Atlas of Structural Geology
Atlas of Structural Geology

Soumyajit Mukherjee
Department of Earth Sciences
Indian Institute of Technology Bombay
Powai, Mumbai 400 076
Maharashtra, India
soumyajitm@gmail.com
# Contents

List of Contributors vii  
Preface xiii  
Acknowledgments xv

1. Folds 1

2. Ductile Shear Zones 49

3. Brittle Faults 79

4. Boudins and Mullions 107

5. Veins 119

6. Various Structures 125

Author Index 159  
Subject Index 163
This page intentionally left blank
List of Contributors

Max Arndt, E-mail: max.arndt@emr.rwth-aachen.de Info: EMR - Energy & Mineral Resources Group, Geologie - Endogene Dynamik, RWTH Aachen University, Lochnerstrasse 4-20, D-52056 Aachen, Germany; Tel: +49-241-80-98438

Paola Ferreira Barbosa, E-mail: paolafeba@yahoo.com.br Info: Center of Microscopy, Universidade Federal de Minas Gerais, Avenida Perimetral Sul, 91-129 - Campus da UFMG, Belo Horizonte - MG, Brazil; CEP: 31255-040; Tel: (55 31) 3409-7575

Ananya Basu, E-mail: an.basuju@gmail.com Info: Department of Geological Sciences, Jadavpur University, Kolkata, West Bengal, India; Pin-700 032; 091900768473 (M)

Andrea Billi, E-mail: andrea.billi@cnr.it Info: Consiglio Nazionale delle Ricerche, IGAG, c.o. Dipartimento Scienze della Terra, Sapienza Università di Roma, P.le A. Moro 5, 00185, Rome, Italy; 390649914955 (M)

Tuhin Biswas, E-mail: tbthuin24@gmail.com Info: Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra, India; Pin-400 076; 919167517063 (M)

Chloë Bonamici, E-mail: chloeebe@lanl.gov Info: Los Alamos National Laboratory, Chemistry Division (C-NR), Los Alamos, NM 87545; +1 505 664 0115

Svetoslav Bonchev, E-mail: sbonchev@gmail.com Info: Graf Ignatiev St. 53 G 1142, Sofia, Bulgaria; 359-884 338 115

Narayan Bose, E-mail: narayan.bghs@gmail.com Info: Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra, India; Pin-400 076; 919029787238 (M)

Luis A. Buatois, E-mail: luis.buatois@usask.ca Info: Department of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, Saskatchewan, Canada, S7N 5E2; Phone: 1-306-966-5730

Paul K. Byrne, E-mail: py Byrne@carnegiescience.edu Info: Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd., Houston, TX 77058; Phone office: 281-486-2140

Jonathan Saul Caine, E-mail: jscaine@usgs.gov Info: U. S. Geological Survey, P. O. Box 25046, MS 964, Denver, CO 80225-0046; 303 236 1822

Sadhana M. Chatterjee, E-mail: sadhanamahato@gmail.com Info: Department of Geological Sciences, Jadavpur University, Kolkata, West Bengal, India; Pin-700 032; 9434217749 (M)

Sreejita Chatterjee, E-mail: sreechitach@gmail.com Info: Department Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra, India; Pin-400 076; 887904571 (M)

T.R.K. Chetty, E-mail: trkchetty@gmail.com Info: National Geophysical Research Institute, Hyderabad, Andhra Pradesh, India; Pin-500 007; 9885676086 (M)

Mainak Choudhuri, E-mail: mainak.ch@yahoo.co.in Info: Reliance Industries Limited, Petroleum Business (E & P), Mumbai, India; Pin-400 071; 91996755923 (M)

Sankha Das, E-mail: sankhad56@gmail.com Info: Geological Survey of India, State Unit, Andhra Pradesh, Southern Region, Bandlaguda, Hyderabad, Andhra Pradesh; Pin-500068; 09642276706 (M), 09830154951 (M)

Rohini Das, E-mail: romiyadas@gmail.com Info: Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India; Pin-247 667; 8126694552 (M), 9831518422 (M)

Sudipta Dasgupta, E-mail: sudipta.dasgupta@usask.ca Info: Department of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, Saskatchewan, Canada S7N 5E2; 13069662457 (O)

Swagato Dasgupta, E-mail: swagato.dg@gmail.com Info: Reliance Industries Ltd., Exploration & Production, Navi Mumbai, Maharashtra, India; Pin-400 701; 919987538641 (M)

Bhushan S. Deota, E-mail: bdeota@rediffmail.com Info: Department of Geology, Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat; 390002; 9898097211 (M)

Tine Derez, E-mail: Tine.Derez@ees.kuleuven.be Info: Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E box 2410, B-3001 Heverlee, Belgium; +32(0)496502579
Natalie Deseta, E-mail: suridae@gmail.com Info: School of Geosciences, University of the Witwatersrand, Private Bag 3, WITS 2050; 27796092695 (M)

Arindam Dutta, E-mail: arindamdutta2000@gmail.com Info: Department of Geological Sciences, Indian Institute of Technology Kharagpur, India; 9830956422 (M)

Dripta Dutta, E-mail: dripta.dutta@gmail.com Info: Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra, India; Pin-400 076; 919167521824 (M)

Amy Ellis, E-mail: amyellis@hotmail.co.uk Info: Ikon Science Ltd, Rivergreen Centre, Durham, DH1 5TS, UK; +44 (0) 191 383 7362 (M)

Ake Fagereng, E-mail: FagerEng@cardiff.ac.uk Info: School of Earth & Ocean Science, Cardiff University, Main Building, Park Place, Cardiff, CF10 3AT, UK; +44 (0)29 208 70760 (O)

Carlos Fernández, E-mail: fcarlos@uhu.es Info: Departamento Geodinámica y Paleontología, Facultad de Ciencias Experimentales, Universidad de Huelva, Campus El Carmen, Avenida 3 de Marzo, 21071 Huelva, Spain; Phone: +34 959219857

Luigi De Filippis, E-mail: luigidefilippis@gmail.com Info: Dipartimento di Scienze, Università Roma Tre, Largo S.L. Murialdo 1, I-00146 Roma; +39-3286138869

