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# Deformation Microstructures in Rocks

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# Deformation Microstructures in Rocks

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Soumyajit Mukherjee
Department of Earth Sciences
Indian Institute of Technology Bombay
Mumbai
India

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*Dedicated to my grandfather late Mr. Sukhamoy Mukherjee who continues to remain my role model*

# Preface

Study of microstructures is an indispensable component of understanding structural geology of any terrain. A number of 'new' microscopic structures, such as 'flanking microstructures', trapezoid-shaped mineral grains, micro-duplexes, reversal of ductile shear sense, migration of grain boundaries, pull-aparts of V- and parallel types, and new minerals nucleated inside host minerals have recently been described in individual papers. However, for the sake of brevity, these microstructural papers could not present numerous variations in their morphologies. *This book aims to highlight these structures selectively*. Nearly all these photomicrographs come from different western Himalayan shear zones. Ductile and brittle shear senses, where possible to interpret, have been referred in the captions. This book starts with photos of mineral fish that are perhaps the most common ductile shear sense indicators. Captions for photographs have intentionally been kept brief. For full-length discussion of these structures, kindly consult the 'References' section. Students and researchers of structural geology will find this book useful. Please send me comments and counter-arguments on interpretations of the presented microstructures at: soumyajitm@gmail.com

# Acknowledgments

Editorial handling by Helen Rachner, Christian Witschel, Christian Bedall, Annett Büttner (‘Earth Sciences & Geography’ division, Springer), S.A. Shine David (Scientific Publishing Services (P) Ltd), and Nithiya Sivaraman (Production Editor, Springer). Mentored by Chris Talbot (retired from Uppsala University). Geology students of Indian Institute of Technology Roorkee whom I acted as a Teaching Assistant during 2002-2007 raised many unconventional questions on micro-structures. Discussions with Achyuta Ayan Misra and Rajkumar Ghosh (IIT Bombay) were fruitful. Roberto Weinberg (Monash University) provided thin sections from which two photos- Figs. 4.11 and 4.12- were taken. I am grateful to Bhim Bhatt and Ramesh Chand (IIT Roorkee), and Anil N Waghmare, Niranjan Panda, Narendra Vengurlekar, and Vasant Kashiram Dalvi (IIT Bombay) for preparing many thin-sections. Thanks to my wife Payel Mukherjee for bearing loneliness while I wrote this book.

# Contents

# Chapter 1
# Mineral Fish and Ductile Shear Senses

Mineral fish are either single or aggregates of minerals that are ductile sheared (Figs. 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 1.10, 1.11, 1.12, 1.13, 1.14, 1.15, 1.16, 1.17, 1.18, 1.19, 1.20, 1.21, 1.23, 1.24, 1.26, 1.29, 1.30, 1.31, 1.32, 1.33, 1.34, 1.35, 1.36, 1.37, 1.38, 1.40, 1.41, 1.42, 1.43, 1.44, 1.45, 1.46, 1.48, 1.49, 1.50, 1.51, 1.52, 1.53, 1.54, 1.55, 1.56, 1.57, 1.58, 1.59, 1.60, 1.62, 1.63, 1.64, 1.65, 1.66, 1.67, 1.68, 1.72, 1.73, 1.83, 1.85). Three common shapes of mineral fish are sigmoid, lenticular and parallelogram (ten Grotenhuis et al. 2003; Mukherjee 2011). These fish are bound by parallel (Figs. 1.3, 1.5, 1.9, 1.13, 1.15, 1.21, 1.23, 1.24, 1.37, 1.38, 1.49, 1.56, 1.59, 1.62), and rarely by non-parallel primary shear C-planes (Figs. 1.25, 1.26). Migration of quartzofeldspathic minerals and sometimes high-grade metamorphic index minerals towards them destruct their ideal morphologies. A top-to-S/SW ductile shear sense is revealed from these mineral fish from most of the Himalayan ductile shear zones. This indicates foreland vergent fore-thrusts of the northern portion of the Indian plate (Mukherjee et al. 2012; Mukherjee in press-1, 2). (Figs. 1.22, 1.27, 1.28, 1.39, 1.47, 1.69, 1.70, 1.71,. 1.74, 1.75, 1.76, 1.77, 1.78, 1.79, 1.80, 1.81, 1.82, and 1.84). How shear heat (Mukherjee and Mulchrone 2013), and reinterpreted ductile shear kinematics (Mukherjee 2012; Mukherjee and Biswas, submitted) affect shear fabric need to be studied further.

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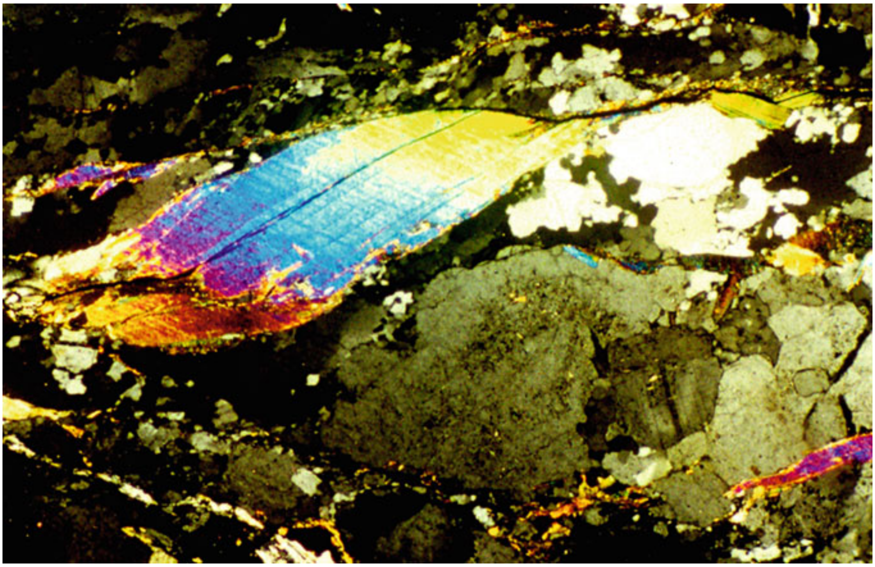


**Fig. 1.1** A sigmoid mica fish. *Top-to-right* shear. Recrystallized and sheared quartzofeldspathic minerals in the matrix, above the fish, shows the same shear sense within a *narrower zone*. The primary shear C-plane is characterized by fine grained micas. Reproduced from Fig. 1.3b of Mukherjee (2011). Cross-polarized light. *Location* Karakoram Shear Zone (India). Mukherjee (2012) presented a reinterpretation of ductile (simple) shear. *Width of view* 2 mm

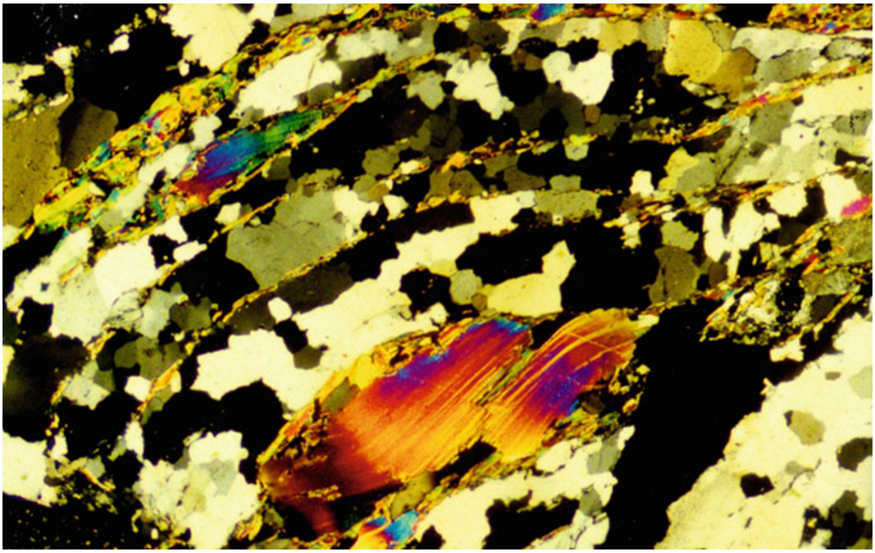


**Fig. 1.2** Two adjacent sigmoid mica fish. *Top-to-right* shear. Trails of micas bound sigmoid quartzofeldspathic domains of same shear sense. Reproduced from Fig. 1.3a of Mukherjee (2011). Cross-polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 2 mm

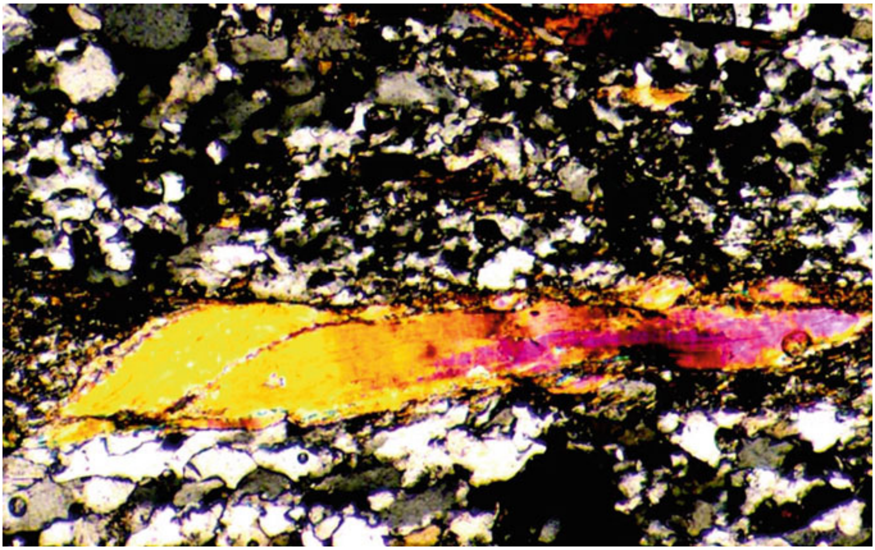
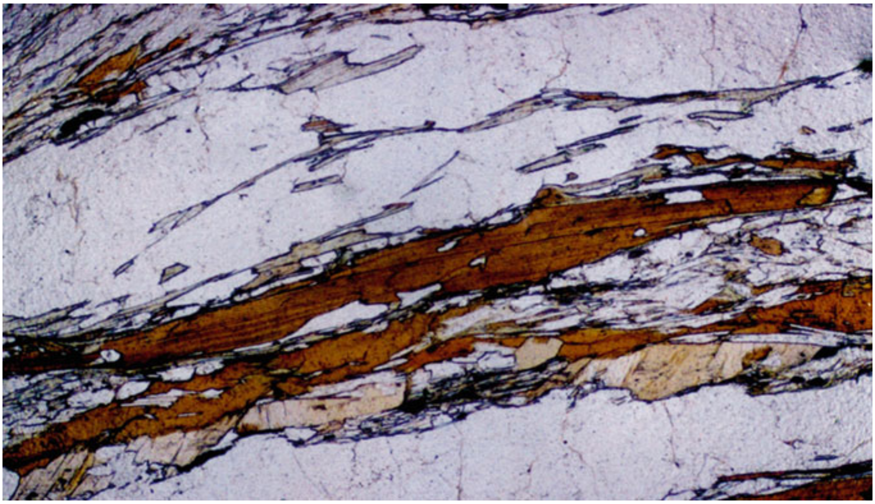


**Fig. 1.3** Sigmoid mica fish side by side. The primary shear planes and the margins of these fish are irregular. *Top-to-right* shear. Cross-polarized light. *Location* Shyok Suture Zone (India). *Width of view* 4 mm



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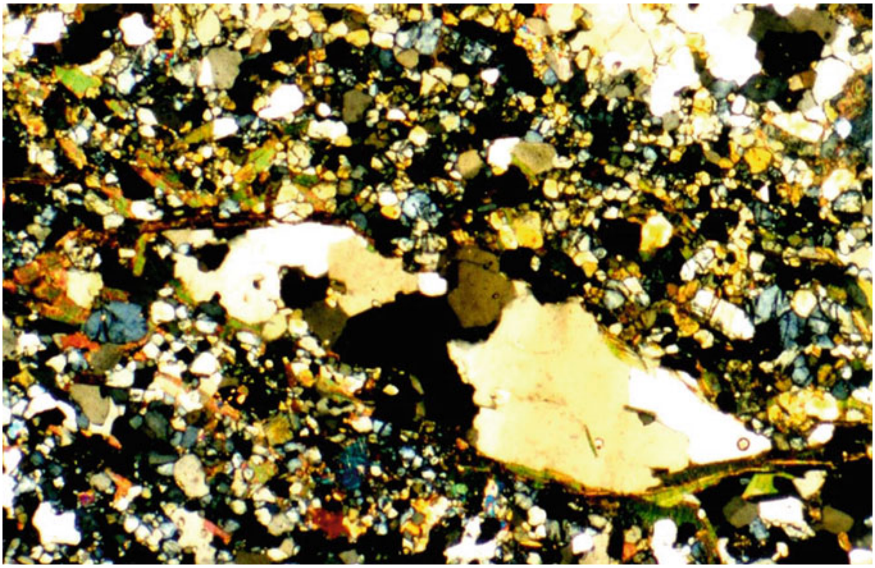

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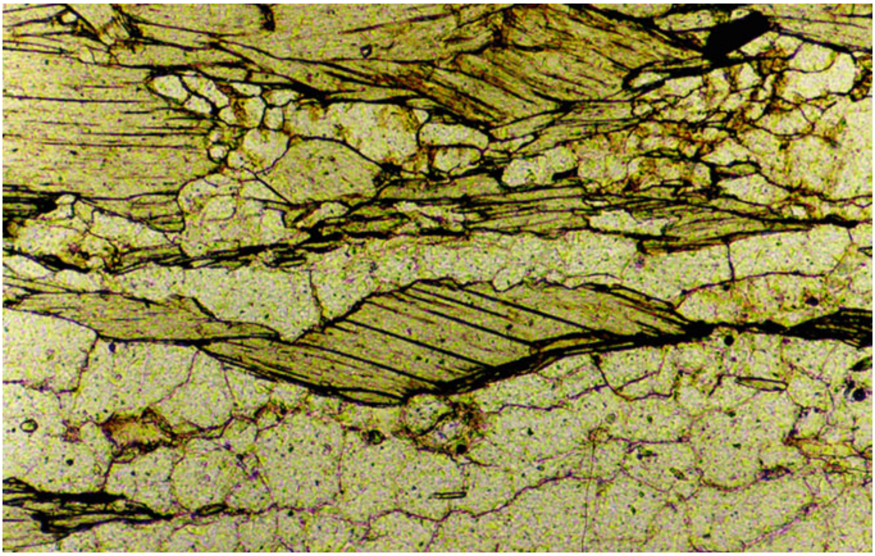

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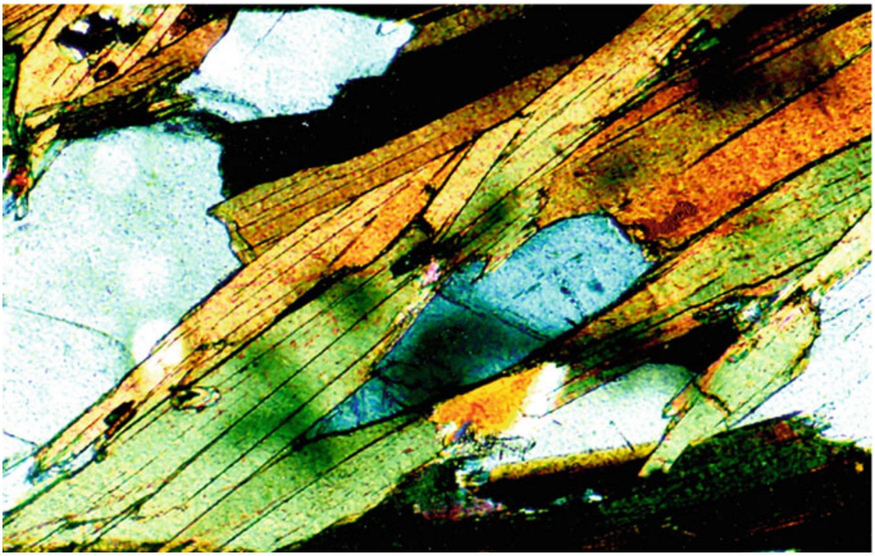

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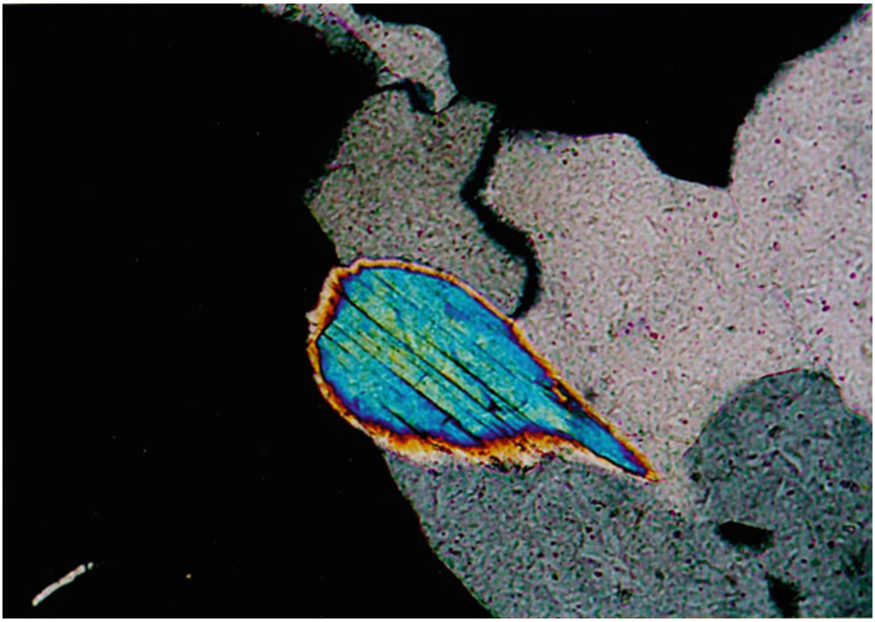

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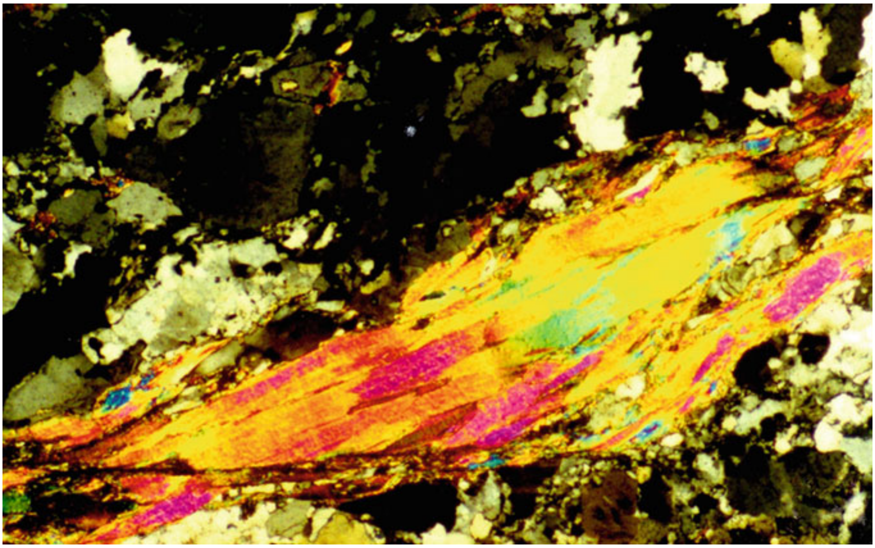

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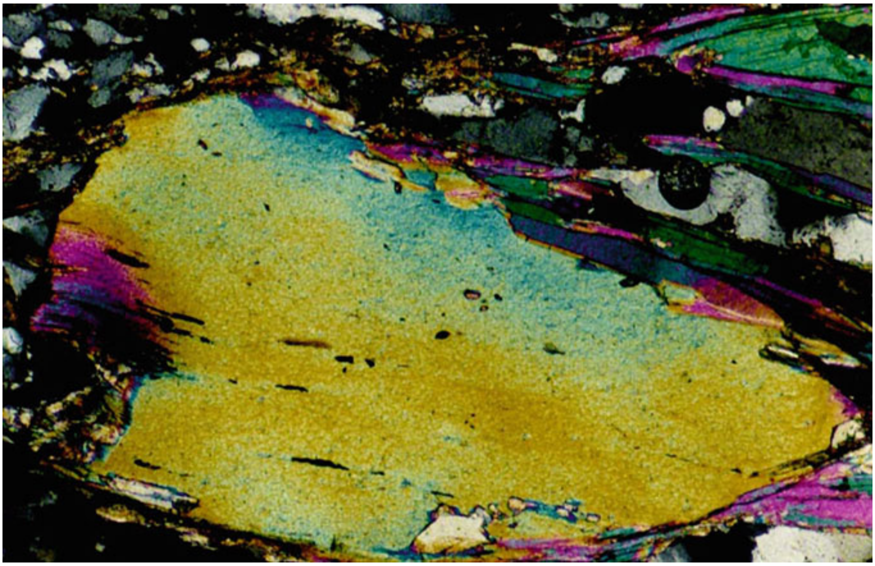

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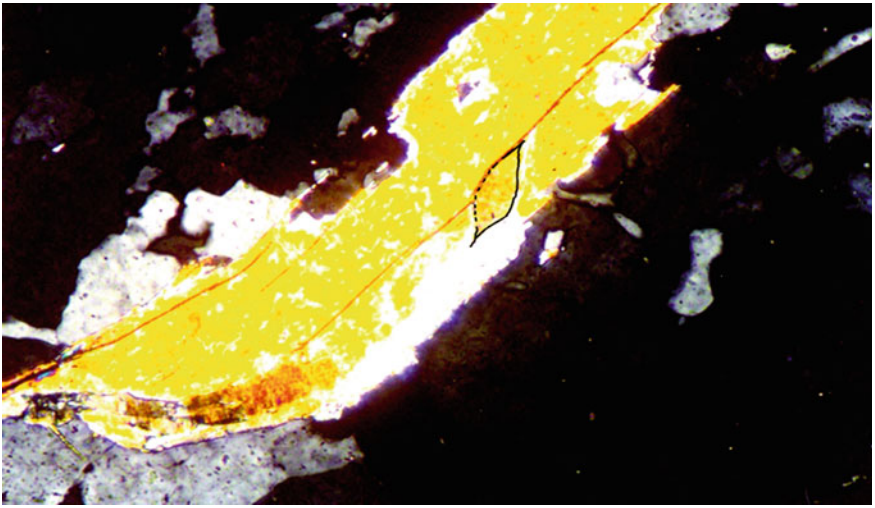

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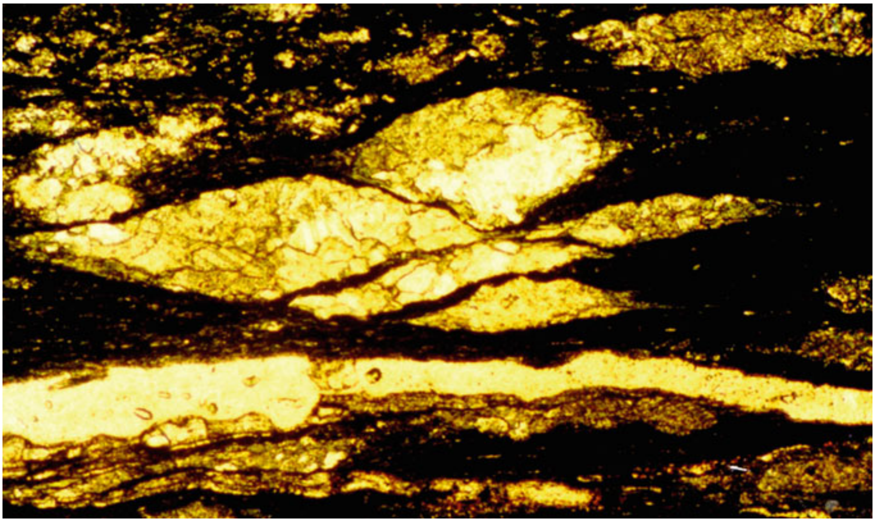

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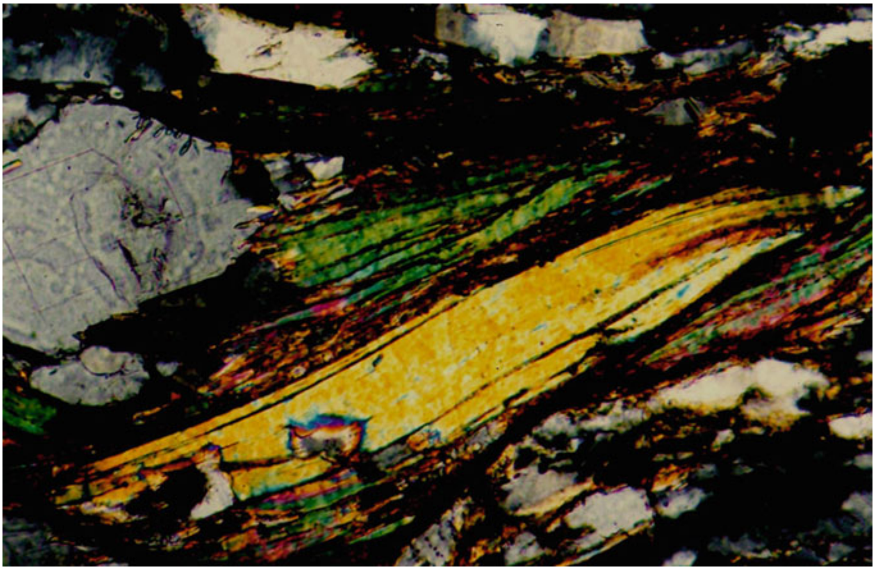


**Fig. 1.13** A sigmoid mica fish (*top-to-right* shear) with inclusions of quartzofeldspathic minerals inside and at its boundary. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

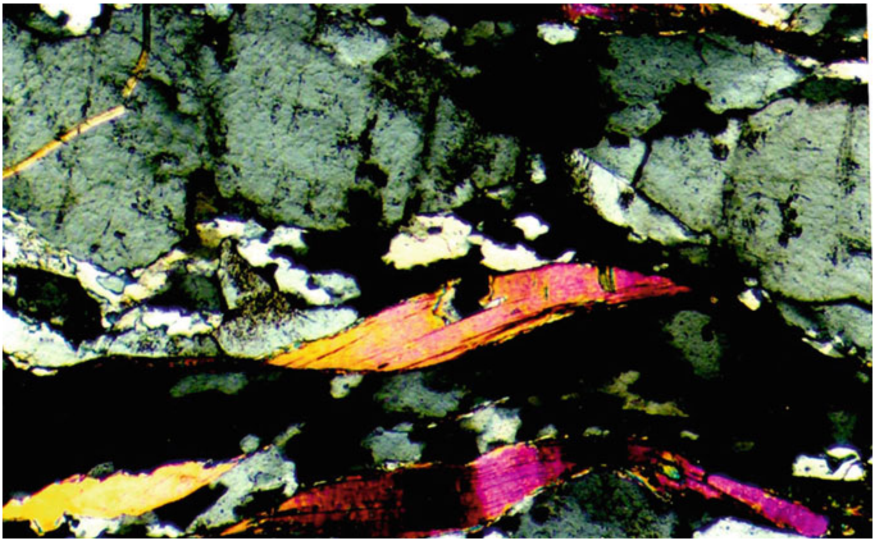
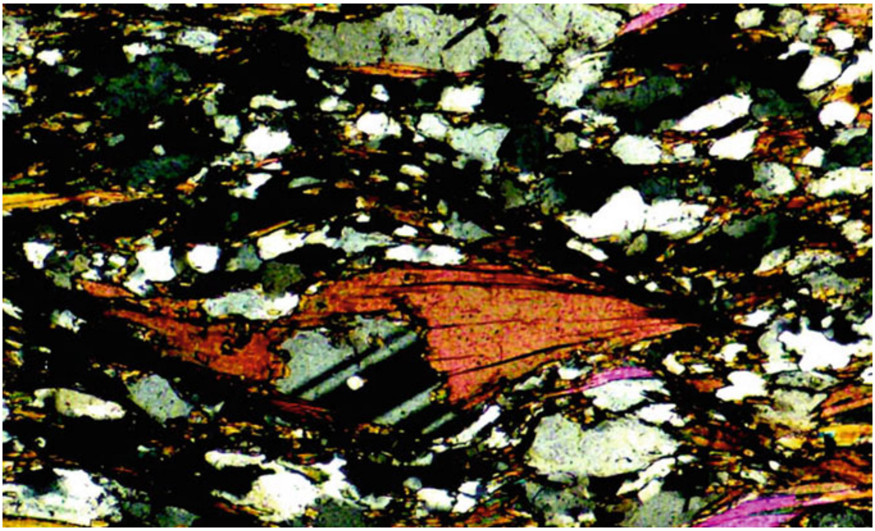


**Fig. 1.14** Quartzofeldspathic matrix migrated inside a sigmoid mica fish. A *parallelogram-shaped* mica fish at *bottom* left also shows the same shear sense. The fish shows a *top-to-right* shear. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm



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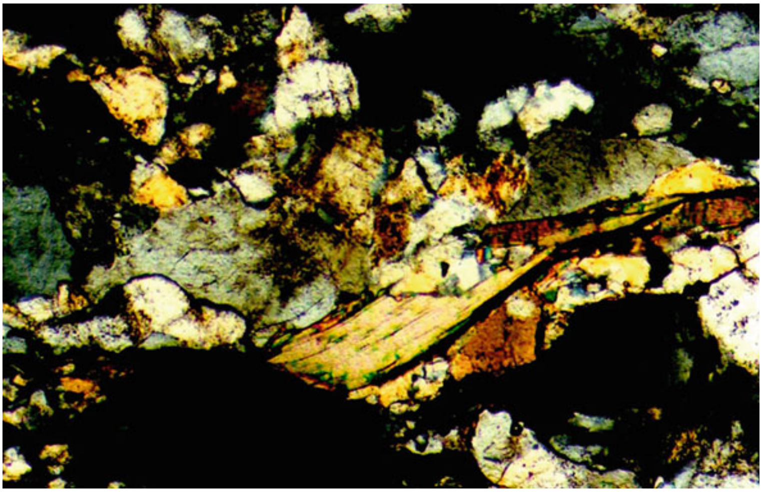

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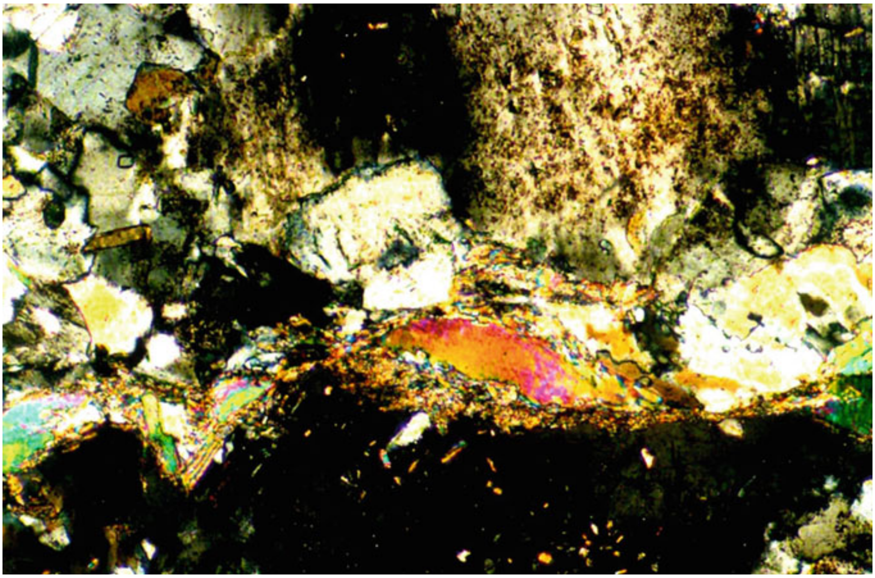

**Fig. 1.17** Extensively dynamically recrystallized mica fish (*top-to-left* shear). *Top-to-left* (*down*) synthetic secondary shear developed at *left*. Recrystallization layers define the primary and the secondary shear planes. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm. A recent review on recrystallization can be found in Paterson (2013)

