tectonics and neotectonics to provide a more powerful understanding of deformation processes and systems. Given the visual nature of the discipline, supplementary materials that portray the data and analysis in 3-D or quasi 3-D manners, including the use of videos, and/or graphical abstracts can significantly strengthen the impact of contributions.*"

Geoscience students with B.Sc. and M.Sc. degrees can be hired for various geoscientific assignments, and not all of them will handle structural geological issues. As a real (broad) example, a student who is a geologist by training has been asked to undertake geophysical studies in a private company. It is therefore very important for any geology students to know how structural geology can work with other geoscientific branches.

The syllabus of structural geology courses in the Appendix shows no such multidisciplinary aspect of the subject that is presently taught. In this situation, students are left to learn multidisciplinary aspect of the subject after joining their jobs and through their experiences. This can be well avoided, and the instructors can take more charge by upgrading their course contents. Just as an example, techniques of identifying faults in the field are compulsorily taught to geology students following standard textbooks, e.g., Billings (1954) and Fossen (2016). But there is an altogether different approach of identifying faults based on geomorphologic and image studies (e.g., Keller and Pinter 2002; Misra et al. 2014; Dasgupta and Mukherjee 2017, submitted; Kaplay et al. 2017), and seismic reflection studies (e.g., Misra and Mukherjee 2018a, b; Misra et al. 2018a, b) as well. Active faults in terrains, especially out-of-sequence faults (Mukherjee et al. 2012; Thakur 2013), can be identified based on geomorphologic criteria. Such faults can be seismogenic. Students joining any remote sensing organization or co-working with geomorphologists would require such knowledge. To add such inputs in classroom teaching, the instructor needs to undertake "*research for the sake of teaching.*" The instructor can argue that due to time constraint in semester mode of teaching, it is not possible to add more components in his/her lecture. But it may be still possible to achieve if PowerPoint presentations are prepared for "smarter" presentations that can use time economically in the classroom.

A second concern arises after noting the existing structural geology syllabus (Appendix) for the master's students in Earth Sciences Departments in IIT Roorkee and IIT Bombay. The present syllabus does not empower students to study the deformation mechanism independently. Traditionally geological teaching in India has been providing chunk of information that seldom explains the true reasons. The standard statement in the class has been: "If X and Y conditions exist, P and Q would be the result." In contrast, if the structural geology instructor really wants her students to solve problems independently, the students must be made well acquainted with 3D geometry, tensor operation, solid and fluid mechanics (e.g., Burgmann and Dresen 2008; Mukherjee 2013), statics (e.g., Ghosh 1993; Mukherjee 2017b, 2018a, b, c), rheology, graph theory (e.g., Sanderson and Nixon 2018, Mukherjee in press), thermodynamics, computer programming, finite elements and finite difference methods, software that can simulate deformation such as COMSOL (e.g., Lunn et al. 2008; Bose et al. 2018), etc. These can be done through structural problems of moderate difficulty level posed by the faculty. Billi and Fagereng (in press) provide few such problems and solutions.

Structural geologists for non-specialists such as geophysicists and civil engineers are another aspect. Wiley has been publishing such books in different branches (e.g., Allen 2010). Structural geology and tectonics text written in this problem-solving format would be much required. The geoscientific community has at present a few books on numerical problem solutions in structural geology (e.g., Allmandinger et al. 2012), but they look difficult for the beginners.

2 Students as Evaluators

Marcel Frehner (ETH Zurich), in Chap. 2 of this book, refers students' evaluation technique that is being used to grade students. Interestingly, I have been conducting an evaluation technique with students with the following workflow. This takes about 4 h to conduct, so ideally a laboratory class is used for this purpose.

I. One specific structural geological issue, I conduct some seven lectures.
II. Students are informed to study the content well and come prepared for an exam.
III. Students set questions of 10 marks in question paper-cum-answer sheet. They are asked not to set flat question such as “Define X.”
IV. The question papers are then interchanged with the other students. Students now need to answer those questions within say one hour.
V. After the exam gets over, students get back those sheets where they set questions. They need to check all answers, assign numbers, write comments, etc., within around 40 min.
VI. The annotated sheets now go back to the students who answered them. They now sit along with the question setters and seek clarification for marks deducted and comments made.