László Fodor, E-mail: asz.fodor@yahoo.com Info: Hungarian Academy of Sciences MTA-ELTE, Geological, Geophysical and Space Sciences, Research Group at Eötvös University, Pázmány P. sétány 1/C; Phone: 36-1-3722500/8714

Chiara Frassi, E-mail: chiarafrassi@yahoo.it Info: Dipartimento di Scienze della Terra, Università di Pisa, via S. Maria, 53, 56100 Pisa, Italy; +39 050 2215781

M.S. Gadhai, E-mail: mahendrasinh@gmail.com Info: Civil Engineering Department, L. D. College of Engineering, Ahmedabad, 380 015 Gujarat, India; +91-9426272328 (M)

Rajkumar Ghosh, E-mail: rajkumarghgeol@gmail.com Info: Department of Geosciences, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra, India; Pin-400 076; 9167520347 (M)

Guido Sibaja Rodas, E-mail: guisibro@gmail.com Info: Department of Earth Sciences, Università degli Studi di Milano; San Isidro de Coronado. 50 m al este de la entrada al Restaurante Lone Star Grill, Condominio Quintana de los Reyes número 21. Vázquez de Coronado. San José, Costa Rica; (506) 2292-2296, (506) 8998-6018

Tapos Kumar Goswami, E-mail: tapogoswami@gmail.com Info: Department of Applied Geology, Dibrugarh University, Dibrugarh, Assam, India; Pin-786 004; 919435352889 (M)

Sukanta Goswami, E-mail: sukantagoswami@iith.ac.in Info: Atomic Minerals Directorate for Exploration and Research (AMD), Department of Atomic Energy (DAE), Southern Region, Nagarbhavi, Bangalore, India; Pin-560 072; 8088723838 (M)

Jens Carsten Grimmer, E-mail: jens.grimmer@kit.edu Info: Institute of Applied Geosciences, Adenauerring 20b, 76131 Karlsruhe, Germany; +49 721 608 41888

Ranjan Gupta, E-mail: gupta.ranjan256@gmail.com Info: Rampura Agucha Mine, Hindustan Zinc Limited, Rajasthan, India; 91-9799175999 (M)

Saibal Gupta, E-mail: saib2008@gmail.com Info: Department of Geological Sciences, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India; Pin: 721302; +91-3222-283370 (M)

Tomokazu Hokada, E-mail: hokada@npr.ac.jp Info: Geology Group, National Institute of Polar Research, 10-3 Midori-cho, Tachikawa, Tokyo 190-8518, Japan; Phone: +81-42-512-0714

Guillermo Alvarado Induni, E-mail: GAlvaradoI@ice.go.cr Info: Área de Amenazas y Auscultación Sismológica y Volcánica, C.S. Exploración Subterránea/NIC-Electricidad. Apdo 10032-1000; Landline: 00506 89383752

Scott Johnson, E-mail: johnsons@maine.edu Info: School of Earth and Climate Sciences, 5790 Bryand Global Sciences, University of Maine, Orono, ME 04469-5790, USA; (207)581-2142

Aditya Joshi, E-mail: adityaajoshi@gmail.com Info: Department of Geology, Faculty of Science, The M.S. University of Baroda, Vadodara, Gujarat, India; Pin-390 002; 918000421451 (M)

Eirin Kar, E-mail: sakurakar5@gmail.com Info: Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India; Pin-247 667; 8439731513 (M)

Rahul Kar, E-mail: rkvar48@gmail.com Info: Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, West Bengal, India; Pin-721 302; 919749469334 (M)

R.V. Karanth, E-mail: r_v_karanth@yahoo.co.in Info: 104 - Aarth Apartments, 29 - Pratapgunj, Vadodara - 390 002, Gujarat, India; 919998485468 (M)

Miklós Kázmér, E-mail: mkazmer@gmail.com Info: Department of Palaeontology, Eotvos University, Pazmany Peter setany 1/c; 36-20-494-5275

Subodha Khanal, E-mail: skhanal@crimson.ua.edu Info: Department of Geological Sciences, University of Alabama, Tuscaloosa, AL, 35487, USA; (347)400-3645
Jorge Pamplona, E-mail: jopamp@ct.d.uminho.pt Info:
ICT, Departamento de Ciências da Terra, Escola de
Ciências, Universidade do Minho, Campus de Gualtar,
4710-057 Braga, Portugal; +351 253604300

M.K. Panigrahi, E-mail: mkp@gg.iitkgp.ernet.in Info:
Department of Geological Sciences, Indian Institute of
Technology Kharagpur, Kharagpur, West Bengal, India;
Pin: 721302; +91-3222-283376 (O)

Jyotirmoy Paul, E-mail: djyo.geos01@gmail.com Info:
Department of Geological Sciences, Jadavpur
University, Kolkata, West Bengal, India; Pin-700 032;
0919051469485 (M)

Victoria Pease, E-mail: vicky.pease@geo.su.se Info:
Department of Geological Sciences, PetroTectonics
Facility, Stockholm University, SE-106 91 Stockholm,
Sweden; 468674-7321

Giorgio Pennacchioni, E-mail: giorgio.pennacchioni@
unipd.it Info: Dipartimento di Geoscienze, University
of Padova, Via Gradenigo 6, Italy; +39 338 6718488 (M)

Roberto Vizeu Lima Pinheiro, E-mail: vizeu@ufpa.
br Info: Universidade Federal do Para - Faculdade de
Geologia - Brazil; (0055 91) 32017393

Suellen Olívia Cândida Pinto, E-mail: suellen_ olivia@yahoo.com.br Info: Federal University of
OuroPreto, Geology Engineering Department, Ouro
Preto, Brazil

Andrés Pocovi, E-mail: apocovi@unizar.es Info:
Geotransfer Res. Group, Department of Earth Sciences,
Pedro Cerbuna 12, 50009 Zaragoza; +34 976 76 20 72

Brian R. Pratt, E-mail: brian.pratt@usask.ca Info:
Department of Geological Sciences, University of
Saskatchewan, 114 Science Place, Saskatoon,
Saskatchewan, Canada, S7N5E2; Phone: 1-306-966-
5725