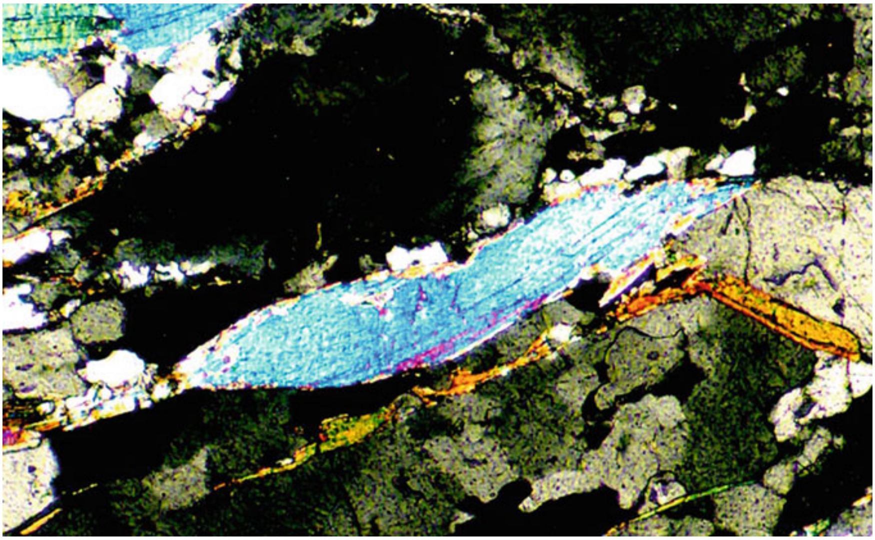

**Fig. 1.18** Quartzofeldspathic matrix migrated from several places inside a mica fish. The fish shows a *top-to-right* shear. Cross-polarized light. *Location* Shyok Suture Zone (India). *Width of view* 4 mm

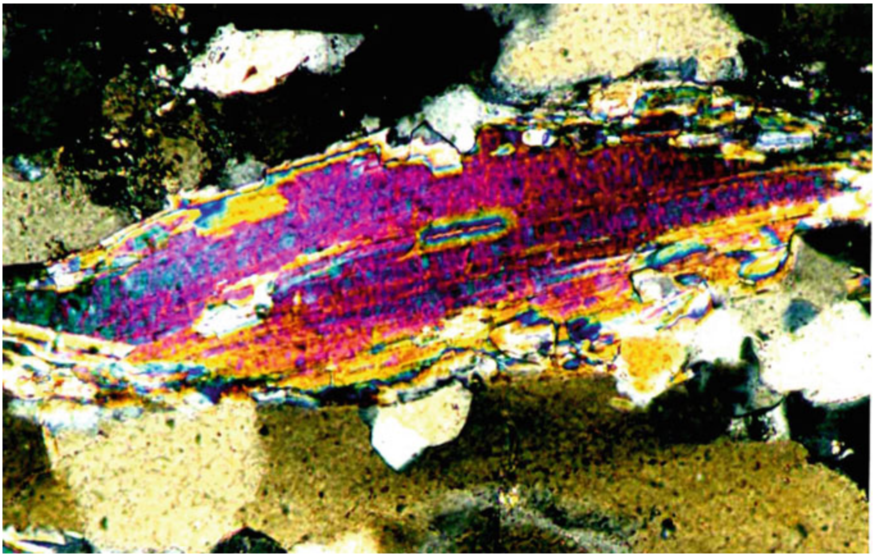

**Fig. 1.19** Quartzofeldspathic matrix migrated from several places inside a mica fish. The fish shows a *top-to-right* shear. The partial and complete inclusions themselves are not sheared. Cross-polarized light. *Location* Shyok Suture Zone (India). *Width of view* 4 mm

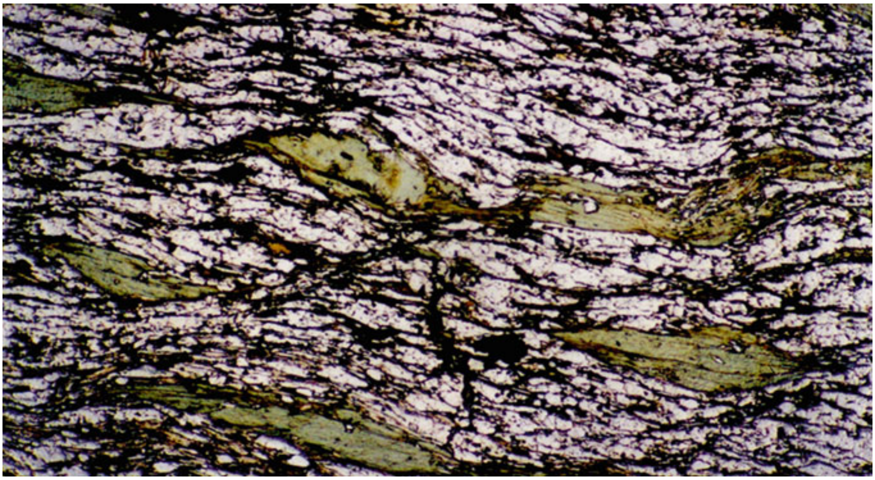

**Fig. 1.20** Sigmoid fish of chlorite and quartzofeldspathic minerals of different aspect ratios. Primary shear: *top-to-left*; synthetic secondary shear: *top-to-left-down*. Reproduced from Fig. 1.6a of Mukherjee (2011). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

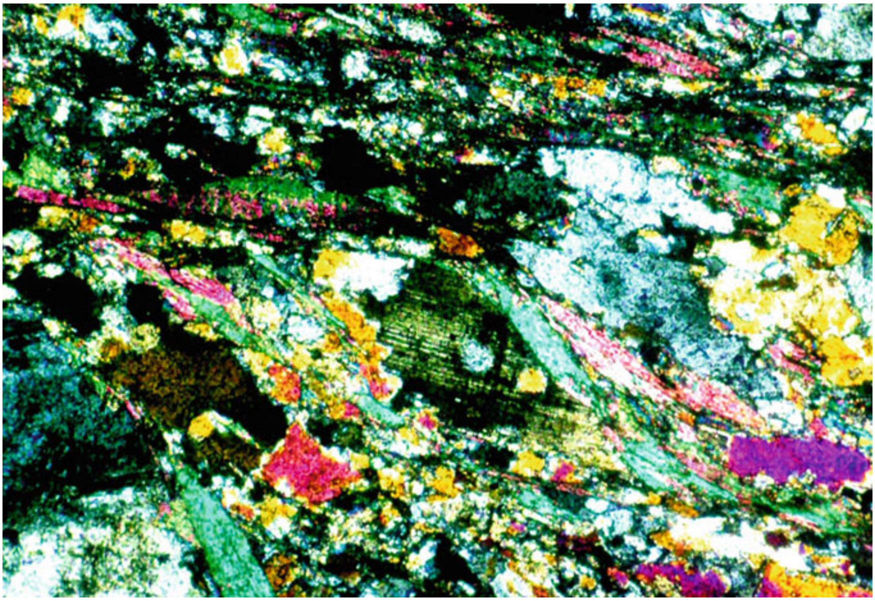

**Fig. 1.21** A sigmoid plagioclase feldspar fish (*top-to-left* shear) with grain boundary migration especially at the two tapering portions. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

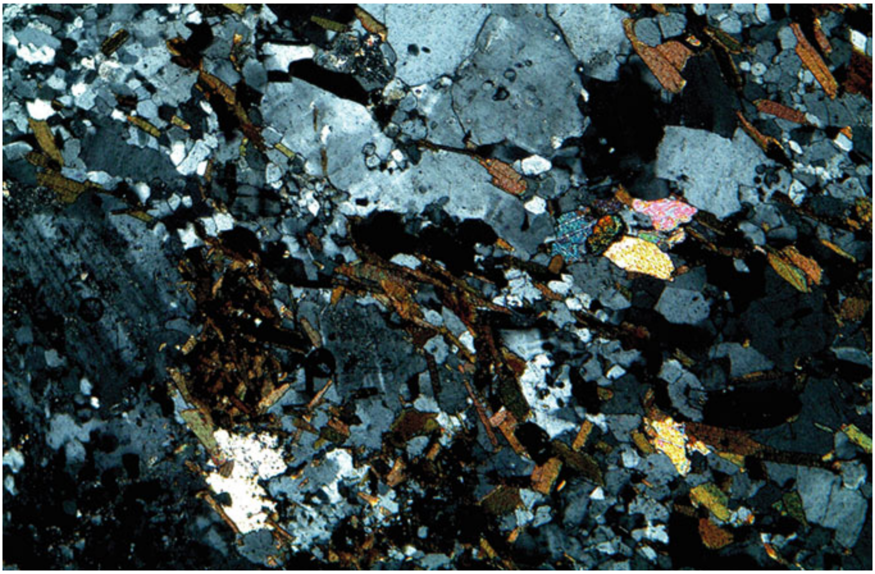

**Fig. 1.22** A *Top-to-left* shear indicated by biotite grains that overall define S-fabrics. Cross-polarized light. *Location* Karcham, Higher Himalaya (Himachal Pradesh, India). *Width of view* 2 mm

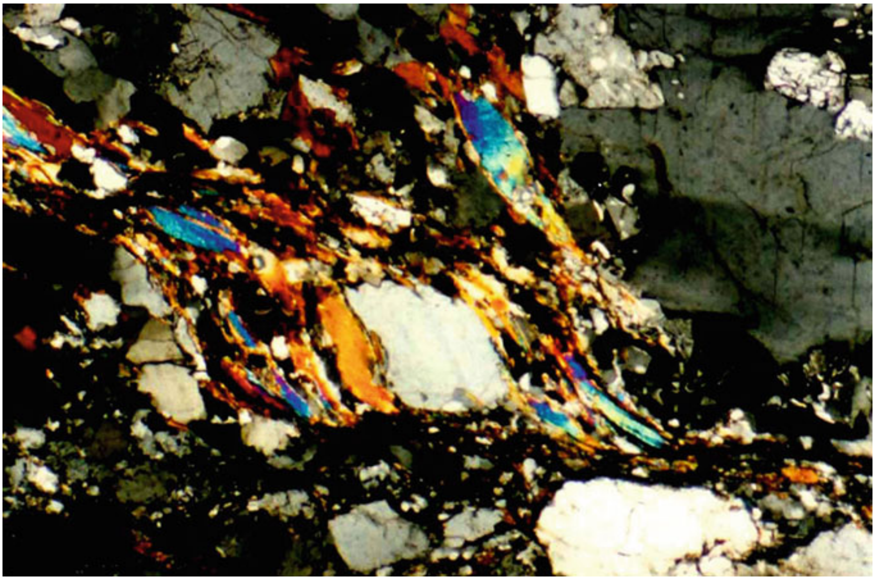

**Fig. 1.23** A composite sigmoid fish of quartzo-feldspathic minerals. Internal deformation of the quartzofeldspathic minerals is evident from its weak wavy extinction. *Location* Zanskar Shear Zone (India). *Top-to-left* shear. Cross-polarized light. *Width of view* 4 mm

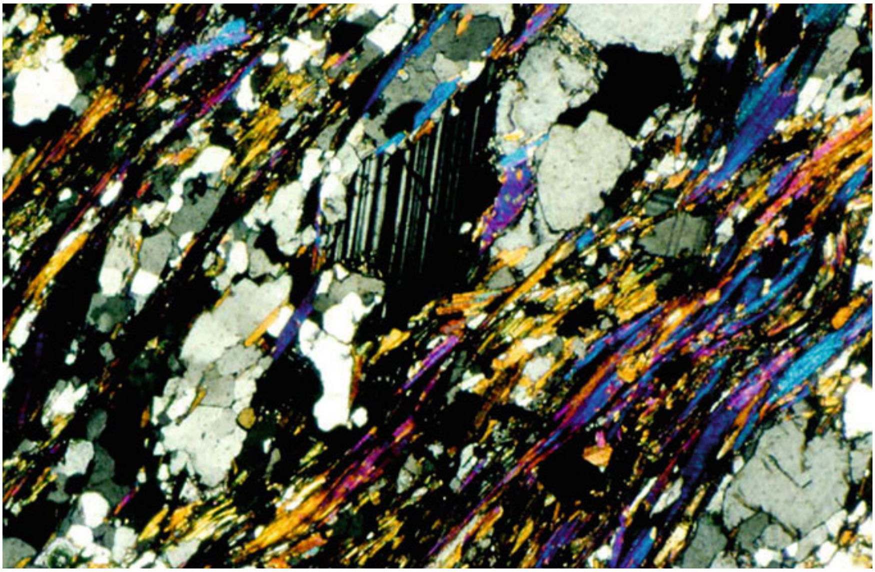

**Fig. 1.24** Migration of quartzofeldspathic minerals inside a *sigmoid/parallelogram-shaped* plagioclase fish (*top-to-right-up* shear) partially destructed the *fish shape*. S-fabric with same shear sense is also defined by quartzofeldspathic bands *left* to the fish. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

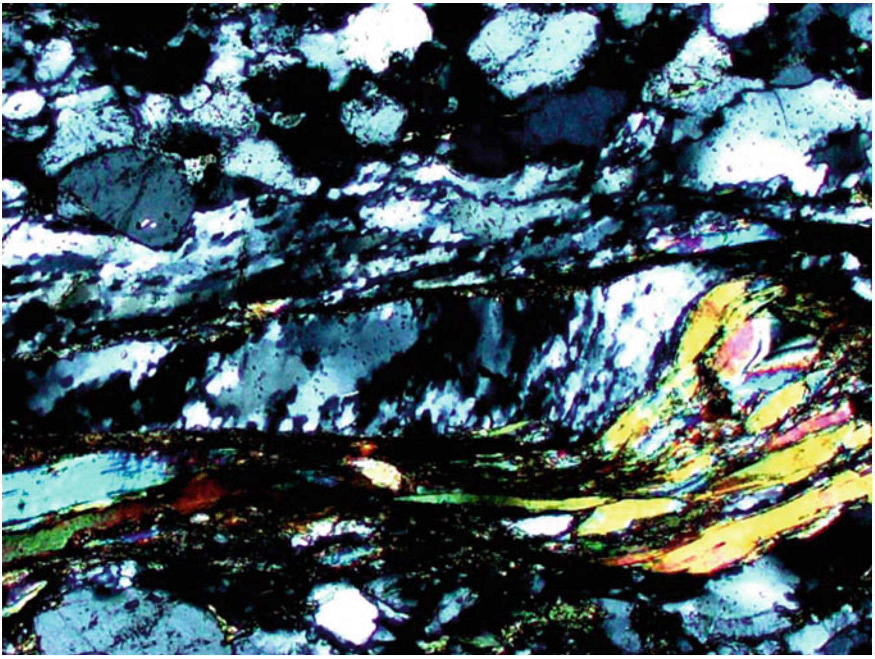

**Fig. 1.25** Ductile deformed quartzofeldspathic matrix and mica aggregates defined S-fabric. Primary shear C-planes converge towards *left*. *Top-to-right* shear. Reproduced from Fig. 1.4a of Mukherjee (2010b). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

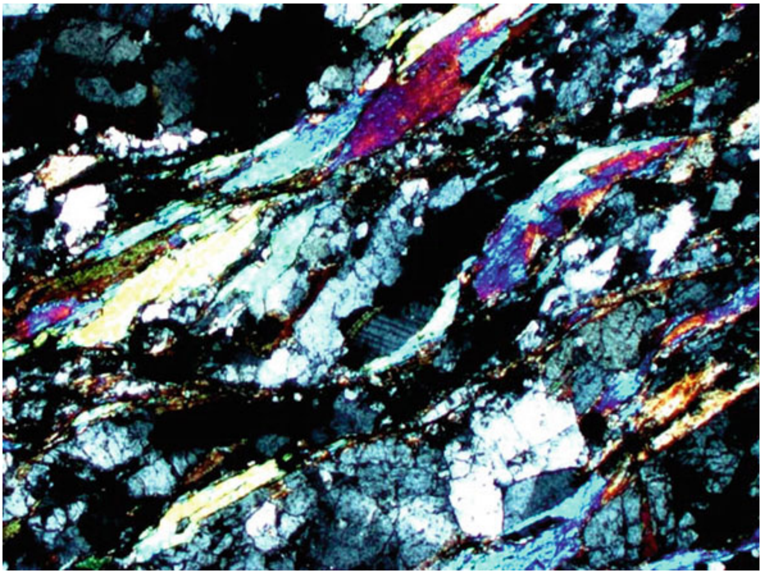

**Fig. 1.26** Sigmoid fish of quartzofeldspathic minerals and micas side by side. *Top-to-right-up* shear. Primary shear C-planes converge towards *left*. Reproduced from Fig. 1.3c of Mukherjee (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

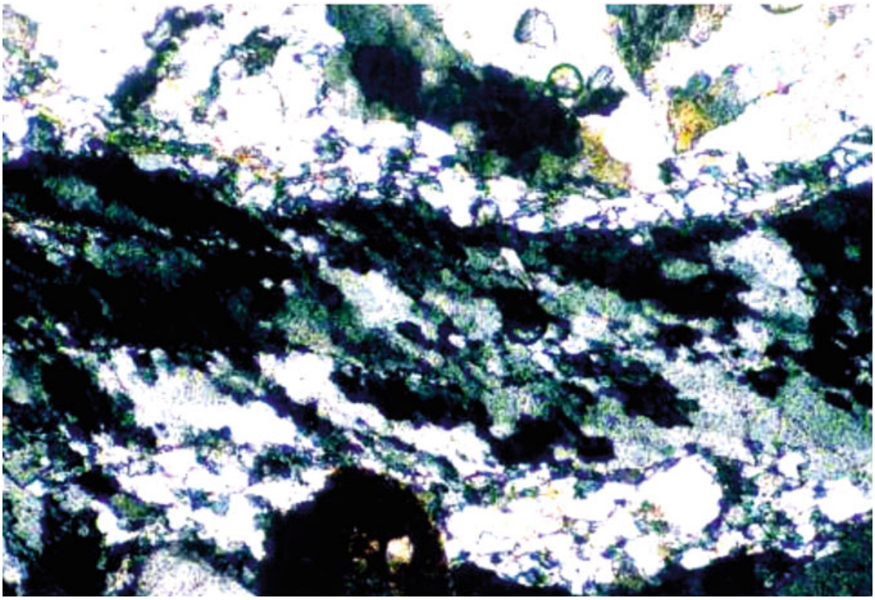

**Fig. 1.27** Recrystallized quartz grains, mostly elongated, reveal a *top-to-left* shear. The C-plane is a little *curved* and is defined by smaller grains. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 5 mm

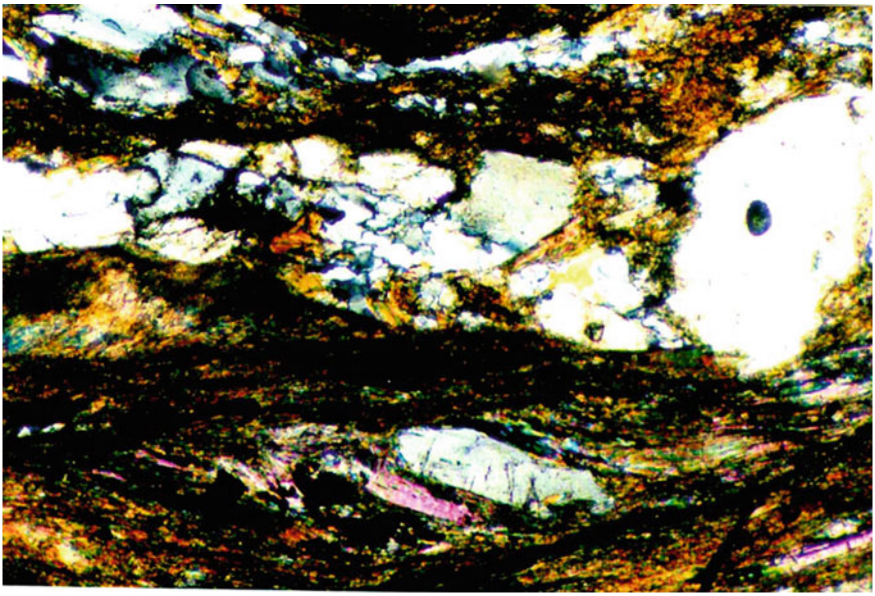

**Fig. 1.28** Inside a lens surrounded by foliation micas, inclined micas and feldspar grains define the S-fabric. *Top-to-left* shear. Shear sense is indistinct at the *top* quartofeldspathic layers. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

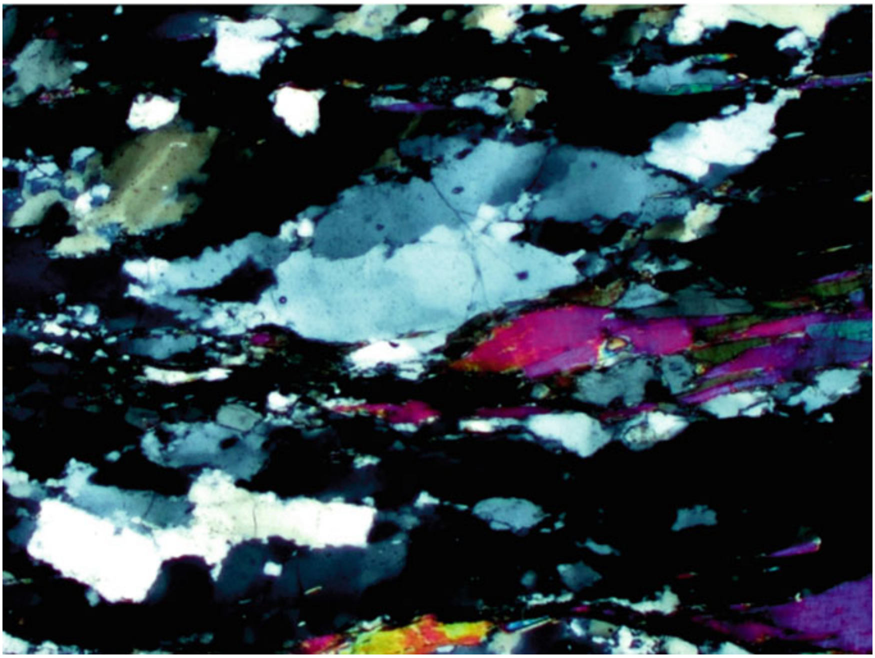

**Fig. 1.29** An internally deformed quartz fish shows undulose extinction and a *top-to-right* shear. Much smaller mica fish at *right* also indicate the same shear sense. Reproduced from Fig. 1.4c of Mukherjee (2011). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2.5 mm

**Fig. 1.30** A sigmoid tourmaline fish with notch at *right* corner, and parallel pull apart/boudinage at *left*. *Top-to-right* shear. Plane polarized light. *Location* Higher Himalaya in the Sutlej section (Himachal Pradesh, India). *Width of view* 2 mm

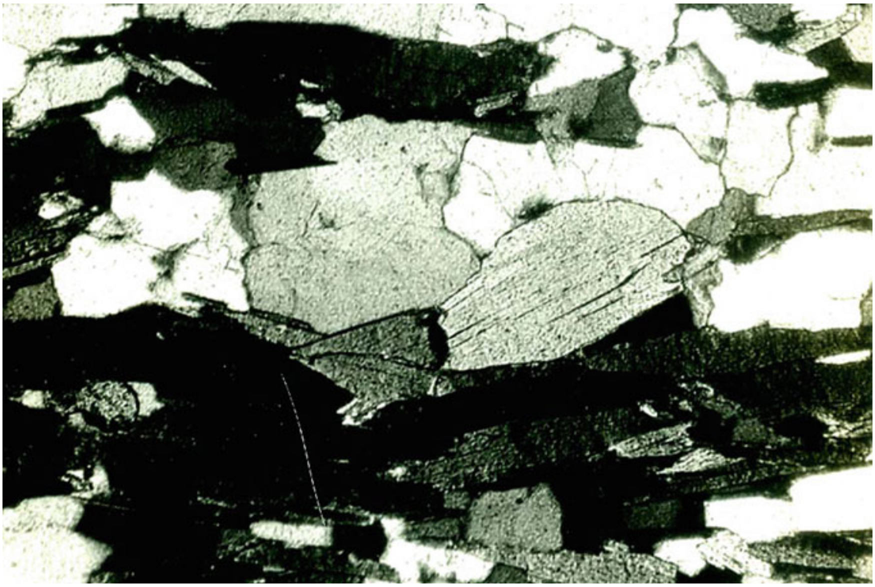

**Fig. 1.31** A mica fish (*top-to-right* shear) with a notch/mouth at one of the sides. The other side is irregularly (*parallel*) pulled apart. Cross-polarized light. *Location* Shyok Suture zone (India). *Width of view* 4 mm

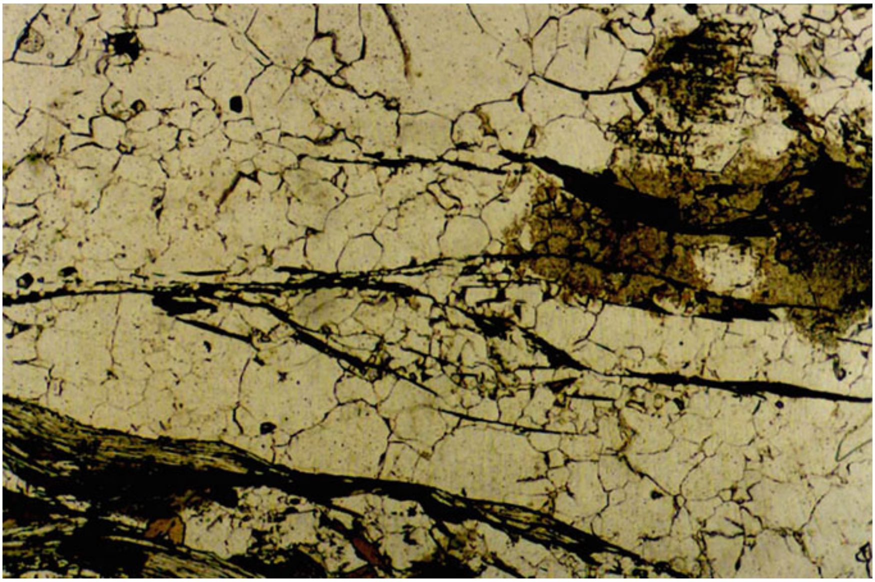

**Fig. 1.32** Isolated *curved* biotites define a sigmoid composite fish within coarser matrix of quartzofeldspathic minerals with angular margins. *Top-to-left* shear. *Location* Higher Himalaya in Goriganga section (India). Plane polarized light. *Width of view* 4 mm

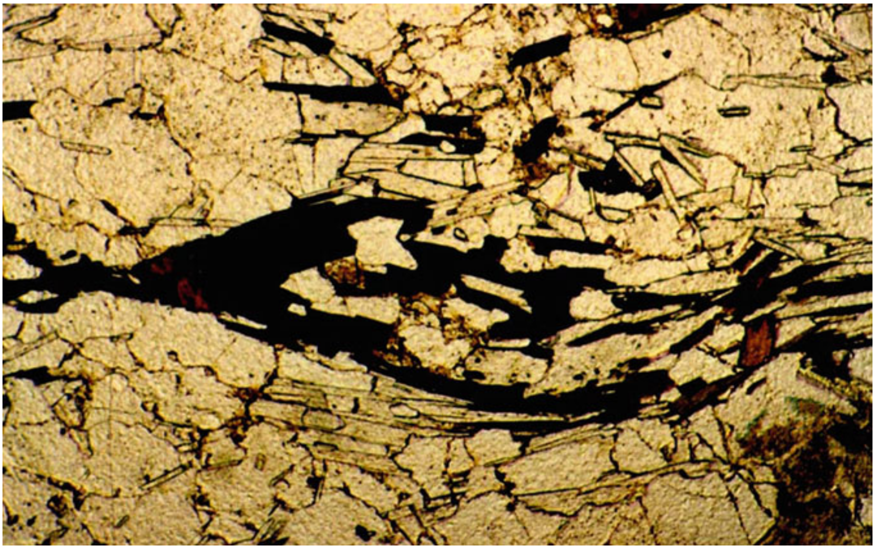

**Fig. 1.33** Biotites of different orientations and angular quartzofeldspathic matrix overall define a composite sigmoid fish. *Top-to-left* shear. Plane polarized light. *Location* Higher Himalaya in Goriganga section (India). *Width of view* 2 mm

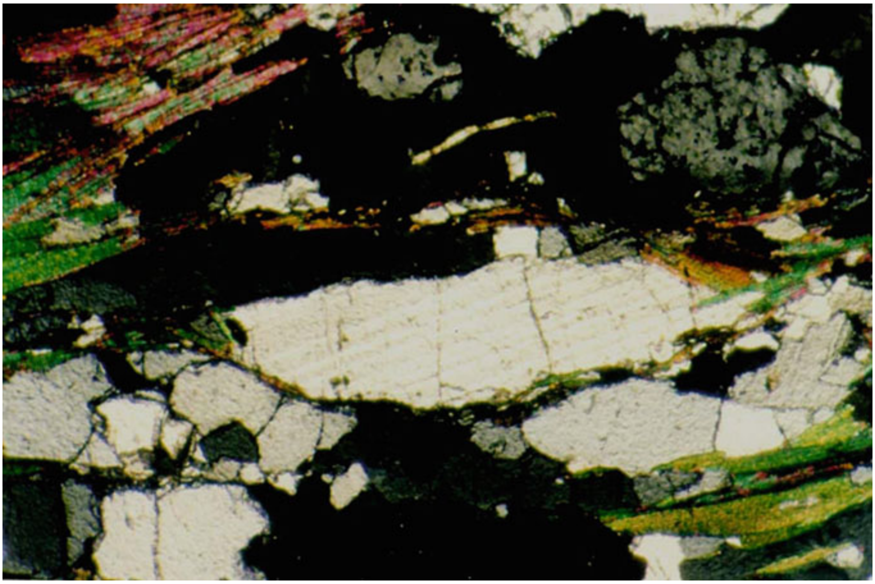

**Fig. 1.34** A lenticular/sigmoid plagioclase feldspar fish partly mantled by micas. Shear sense indistinct. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

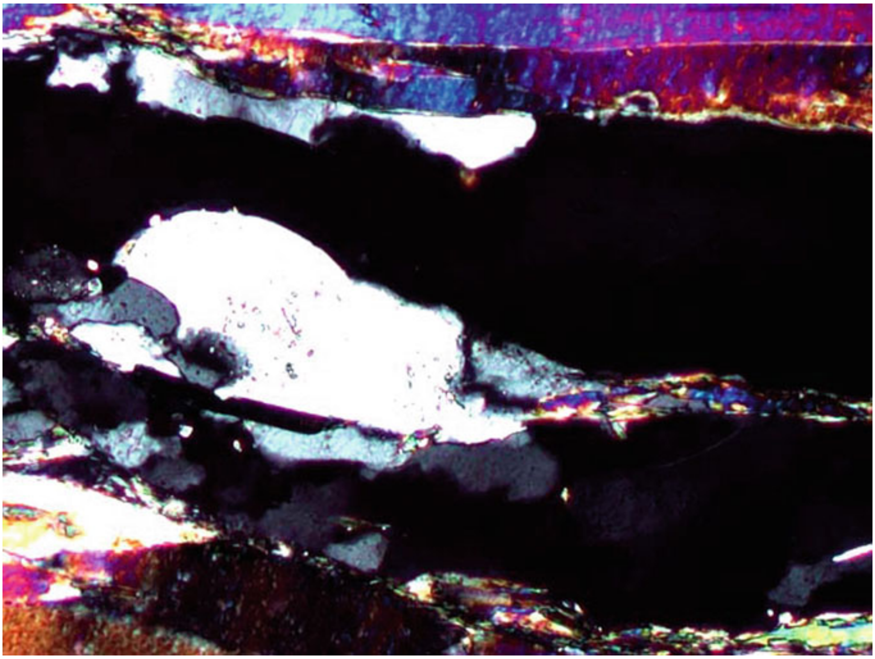

**Fig. 1.35** A sigmoid quartz fish. *Top-to-left* shear. Reproduced from Fig. 1.4d of Mukherjee (2010b). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

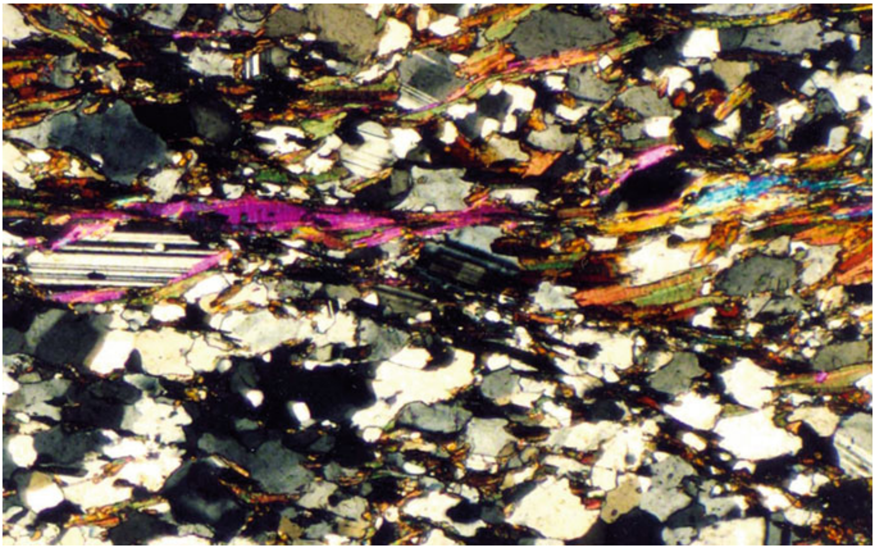

**Fig. 1.36** At *left*, a sigmoid plagioclase feldspar fish mantled by less competent micas. *Top-to-right* shear. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