I join as another examiner in the two following cases, which sometimes arise:

(i) The question setter student cannot justify why he deduced marks.
(ii) The students answering text point out that some of the questions are incorrect.

In this way, a very interactive session is developed, where even the most introvert student is forced to speak out and discuss. Having even number of students makes this exercise easy to undertake. In case the student number is odd, I usually ask one of the students to answer her questions herself, and then I check her questions and answers. However, I do not add the marks assigned by the students in my formal evaluation and in assigning grades. This exercise enables students to frame correct questions in the subject, and probably for the first time to check answer sheets.

3 Group Discussions

Another activity I conduct is the “group discussion.” Typically after finishing a single issue, such as doming and diapirism (e.g., Talbot and Pohjola 2009; Mukherjee et al. 2010), I instruct students to come well prepared for a discussion. Students also need to study what has not been covered in the class by looking at textbooks and research papers. The group discussion involves unconventional questions instantly raised by students, and the most plausible geological answers. Examples could be: does diapirism necessarily involve thinning of the overlying rock/sediment layer? As per Ramsay’s scheme, which class of fold is expected by flexing this sediment layer? Can one explain how the profiles of the thermal and the electrical conductivity will look like across a salt dome? The advantage of brainstorming leads to new ideas, and admittedly not always the participants can answer them instantly. Students are asked to visit library to find answers to unresolved issues and submit logical answers along with references.

4 Fieldwork

Geology students of my department compulsorily undergoing field training have been visiting usually at Ambaji (Gujarat, India; Biswal et al. 2010; Singh et al. 2010; Mahadani et al. 2015; Fig. 1). Prof. T. K. Biswal, a passionate field-based structural geologist, studied this terrain in a great extent and passed his knowledge to the younger faculty members. This is a unique terrain where all kinds of rocks and tremendous variation of deformation features are available to demonstrate. Surpagla is an area, in between the Ambaji temple and the Abu Road railway station, where diverse and clear-cut structures exist. Even junior school students without any exposure to geoscience can be brought here and be convinced with the structures. Similarly, Taleti is another place where superposition and order of folds can be quite well demonstrated in a small area. Surpagla and Taleti are areas where no climbing is required to undertake the fieldwork. Therefore, one can focus on the structures. My approaches with students regarding fieldwork course have been:

I. Each student can make an oral presentation for about 10 min on different geoscientific issues of Ambaji area in my class, before visiting for fieldwork.
II. They submit a report on geology, structures, and tectonics of this terrain before going out for fieldwork. All minerals and rocks reported from this terrain are listed, and their distinguishing properties are jotted down.

Fig. 1 Relaxed moment during fieldwork at Surpagla area, Ambaji, in 2015, with the then M.Sc. first-year applied geology students. S. Mukherjee is located at the fourth position from left in the front row

III. In field: The first day is spent on basic measurement techniques using both conventional clinometer and brunton. Measurements using mobile phones are also done and accuracy of the mobile phone derived data is checked carefully.
IV. *Second day*: Mine visit is done. The abandoned Deri Cu mine is visited and rocks and minerals are identified using a hand lens. This is followed by visiting a limestone opencast mine. The mining geologist/engineer explains the mining operation. Mine visit is traditionally done in fieldwork at the last day when students' energy and interest go down. To avoid this, I usually keep the second day of the fieldwork for mine visit.
V. Rest of the days: Identification of structures with the partial assistance of the faculty members. Students are then encouraged to explore more. A day or two days are kept for independent mapping of litho-contacts for several kilometers, near the Koteshwar area. Likewise, one or two days are kept for plane paper mapping. It is ensured that students work both in groups and also individually. Coming back from field, students are asked to cross-check in Google Earth image whether the drawn litho-contacts are also revealed in any other (geomorphologic) ways.
VI. Every night, students need to submit the resume of fieldwork and one-to-one discussions are made with them. Besides, every night, five to six students need to make oral presentation using laptop where both students and faculty ask more questions. The aim is to push interpretations to be more detailed.
VII. Coming back from fieldwork, students need to submit individual reports of fieldwork, usually within 40 days. Students are encouraged to send soft copies of their reports 7 days before formal submission dates, so that I have a look and suggest improvements, and I also run the entire report in plagiarism checker. Reports with copied sentences from previous literature/batch mate's reports are returned, and the students are asked to rewrite in their own language.
VIII. Spread over almost an entire semester, students deliver oral presentations for about 10 min on specific issues of Ambaji geology and the fieldwork done.