Emilio L. Pueyo, E-mail: unaim@igme.es Info:Unidad
de Zaragoza, Instituto Geologico y Minero de Espana,
C/ Manuel Lasala 44, 9ºB, 50006 Zaragoza, Spain; +34
976 55 51 53 (ext 31)

Benedito Calejo Rodrigues, E-mail: bjcrodrigues@
gmail.com Info: ICT, Rua do Campo Alegre 687, 4169-
007 Porto, Portugal; +351 220402472

Federico Rossetti, E-mail: federico.rossetti@uniroma3.
it Info: Dipartimento di Scienze, Università degli Studi
Roma Tre, L.go S.L. Murialdo, 1, 00146 Rome, Italy;
+39 06 57338043 (M)

Rajib Sadhu, E-mail: imrajib.ge@gmail.com Info:
Office address: Premiere Miniere Du Katanga P.M.K.
Sprl 4 Avenue Des Cypres N R C: 10316 ID. NAT:6-118-
N60935L Lubumbashi R.D.Congo; 243-976325555

Dilip Saha, E-mail: sahad.geol@gmail.com Info:
Geological Studies Unit, Indian Statistical Institute, 203 B
T Road, Kolkata, India; Pin-700 108; 919433559563 (M)

Dnyanada Salvi, E-mail: salvidnyanada@gmail.com
Info: Department of Earth Sciences, Indian Institute of
Technology Bombay Powai, Mumbai 400 076,
Maharashtra, India; Phone: +91-022-2576-7251;
9869007336 (M)

Anupam Samanta, E-mail: anupam.jugeology@gmail.
com Info: Department of Geological Sciences, Jadavpur
University, Kolkata, West Bengal, India; Pin-700 032;
91-9046368545 (M)

Elisa M. Sánchez, E-mail: emsanchez@ubu.es Info:
Paleomagnetic Laboratory, Physics Dept. Universidad de
Burgos, Avda. de Cantabria, s/n, 09006 Burgos,
Spain; +34 947 25 8978

Moloy Sarkar, E-mail: moloy.sarkar1992@gmail.
com Info: Department of Earth Sciences, Indian Institute of
Technology Roorkee, Roorkee, Uttarakhand, India;
Pin-247 667; 09038850981 (M), 08791258153 (M)

Jennifer J. Scott, E-mail: jjscott@ualberta.ca Info:
Department of Geological Sciences, University of
Saskatchewan, 114 Science Place, Saskatoon, SK,
Canada S7N 5E2

Souvik Sen, E-mail: souvikseniit@gmail.com Info:
Department of Earth Sciences, Indian Institute of
Technology Bombay, Powai, Mumbai, Maharashtra,
India; Pin-400 076; 918348690112 (M)

Sudipta Sengupta, E-mail: sudiptasg@yahoo.com Info:
Department of Geological Sciences, Jadavpur
University, Kolkata, West Bengal, India; Pin-700 032;
0910332457 2712 (O)

Hetu Sheth, E-mail: hcsheet@iith.ac.in Info: Department
of Earth Sciences, Indian Institute of Technology
Bombay, Powai, Mumbai, Maharashtra, India;
Pin-400 076; 910225767264 (O)

Ichiko Shimizu, E-mail: ichiko@eps.s.u-tokyo.ac.jp Info:
Department of Earth and Planetary Science,
University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo
113-0033, Japan; 81-3-5841-4513

Toshihiko Shimamoto, E-mail: shima_kyoto@yahoo.
co.jp Info: State Key Laboratory of Earthquake
Dynamics, Institute of Geology, China Earthquake
Administration, P. O. Box 9803, Beijing 100029, China;
18600262139 (M)

Kazuyuki Shiraishi, E-mail: kshiraishi@nipr.ac.jp Info:
Geology Group, National Institute of Polar Research,
10-3 Midori-cho, Tachikawa, Tokyo 190-8518, Japan;
Phone: +81-42-512-0603
Luiz Sérico Amarante Simões, E-mail: lsimoes@rc.unesp.br Info: Universidade Estadual Paulista Júlio de Mesquita Filho, Institute of Geosciences and Exact Sciences of Rio Claro, Department of Petrology and Metallogeny, Av. 24-A, nº 1515, Bela Vista, CEP: 13506-900, Rio Claro, SP – Brazil; Tel: (55 19) 3526-9257

Bikramaditya Singh, E-mail: rkaditya17@rediffmail.com Info: Wadia Institute of Himalayan Geology, GMS Road, Dehradun, Uttarakhand, India; Pin-248 001; 01352525103 (O)

Aabha Singh, E-mail: aabs_22@yahoo.co.in Info: Department of Geology, Fergusson College, F.C. Road, Shivaji Nagar, Pune, Maharashtra, India; Pin-411 004; 9920166093 (M)

Shailendra Singh, E-mail: singhgaur4@gmail.com Info: Geological Survey of India, GSITI, FTC Bhimtal, Northern Region, Lucknow, Uttarpradesh, India; 9450093216 (M)

Manuel Sintubin, E-mail: manuelsintubin@ees.kuleuven.be Info: Geodynamics & Geofluids Research Group, Department of Earth & Environmental Sciences, KU Leuven, Celestijnenlaan 200E - box 2410, BE-3001 Leuven; Phone: +32 (0)16 32 64 47 - +32 (0)16 32 78 00

Ruth Soto, E-mail: r.soto@igme.es Info: Instituto Geológico y Minero de España (IGME), Unidad de Zaragoza. C/ Manuel Lasala, 44, 9B, 50006 Zaragoza, Spain; +34 976 555 153 (ext 26)

Frank Strozyk, E-mail: frank.strozyk@emr.rwth-aachen.de Info: EMR - Energy & Mineral Resources Group, Geological Institute, RWTH Aachen University, Wuellnerstr. 2, 52062 Aachen, Germany; Phone: +49-241-80-95718

Yutaka Takahashi, E-mail: takahashi-yutaka@aist.go.jp Info: Orogenic Process Research Group, Institute of Geology and Geoinformation, Geological Survey of Japan, AIST, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8567, Japan; Phone: +81-29-861-3933