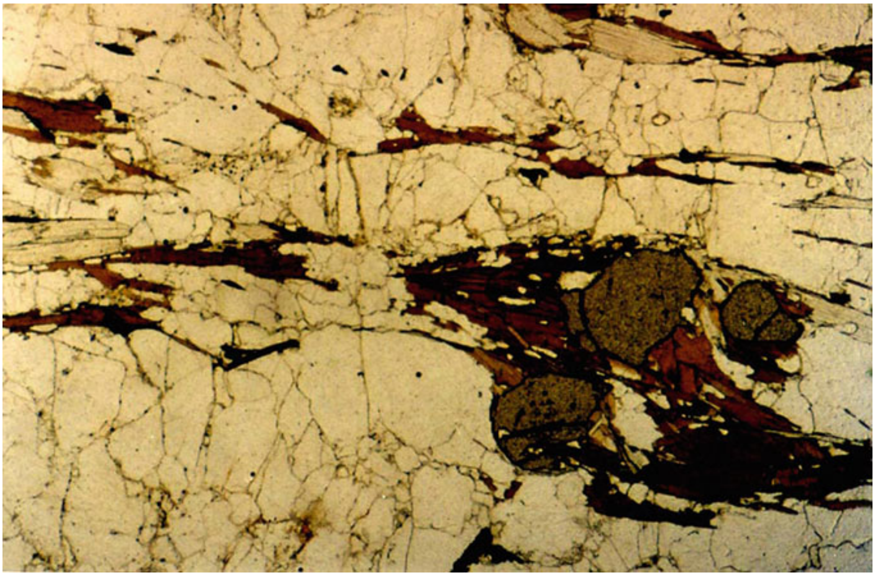

**Fig. 1.37** A composite sigmoid biotite fish (*top-to-left* shear). Garnets grew and partially destructed the ideal *fish shape*. Garnet grains are unsheared, and could be post-tectonic. Plane polarized light. *Location* Karcham, Higher Himalaya (Himachal Pradesh, India). *Width of view* 4 mm

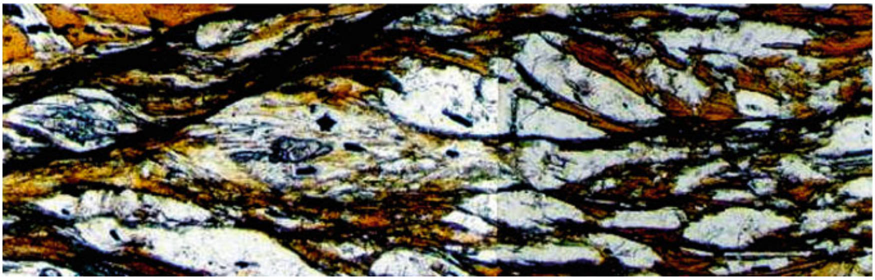

**Fig. 1.38** Sigmoid-like quartz fish at *bottom right*: *top-to-right* shear. Bigger quartz fish with notches nearly at the *center* of the photo indicate a reverse *top-to-left* shear. A *top-to-left-down* shear (at *left* side of the photo) postdates the two previous shear mentioned. The S-fabric of the latter shear is given by sigmoid composite fish defined by staurolite at the core and micas as the rim. Reproduced from Fig. 1.2a of Mukherjee and Koyi (2010). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 cm

**Fig. 1.39** A *top-to-right-down* ductile synthetic secondary shear dragged significantly an aggregate of quartzofeldspathic minerals. Some of the individual minerals themselves are also sigmoid. Reproduced from Fig. 1.2b of Mukherjee and Koyi (2010). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 5 mm

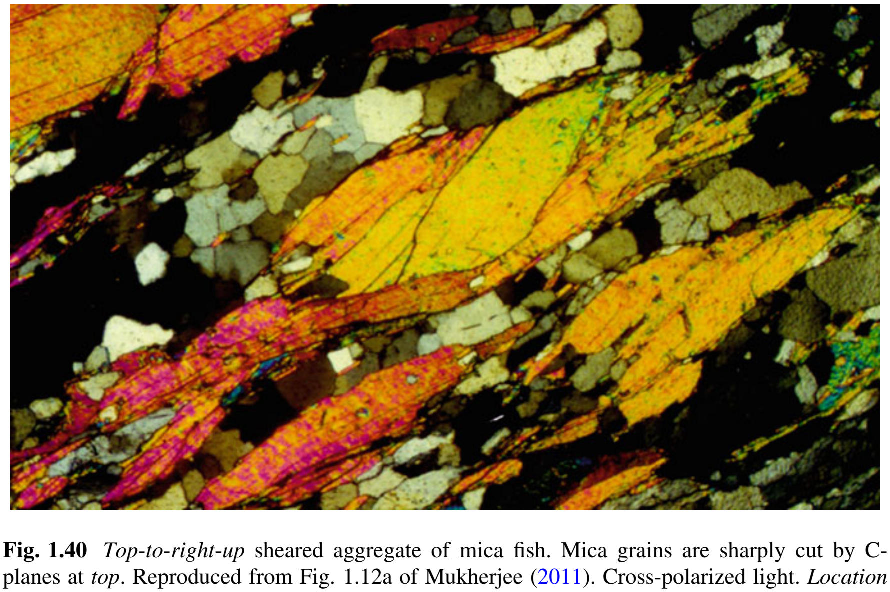

**Fig. 1.40** *Top-to-right-up* sheared aggregate of mica fish. Mica grains are sharply cut by C-planes at *top*. Reproduced from Fig. 1.12a of Mukherjee (2011). Cross-polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 2 mm

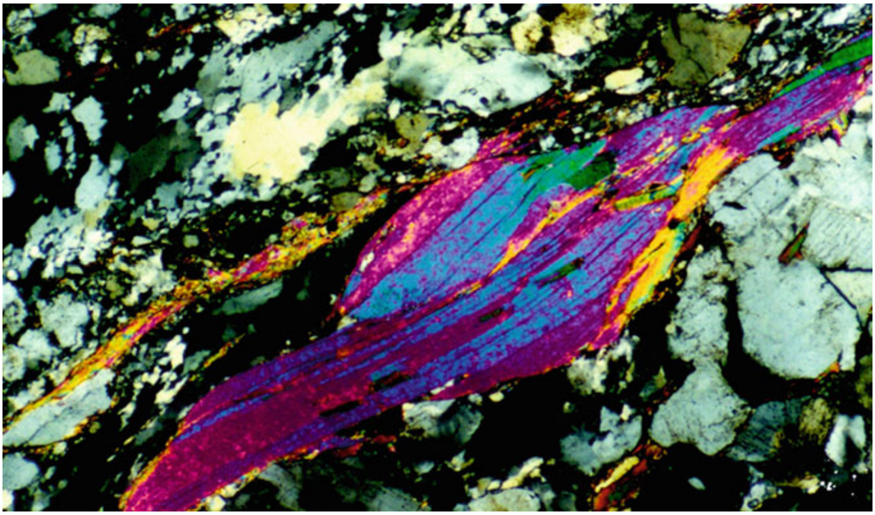

**Fig. 1.41** Weavy aggregate of sigmoid mica fish. Matrix quartzofeldspathic minerals are not tilted uniformly towards any single direction. Shear sense difficult to decipher. Reproduced from Fig. 1.12b of Mukherjee (2011). Cross-polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 1 mm

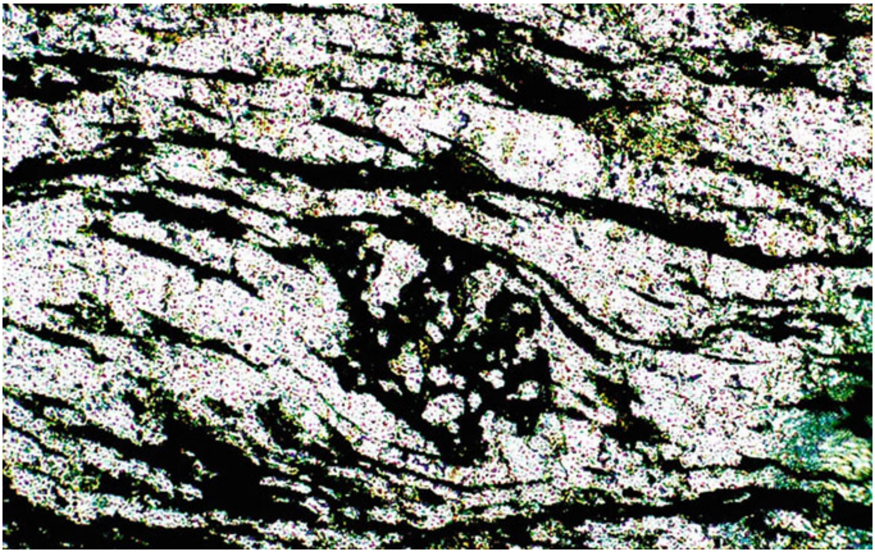

**Fig. 1.42** A skeletal garnet fish. *Top-to-left* shear. Inclusions that migrated from the matrix seem unsheared. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm. Ductilely deformed garnet indicates a temperature of 600–800 °C (Passchier and Trouw 2005 and references therein). Detail of ductile deformation of garnet can be found at Vollbrecht et al. (2006). Garnet fish has been known since long (e.g. Seyfert 1987 or still earlier)

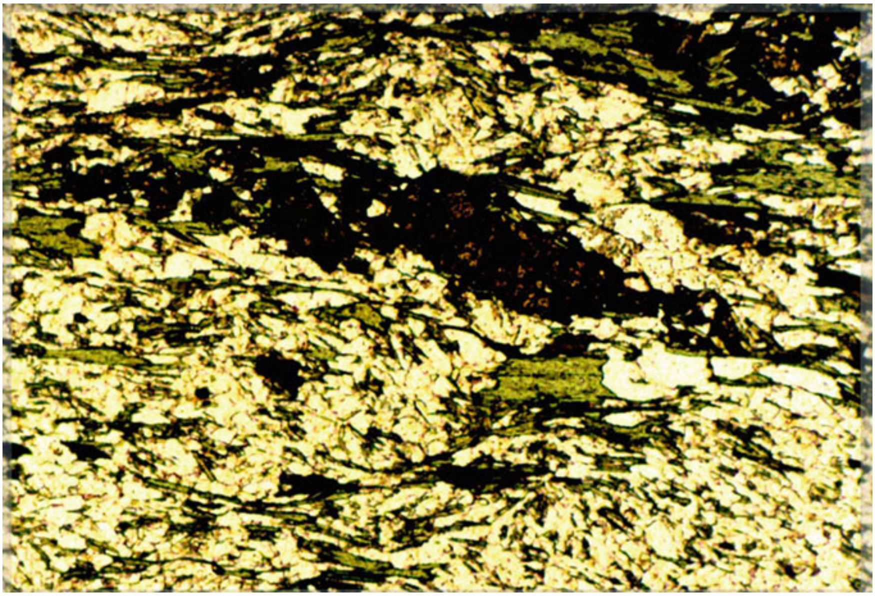

**Fig. 1.43** A brittle faulted garnet fish. *Top-to-left* ductile shear. Discrete chlorite grains in the matrix overall define S-fabrics that also give the same shear sense. Plane polarized light. *Location* Shyok Suture Zone (India). *Width of view* 2 mm

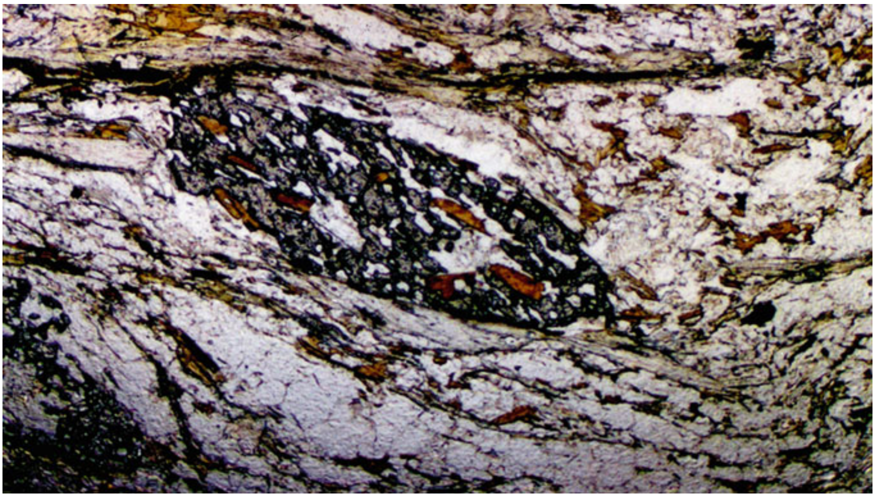

**Fig. 1.44** A lenticular garnet fish. *Top-to-left* shear. Inclusion patterns inside the garnet grain and micas outside it are oriented sympathetic to shear sense. Reproduced from Fig. 1.6c of Mukherjee (2011). Plane polarized light. *Location* Karakoram Shear Zone (India). *Photo width* 2 mm

**Fig. 1.45** A sigmoid garnet fish rimmed mainly by more incompetent biotites and some muscovites. Together they define a sigmoid composite fish. *Top-to-right* shear. Unlike Fig. 1.44, near linear inclusion patterns inside the garnet are oriented antithetic to the shear sense. Shyok Suture Zone. Plane polarized light. *Width of view* 2 mm

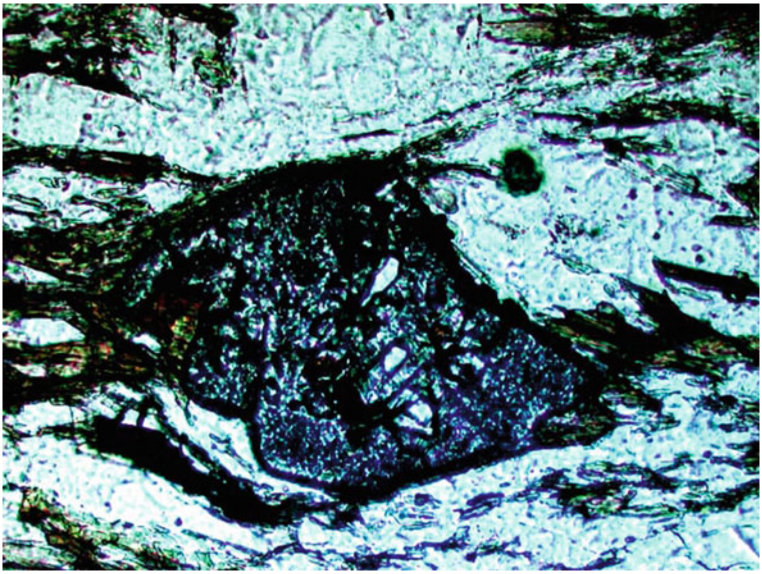

**Fig. 1.46** A sigmoid garnet fish with very few inclusions that do not have any pattern. *Top-to-left* (*down*) secondary shear. The shear sense is also indicated by isolated curved mica grains at right side of the garnet fish. Reproduced from Fig. 1.4b of Mukherjee (2010b). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

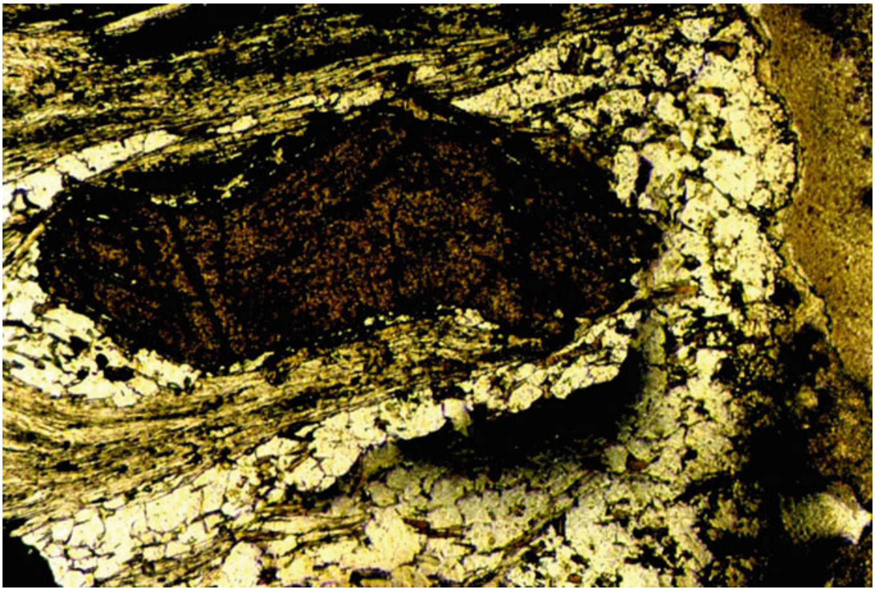

**Fig. 1.47** A folded garnet grain with nearly straight limbs. Inclusions parallel the limb. Micas that rim this garnet grain are not folded significantly. Plane polarized light. *Location* Higher Himalaya, at Karcham (Himachal Pradesh, India). *Width of view* 1.5 mm

**Fig. 1.48** A sigmoid garnet fish. *Top-to-right* shear. *Curved* inclusion patterns oriented sympathetic to the shear sense. Plane polarized light. *Location* Shyok Suture zone (India). *Width of view* 1.5 mm

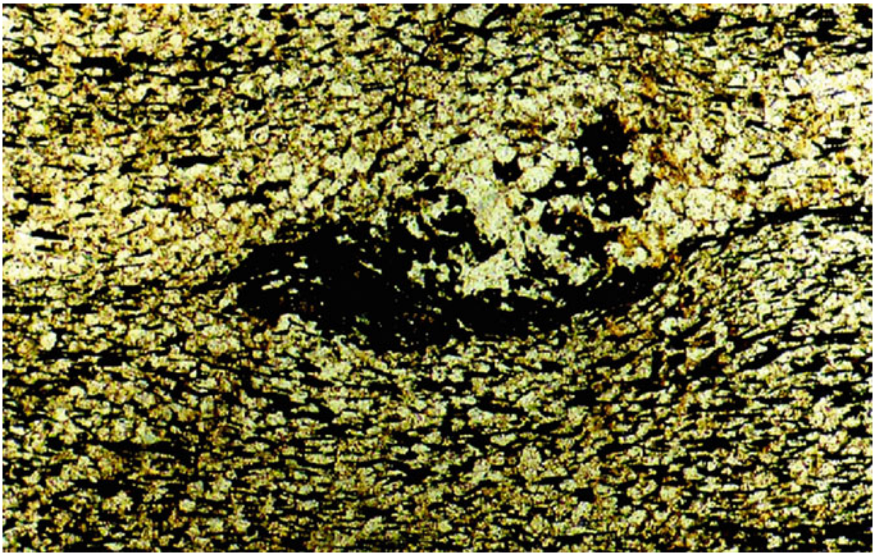

**Fig. 1.49** A sigmoid-shaped garnet fish. Inclusion patterns parallel the relict garnet morphology. *Top-to-left-down* synthetic secondary shear. Reproduced from Fig. 1.10b of Mukherjee (2010a). Plane polarized light. *Location* Higher Himalaya, at Karcham (Himachal Pradesh, India). *Width of view* 1.5 mm

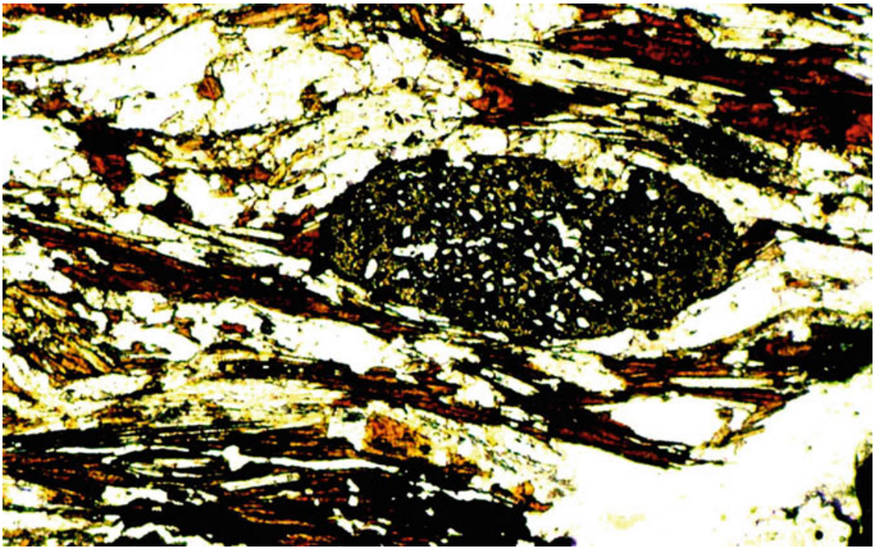

**Fig. 1.50** A lenticular garnet fish with poorly oriented inclusions. No clear cut shear sense displayed. Biotite grains within the matrix also do not reveal shear sense. Plane polarized light. *Location* Shyok Suture Zone (India). *Width of view* 1.5 mm

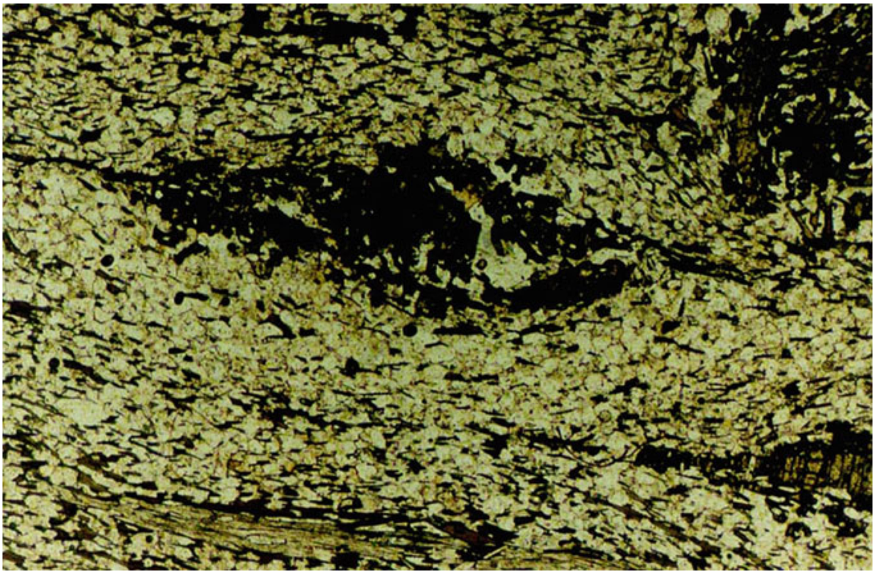

**Fig. 1.51** A *parallelogram/sigmoid* shaped garnet fish with sigmoid inclusion pattern. *Top-to-left* shear. Isolated mica grains right to the garnet grain distinctly show the S-fabric and the same shear sense. Plane polarized light. *Location* Higher Himalaya, at Karcham (Himachal Pradesh, India). *Width of view* 1.5 mm

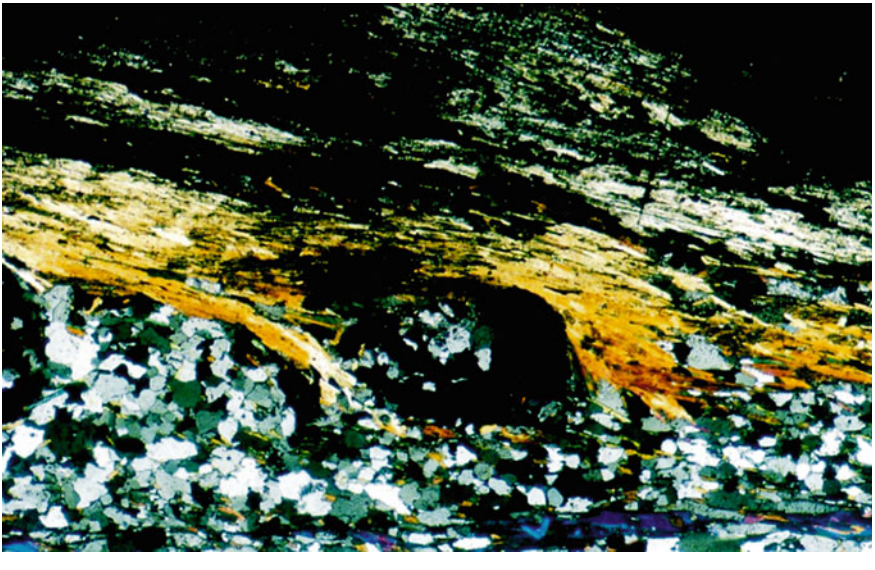

**Fig. 1.52** A nearly sigmoid garnet fish with irregular/spiral (?) inclusion pattern. *Top-to-left* shear. Reproduced from Fig. 1.10d of Mukherjee (2010a). Cross-polarized light. *Location* Higher Himalaya, at Karcham (Himachal Pradesh, India). *Width of view* 1.5 mm

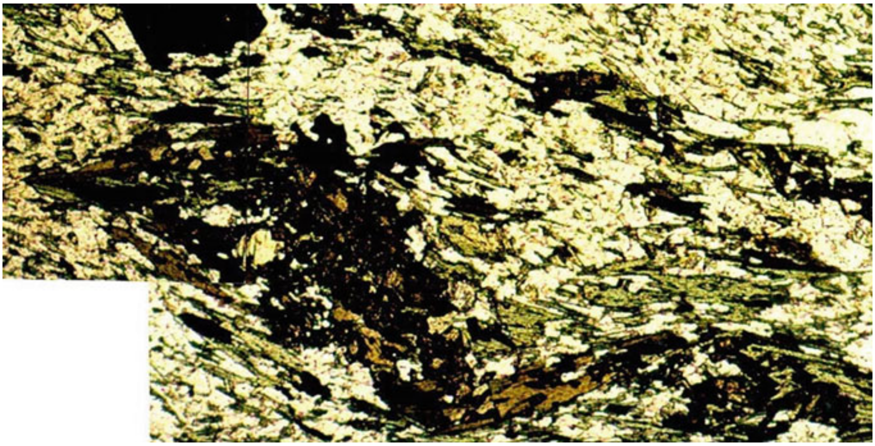

**Fig. 1.53** A composite sigmoid fish of garnet, biotite, muscovite and chlorite affected by prominent secondary synthetic shear (*top-to-left-down*). *Top-to-left* primary shear. Plane polarized light. *Location* Shyok Suture Zone (India). *Width of view* 2 mm

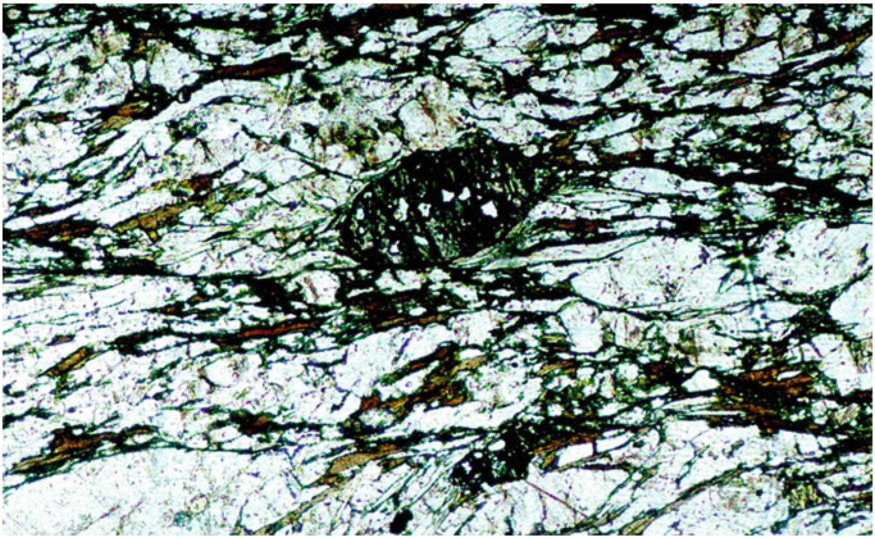

**Fig. 1.54** A lenticular garnet fish with haphazard and angular inclusions. *Top-to-right* shear. The primary shear plane is defined as a *curvilinear line*. Plane polarized light. *Location* Higher Himalaya, at Karcham (Himachal Pradesh, India). *Width of view* 4 mm

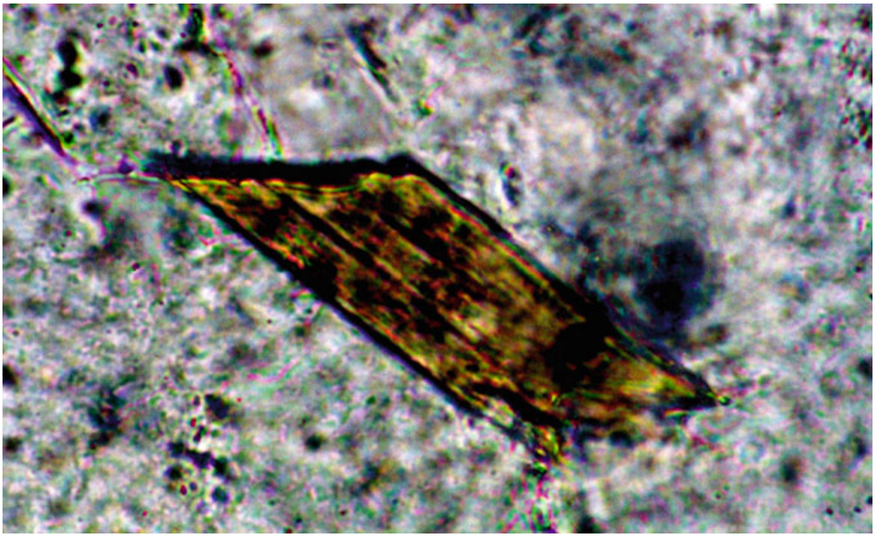

**Fig. 1.55** A nearly *parallelogram-shaped* biotite fish. *Top-to-left* shear. However, no primary shear C-plane defined at its corners. Reproduced from Fig. 1.8b of Mukherjee (2011). Cross-polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 4 mm

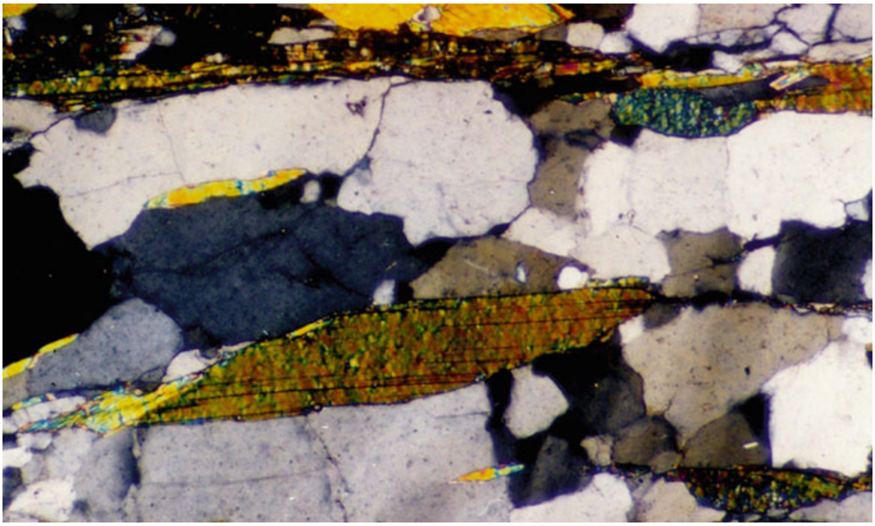

**Fig. 1.56** A *parallelogram-shaped* mica fish. Its cleavages parallel the primary shear C-plane. *Top-to-right* shear. The C-plane is defined as a *thick line* at the *right side* of the fish. The matrix quartzofeldspathic minerals are not sigmoid-shaped; hence do not give shear sense. Reproduced from Fig. 1.8a of Mukherjee (2011). Cross-polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 4 mm