Grades are awarded based on all the activities *I* to *VIII*. Field diaries are also checked along with the field reports. Things checked in the report: diagrams/sketches, data collected, daily resume, etc.

5 Syllabus and Beyond

When allotted to instruct structural geology for the geology students, I cover the syllabus and in addition touch the following subjects: (i) principles of analogue modeling (geometric, dynamic, and kinematics; I am yet to add up centrifuge modeling techniques and numerical problems), (ii) cross section balancing, (iii) well bore stability, (iv) rock rheology, (v) pore pressure prediction, (vi) statics (moment and product of inertia, isostasy, center of gravity for rock column with known density variation), (vii) growth folds and growth faults, compaction folds, diapir mechanism, (viii) Poiseuille flow mechanism and strain profiles for Newtonian and non-Newtonian fluids, (ix) preliminary other aspects of fluid mechanics, etc.

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Appendix

Syllabus of Structural Geology at the Department of Earth Sciences, IIT Roorkee (Internet Reference-2)

ES 203

Geological significance and recognition of unconformities
Morphology of folds
Geometric classifications of folds
Genetic classifications of folds
Mechanism and causes of folding
Strain distribution in different types of folds
Outcrop patterns of different types of folds
Geometric and genetic classification of faults, effects of faulting on outcrops, large-scale faults, and their tectonic significance
Geometric and genetic classification of joints
Foliation, their descriptive terminology, origin, and relation to major structures
Different types of lineations, their origin, and their relation to major structures
Different types of shear zones and their development.

Practical

Contour, stratum contour, dip, and strike problems
Plunge and pitch of lineations
Completion of outcrop pattern
Geological maps—cross section through different types of structures and geological history
Dip isogon studies and classification of folds
Geological structures in hand specimen.

ES 204: Field Training-1

Study of toposheets and geological maps
Determination of location on maps
Measurements of dip and strike of planar surfaces
Measurement of lineation
Measurement of stratigraphic columns
Geological mapping
Plotting and analysis of field data.

ES 304

Stress in homogeneous and inhomogeneous media and analytical techniques
Geometry and analysis of fractures, joints, and faults
Homogeneous strain and techniques of strain analysis including Fry method, grain center method, and Rf/Φ method
Geometry of folds and their classification schemes
Mechanism of folding and internal strain accommodation
Shear zones and techniques of their analysis
Example analysis of foliation and lineation in rocks: geometry, mechanics, and significance
Techniques of structural analysis in areas of superposed folding
Different types of deformation mechanism.

Practical

Techniques of strain analysis: determination of finite strain of deformed objects using long- to short-axis, center-to-center, Fry, and Rf/Φ methods
Determination of finite strain from deformed fossils
Dip isogon method of fold analysis
Determination of strain in ductile shear zones and analysis of brittle fault zones
Structural analysis of folded terrains.

Syllabus of Structural Geology at the Department of Earth Sciences, IIT Bombay (Internet Reference-3)

GS 407

Dynamic and kinematic analyses of rocks in two dimensions
Stress and strain. folds—classification, mechanism of folding

Biot's law—strain within buckled layer, similar fold and shear fold, kink bands, chevron folds, and conjugate fold
Cleavage, lineation, boudinage; deformation of linear structures by flexural slip folding and shear folding
Deformation of planar structures by flexural slip folding and shear folding; superimposed folding
Type 1, 2, and 3 interference pattern
Faults and ductile shear zone.

GS 413 Structural Geology Laboratory

Stereographic plotting and contouring of planes and lines
Analysis of folds, faults, and ductile shear zone
Strain measurements from deformed fossils and other markers
Interpretation of geological maps
Computer aids to analysis of structural data.

GS 450 Geological Fieldwork

Fieldwork in Metamorphic Terrai
Toposheet reading, use of GPS
Recconnaitory traverse
Structural mapping (1:1000) scale
Oriented sampling
Shear zone studies
Visit to mines

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