Tetsuhiro Togo, E-mail: duketogotetsu@gmail.com Info: Institute of Earthquake Volcano Geology, National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-856 Japan; Tel: 81-909699526

Balázs Törő, E-mail: torobala@gmail.com Info: Department of Geological Sciences, University of Saskatchewan, Canada; +1 306 966 5737

Tsuyoshi Toyoshima, E-mail: ttoyo@geo.sc.niigata-u.ac.jp Info: Department of Geology, Faculty of Science, Niigata University, 8050 Ikarashi-2-nocho, Niigata 950-2181, Japan; +81-25-262-6199 (O)

Toshiaki Tsuchiogae, E-mail: tsuchiogae@geol.tsukuba.ac.jp Info: Graduate school of Life and Environmental Sciences (Earth Evolution Sciences), University of Tsukuba, Ibaraki, 305-8572, Japan; Phone: +81 29 853 5239

Janos L. Urai, E-mail: j.urai@gd.rwth-aachen.de Info: EMR - Energy & Mineral Resources Group, Geologie - Endogene Dynamik, RWTH Aachen University, Lochnerstrasse 4-20, D-52056 Aachen, Germany; Tel: +49-241-80-95723

Gianluca Vignaroli, E-mail: gianluca.vignaroli@uniroma3.it Info: Dipartimento di Scienze, Università degli Studi Roma Tre, L.go S.L. Murialdo, 1, 00146 Rome, Italy; +39 06 57338043 (M)

Simon Virgo, E-mail: s.virgo@gd.rwth-aachen.de Info: EMR - Energy & Mineral Resources Group, Geologie - Endogene Dynamik, RWTH Aachen University, Lochnerstrasse 4-20, D-52056 Aachen, Germany; Tel: +49-241-80-98438

Marko Vrabc, E-mail: marko.vrabc@geo.ntf.unij.si Info: University of Ljubljana, Faculty of Natural Sciences and Technology, Department of Geology, Privoz 11, SI-1000 Ljubljana, Slovenia; 38612445412 (O)

Lu Yao, E-mail: yaolu_cug@163.com Info: State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, P. O. Box 9803, Beijing 100029, China; Tel: 86-13426054959

Ran Zhang, E-mail: Ran.Zhang@bhpbilliton.com Info: BHP Billiton Petroleum, 1360 Post Oak Blvd., Ste. 150, Houston, TX 77056-3030 USA; +1 713 297 6568
Preface

Documentation of structures in different scales is the first step in many structural geological studies. This edited atlas gives an overview of diverse structures. Due to lack of space or appropriateness, sometimes interesting structural snaps cannot be published in journals. This book fills that gap.
Acknowledgments

Thanks to Mohanapriyan Rajendran, Priya Srikumar, Marisa LaFleur, Amy Shapiro, Louisa Hutchins, and John Fedor (Elsevier) for editing, and to all the contributors and reviewers. Philippe Herve Leloup, Chris Talbot and an anonymous reviewer are thanked for reviewing the book proposal and for providing positive comments. Research students and teaching assistants helped and I thank them: Tuhin Biswas, Narayan Bose, Achyuta Ayan Misra, Aninda Ghosh, Rajkumar Ghosh, Dripta Dutta, Uddipan Das, and many others. Thanks to my wife Payel Mukherjee for her patience.
Chapter 1

Folds

KEYWORDS
Folds; Folds not related to shear zones; Overturned fold; Shear zone related fold; Sheath fold; Superposed fold.

Two of the most intensely studied aspects in structural geology are morphology and genesis of folds (see Ramsay, 1967; Hudleston and Lan, 1993; Ez, 2000; Harris et al., 2002; Harris, 2003; Alsop and Holdsworth, 2004; Mandal et al., 2004; Carreras et al., 2005; Bell, 2010; Hudleston and Treagus, 2010; Godin et al., 2011; Harris et al., 2012a,b; Llorens et al., 2013; Mukherjee et al., in press). Of particular importance is whether folds found inside ductile shear zones are related to ductile shear (e.g., Mandal et al., 2004; Carreras et al., 2005; Bell, 2010). This chapter presents folds of different geometries and generations, some related with ductile shear zones, from different scales (Figures 1.1–1.87).

![Figure 1.1](image_url)

**FIGURE 1.1** Upright folds and folded boudins resulting from continental collision of East and West Gondwana. The boudins of dark-colored amphibolite (Fb) in light-colored biotite-hornblende gneiss have originally pancake shapes with flattening parallel to compositional layering of gneiss, and resulted from the layer-parallel extension and thinning of crustal rocks within 640–600 Ma (Toyoshima et al., 1995). The folds with wavelengths of 20–30 m are parasitic upright folds of larger-scale upright fold related to 600–560 Ma sinistral transpression and crustal shortening during the collision (Toyoshima et al., 2013). The boudins (Fb) folded by the parasitic folds suggest that the tectonic regime changed from layer-normal to layer-parallel compression (Toyoshima et al., 2013). Osanai et al. (2013) presented SHRIMP U–PB ages for metamorphic rocks from the Sør Rondane Mountains, East Antarctica, and recognized periods of ultrahigh-temperature metamorphism (pre-main metamorphic stage) during 750–700 Ma and granulite-to amphibolite-facies metamorphism during 640–600 Ma. Location: 72°09′42″S, 25°31′50″E, the southern part of Salen in the Sør Rondane Mountains, East Antarctica. (Tsuyoshi Toyoshima, Masaaki Owada, Kazuyuki Shiraiishi)
REFERENCES


Chapter 2

Ductile Shear Zones

KEYWORDS
C-plane; Couette flow; Ductile shear zone; Flanking structure; Mineral fish; Primary shear (C) plane; Pure shear; Shear; Simple shear; Synthetic secondary shear plane.