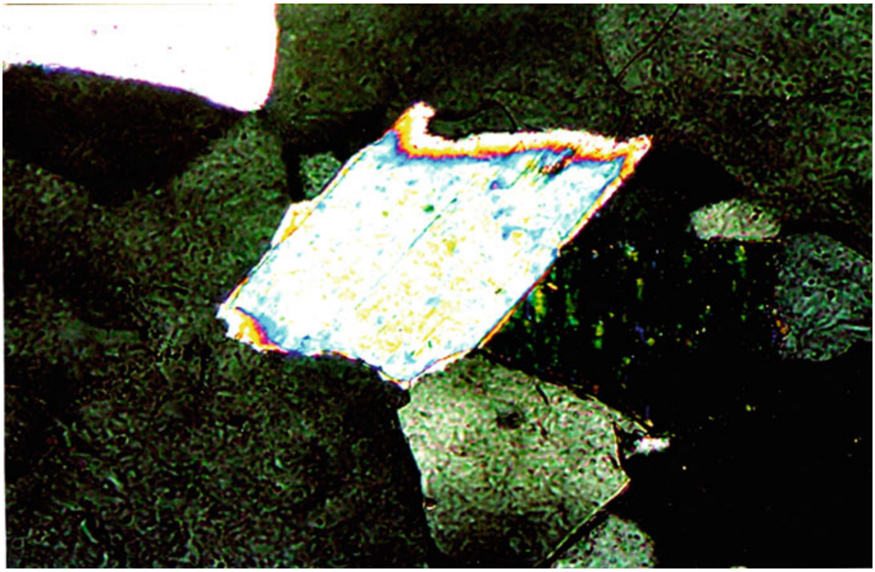

**Fig. 1.57** A nearly *parallelogram-shaped* mica fish devoid of any fish trails/tails. *Top-to-right* shear. Reproduced from Fig. 1.8b of Mukherjee (2010a). *Location* south to Karcham, inside the Higher Himalaya (Himachal Pradesh, India). Cross-polarized light. *Width of view* 1 mm

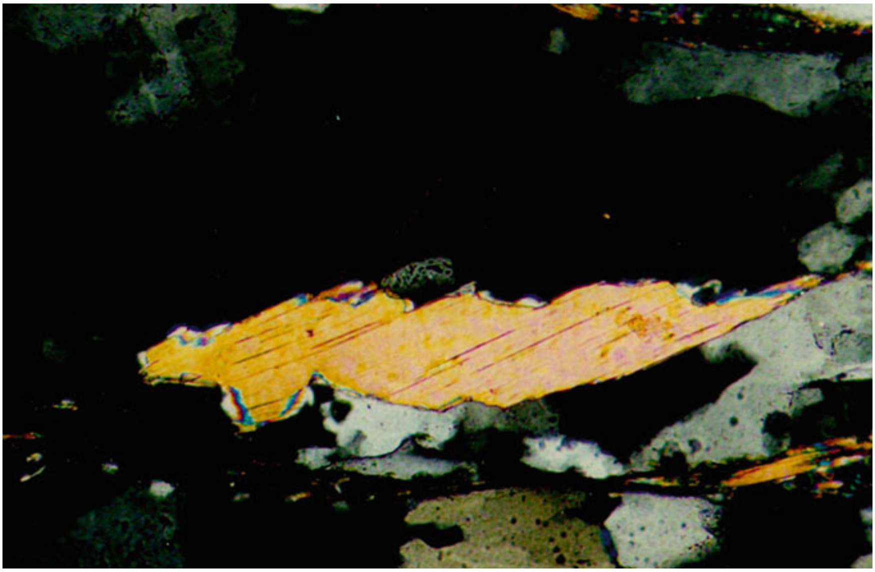

**Fig. 1.58** A near *parallelogram-shaped* mica fish (*top-to-right* sense) with irregular margins. Micas define a *thick line*-like C-plane at *bottom*. Cross-polarized light. *Location* Higher Himalaya in the Sutlej section (Himachal Pradesh, India). *Width of view* 4 mm

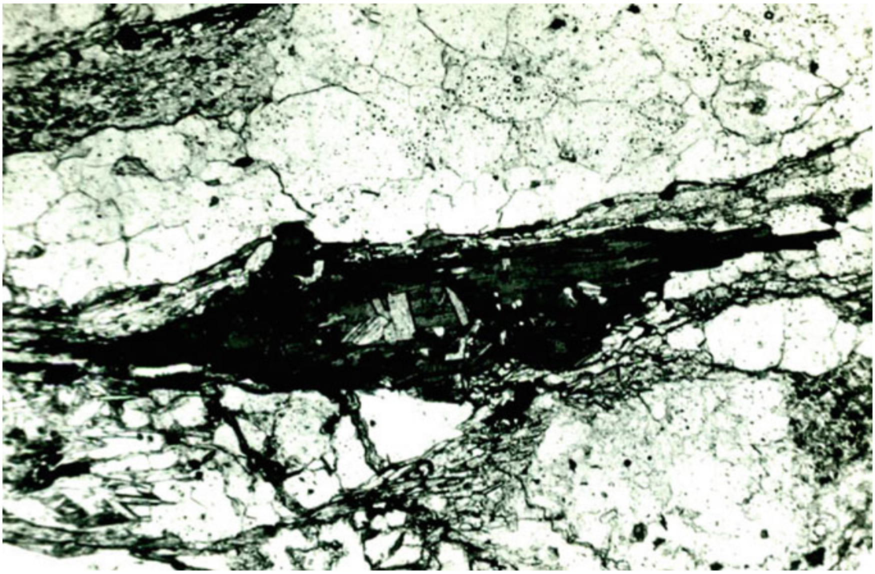

**Fig. 1.59** A composite parallelogram fish of biotite inside rather undeformed quartzofeldspathic matrix. *Top-to-right* shear. A number of biotites inside the composite are randomly oriented. Mica free quartzofeldspathic domains at *top* remained unsheared. Plane polarized light. *Location* Tso Morari dome (India). *Width of view* 2 mm

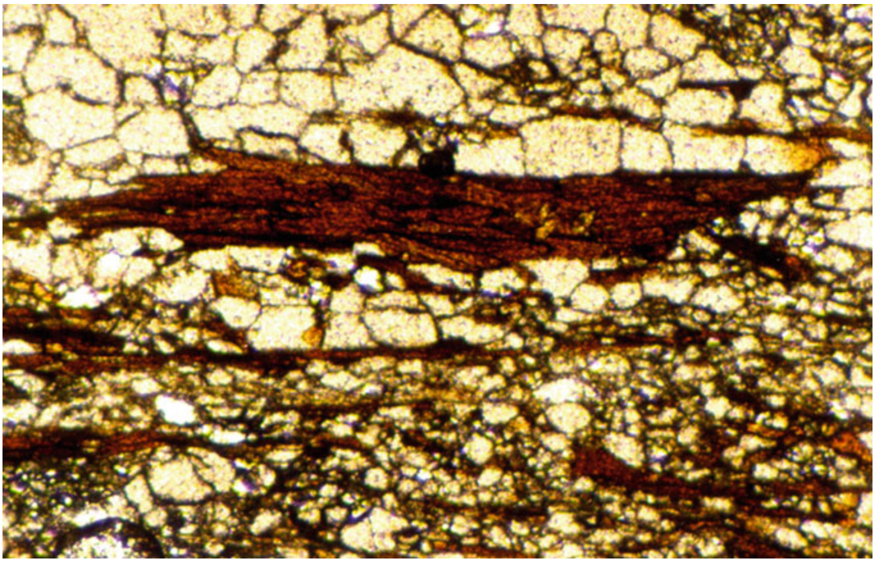

**Fig. 1.60** A composite parallelogram fish of biotite inside rather undeformed quartzofeldspathic matrix. *Top-to-right* shear. Many of the boundaries of minerals in the matrix are either sub-parallel or sub-normal to the shear direction. Reproduced from Fig. 1.10d of Mukherjee (2011). Plane polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 2 mm

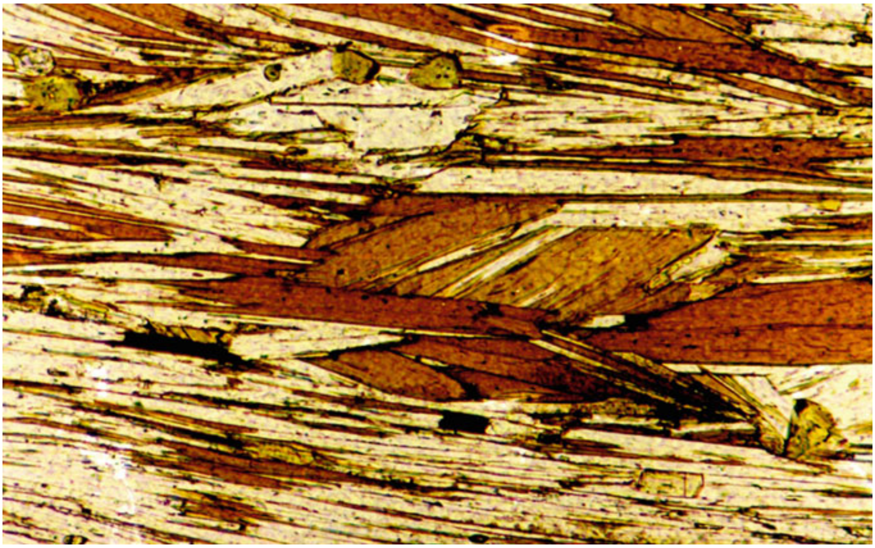

**Fig. 1.61** *Parallelogram-shaped* biotites inside a decussate texture do not necessarily indicate any shear sense. *Parallelogram shape* of a grain may develop by overlap of other grains on the former. Reproduced from Fig. 1.10a of Mukherjee (2011). Plane polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 2 mm

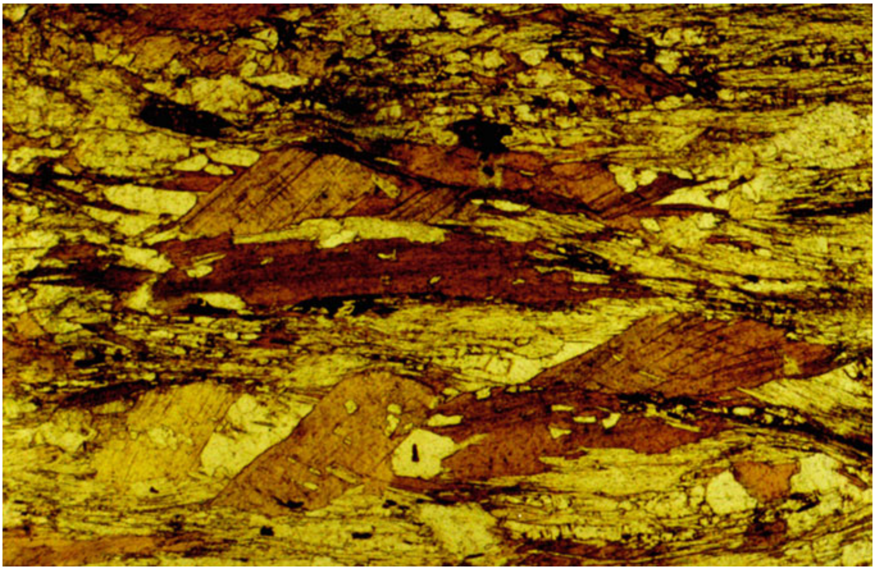

**Fig. 1.62** Sigmoid and near parallelogram biotite fish. *Top-to-right* shear. Synthetic secondary shear at low-angle to the primary shear direction. Reproduced from Fig. 1.3d of Mukherjee (2011). Plane polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 1 mm

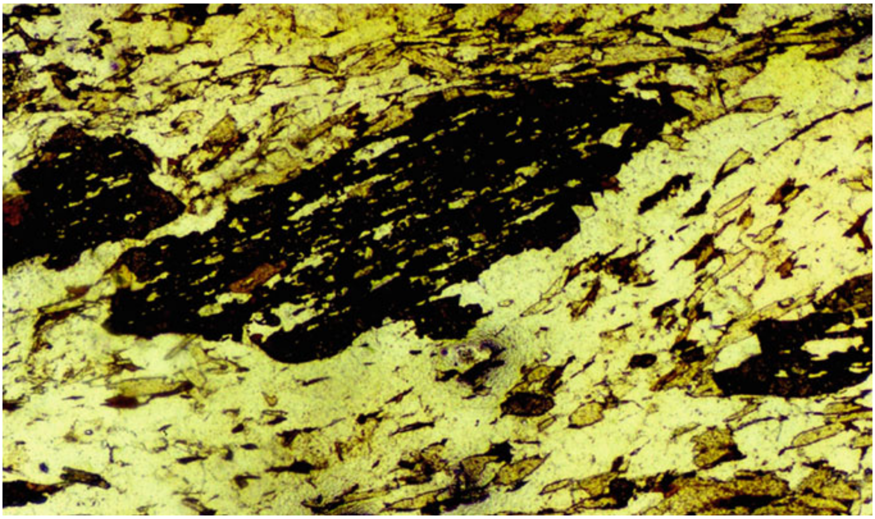

**Fig. 1.63** A *parallelogram-shaped* garnet fish. *Top-to-right* shear. Nearly straight inclusion pattern sympathetic to shear sense. Isolated mica grains overall define S-fabrics and show the same shear sense. Reproduced from Fig. 1.8c of Mukherjee (2011). Plane polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 5 mm

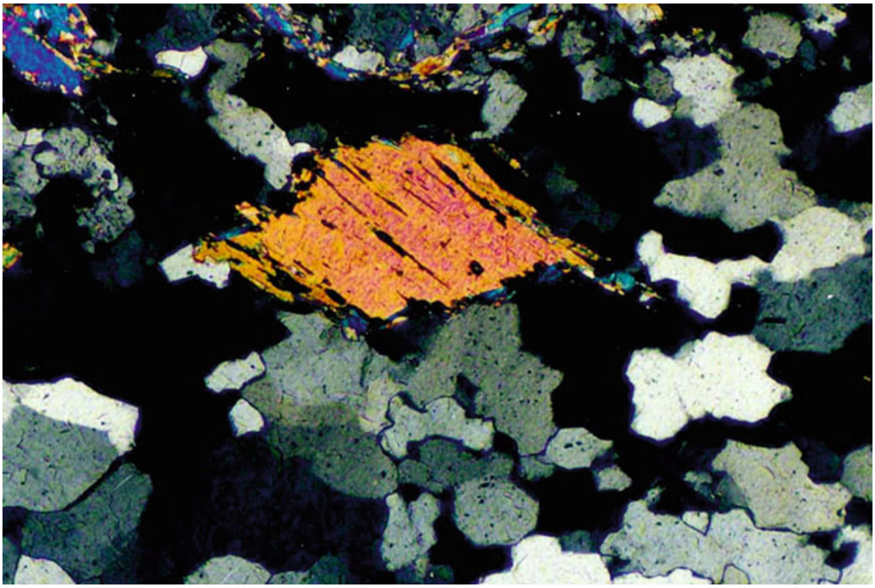

**Fig. 1.64** A nearly symmetric lenticular mica fish with irregular margin. The shape does not reveal shear sense. Can inclination of the cleavages with respect to the primary shear C-plane be used as shear sense indicator reliably?. Here the C-plane is oriented horizontal as deciphered from outside the field of view. Cross-polarized light. *Width of view* 4 mm

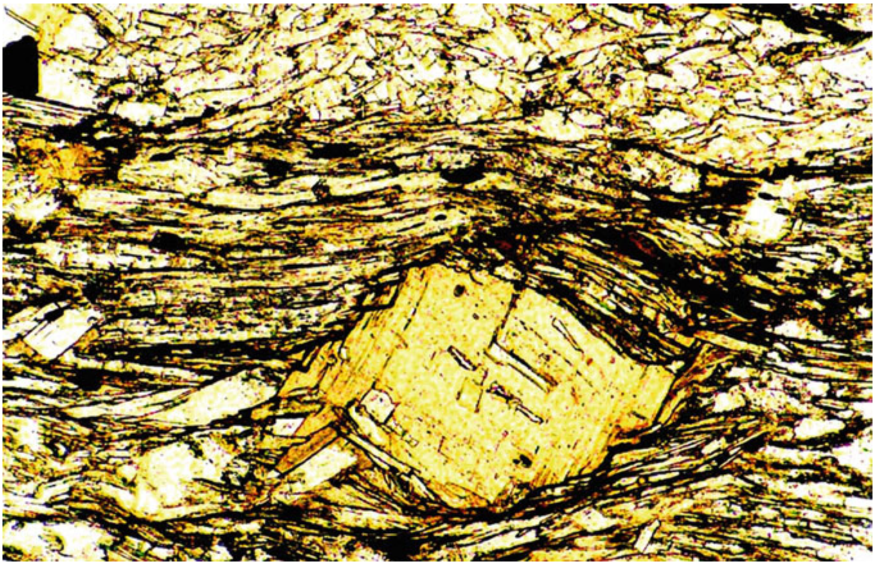

**Fig. 1.65** A sub-circular lenticular/sigmoid biotite fish with irregular margin. *Top-to-left* shear deciphered from sigmoid foliations at *top right* to the fish. Cleavages within the biotite fish are oriented antithetic to this shear sense, whereas many of the inclusions are elongate and oriented synthetic. Plane polarized light. *Width of view* 4 mm

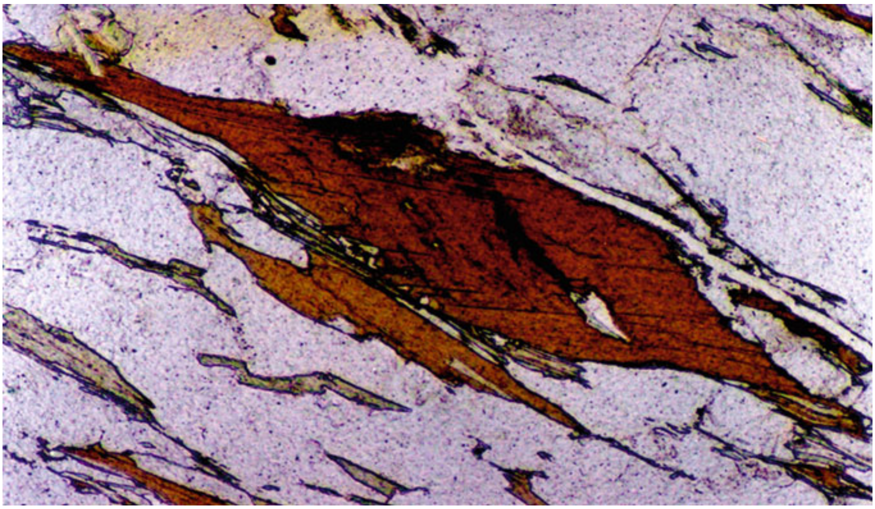

**Fig. 1.66** A lenticular biotite fish. Stretched tips define the primary shear C-plane. Inclination of cleavages probably indicates a *top-to-right-down* shear. Reproduced from Fig. 1.6d of Mukherjee (2011). Isolated mica grains in the matrix define only the C-plane and do not reveal the shear sense clearly. Plane polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 2 mm

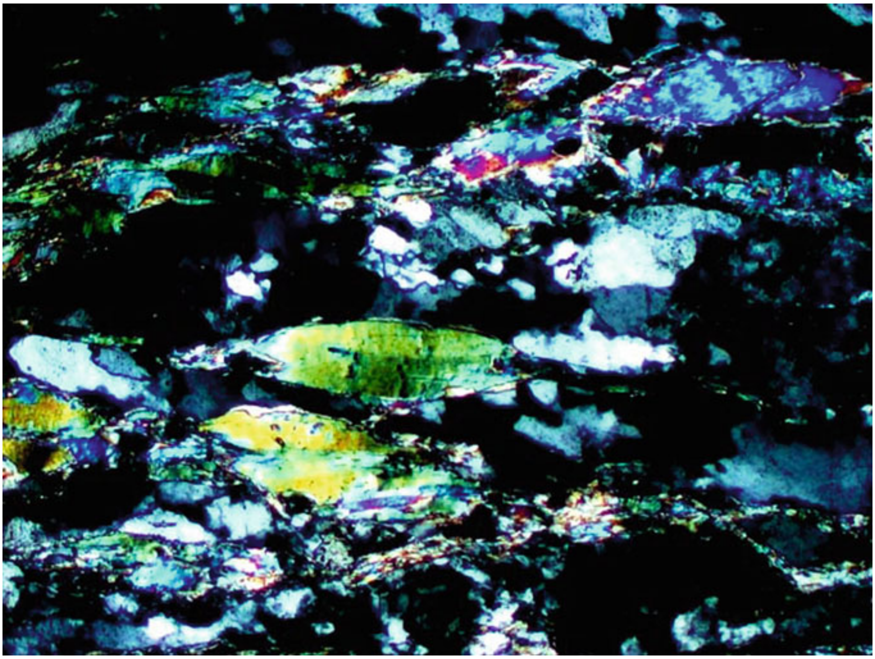

**Fig. 1.67** A lenticular mica fish with notches at corners. The long axis of the lenticle sub-parallels the main foliation/C-shear plane. No shear sense indicated. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

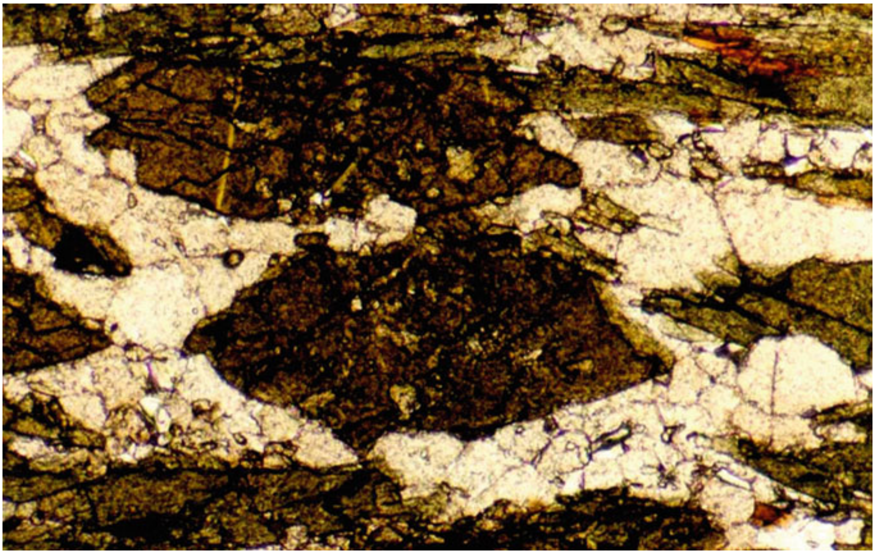

**Fig. 1.68** A lenticular fish of hornblende. No shear sense displayed. Plane polarized light. *Location* Shyok Suture Zone (India). *Width of view* 4 mm

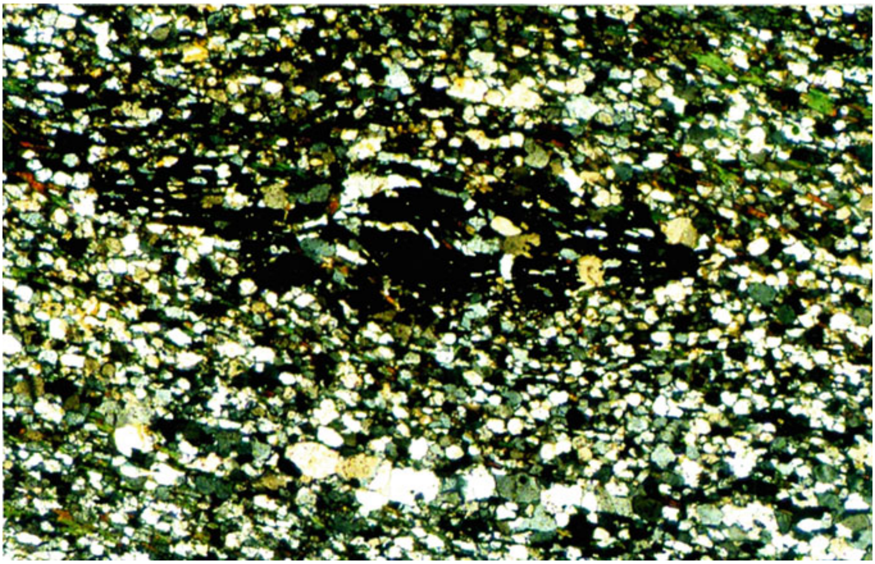

**Fig. 1.69** A syntectonically growth lenticular garnet fish. Foliation plane inside it defined by inclusions (i.e. the '$S_i$') is sub-parallel to that present in the matrix (i.e. the '$S_e$'). Reproduced from Fig. 1.9a of Mukherjee (2010a). Cross-polarized light. *Location* Higher Himalaya, at Karcham (Himachal Pradesh, India). *Width of view* 4 mm

**Fig. 1.70** An irregular-shaped staurolite got parallel pull apart at *left*. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

**Fig. 1.71** A nearly spindle-shaped staurolite porphyroblast. Its tapering side at right is synthetic secondary ductile sheared to *top-to-right-down* sense. This shear sense is demonstrated prominently by dragged elongated sigmoid biotites and quartzofeldspathic mineral grains. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

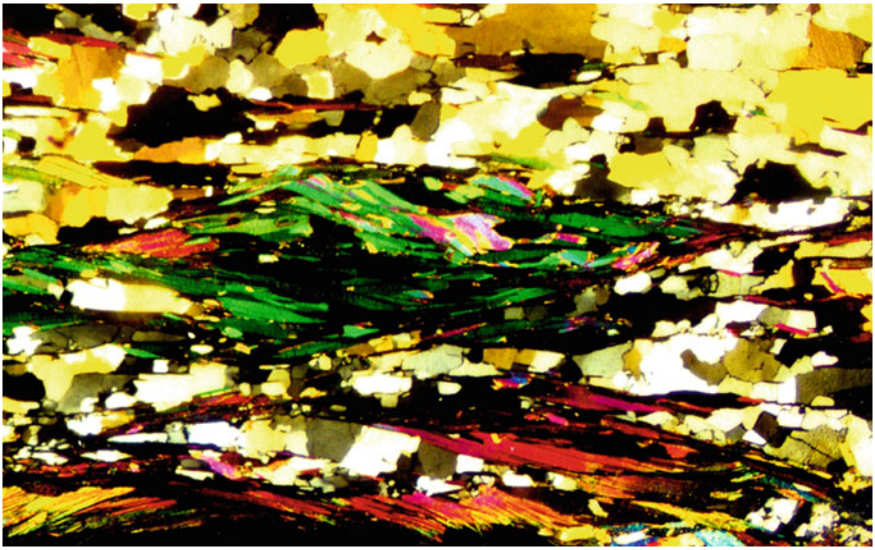

**Fig. 1.72** A sigmoid lenticular fish of micas. No shear sense displayed. Individual mineral grains inside this lenticle should not be used as shear sense indicators. Reproduced from Fig. 1.10c of Mukherjee (2011). Cross-polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 2 mm

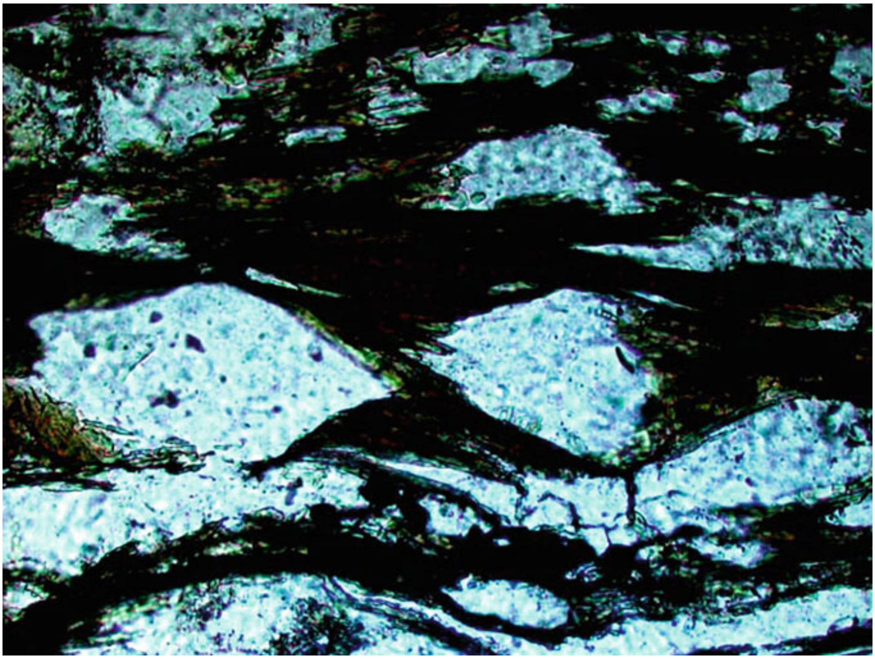

**Fig. 1.73** Near symmetric quartz fish. Shear sense difficult to decipher. Reproduced from Fig. 1.6a of Mukherjee (2010b). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

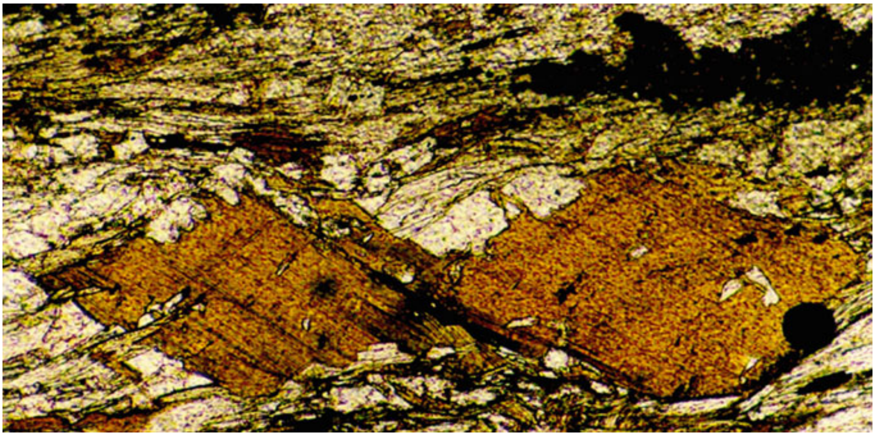

**Fig. 1.74** Two rhombic biotite grains, possibly *top-to-left* sheared. Reproduced from Fig. 1.8d of Mukherjee (2011). Plane polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 2 mm

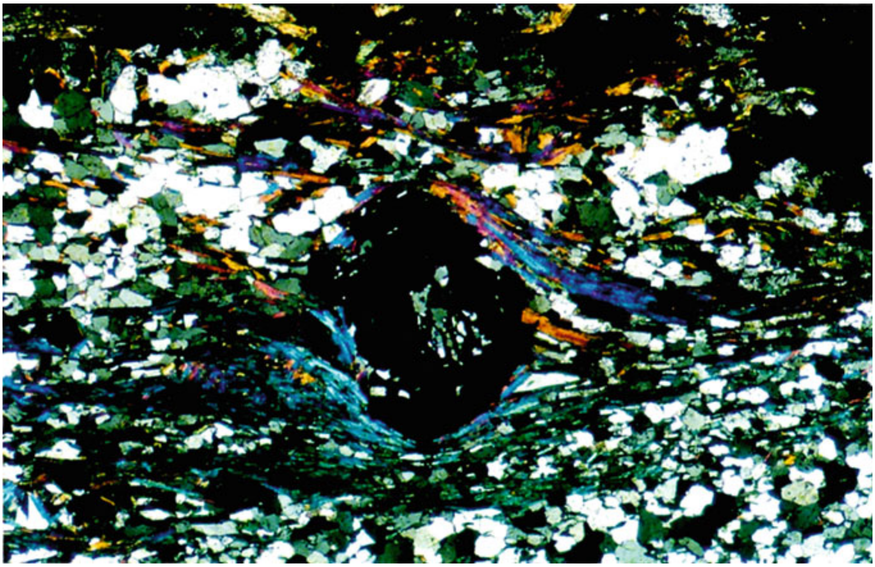

**Fig. 1.75** A garnet porphyroblast grew initially syntectonically leaving behind its sigmoid inclusion pattern. Its inclusion free *middle portion* indicates, however, a post-tectonic growth. Ghosh (1993) presented some such explanation. Matrix foliation wraps around the grain similar to a delta structure. *Top-to-left* shear. Reproduced from Fig. 1.10c of Mukherjee (2010a). Cross-polarized light. *Width of view* 4 mm