“Tabular or sheetlike, planar or curviplanar zones in which rocks are more highly strained than rocks adjacent to the zone” are called ductile shear zones (Davis et al., 2012; also see Mukherjee and Biswas, 2014; in press). Identification and study of ductile shear zones (Figures 2.1–2.55) are important since major plate boundaries are defined by such shear zones (Regenauer-Lieb and Yuen, 2003). We need to study such zones since along them partially molten rocks can flow (review by Clark et al., 2011). Secondly, viscous dissipation related to such zones has been investigated (Nabelek et al., 2011). No slip boundary condition was assumed classically to explain kinematics of ductile shear zones (Ramsay 1980; Mukherjee 2012; etc). However, recently, slip boundary condition is more recognized (Frehner et al., 2011; Mulchrone and Mukherjee, submitted). The ductile shear sense/sense of movement from such zones can be deciphered mainly from asymmetric sigmoid, parallelogram and lenticular clasts and intrafolial folds (Lister and Snoke, 1984; ten Grotenhuis et al., 2003; Mukherjee, 2011a,b, 2013a,b,c, 2014a,b,c; Bhadra and Gupta, in press). See Passchier and Trouw (2005) for review on ductile shear zones, and Mukherjee and Mulchrone (2013) and Mulchrone and Mukherjee (in press) for shear heat pattern in these zones. In addition to such shear sense indicators, this chapter also presents near symmetric clasts that form possibly within shear zones but that do not give the shear sense.

FIGURE 2.1 Domino style normal faults with strike slip component, dipping 50° toward N60°–64°E (rake 70°W), Upper Pliocene–Lower Pleistocene polymictic volcanic breccia. A transtension component with western extension, is likely due to the parallelism of the Cordillera with the NW-trending Middle America trench located ~160 km to the W. The Cordillera de Tilarán is an andesitic extinct volcanic range, a paleoarc genetically associated with the Costa Rica subduction zone. There most of the ongoing and recent maximum and minimum horizontal stress are generated. Campos de Oro Arriba (10°22′4.09″N – 84°54′57.77″W), Guanacaste Province, Costa Rica. See Dabrowski and Graseman (2014) as a latest paper on domino type structure. (Guillermo Alvarado Induni)
REFERENCES


Chapter 3

Brittle Faults

KEYWORDS
Brittle shear zone; Brittle tectonics; Conjugate faults; Faults; Kinematic indicators; P-plane; Slickensides; Y-plane.

Brittle shear zones/fault zones are usually defined by curved brittle P-planes bound by usually straight Y-planes (Passchier and Trouw, 2005). These shears may affect as a narrow zone within the rock bodies (Misra et al. 2015). Brittle sheared lenses of rocks vary in geometry, and the P-planes may curve only near the Y-planes (Mukherjee, 2014a,b). Fault gouge zones sometimes contain P-planes that help to deduce the shear sense. Fault planes/Y-planes may contain slickensides. See Doblas (1998) for detail of slickenside types and their reliable use in shear sense determination. This is despite Tjia (1964) questioned reliability of slickensides as shear sense indicators. Deformational structures and especially faulted units within soft-sedimentary structures are quite common (Byrne, 1994) (Figures 3.1–3.49). In collisional tectonic regimes, brittle faults can form either in an in-sequence or in an out-of-sequence manner (Mukherjee, in press).

FIGURE 3.1  Road-cut exposure of the Coal Creek fault zone, central eastern Front Range, Colorado, USA (39°54′14″N, 105°20′46″W). This reverse fault zone occurs within the 1.7 Ga Boulder Creek, granodiorite batholith and hosts ~620-m west directed slip. The exposure shows a discrete, clay-rich gouge fault core and surrounding damage zone (cf. Caine et al., 1996). The damage zone is characterized by relatively low-temperature hydrothermal alteration concentrated mainly in hanging wall fractures juxtaposed against the pervasively and moderately altered clay-rich, white footwall. See Caine et al. (2010) for details. (Jonathan Caine)


Chapter 4

Boudins and Mullions

KEYWORDS
Boudins; Mullions; Pinch and swell structures; Scar folds.

Local brittle–ductile extension partially or completely separate clasts. These segmented clasts are called boudins. Asymmetric boudins can be used to decipher shear sense (Goscombe et al., 2004). See Abe et al. (2013) for fracture patterns in boudinage. Mullions are linear fluted structures developed within a rock or at lithological interfaces (Twiss and Moores, 2007). Depending on their genesis, Twiss and Moores (2007) classified them into three types: “fold mullion,” “fault mullion,” and “irregular mullion.” Viscosity contrast between the boudinaged/mullion material and the host rock is one of the controlling factors of their geometries (Sokoutis, 1990; Talbot, 1999; Schmalholz et al., 2008; Schmalholz and Maeder, 2012). Maeder et al. (2009) used the term “segment structure” to describe boudins and mullions together (Figs. 4.1–4.18). Mukherjee (2014a,b) reviewed terms to describe boudins in the light of flanking structures.

FIGURE 4.1 Photograph from the Gaub Canyon, Namibia, showing a boudinaged metabasalt layer enveloped by metaturbidites in the Southern Marginal Zone of the Damara Belt. The rocks deformed during Neoproterozoic to Cambrian, Pan African assembly of Gondwana (e.g., Barnes and Sawyer, 1980), with peak metamorphic conditions in the amphibolite facies. The rock assemblage comprises metamorphosed basalt, sandstone, mudstone, and chert, which represent intercalated continental and oceanic materials that were likely deformed in an accretionary prism (Kukla and Stanistreet, 1991). The photo highlights the rheological contrasts that develop through intercalation of lithologies of variable viscosity. In this case, the basaltic layer has fractured in the boudin neck, allowing formation of a quartz vein, whereas metasediments are locally folded to fill the gap between boudins of metabasalt. This provides an example of mixed brittle–viscous deformation at temperatures in excess of the brittle to viscous transition in quartzofeldspathic rocks, and a possible geological analogue to the mixture of transient creep and episodic brittle failure inferred to be responsible for deep tremor and slow slip in active subduction zones (Fagereng et al., 2014). Photo width: ±2 m. (Ake Fagereng)
REFERENCES


REFERENCES


Chapter 6

Various Structures

KEYWORDS
Columnar joints; Crater; Fissures; Fractures; Pull apart structure; Spheroidal weathering; Xenoliths.

This chapter presents various structures some of which are not worked intensely by structural geologists. Grain boundary migration in rocks observed under optical microscope can constrain the temperature the rock underwent (Stipp et al., 2002). Stability of buildings and fracturing during earthquakes has been a research topic to geoscientists (Krishnan et al., 2006). Study of faults and other structures has helped geoscientists to paleohydrology (Treiman, 2008) (Figures 6.1–6.60).

FIGURE 6.1  Columnar joints, colonnade and entablature. Thick solidifying lava flows develop contraction fractures that propagate from their cooling margins toward hotter interiors. These fractures, called columnar joints, divide a lava flow into columns, with polygonal (ideally hexagonal) shapes in plan. A subhorizontal basaltic lava flow of the Talisker Bay Group, Isle of Skye, Scotland is shown in the figure. The lower part of the flow shows well-developed vertical columns, suggesting nearly horizontal isotherms (contours of constant temperature within the lava flow). Such a columnar tier is called a colonnade. The upper part of this flow shows a highly chaotic and distorted internal structure, as would develop during rainfall or stream flow supplying water into the cooling flow interior and disturbing isotherms. This tier is known as an entablature. The colonnade and the entablature, though with greatly different field appearance, are part of a single lava flow. Here, the combined thickness of both is 120 m. (Hetu Sheth)
FIGURE 6.60 The Caloris basin is the largest preserved impact structure on Mercury. With an E–W diameter of 1640 km, the floor of the basin subtends ~40° of arc. The interior of the basin, which has been filled with voluminous, low-viscosity lavas, is replete with both contractional (wrinkle ridges) and extensional (graben) structures. The origin of these structures is not clear. The graben may have formed by thermal contraction of the interior lavas, similar to what is observed within Goethe basin, for example. Yet the pronounced radial orientations of the innermost graben are yet to be explained. The wrinkle ridges may be the result of subsidence of the Caloris interior lavas; however, in many places they remained active after the graben, and so could be due to the sustained global contraction of Mercury as its interior cooled. The image is in an orthographic projection centered at 31.5°N, 162.7°E. (Image credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington). (Christian Klimczak, Paul K. Byrne)

REFERENCES


Subject Index

Note: Page numbers followed by “f” indicate figures.

A
Alkali feldspar, 19f
Antigorite fibers, 96f

B
Bedding-cleavage relationship, 140f
Boudins/mullions
calc-schist
boudinaged quartz veins in, 112f
rectangular boudinaged quartz veins in, 112f
chocolate tablet boudins, 111f
composite boudins, 108f
definition, 107
fracture planes, boudinaged quartz vein within metagreywacke, 108f
gray conglomerate overlying red mud horizon, Wine Strand, 116f
low-grade metamorphic carbonate sequence, domino boudins within, 113f
metaturbidites, boudinaged metabasalt layer enveloped by, 107f
migmatite gneiss sequence, boudinaged amphibolite layer, 109f
neoproterozoic quartzites, mullions and vertical columns, 114f-115f
pinch and swell structures, 109f-110f
pennsylvanian orthoquartzite, Aravalli Supergroup, 116f
quartz vein boudinaged, 111f
ultramylonitized peridotite, microboudinage structure in, 110f
Brittle fault zones
accretionary wedge, 92f
active Hronov–Poříčí Fault Zone, main faults of, 101f
along-dip segmented normal fault and fault-related fold, 89f
amphibolite gneiss, fault plane of, 96f
antiformal stack duplex, 84f
antigorite fibers, 96f
asbestos mineralization, structural control on, 97f-98f
brittle tectonics, 93f
centimeter-scale top-to-NW brittle reverse fault, 86f
chloritotischn lens, 97f
Brittle fault zones (Continued)
Coal Creek Fault zone/Central Front Range, Colorado, 79f
coseismic damage and viscous flow, repeated cycles of, 98f
Cretaceous Bhuj Formation, sand-shale sequence in the, 84f
Cretaceous clastics, synkinematic faults in, 101f
curvilinear fault-bend folding, 83f
definition, 79
detachment faulting, 92f
erosive tectonic tools, 95f
experimental fault gouge, overlapped slip-zone structures in, 99f
fault slickenide containing calcite
slickenfibers, 93f
fold-and-thrust tectonic belt, 90f
gravitational effect, synsedimentary normal fault, 85f
high-al emphaclite, 103f
Kaikoura, 102f
mesoscopic conjugate set, 82f
metamorphic veins, 97f
NNE-SSW-trending Olevano-Antrodocio-Sibillini oblique thrust ramp, 100f
polished fault surface, 95f
pseudomorphs of (PSTs), 86f
multiple generations of, 102f
quartz and clay around quartz-clast, fine-grained matrix of, 100f
quartzite pebble, N-dipping subvertical fault plane, 89f
quartzite pebble, subvertical fault plane cuts across, 88f
Raša fault, fault zone of, 81f
SE-dipping subparallel curved fault planes, 88f
sinistral strike-slip faulted pebble, 87f
slickolites, 94f
small-scale faults, uniform set of, 85f
subvertical brittle shear Y-planes bound tangentially curved brittle P-planes, 82f
tectonic grooves, strie of, 94f
top-to-SW brittle sheared/reverse faulted sandstone, 90f
white/red gouge, 81f
Y- and P-brittle shear planes, fascinating development of, 87f
Brittle tectonics, 93f

C
Calc-silicate gneiss, 29f
Caloris basin, 155f
Chloritotischn lens outcropping, 97f
Crosscutting veins
definition, 119
dilatant faults, 120f
gneissic foliations, quartz vein, 121f
limestone high-pressure cell in, 119f
semi-dextral shear zone in, 120f
mylonitized gneiss, quartz-rich vein in, 121f
quartz vein network, 123f
thin curved quartz vein, 122f