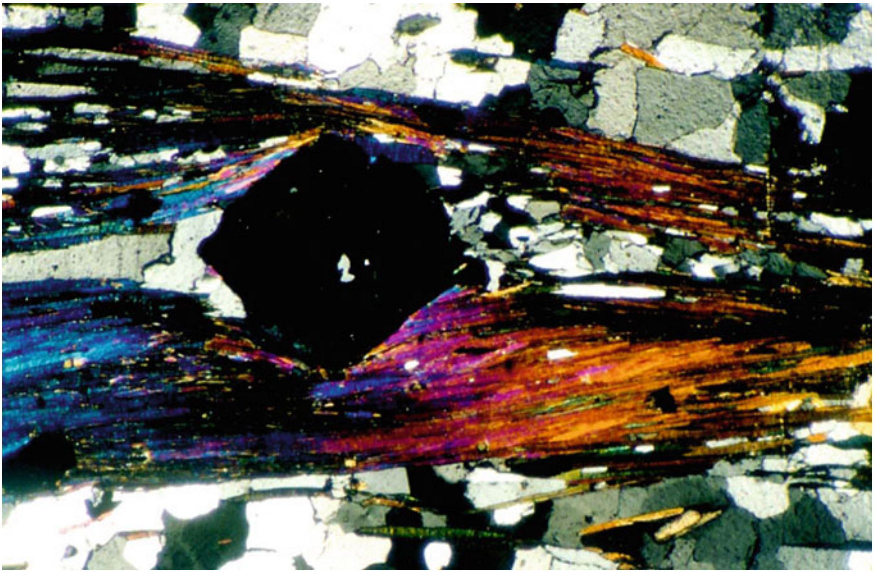

**Fig. 1.76** An (undeformed?) garnet grain with symmetric pressure shadows. The pressure shadow at *left* consists of quartzofeldspathic grains coarser than that at *right*. No shear sense revealed. Cross-polarized light. *Width of view* 4 mm

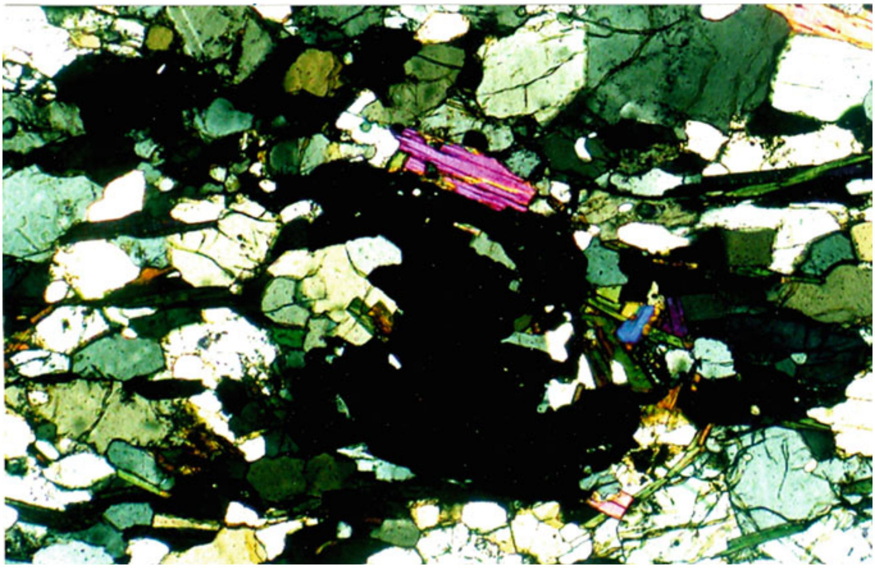

**Fig. 1.77** An irregular garnet porphyroblast. Quartzofeldspathic minerals migrated inside it from two sides. *Top-to-left* shear? Reproduced from Fig. 1.9b of Mukherjee (2010a). Cross-polarized light. *Location* Higher Himalaya, at Karcham (Himachal Pradesh, India). *Width of view* 4 mm

**Fig. 1.78** A retrogressed garnet with chlorite developed at its irregular margins. Chlorite resembles symmetric pressure shadow. Was chloritization coeval to (any) ductile shear? Plane polarized light. *Location* Tso Morari dome (India). During its channel flow buoyant extrusion (Mukherjee and Mulchrone 2012), garnet within ecogite patches inside the Tso Morari gneissic dome underwent retrogression. Thus, we are looking at micro-structural output of extrusion. *Width of view* 4 mm

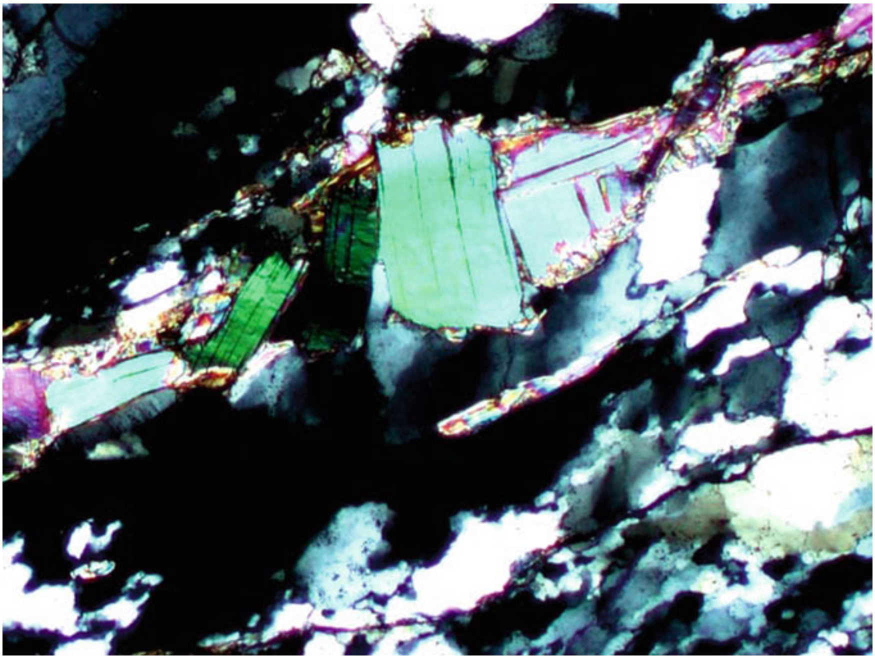

**Fig. 1.79** Brittle slip and rotation of muscovite grains. *Top-to-right-up* shear. Reproduced from Fig. 1.8a of Mukherjee (2010b). Photo in cross-polarized light. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

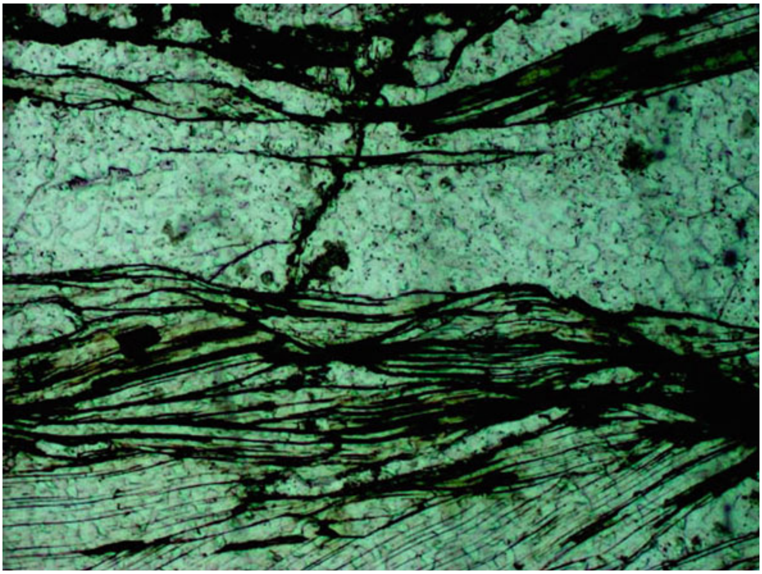

**Fig. 1.80** Conjugate ductile shear on foliation micas developed horst and graben like structures in micro-scale. More rigid white quartzofeldspathic layer *above* is not affected by these shears. Reproduced from Fig. 1.8a of Mukherjee (2010b). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

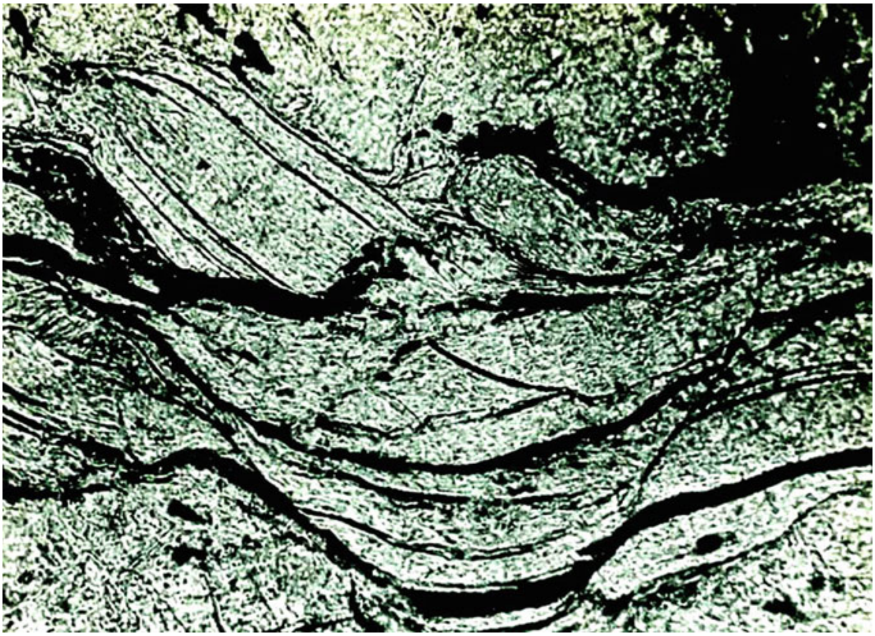

**Fig. 1.81** Conjugate ductile sheared muscovite led to horst/graben-like structure developed in micro-scale (similar to Fig. 1.80). In this photo orientation, the 'down-sagged' portion is *curved*. *Location*: Tso Morari Dome (India). Interestingly, conjugate shear was related to the extrusion of the Tso Morari Dome (see Fig. 3 of de Sigoyer et al. 2004).*Width of view* 2 mm

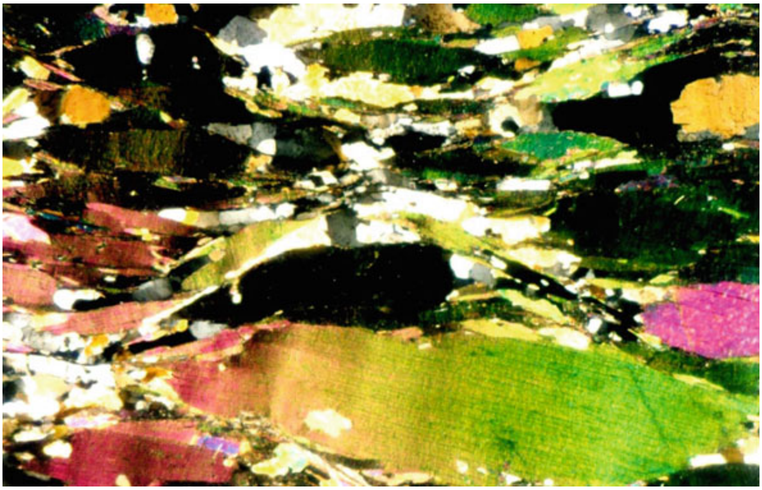

**Fig. 1.82** Conjugate ductile shear planes dragged nearly lenticular mica grains. Thinner quartzofeldspathic layers are dragged significantly. Cross-polarized light. *Location* Tso Morari Dome (India). *Width of view* 2 mm

**Fig. 1.83** Two biotite fish—one *sigmoid* and the other *parallelogram*. They indicate probably reverse ductile shear senses: the former a *top-to-right* and the later a *top-to-left*. Biotite fish below indicate a *top-to-right* sense. Plane polarized light. *Location* Tso Morari dome (India). *Width of view* 4 mm

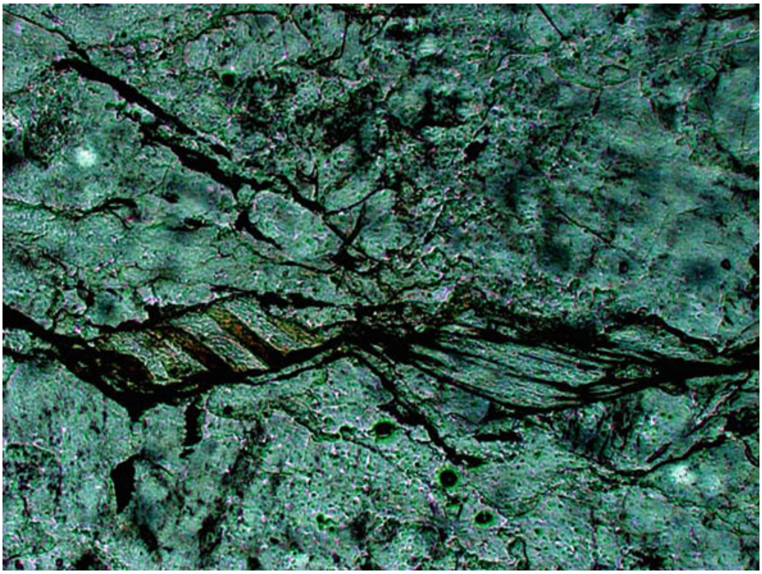

**Fig. 1.84** Two *sigmoid-shaped* mica fish side by side probably reveal reverse shear (*left one*: *top-to-right* sense; *right one*: *top-to-left* sense). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

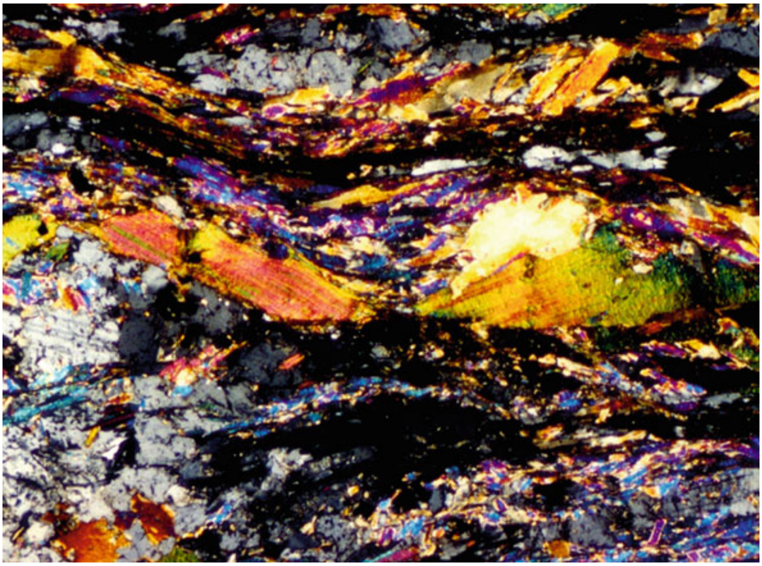

**Fig. 1.85** Two *parallelogram-shaped* mica fish. Do they indicate reverse shear (i.e. *left one*: *top-to-left* sense; *right one*: *top-to-right* sense)? Cross-polarized light. *Location* Tso Morari dome (India). *Width of view* 4 mm

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# Chapter 2
# Trapezoid-Shaped Minerals and Brittle Shear Senses

Brittle thrusting in micro-scale produces trapezoid shapes in minerals, most commonly in micas (Figs. 3a-c of Holyoke and Tullis 2006; Mukherjee 2012a, b; Mukherjee and Koyi 2010a, b) (particularly Figs. 2.2, 2.6, 2.7, 2.11). The brittle shear planes that bound them may be characterized by recrystallization (Figs. 2.2, 2.3, 2.7, 2.9). Similar to crustal slices in meso-scales, symmetric stacks of trapezoid-shaped minerals do not reveal any shear sense (Figs. 2.10, 2.11, 2.12). A top-S/SW brittle shear is revealed by the asymmetric trapezoids from some of the Himalayan shear zones (Figs. 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9). Inclinations of their longest margins and cleavage planes with the shear planes are used to decode the shear sense. The brittle shear sense matches with those given by duplexes from the same terrain (e.g. Mukherjee and Koyi 2010a, b; Mukherjee 2012b). Thus, these microscopic trapezoids exemplifies foreland vergent brittle thrusting. In those shear zones where two opposite directions of brittle thrusting have been reported (e.g. Mukherjee in press), whether trapezoids of two opposite orientations are encountered in thin-sections is to be cross checked. Deciphering brittle shear sense based on P- and Y-planes, on the other hand, is clear cut (Bhattacharya et al. submitted).

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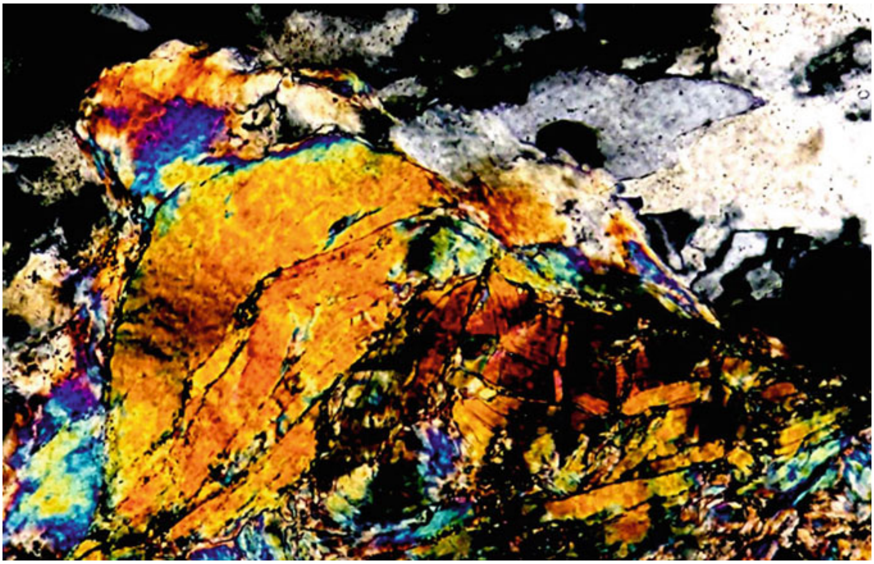

**Fig. 2.1** Less competent micas develop *top-to-right* brittle sheared duplex. The 'core' portion shows an 'anticlinal stack' with nearly *straight* limbs and *sharp* hinges. More competent quartzofeldspathic minerals in the matrix did not develop any duplex. Photo in cross-polarized light. Reproduced from Mukherjee (2012a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

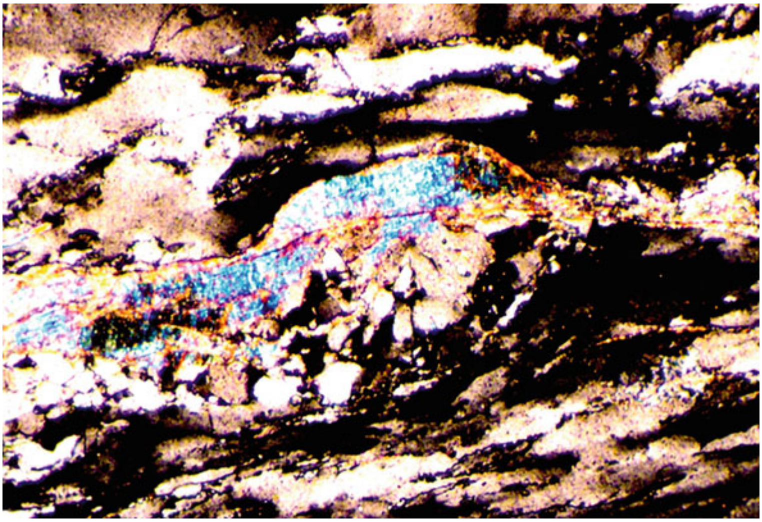

**Fig. 2.2** *Top-to-right* sense brittle faulted mica grain. The *top* fragment is *trapezoid*-shaped with gently *curved* margins. The brittle shear plane is marked by recrystallized micas. Reproduced from Fig. 7b of Mukherjee (2012b). Cross-polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 2.5 mm

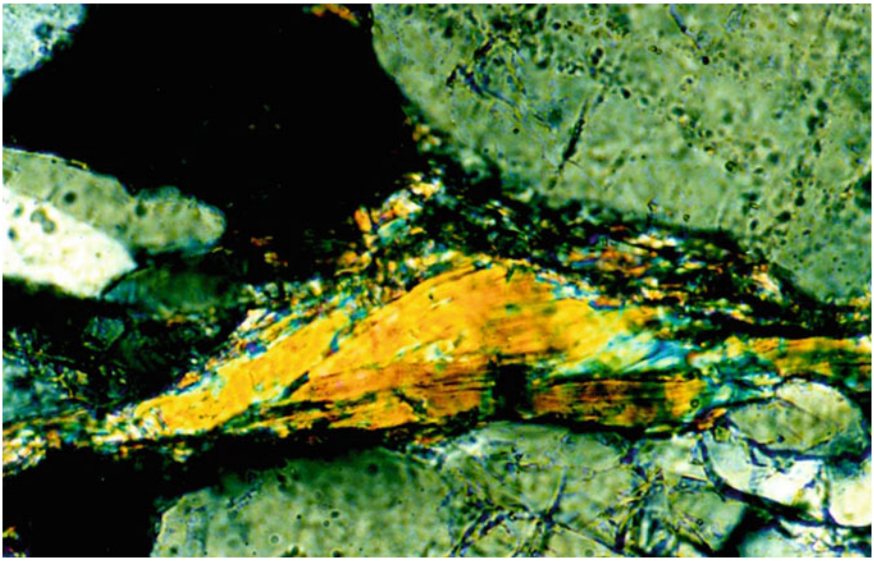

**Fig. 2.3** *Top-to-right* brittle sheared micas. A *thick* recrystallized portion at the *top*. Photo in cross-polarized light. Reproduced from Fig. 9c of Mukherjee and Koyi (2012a). *Location* Zanskar Shear Zone (India). *Width of view* 2.5 mm

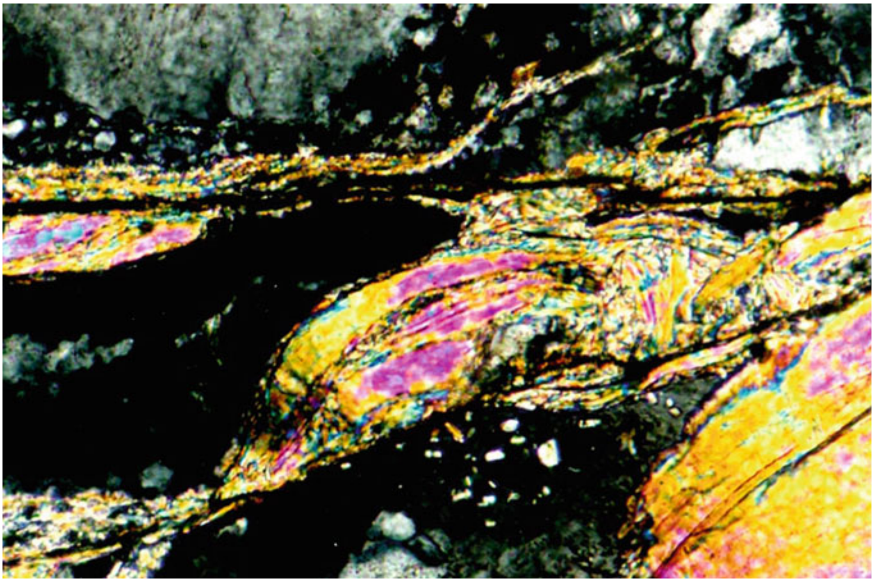

**Fig. 2.4** *Top-to-right-up* brittle sheared muscovite layers. Muscovite grains folded and crushed at *right*. Same as Fig. 10c of Mukherjee (2012b) but at a different orientation of the stage. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2.5 mm

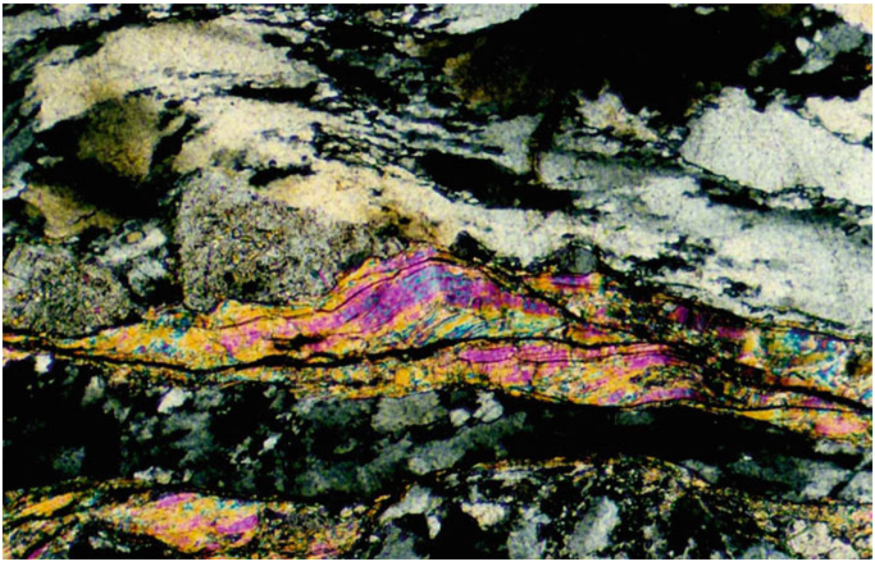

**Fig. 2.5** Sheared mica layers. *Top-to-right* sense. Sigmoid grain boundaries near the *left* margin and in the *central* portion. Sheared quartzofeldspathic minerals and near *parallelogram*-shaped mica fish (at *bottom*) show the same shear sense. Synthetic secondary shear planes at *right*. Cross-polarized light. *Width of view* 4 mm

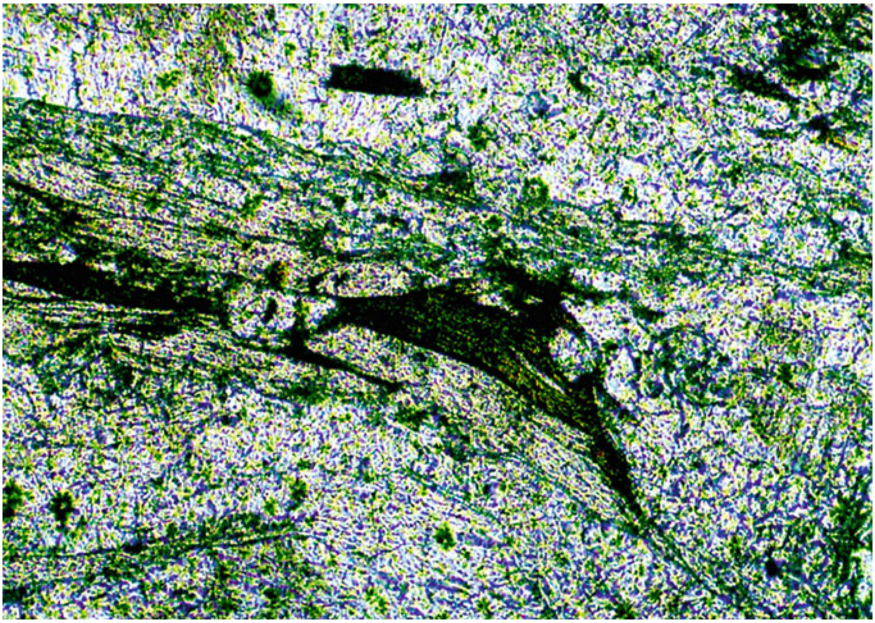

**Fig. 2.6** Adjacent muscovite and biotite *trapezoids* with their longest margins a little kinked. *Top-to-left* shear. Reproduced from Fig. 6b of Mukherjee (2012b). Plane polarized light. Higher Himalaya (Himachal Pradesh, India). *Width of view* 2.5 mm

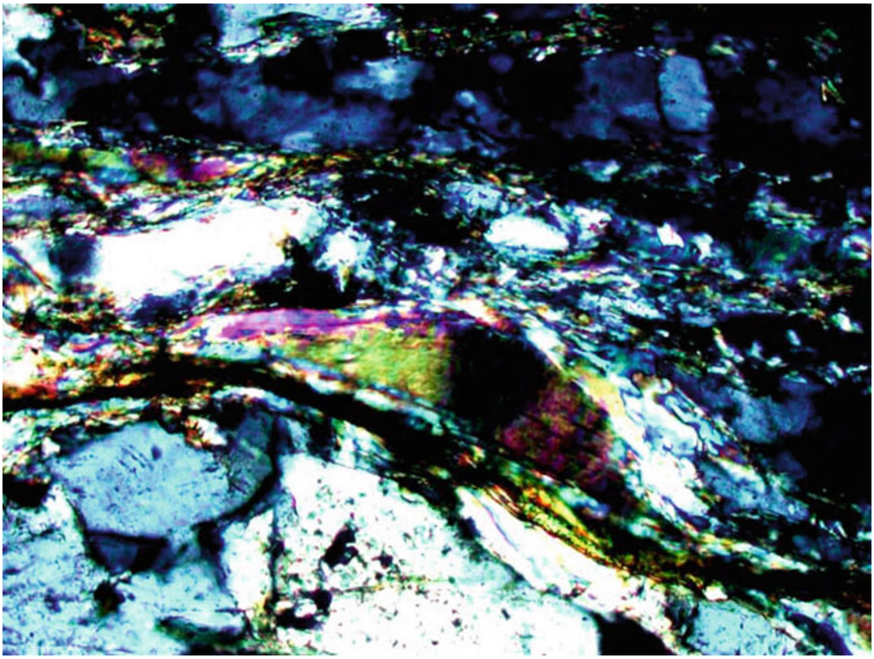

**Fig. 2.7** A muscovite grain sheared over quartzofeldspathic minerals. *Top-to-left* sense. Extensive recrystallization at the margin of the muscovite grain. The brittle shear zone is characterized by grain size reduction. Reproduced from Fig. 9a of Mukherjee and Koyi (2010a). *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 5 mm

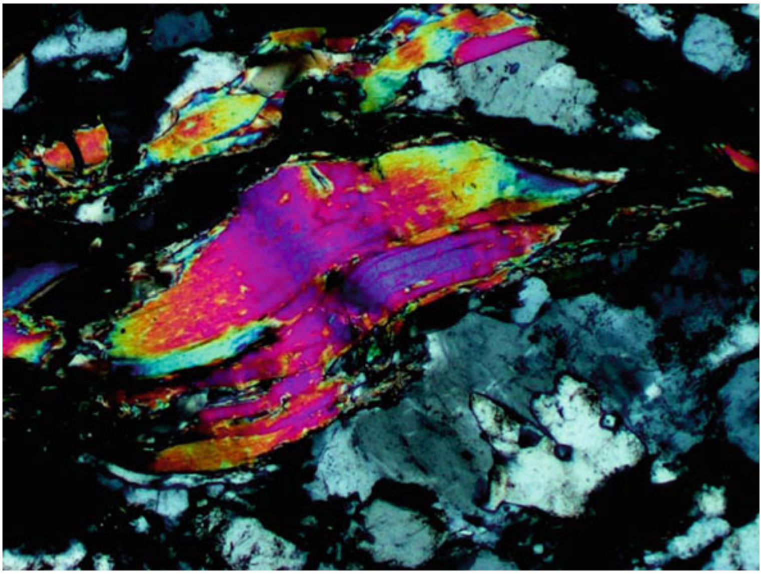

**Fig. 2.8** *Hat*-shaped/*trapezoid* mica grains sheared over quartzofeldspathic minerals. The hats are mantled by a zone of grain size reduction. *Top-to-right* sense. Reproduced from Fig. 9b of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 5 mm

**Fig. 2.9** *Top-to-right* brittle sheared slices of micas of somewhat *trapezoid* shapes. Notice that mica minerals are more prone to *trapezoid* shapes than the quartzofeldspathic matrix. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

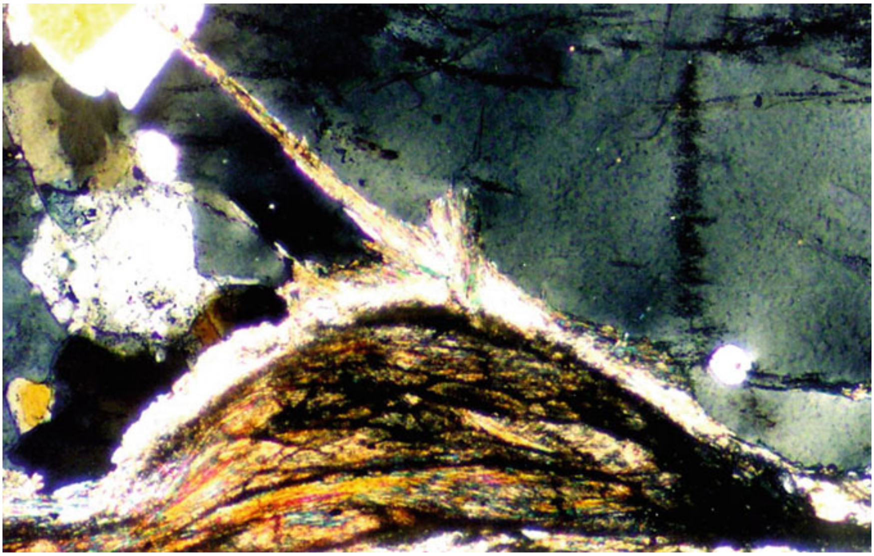

**Fig. 2.10** A symmetrically stacked duplex of staurolite grains. No shear sense is indicated. Kyanite mantles this duplex and forms a peculiar 'horn'. This is the cross-polarized light version of Fig. 9d of Mukherjee and Koyi (2010a). *Location* Zanskar Shear Zone (India). *Width of view* 2.5 mm

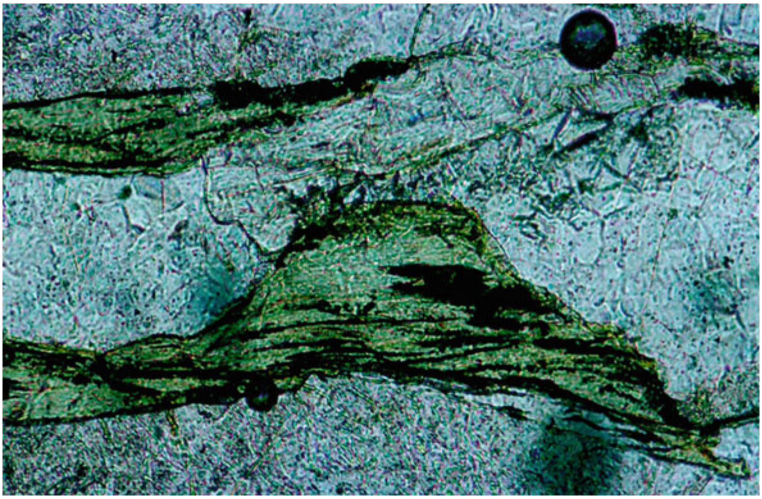

**Fig. 2.11** Symmetrically stacked *trapezoid*-shaped chlorite grains. No shear sense is indicated. Cleavages parallel the longest margin of the *trapezoid*. Reproduced from Fig. 9a of Mukherjee (2012b). Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 2.5 mm

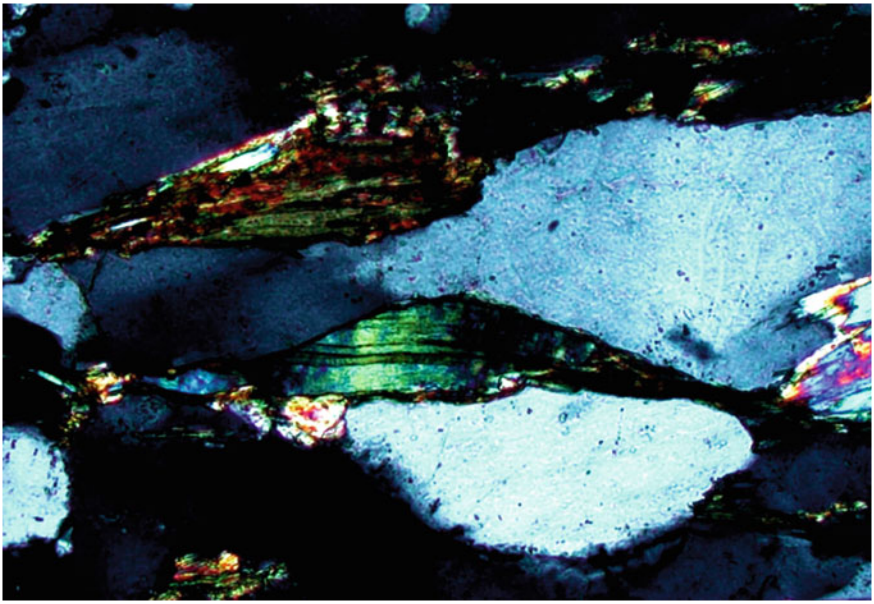

**Fig. 2.12** An irregular brittle plane, *horizontal* in the photo, sharply cuts across a quartz grain. Reproduced from Fig. 8a of Mukherjee (2012b). Near symmetric near *trapezoidal* slice of mica at the other side of the fault plane. No shear sense is indicated. Cross-polarized light. *Width of view* 2.5 mm

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# Chapter 3
# Flanking Microstructures and Nucleations

Passchier (2001) described 'Flanking structures' as 'deflection of planar or linear fabric elements in a rock alongside a cross-cutting object'. Following this, a number of papers came up on its morphology and mechanism (review and original work by Mulchrone 2007; also see Mukherjee submitted). The concept was subsequently extended for microscopic observations (Mukherjee 2007; Mukherjee and Koyi 2009; Mukherjee 2011; also see Koyi et al. 2013) where nucleated minerals cross-cuts, slips and drags cleavage planes and grain margins of the host minerals. However, not all nucleated minerals can be proved to slip and drag cleavages and grain boundaries (Fig. 3.29). Those are not to be considered as 'flanking microstructures'. Shape asymmetry of parallelogram-shaped nucleated grains in flanking micro-structures from the western Himalayan shear zones indicates a top-to-S/SW ductile shear. The cross-cutting element viz. the parallelogram-shaped minerals are considered to have nucleated either prior or simultaneous to the regional top-to-S/SW ductile shear. The shear senses indicated by these nucleations match with those indicated by mineral fish (see Mukherjee and Koyi 2009 for discussions). (Figs. 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.12, 3.13, 3.14, 3.15, 3.16, 3.17, 3.18, 3.19, 3.20, 3.21, 3.22, 3.23, 3.24, 3.25, 3.26, 3.27, 3.28)

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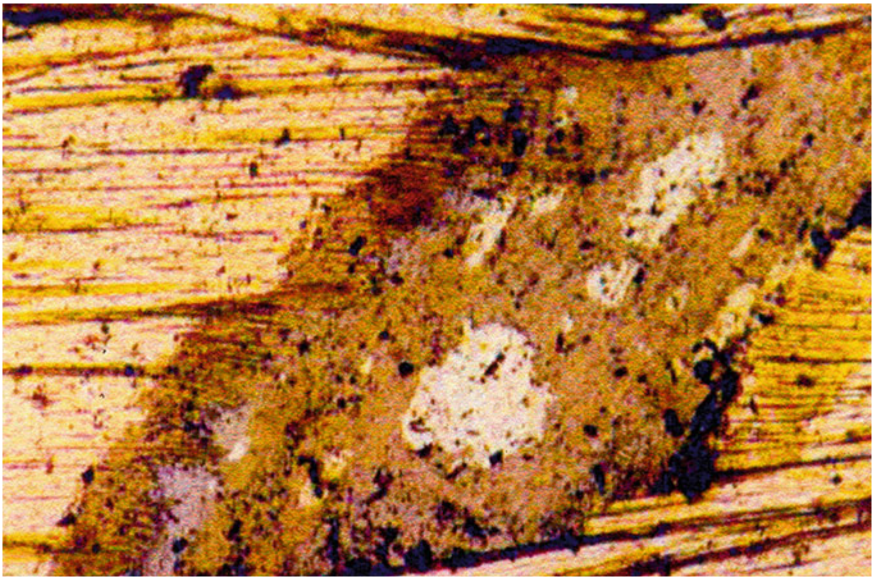

**Fig. 3.1** Flanking microstructure: a *parallelogram-shaped biotite* inclusion inside a *biotite* host mineral. *Top-to-right* shear. Cleavages of the host mineral at the contact planes with the inclusion are dragged to opposite senses. Reproduced from Fig. 2a of Mukherjee and Koyi (2009). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

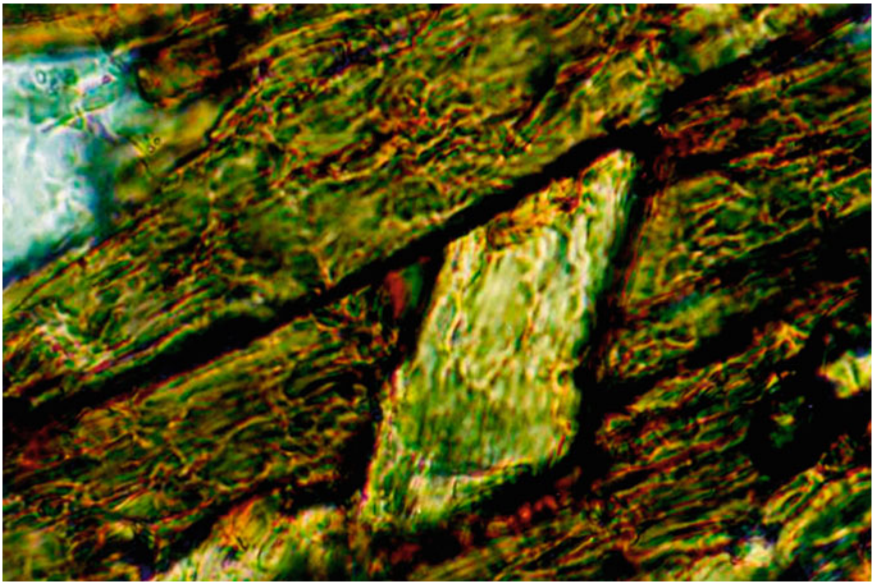

**Fig. 3.2** Flanking microstructure: inclusion of a *parallelogram-shaped biotite* (*top-to-right-up* sheared) inside a *biotite* host mineral. A few cleavages of the host mineral swerve where they touch the inclusion. Cleavages of the nucleated mineral seem to be curved. This indicates its internal deformation. Reproduced from Fig. 5c of Mukherjee (2011). Plane polarized light. *Width of view* 0.5 mm

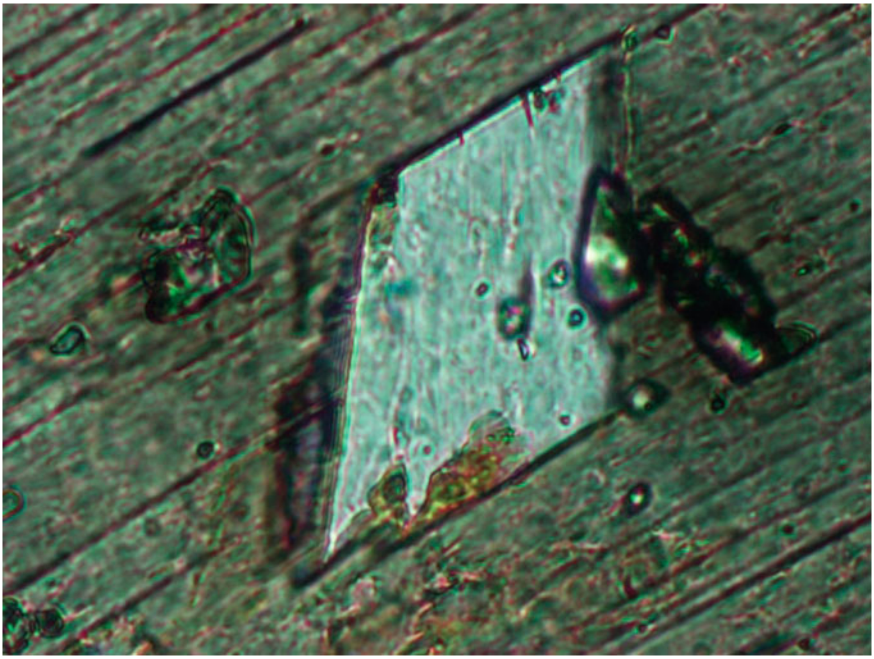

**Fig. 3.3** Flanking microstructure: A *parallelogram*-shaped *muscovite grain* nucleated inside within a *biotite grain*. The former shows a *top-to-right-up* shear. A few cleavages of *biotite curve* near their contacts with the *muscovite grain*. Reproduced from Fig. 5d of Mukherjee (2011). Plane polarized light. *Width of view* 0.5 mm

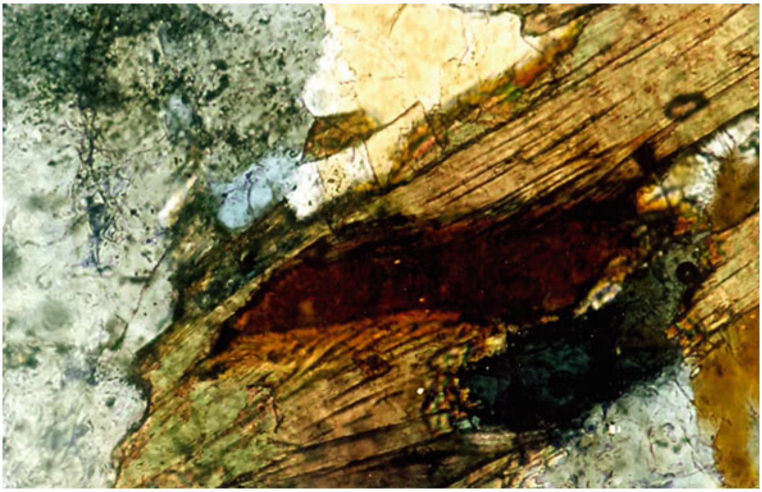

**Fig. 3.4** A *parallelogram-shaped* inclusion of *biotite* inside a host of *biotite*. *Top-to-left-down* shear. Cleavages of the host mineral curved in opposite sense near their contact with the *biotite* inclusion. Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 1 mm

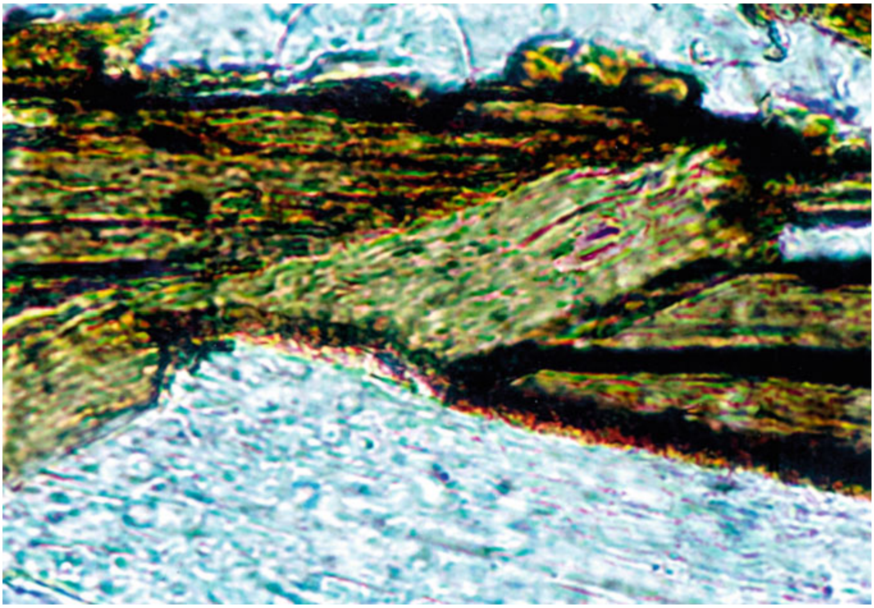

**Fig. 3.5** Flanking structure: a *biotite grain* cuts across other *biotite grains*. Cleavages of the latter grains swerve near the cross-cutting grain. Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 1 mm

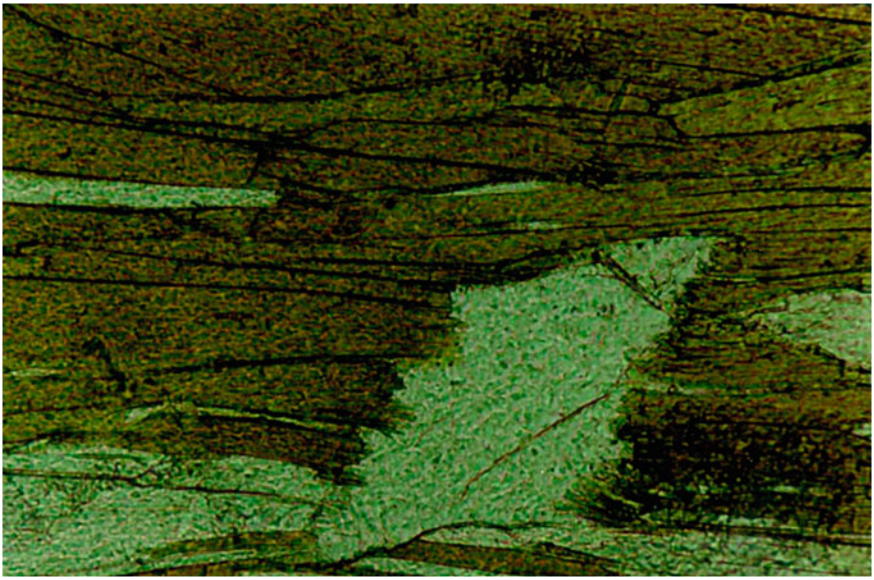

**Fig. 3.6** Flanking microstructure: a nearly *parallelogram-shaped muscovite* swerved cleavages of several *biotite grains* into opposite senses across its opposite margins. Some of the *biotites* penetrate the *muscovite grain*. *Muscovite shape* indicates a *top-to-right* shear. Plane polarized light. *Width of view* 1 mm

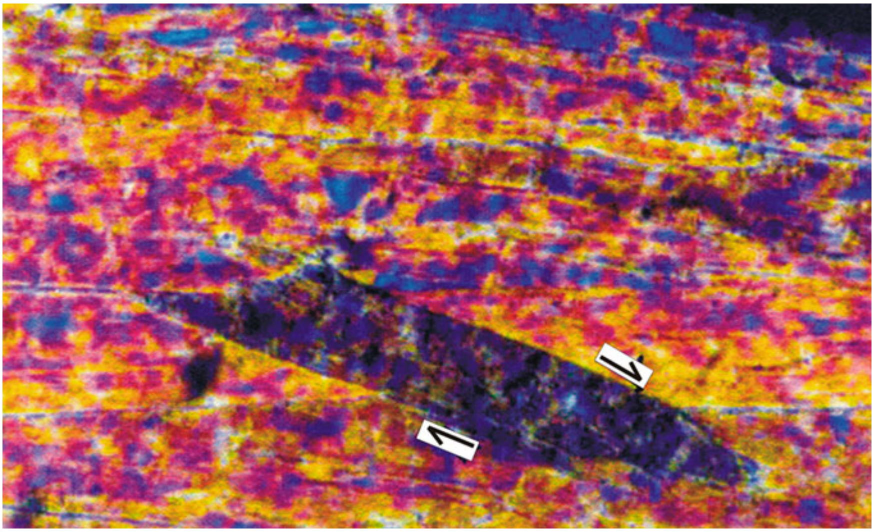

**Fig. 3.7** A nearly *parallelogram-shaped* mica nucleated inside an aggregate of mica host minerals. One of the margins of the host mica slipped at opposite margins of the nucleated grain of mica. Reproduced from Fig. 2d of Mukherjee and Koyi (2009). Cross polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

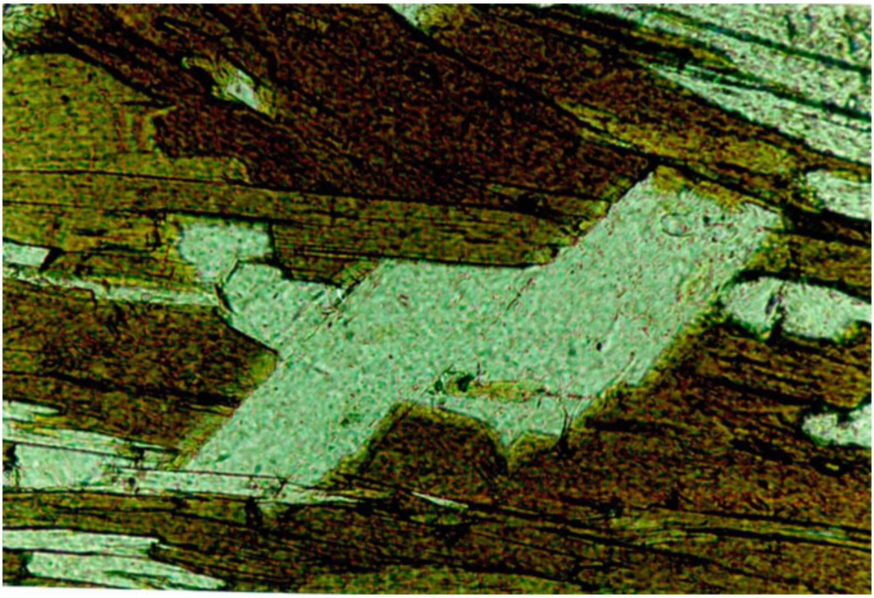

**Fig. 3.8** Two *adjacent parallelogram-shaped muscovite grains* nucleated over a number of *biotites*. Do they indicate a slip? Plane polarized light. *Location* Karakoram Shear Zone (India). *Width of view* 1 mm

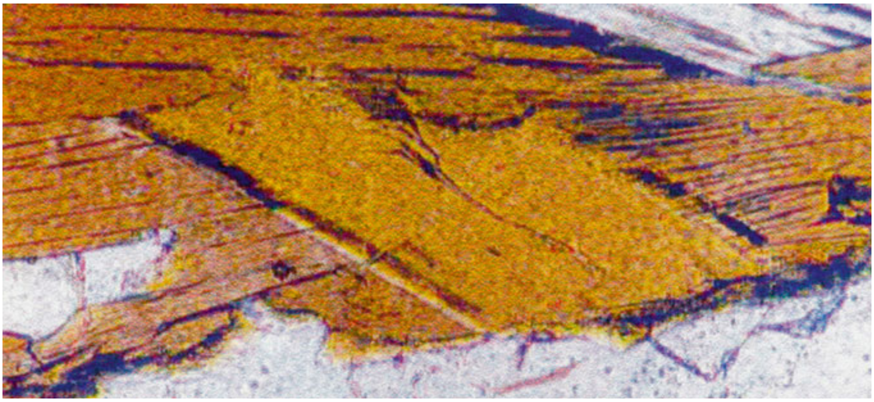

**Fig. 3.9** Flanking microstructure: inclusions of *biotite* within a *biotite* reveal that some of the cleavages of the latter swerve gently near the inclusions. Shape of inclusion *biotites* indicates a *top-to-left* shear. Reproduced from Fig. 2b of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 1 mm

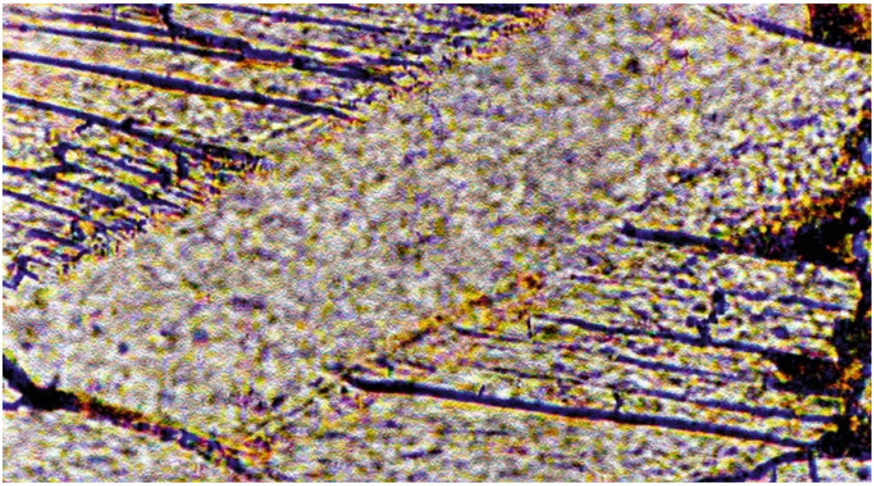

**Fig. 3.10** Flanking microstructure: an inclusion of *muscovite* within another *muscovite* reveals that the some of the cleavages of the latter swerve gently near the inclusion. Reproduced from Fig. 3d of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 1 mm

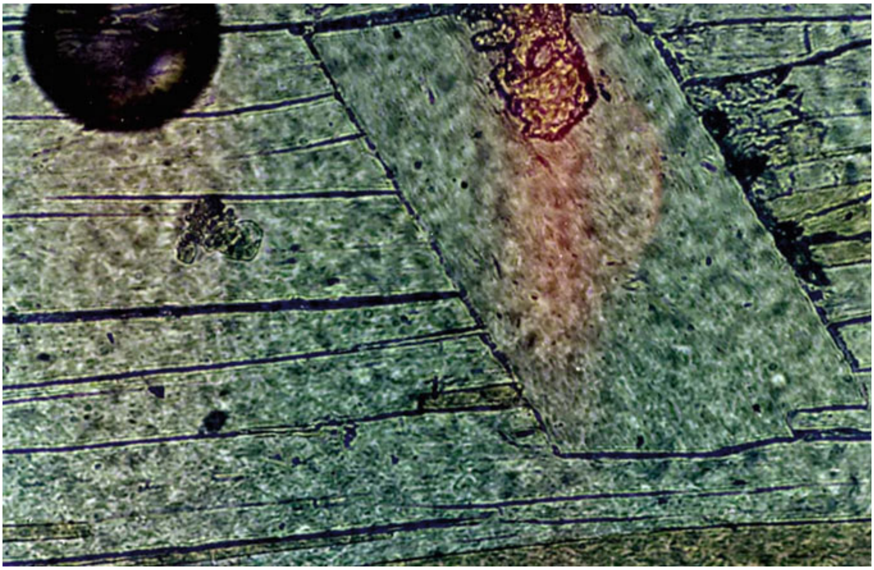

**Fig. 3.11** Flanking microstructure: a nearly *parallelogram-shaped* inclusion of *muscovite* inside another *muscovite grain*. Few cleavages of the host minerals swerve where they touch the inclusion. Shape of the *muscovite* inclusion indicates a *top-to-left* shear. Reproduced from Fig. 6c of Mukherjee (2011). Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 0.5 mm

**Fig. 3.12** Flanking microstructure: a *biotite* inclusion inside a *muscovite* host mineral. Departure from its rectangular geometry and gently curved margins indicate internal deformation of the inclusion. A few cleavages of the *muscovite grains* are curved a little at their contacts with the *biotite grain*. Reproduced from Fig. 4a of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 0.5 mm

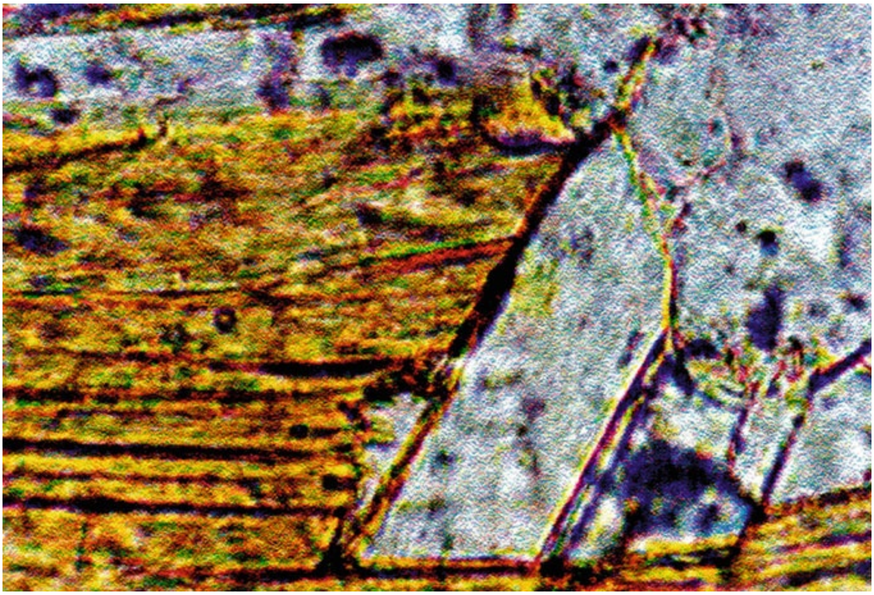

**Fig. 3.13** Flanking microstructure complicated by grain boundary migration. Cleavages of a *biotite grain* swerve near the contact of a *muscovite grain*. Quartz in the matrix migrated towards the *muscovite grain* and destructed its initial (possibly) *parallelogram shape*. The *muscovite grain shape* indicates possibly a *top-to-right* shear. Reproduced from Fig. 4a of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 1 mm

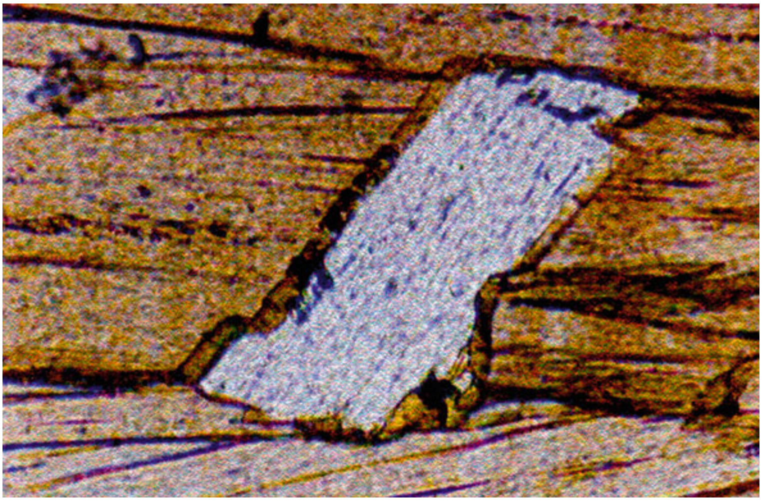

**Fig. 3.14** Flanking microstructure: a nearly *parallelogram-shaped muscovite* inclusion inside a *biotite* host. *Top-to-right* shear. Cleavages of the latter in contact with the inclusion form *thin zones*. This *zone* is zoomed in Fig. 3.15. Reproduced from Fig. 4b of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 2 mm

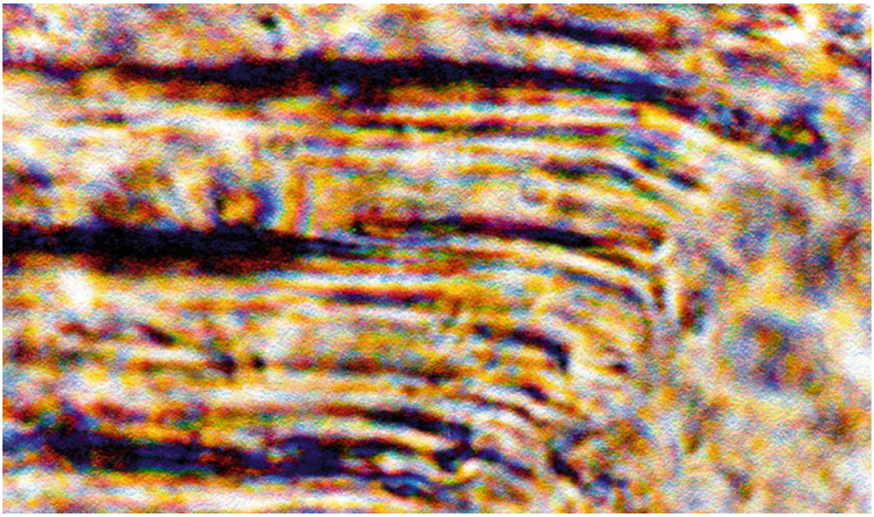

**Fig. 3.15** Flanking microstructure: the contact between cleavage planes of a host mineral and the margin of a nucleated mineral (in Fig. 3.14) reveals under a very high magnification the cleavage planes to be folded. Reproduced from Fig. 4b of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 0.2 mm

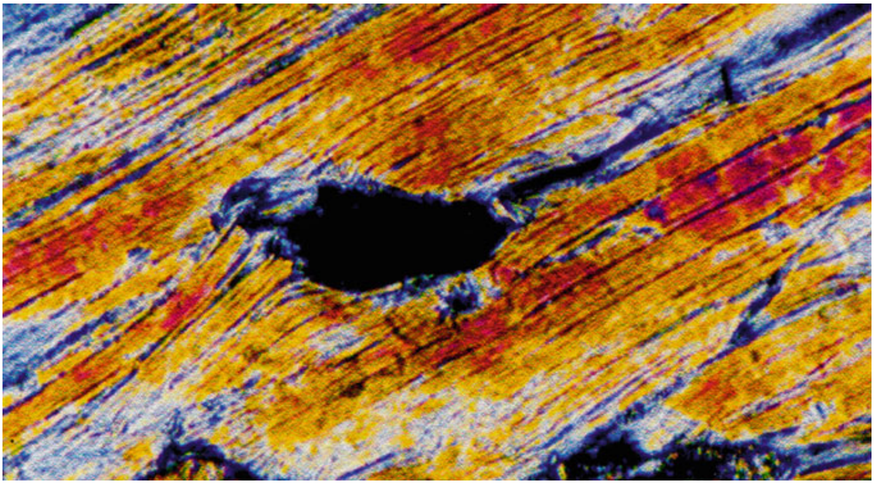

**Fig. 3.16** Flanking microstructure: a *sigmoid alkali feldspar grain* (*top-to-left-down* shear) as an inclusion within a mica grain. Cleavages of the mica grain in contact with the inclusion are dragged variably. Reproduced from Fig. 3c of Mukherjee and Koyi (2009). Cross-polarized light. *Width of view* 1 mm