D
Dharwar rocks, Basalt porphyry from, 139f
Ductile shear zones, 1
antigorite mylonite and asymmetric sheared composite olivine-pyroxene clasts, 73f
around m-scale delta-type asymmetric–feldspar clast, 55f
gneiss gneiss, post D2, syn-D4 ultramylonite shear zone in, 61f
boudinaged quartz veins, 59f
calc-schist, type I foliation structure in, 55f
chloritoid, syntectonic microscopic porphyroblast of, 70f
classic shear band boudin, 56f
definition, 49
deformed amygdalae, 74f
deformed radiolarian fossils, 75f
dilatant jog, 62f
dominostyle normal faults, 49f
ductile sheared quartz vein, 51f
extensional shear bands, 50f
feldspar o-typ porphyroclast, 52f
fine-grained recrystalized matrix, plagioclase feldspar porphyroclast in, 60f
fold-boudin, 67f
evolutive sequence of, 67f
foliation parallel train of boudins, schistose quartzite, 52f
fractured garnet porphyroblast, 72f
Funatsu Shear Zone, augen gneiss/granite mylonite in, 63f
garnet bearing schist, sigmoidal quartz lens in, 53f
Ductile shear zones (Continued)
granite mylonite, polished slab of, 59f
heterolitic sandstone-shale, cleavage
refraction across, 63f
imbricate thrust structure in flysch, 103f
incipient localized dextral shear zones, 58f
initial fracture, typical paired shear zones to,
58f
K-feldspar, delta mantled porphyrocast of, 53f
kyanite-garnet gneiss, 66f
localized heterogeneous shear zone, 57f
mylonitic garnet-micaschists, asymmetric
sheared granite pebble in, 65f
mylonitic micaschists, asymmetric quartz
ribbon from, 73f
mylonitic peridotite cropping, 74f
mylonitic quartz-mica-feldspar-matrix,
kinematically grown magnetite (mag) in, 64f
mylonitized mica schist, 65f
Num orthogneiss, biotite + kyanite-bearing
micaschists from, 72f
olivine, microstructure of, 70f
paleoproterozoic S-type Lesser Himalayan
Granitoids, plane polarized light of, 51f
parallellogram/sigmoid mud unit, 68f
plane polarized light, syntectonic
micrographic garnet under, 71f
post-D3 sigmoidal quartz vein in
amphibolite, Bastar Craton, Sambalpur,
50f
precursor heterogeneities, heterogeneous
ductile shear zones on, 57f
quartzite veinlet, 54f
sheared quartzofeldspathic gneiss, asymmetric
quartz porphyrocasts in, 61f
shear fabrics display, 75f
sigmoid inclusion pattern, syntectonically
grown garnet with, 76f
soft-sediment, sigma clasts/S-C structures in,
66f
spiral, early foliations, sheared microscopic
garnet with, 71f
stacked-folds-boudins, 68f
strike slip fault system, duplex structure in, 60f
top-to-right/west sheared intercalations, 56f
top-to-SW sheared sigmoid quartz veins, 62f
trapezoidal boudination quartz vein, 54f
ultramylonitic peridotite, delta-like structure in,
69f
ultramylonitic shear zone, titane
porphyrocast in, 69f
winged b-microstructure of olivine, 76f
Y-planes in matic schist, Sigmoid brittle
P-planes bound by, 64f

E
Erosive tectonic tools, 95f

F
Folds
alternate layers of ferrugineous and quartzose
materials, folded banded iron formation of, 11f
Folds (Continued)
banded gneiss, small-scale folds in, 22f
Bastar Craton-Rengali Province boundary shear
zone, rotation of F2 fold hinges, 28f
boudinated sheath fold, 26f
Bownmore crenulation cleavage, 14f
calcareous matrix, quartzofeldspathic layers
interlayered in, 35f
calc-silicate, doubly plunging round hinge
isolcinal folds in, 27f
calc-silicate gneiss, 29f
chevron-like fold in amphibolite, dismember
block, 17f
continental collision, upright folds and folded
boudins resulting from, 1f
curved axial plane, noncylindrical fold with,
34f
curved hinge line, plane noncylindrical fold
with, 35f
Cuspat folds of quartz vein, Udaipur,
Rajasthan, 8f
definition, 1
dolomitic host rock, tightly folded quartz
vein in, 20f
dolomitic rock, folded quartz vein in, 30f
fault-bend-fold, 2f
ferroenous sandstone, plunging fold in, 24f
folded anhdyrite layers, 38f
folded layer of chert, 25f
folded migmatic rock, 9f
folded quartz vein, Bhedaghat, Jabalpur, 8f
folded quartz vein within meta-greywacke, 36f
fractured anhydrite, red salt in, 39f
garnetiferous banded gneiss, crenulation
cleavage in, 22f
Gravifssum, 44f
Gulchera Quartzite, 6f
Higher Himalayan gneisses, 20f
high-grade quartzite rock, type 3 interference
pattern/hook-shaped pattern in, 42f
horizontal E-W fold plunges, complex
folding with, 41f
hornblende gneiss, recumbent fold plunging
toward E in, 24f
interlayered sandstones and mudstones, 11f
intrafolial folds, 23f
isolcinal folded chert layers, 26f
Karakoram fault, Ayishan detachment lies
between, 6f
khaki green shale, Jitpur, 7f
kink folded intercalated layers of shales and
limestones, 7f
lacrustine organic rich dolomitic lime
mudstone/oil-shale deposits
disharmonic folding in, 37f, 43f
disturbed layer in, 16f
large-scale folded banded magnetite quartzite
and magnetite garnet biotite schist
intercalation, 10f
Los Cabos Series quartzites, similar folds
within, 16f
lower greenschist facies, quartzite rock, two-generation folding in, 42f
matic mineral rich gneiss, feldspatic layer
in, 44f
Folds (Continued)
Mesoproterozoic garnetiferous mica schist,
cross-nichol of, 15f
mesoscale, recumbent fold in, 5f
mesoscopic disharmonic folding, 30f
metamorphosed granitic host rock,
ampithe diorite-rich layer in, 21f
metasedimentary rock, stretched quartz
boudins in, 19f
meta-siltstone, 3f
meta-siltstone, disjunctive spaced cleavage in,
14f
mica gneiss, microfolded cordierite in, 13f
mica schist, folded quartzite intercalated
with, 18f
Middle Siwalik, micaceous dallas sandstone
of, 21f
morphology and genesis of, 1
neoproterozoic marble, conjugate folds in,
36f
neutral folding, 28f
nonuniform geometry, pytomatic folds of, 33f
originally rectangular intraformational
mudstone rip-up clast set, 37f
out-of-syncine fold accommodation fault, 3f
overprinting crenulation cleavages, 15f
parasitic fold, 23f
planar limbs and sharp/pointed hinge,
chevron fold with, 10f
potassium salt, structures of, 40f
prominent axial depression, doubly plunging
fold with, 33f
quartz vein, fractured pytomatic fold of, 40f
rock salt, anhydrite diapir in, 39f
sheath fold, 25f
Siang fold-and-thrust belt, eocene limestone-
shale sequences, 4f
subvertical (100/785) ferrugeneous quartzite
layer, elongated dome and basin
structures on, 38f
thrust fault and related footwall syncline, Mt
Prena, 4f
Tibetan Himalaya, folded strata in, 5f
tight isoclinal fold
intensely deformed lower limb of, 9f
limbs and hinge regions, 18f
tourmaline-bearing garnet-mica schist,
angular asymmetric folds in, 13f
tri shear fault-propagation folding, 2f
type III fold interference, 34f
type 2 interference pattern, 41f
type 3 interference pattern of, 32f
undeformed massive sandstone turbidite
beds, rhythmic occurrence of, 12f
Variscan basement, fold interference pattern
in, 32f
Fractures
developing triangular zone, three nonparallel
fractures intersect to, 138f
fine phanerocrystalline, tension fracture
surface with, 136f
fracture planes, boudinated quartz vein
within metagreywacke, 108f
fractured anhydrite, red salt in, 39f
fractured garnet porphyroblast, 72f
Fractures (Continued)
initial fracture, typical paired shear zones to, 58f
placing pens/inside Deccan basalt, rounded fracture plane, 138f
quartz vein, fractured pytmonic fold of, 40f