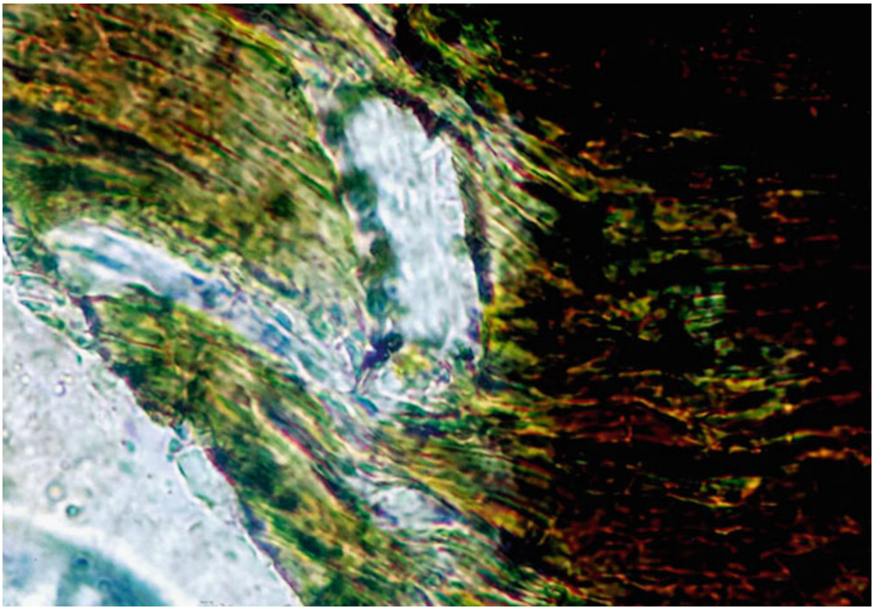

**Fig. 3.17** Flanking microstructure: a nearly *parallelogram-shaped muscovite* inclusion (*top-to-right-up* sheared) inside a *biotite* host. Cleavages of the *biotite grain* are dragged oppositely at the two sides of the *muscovite grain*. Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 0.5 mm

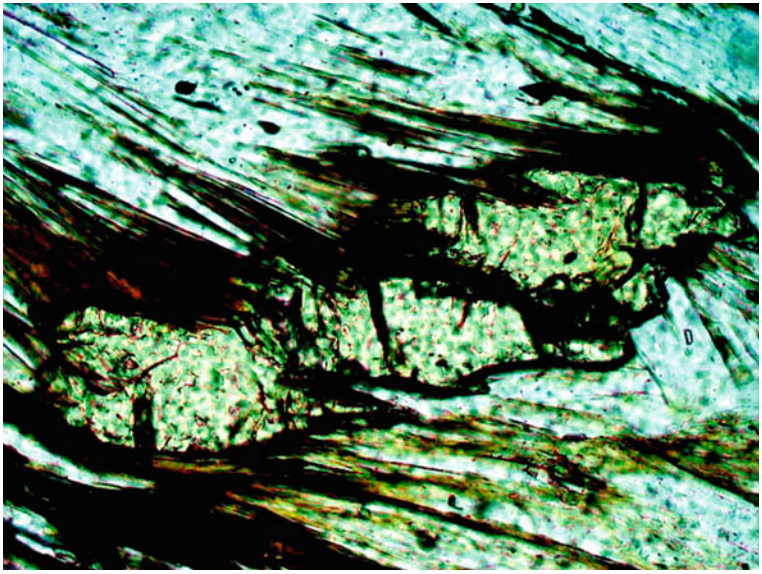

**Fig. 3.18** Flanking microstructure: across a number of sheared *staurolite grains* (*top-to-right-down*) *biotites* are dragged in opposite sense. Same as the photo in plane polarized light in Fig. 6a of Mukherjee (2010). Plane polarized light. *Width of view* 1 mm

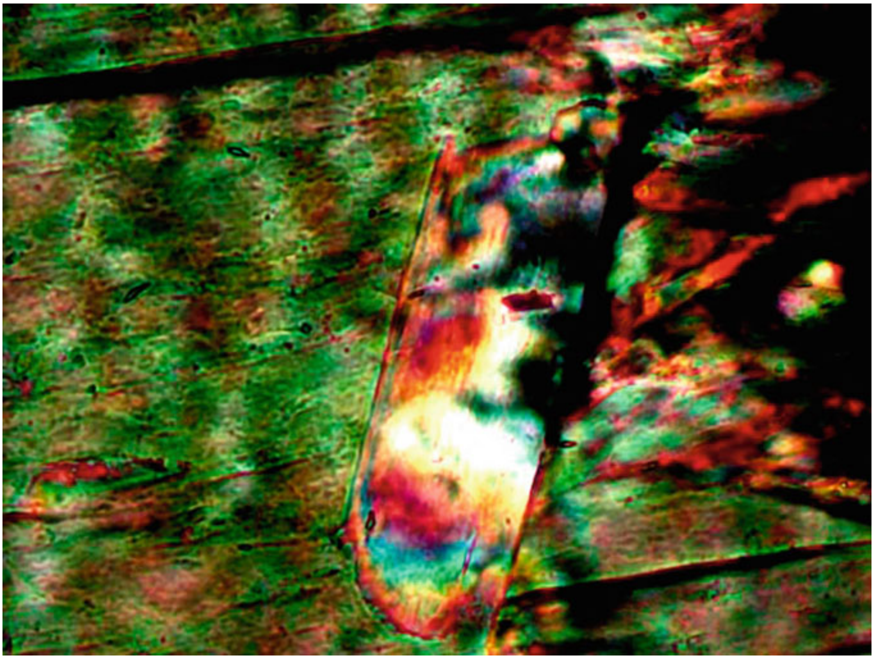

**Fig. 3.19** Flanking microstructure: a *muscovite* inclusion within a *biotite* host swerved cleavages of the latter to opposite sense across it. The degree of curvature of cleavage planes vary significantly at the right side of the inclusion. Same as Fig. 6a of Mukherjee (2011) but in cross-polarized light. *Width of view* 0. 5 mm

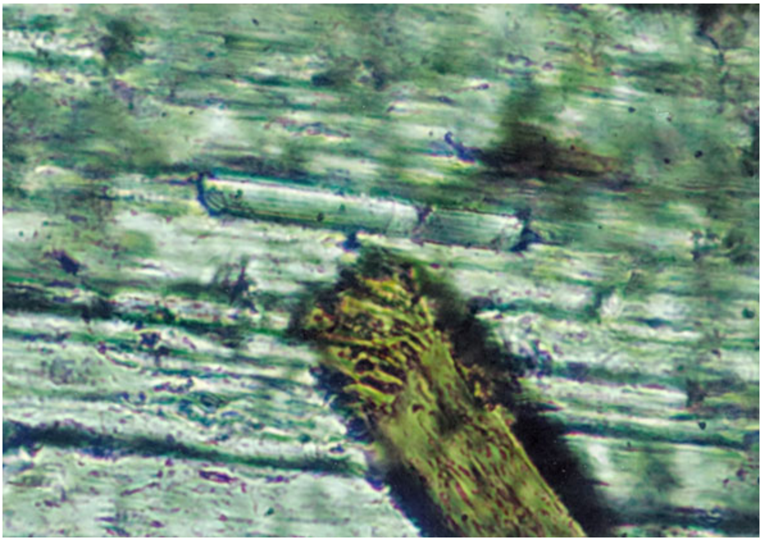

**Fig. 3.20** A *top-to-left* sheared inclusion of *biotite* inside a *muscovite grain*. Cleavages of *muscovite* penetrated significantly inside the *biotite grain*. Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 0.5 mm

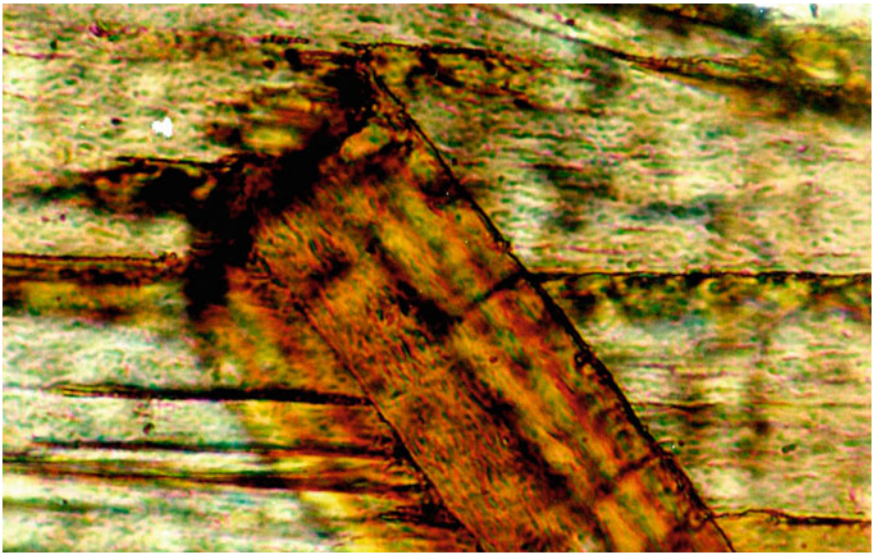

**Fig. 3.21** A *biotite* nucleated inside a *muscovite grain*. Cleavage planes of the host grain are cut sharply by the inclusion. The cleavages are not dragged. Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 0.5 mm

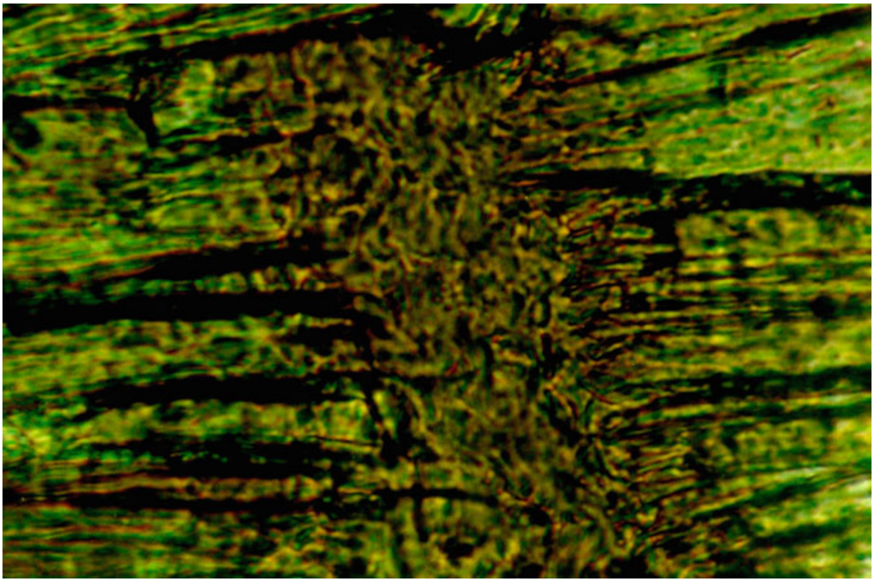

**Fig. 3.22** Flanking microstructure: a *biotite* nucleated inside a *biotite* host swerved the cleavages of the later. The sense of drag of the cleavage planes across the nucleated grain are nearly the same. Plane polarized light. *Width of view* 0.5 mm

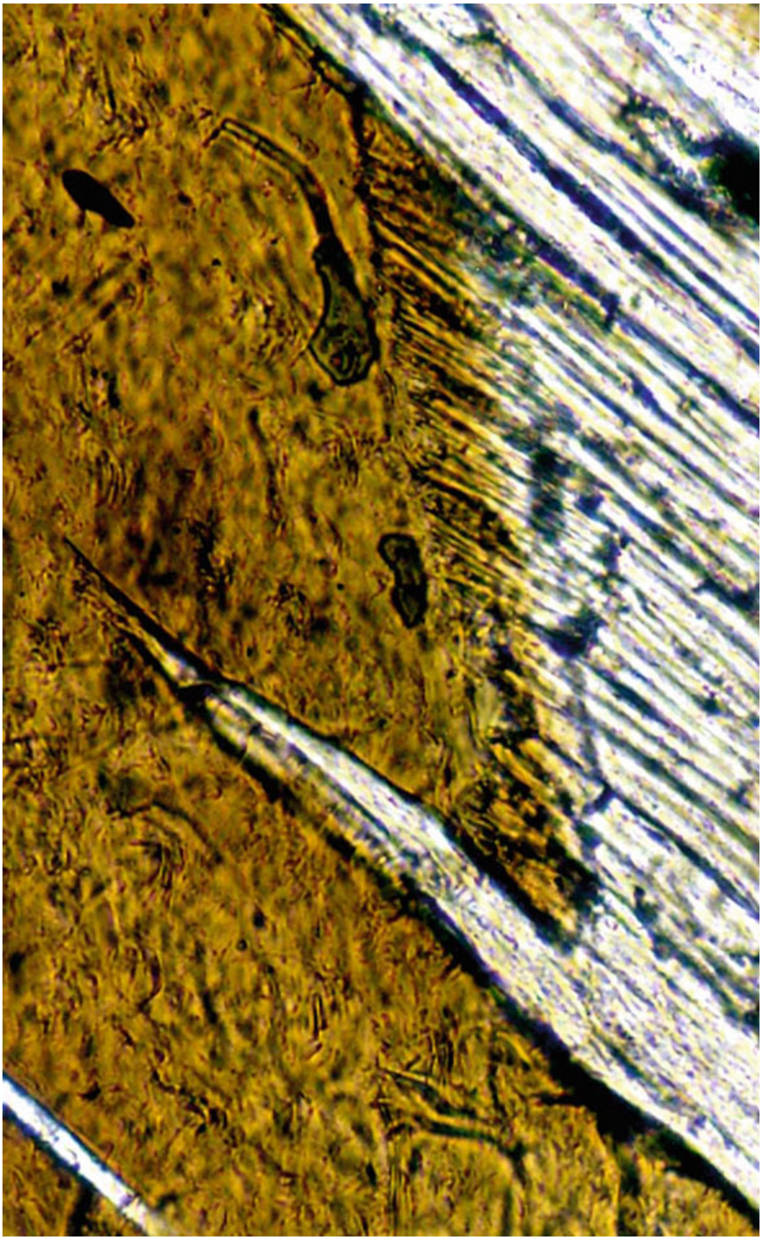

**Fig. 3.23** The contact between a *biotite* included within a *muscovite* host is zoomed. A little curved cleavages of *muscovite* penetrate the *biotite grain*. Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 0.5 mm

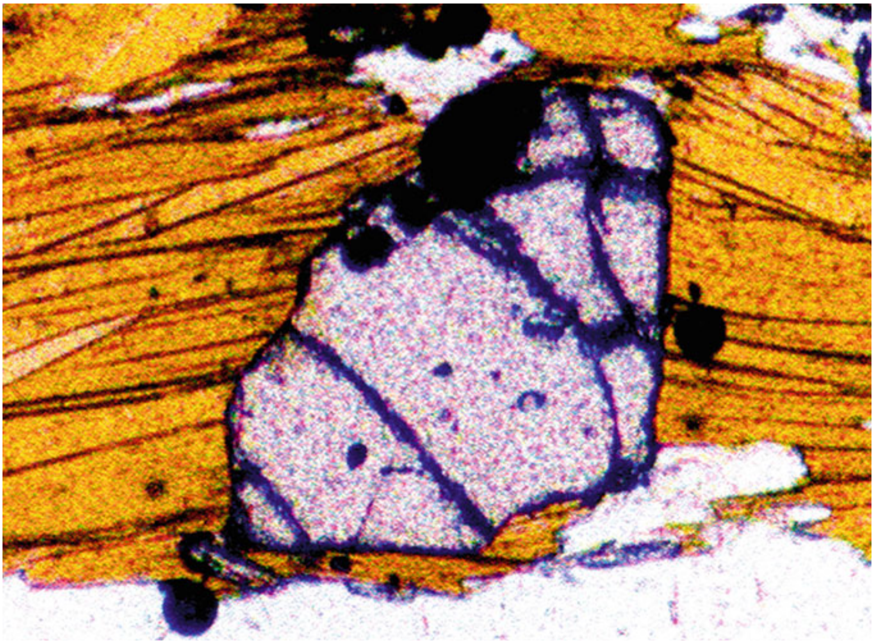

**Fig. 3.24** Flanking microstructure: a *garnet* due to its growth swerved the cleavages of *biotite* in contact with it. Reproduced from Fig. 3b of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 0.5 mm

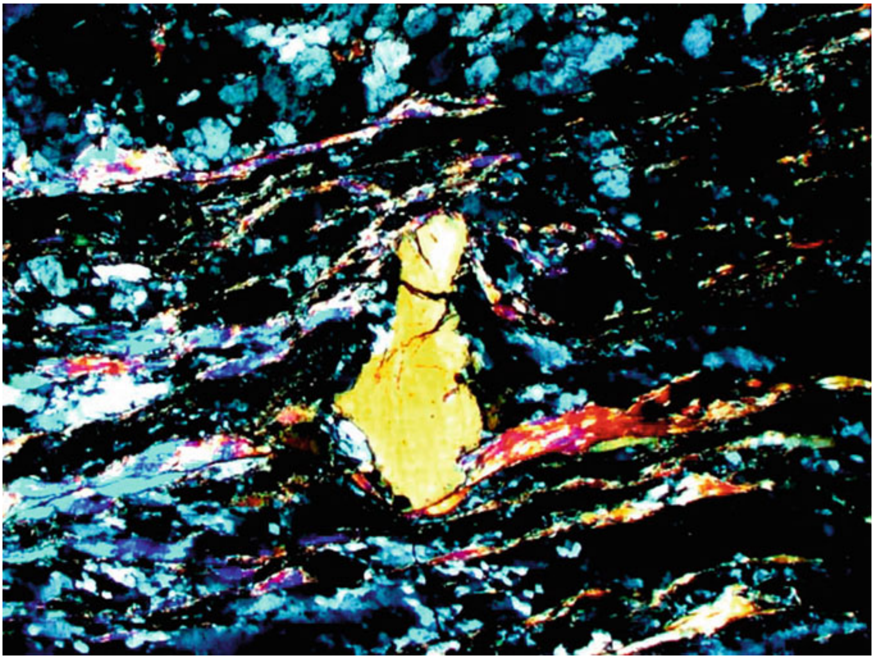

**Fig. 3.25** Flanking microstructure: an *irregular-shaped biotite grain* cut and dragged foliation planes. Reproduced from Fig. 8a of Mukherjee (2011). Cross-polarized light. *Location* Zanskar Shear Zone. *Width of view* 0.5 mm

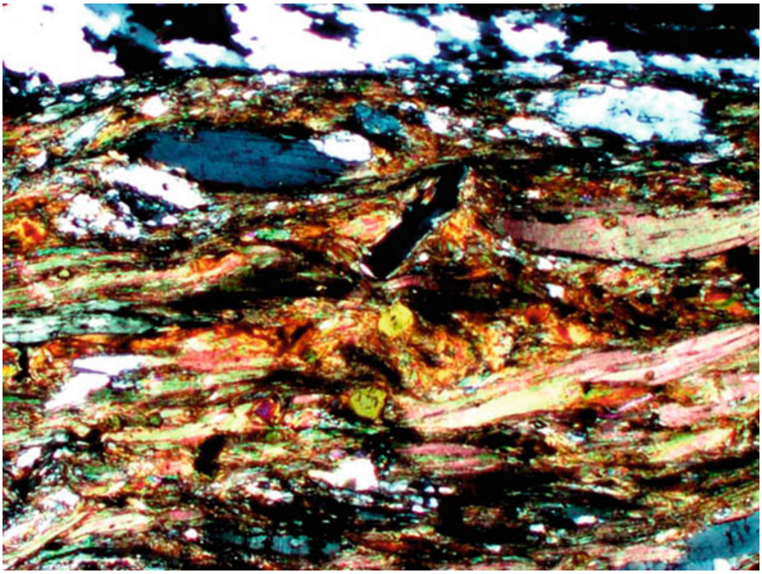

**Fig. 3.26** Flanking microstructure: an elongated grain of *alkali feldspar* cut and dragged foliation planes. The photo is the cross-polarized light version of Fig. 8b of Mukherjee (2011). *Location* Zanskar Shear Zone (2012b). *Width of view* 0.5 mm

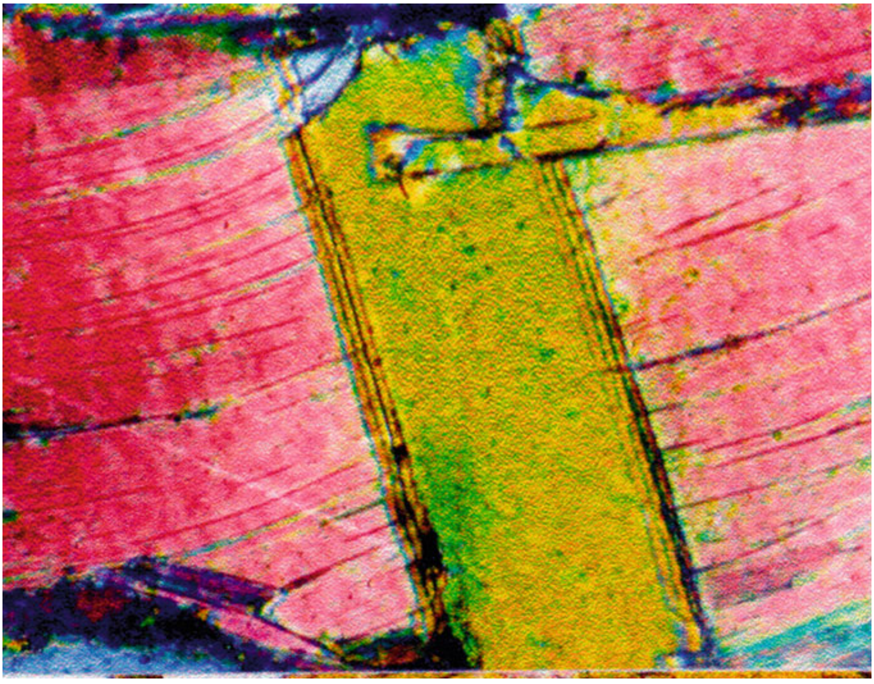

**Fig. 3.27** Flanking microstructure: nucleation and growth of a mica inside another mica host swerved cleavages of the latter. The sense of drag of cleavages of the host mica across the inclusion mica is the same. Cleavages also penetrated a little inside the nucleated mica grain. Reproduced from Fig. 3a of Mukherjee and Koyi (2009). Cross-polarized light. *Width of view* 0.5 mm

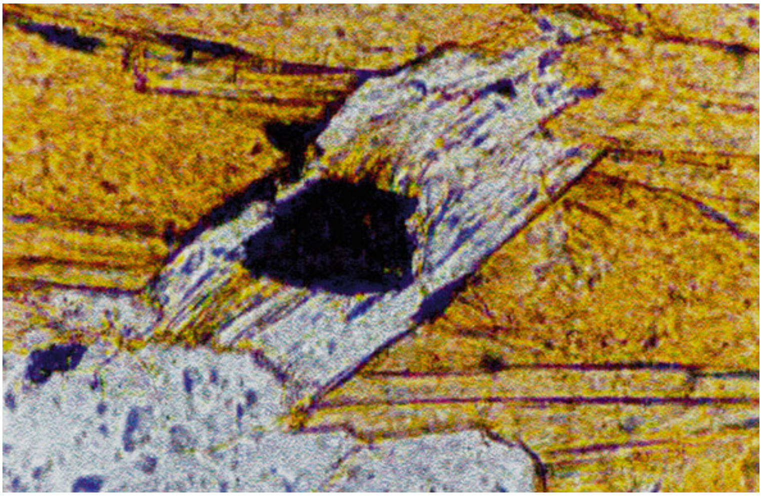

**Fig. 3.28** Flanking microstructure: a *muscovite* inclusion inside a *biotite* host mineral swerved cleavages of the latter. Further, an opaque mineral grew inside the *muscovite grain* and dragged the cleavages of the latter. Reproduced from Fig. 4d of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 0.5 mm

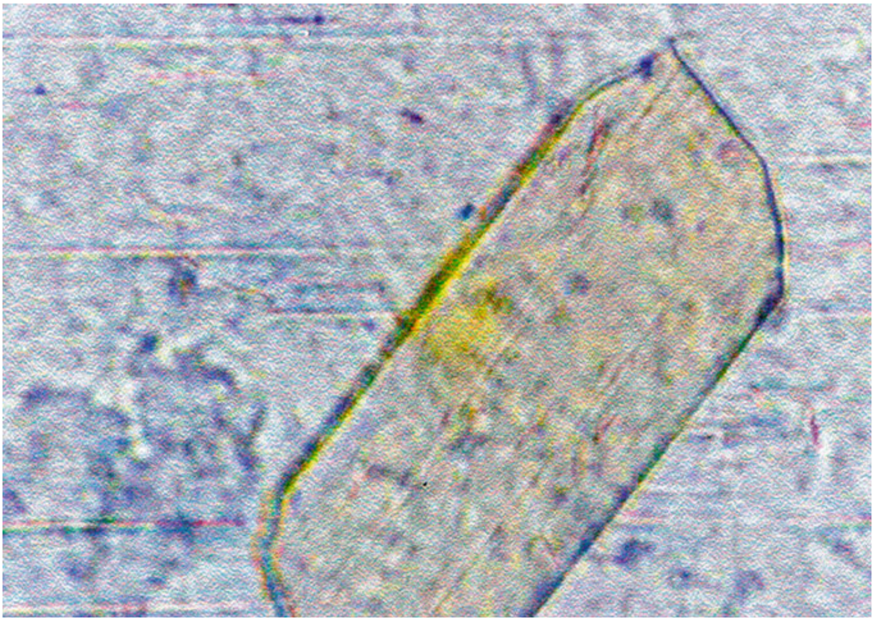

**Fig. 3.29** A nucleation of *muscovite* inside a *muscovite* host mineral. The cleavages of the latter are *not* dragged near the inclusion. Reproduced from Fig. 2a of Mukherjee and Koyi (2009). Plane polarized light. *Width of view* 0.5 mm

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# Chapter 4
# Intrafolial and Other Folds in Shear Zones

Intrafolial folds are tight to isoclinal syn-shear overturned folds in ductile shear zones (Figs. 4.4, 4.5, 4.6). These folds could be bound by both primary- and secondary ductile shear planes. Their vergence indicates primary/secondary ductile shear sense. Micas and quartz are most commonly found in micro-scale to be intrafolially folded. Rarely, high grade index minerals also fold (Figs. 4.6, 4.8, 4.9, 4.10). Ductile shear senses indicated by intrafolial folds match with those given by S-C structures in meso-scale and mineral fish in micro-scale (Mukherjee and Koyi 2010a, b for the cited examples). Thus, such folds indicate a top-to-S/SW regional ductile shear in several Himalayan shear zones. (Mukherjee et al. submitted; Figs. 4.1, 4.2, 4.3, 4.7, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16, 4.17).

**Fig. 4.1** Ductile sheared fish trail developed asymmetric box folds and overturned folds. *Top-to-left* sheared. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

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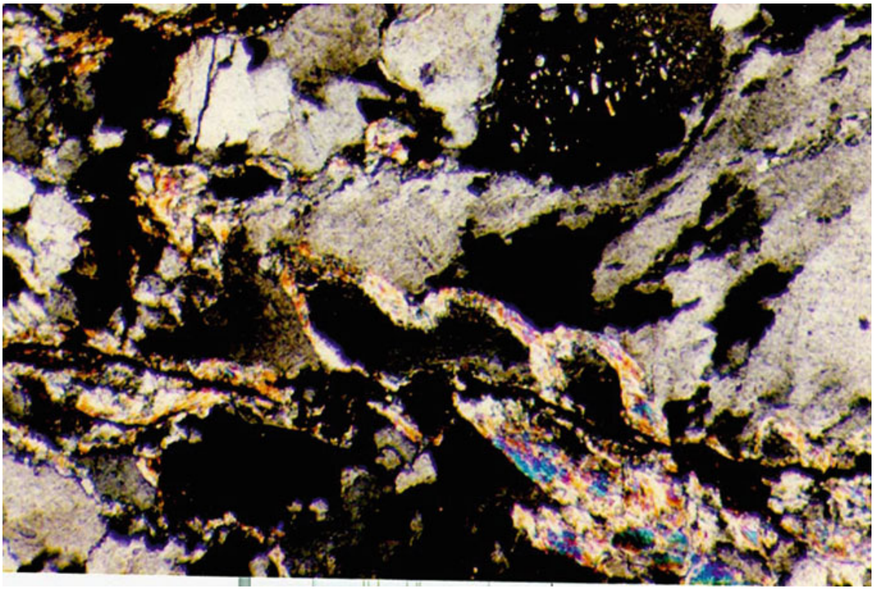

**Fig. 4.2** *Round hinged* fold of an aggregate of fine grained micas is bound at *bottom* by *top-to-left-up* shear plane. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

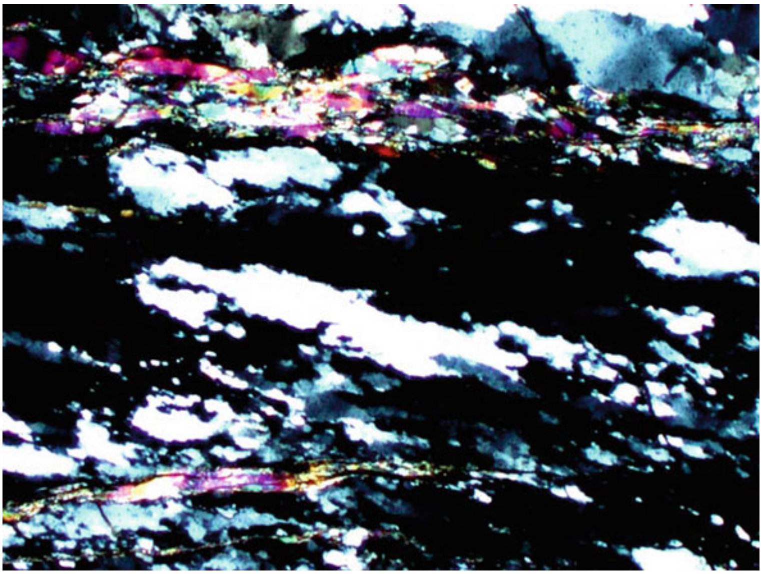

**Fig. 4.3** *Overturned* fold of recrystallized quartz. Limbs are of quite different thicknesses and lengths. *Top-to-left* sheared. Reproduced from Fig. 4d of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 3 mm

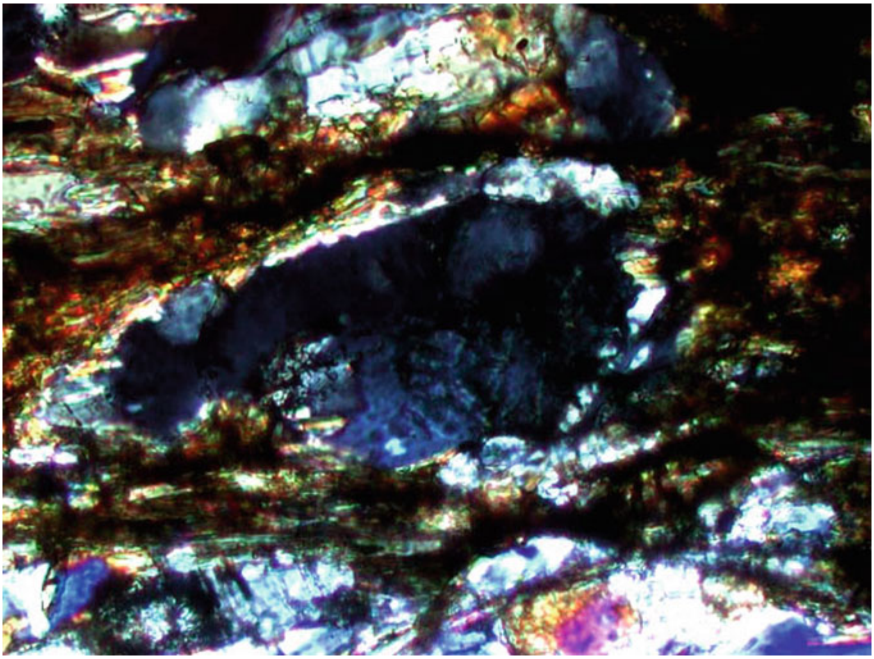

**Fig. 4.4** A rootless intrafolial *overturned round* hinged fold of quartz. *Top-to-right* shear. Reproduced from Fig. 5d of Mukherjee (2010b). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