G
Grain boundary area reduction (GBAR), 145f
Grain boundary migration, 125
Grain-size reduced scapolite, 19f
Granodiorite of the Eagle Wash Intrusive Complex, 92f
Gran Sasso thrust system, 4f
Granulite-to-amphibolite-facies metamorphism, 1f

H
Highly foliated garnetiferous gabbroic rocks, 9f

I
Intrafolial folds, 23f

K
Kumbhalgarh Formation, 8f, 36f

L
Lameta Ghat, 111f
Light-colored biotite-hornblende gneiss, 1f

M
Mesoscopic conjugate set, 82f

P
Planar subvertical axial plane, 10f

S
Shear zones (Continued)
active shear morphology, 1400-m high East wall of Monte Viso, 133f
Akkoy fissure-ridge, banded travertine across, 128f
amphibolite boudins folded and shortened by crustal shortening, 147f
ancient strike-slip fault, frictional to viscous transition in, 141f
augen gneiss, post D2, syn-D4 ultramylonite shear zone in, 61f

Shear zones (Continued)
Bagaces Formation ignimbrites, curved columnar joints, 126f
Bastar Craton-Rengali Province boundary shear zone, rotation of F2 fold hinges, 28f
bedding-bleaching relationship, 140f
biotite in mylonite, “V” pull-apart microstructure of, 145f
biotite rich granite with siltstone xenolith, Tistung Formation, 136f
bulbous chert nodules as structureless dense masses, carbonate rocks of Vempalle Formation, 150f
caloris basin, 155f
coastal area of the Shrikamai Mountains, granodiorite mylonite in, 135f
columnar joints/colonnade and entablature, 125f
dark-colored pseudotachylite, fault veins and injection veins of, 146f
Denizli extensional basin, Kamara active fissure-ridge in, 127f
developing triangular zone, three nonparallel fractures intersect to, 138f
Dharwar rocks, Basalt porphyry from, 139f
dropped keystones and adjacent blocks, 152f
extension (tensile) joints in Archean granite gneisses, Perambalur, 139f
external sierras front, magmatic termination of, 132f
fine plume structure, tension fracture surface with, 136f
floor of Degas crater, 154f
fold and thrust belts, 132f
fold-and-thrust system, 129f
Funatsu Shear Zone, augen gneiss/granite mylonite at, 63f, 134f
gleochronal traversite area, Bridgeport, California, 127f
grain boundary area reduction (GBAR), 145f
grain coarsening, grain boundary migration (GBM) during, 144f
Gulcher Quartzite, Cuddapah basin, 149f
incipient localized dextral shear zones, 58f
initial fracture, typical paired shear zones to, 58f
injection vein, backscattered electron image of, 147f
localized heterogeneous shear zone, 57f
Long Ridge, southeast flank of, 128f
matchless amphibolite, Kuiseb Canyon, Namibia, 131f
microfaulted plagioclase grain, 146f

Shear zones (Continued)
mud cracks produced by desiccation in modern sediment, 148f
optical cross-polarized light and cathodoluminescence (CL), 142f
Paleoproterozoic Gulcher Formation, filled sand cracks in, 149f
Paleoproterozoic metasedimentary rock, crenulation lineations in, 133f
Palghat Cauvery shear zone, 29f
piggeryback porphyroclasts, 137f
placing pens/inside Deccan basalt, rounded fracture plane, 138f
plagioclase in granodiorite, recrystallization of, 141f
precursor heterogeneities, heterogeneous ductile shear zones on, 57f
quartzite, plume structure/hackle plumes in, 134f
regional folding, bedding-bleaching relation associated with, 135f
Roman theater, distributed left-lateral strike-slip deformation in, 152f
sandstones, cleavage planes in, 130f
sandy sediments, ripples in, 150f
seawall of crusader castle, Tartous, 153f
sedimentary dikes in lacustrine, 151f
seismic activity, instrumental record of, 151f
semi-ductile shear zone in, 120f
shear zones, 1
single basaltic lava flow, distinct colonnade and entablature tiers, 126f
small-scale fold, Axial planar cleavage in, 140f
spheroidally weathered Deccan basalt, 137f
thrust fault related landform on innermost planet, Mercury, 153f
thrust sheet stacking, 130f
ultramylonitic shear zone, titanite porphyroclast in, 69f
vein-quartz, intracrystalline deformation microstructures in, 142f–144f
volcanically buried Goethe impact basin, 154f
within sandstone, trapezoid shaped mud inclusion, 148f
Sigmoid-shaped vein, 51f

T
Thrust sheet stacking, 130f

V
Volcanically buried Goethe impact basin, 154f