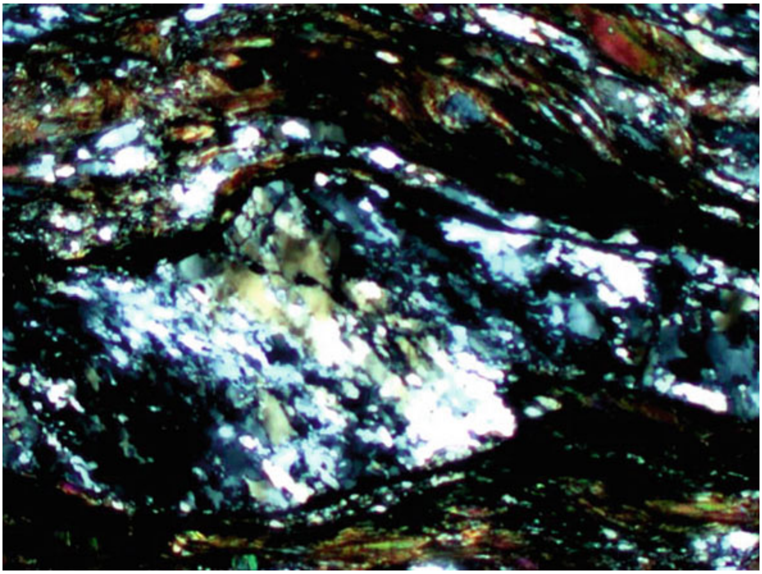

**Fig. 4.5** An *overturned round* hinge folded quartz vein that underwent (coeval to shear?) extensive recrystallization. Notice that the long axes of the recrystallized grains sub-parallel the axial trace of the fold. Reproduced from Fig. 5b of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 3 mm

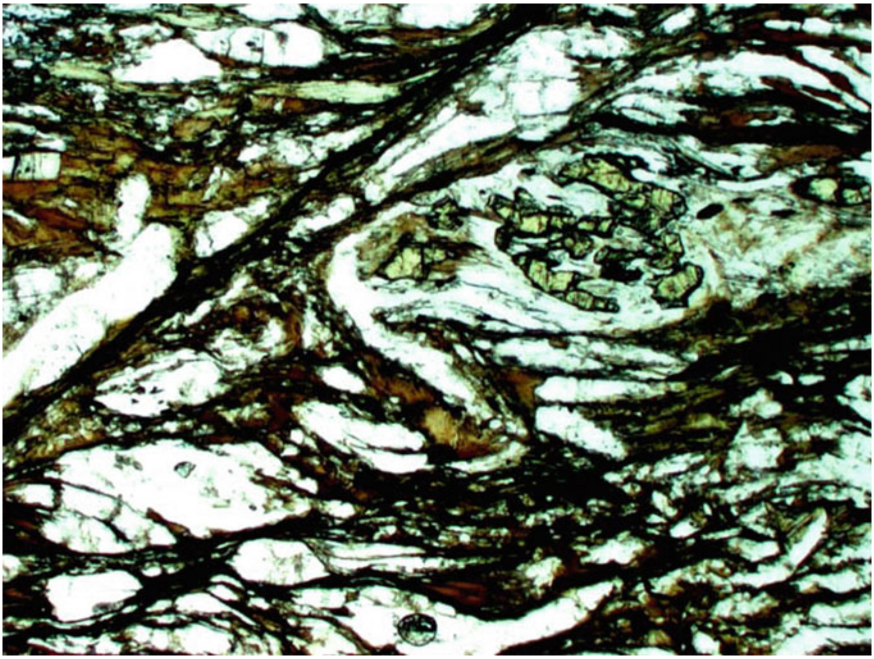

**Fig. 4.6** An aggregate of quartz and staurolite got intrafolial overturned folded due to a *top-to-left-down* synthetic shear. Limbs differ in thickness. Reproduced from Fig. 4a of Mukherjee and Koyi (2010a). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 3 mm

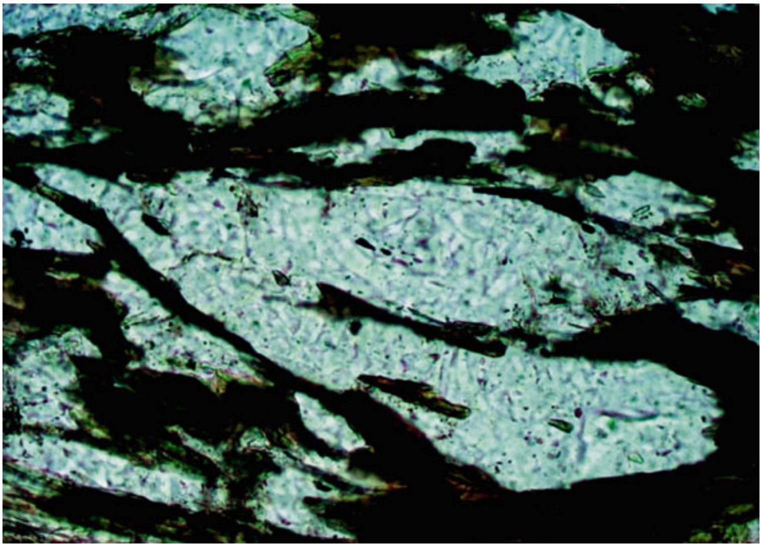

**Fig. 4.7** A rootless *overturned* fold of quartz with *curved* axial trace. *Top-to-left* shear dragged the hinge. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

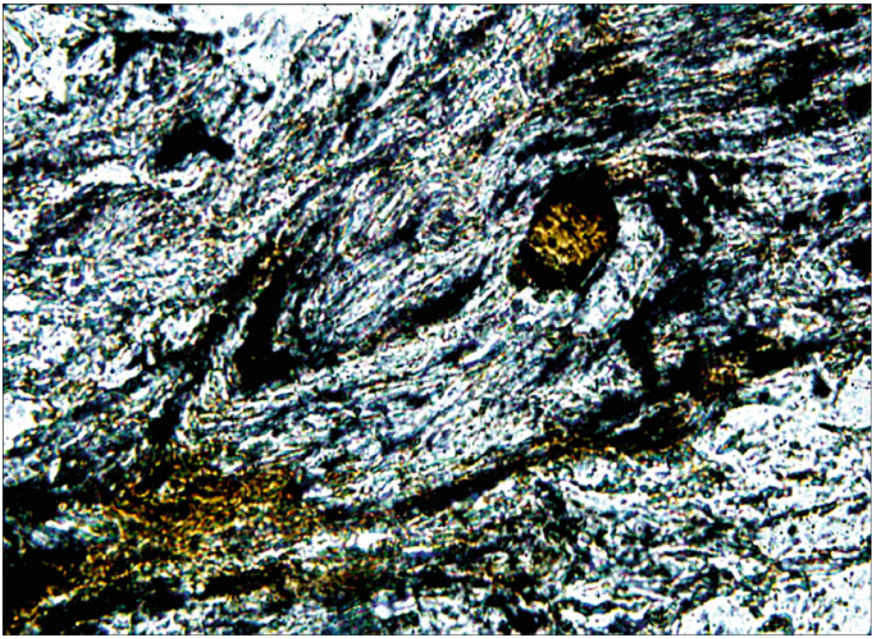

**Fig. 4.8** A rootless fold of sillimanite with angular hinge zone thicker than the limbs. This indicates that during such folding, materials flowed from limbs towards the hinge. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

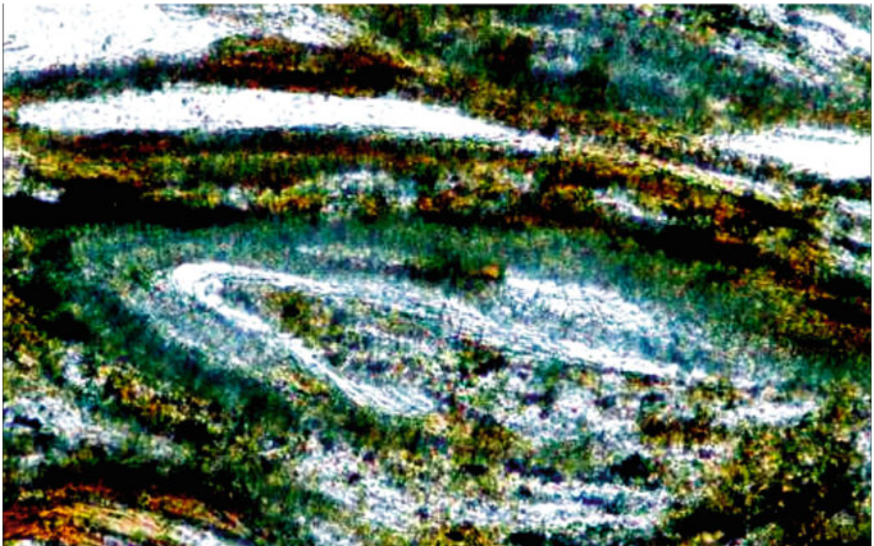

**Fig. 4.9** A *sheared box* fold of sillimanite. *Top-to-left* sheared. Reproduced from Fig. 6a of Mukherjee and Koyi (2010a). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

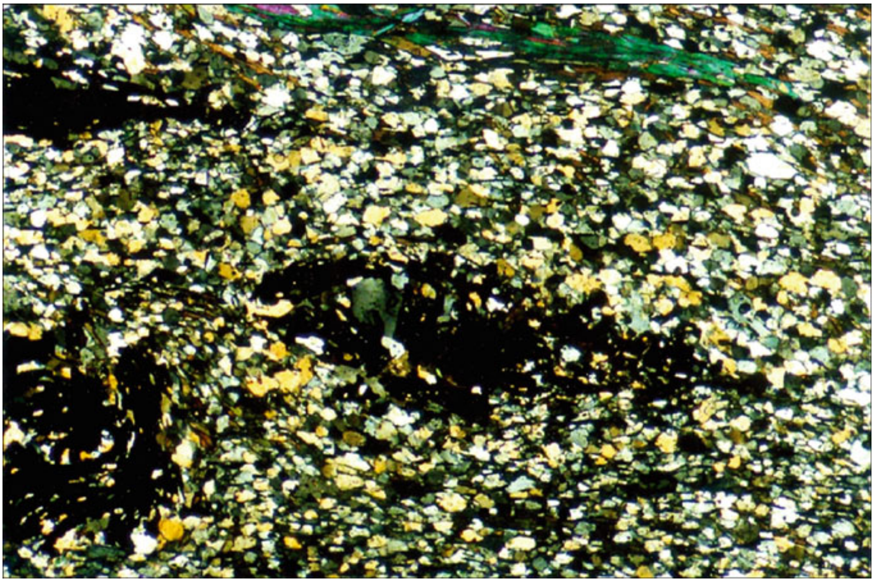

**Fig. 4.10** *Top-to-left* sheared asymmetric garnet porphyroblast with inclusions pattern (the S-internal: '$S_i$') discordant with the foliation within the matrix (the S-external: '$S_e$'). Reproduced from Fig. 9d of Mukherjee (2010a). Cross-polarized light. *Location* Karcham, Higher Himalaya (Himachal Pradesh, India). *Width of view* 4 mm

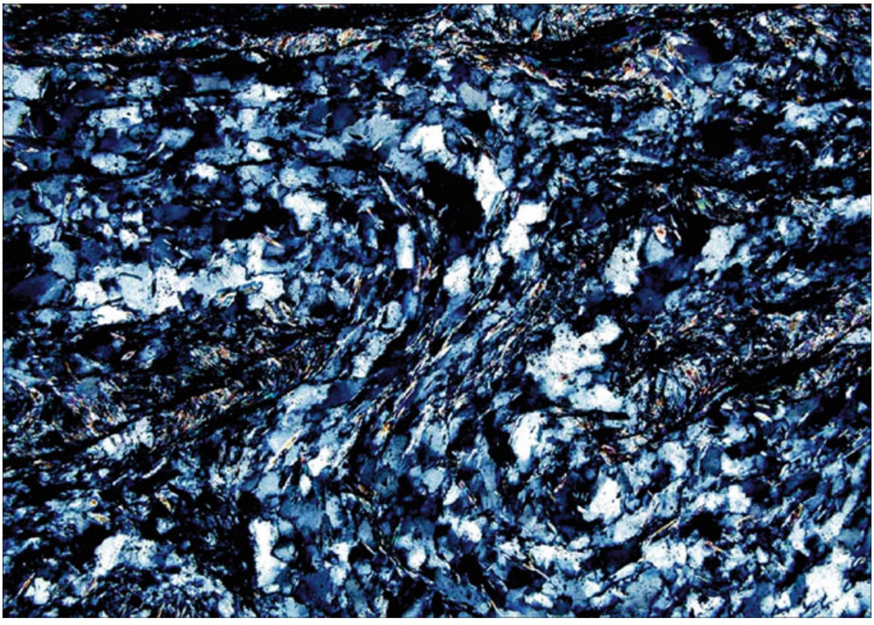

**Fig. 4.11** Broad hinge folded thicker quartzofeldspathic layers and intermediate thinner mica foliations. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

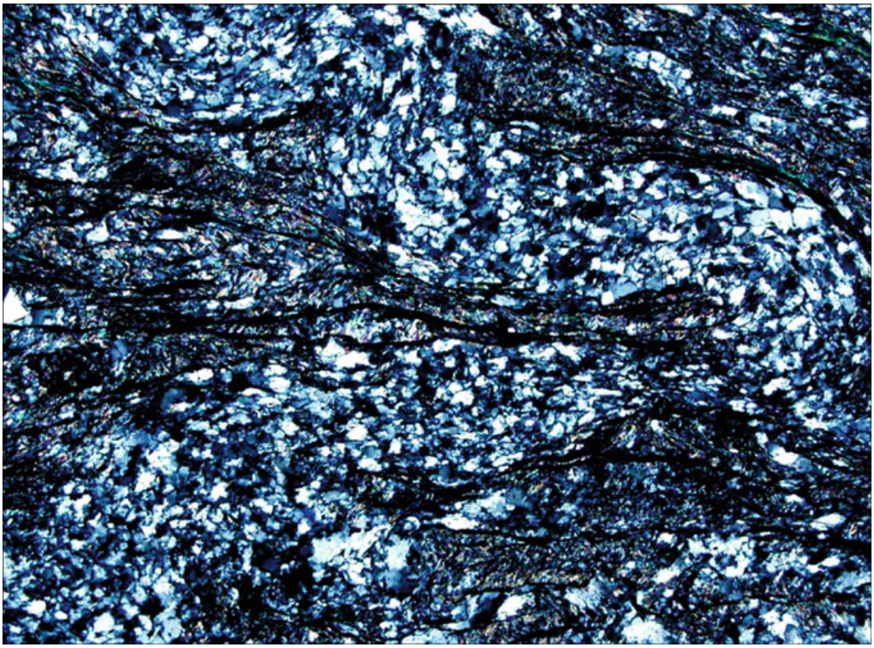

**Fig. 4.12** Broad hinge polyclinally folded thicker quartzofeldspathic layers. Style of folding of the mica layers differ significantly from that of the quartzofeldspathic layers. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

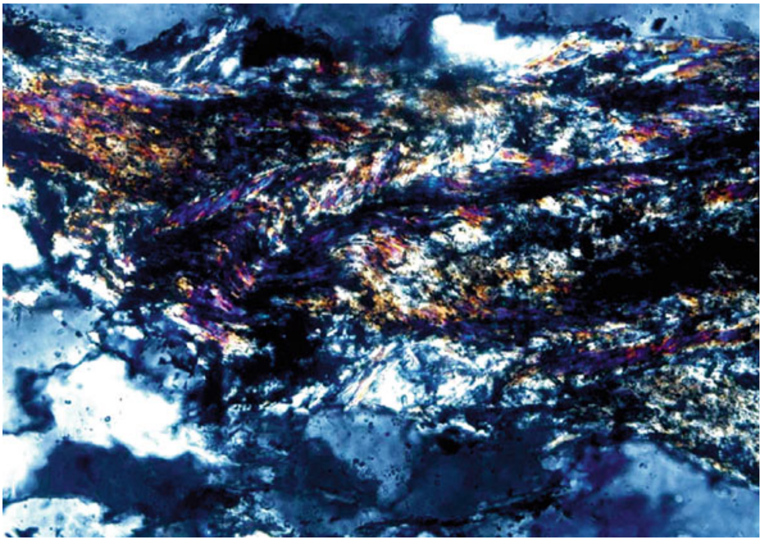

**Fig. 4.13** Less competent micas are kinked whereas the quartzofeldspathic matrix looks undeformed. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

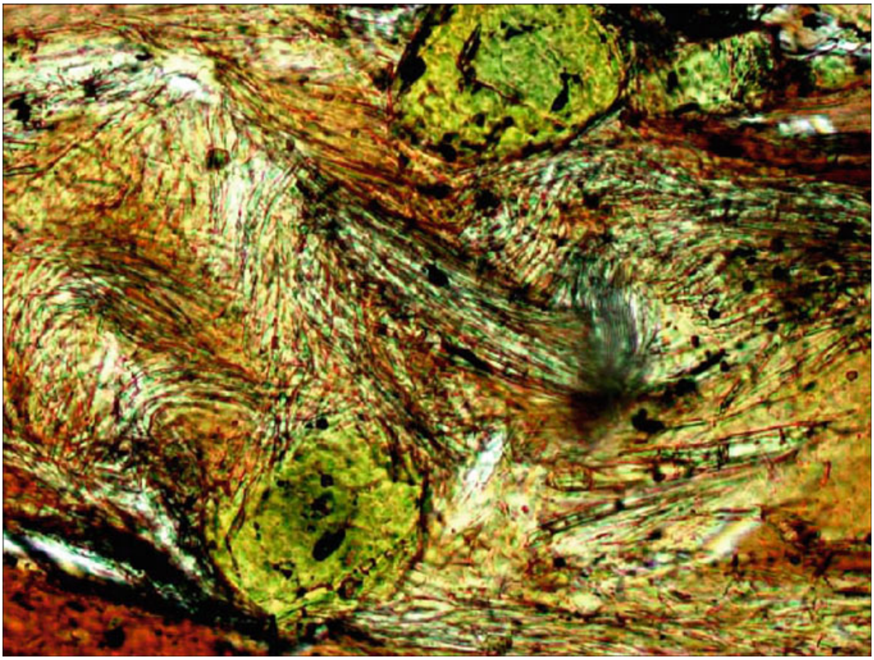

**Fig. 4.14** Kinked and overturned folded aggregate of sillimanites and biotites. Reproduced from Fig. 10d of Mukherjee (2010b). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

**Fig. 4.15** Kinked micas within less a deformed matrix of quartzofeldspathic minerals. Plane-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

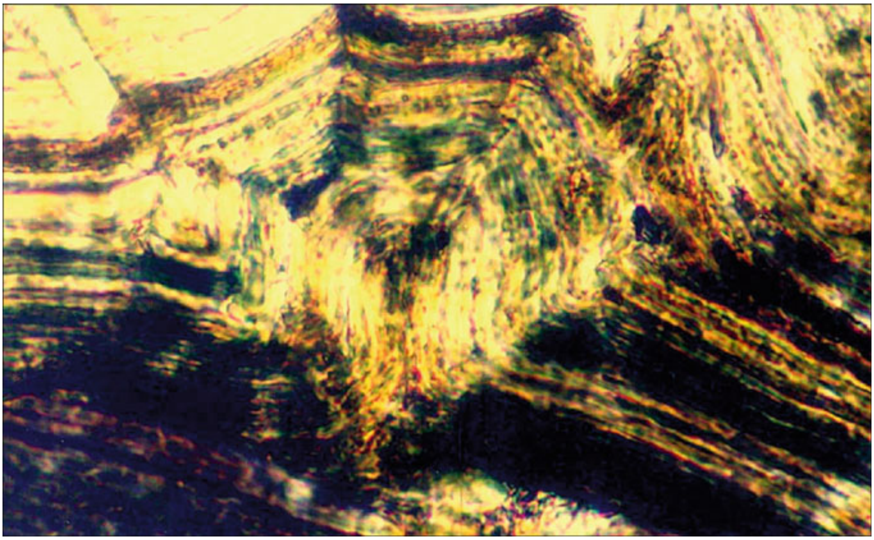

**Fig. 4.16** A polyclinally folded grain of biotite. The geometry of the fold varies from the fold core towards periphery. Reproduced from Mukherjee (2012). *Location* near Mohand, Sub-Himalaya (near Dehradun, India). Plane polarized light. *Width of view* 0.25 mm

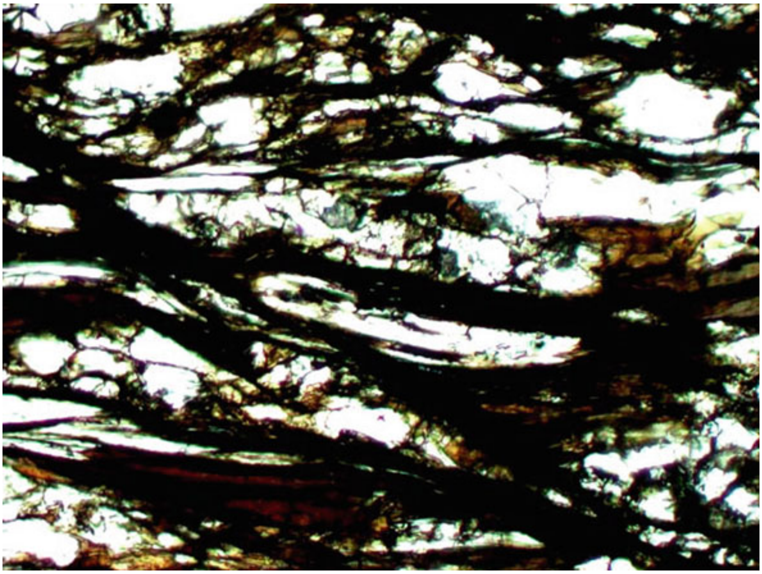

**Fig. 4.17** A *hook-shaped* quartz grain. Could be interpreted as a product of a pro- and a retro ductile shear (*top-to-right* followed by *top-to-left shear*). Same as Fig. 8c of Mukherjee and Koyi (2010a) but in a lower magnification. See Wennberg (1996) for reverse sheared fabrics. Also see Mukherjee (2001) for a review of shear sense reversal. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 5 mm

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# Chapter 5
# Grain Migrations

Migration of one grain into the other destructs the shape of the latter. This brief collection presents rectangular, triangular and sub-circular patterns of migrations. Sometimes migration of two grains towards a single grain leads to a trapezoid-like shape. Such shapes obviously do not indicate shear sense (Figs. 5.1, 5.2, 5.3, 5.4, and 5.5).

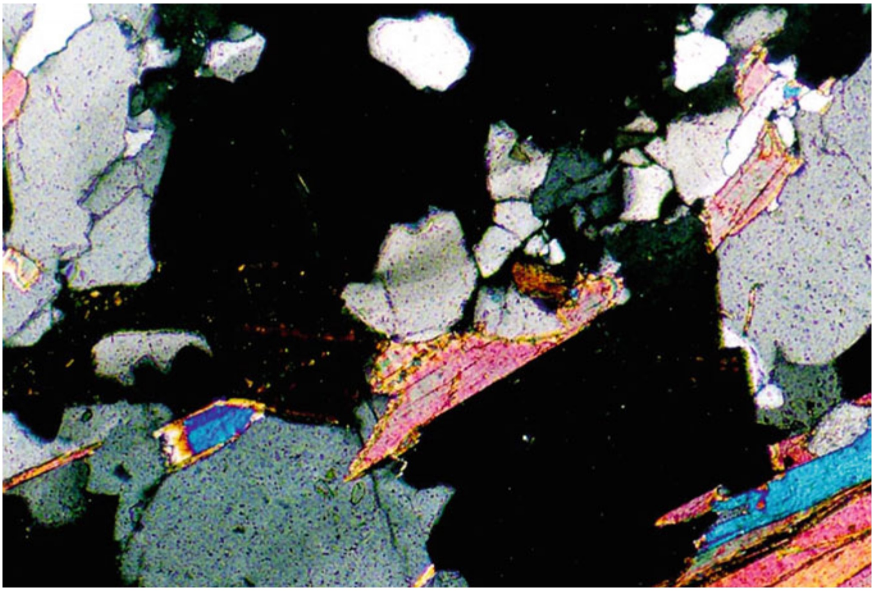

**Fig. 5.1** Migration of quartzofeldspathic minerals from two sides of the mica grain turned the latter nearly *trapezoid-shaped*. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

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Springer Geochemistry/Mineralogy, DOI: 10.1007/978-3-642-25608-0_5,

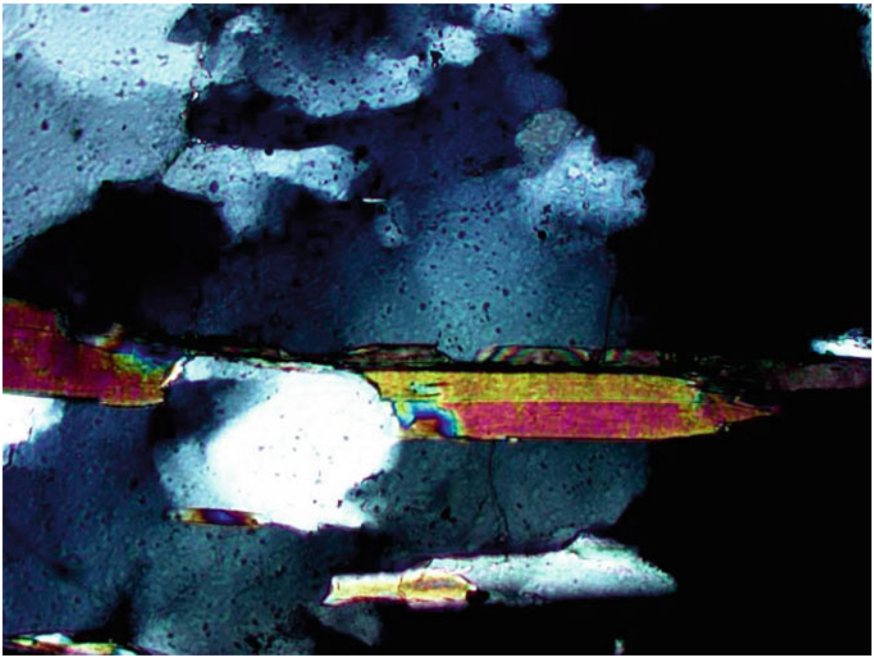

**Fig. 5.2** A 'window microstructure' of Jessel (1987) defined by migration of quartz grain towards an initially *rectangular* mica. Reproduced from Fig. 11 of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2.5 mm

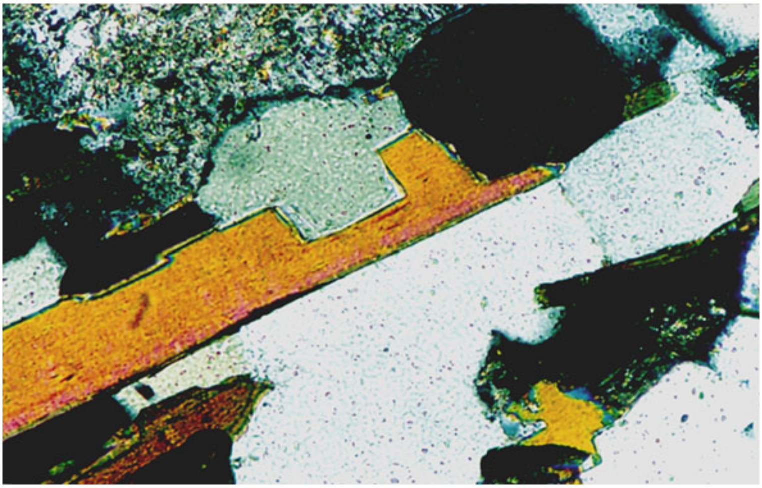

**Fig. 5.3** Alkali feldspars in the matrix migrated towards a mica grain. Reproduced from Fig. 11c of Mukherjee (2010a). Cross-polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 2 mm

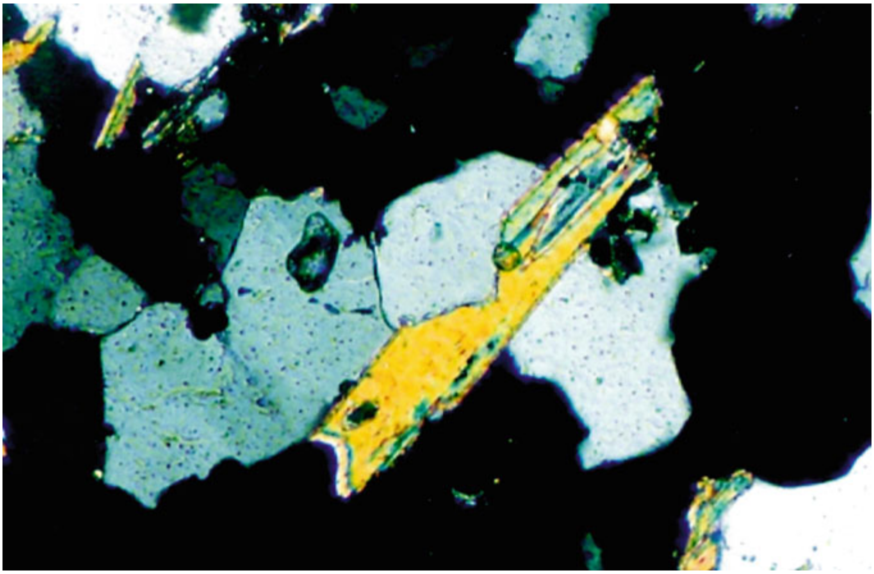

**Fig. 5.4** An alkali feldspar grain in the matrix migrated towards a mica grain. Reproduced from Fig. 3a of Mukherjee (2010a). Cross-polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 2 mm

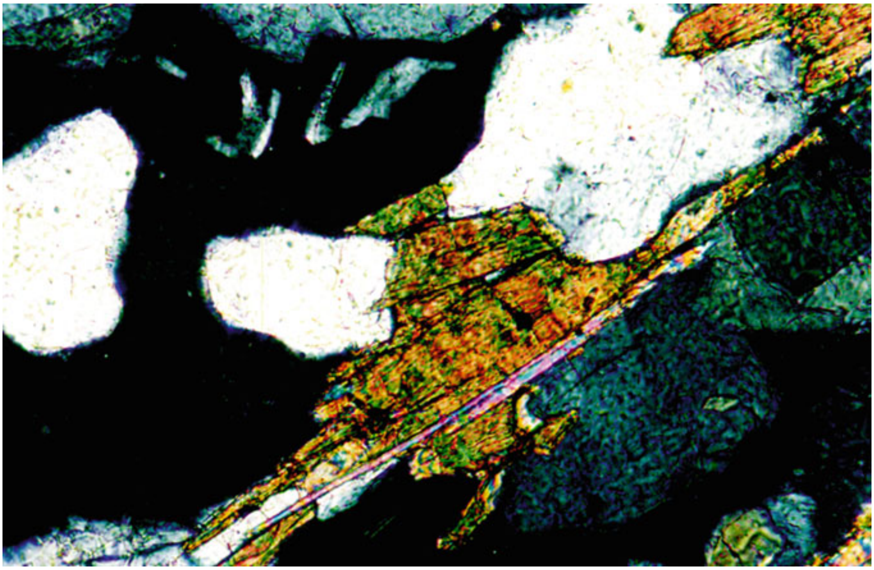

**Fig. 5.5** *Trapezoid-shaped* aggregate of micas. The shape might be produced by migration of quartzofeldspathic minerals from opposite sides of originally *rectangular* mica grains. Therefore, here the *trapezoid shape* does not indicate shear sense. Reproduced from Fig. 10d of Mukherjee and Koyi (2010a). *Location* Higher Himalaya (Himachal Pradesh, India). Cross polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

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# Chapter 6
# Mineral Inclusions

Nucleation and growth of one mineral inside the other is commonly seen microscopically under a high magnification (especially Figs. 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10, 6.11). These inclusions may grow along the cleavage planes of the host minerals (particularly Figs. 6.1, 6.3), or across them (Figs. 6.2, 6.8, 6.9, 6.11). The inclusions could be rectangular, parallelogram trapezoid, sub-circular or irregular-shaped. Ductile shear (along the cleavage planes?) sometimes deform these inclusions (Figs. 6.5, 6.8). Trapezoid-shaped inclusions seem to be a new observation (Figs. 6.4, 6.6). Inclusion patterns inside porphyroblasts have long been used as shear sense indicators, and to judge relative timing between the growth of porphyroblasts and deformation (see Griera et al. (2013) for review). (Figs. 6.12, 6.13, 6.14, 6.15).

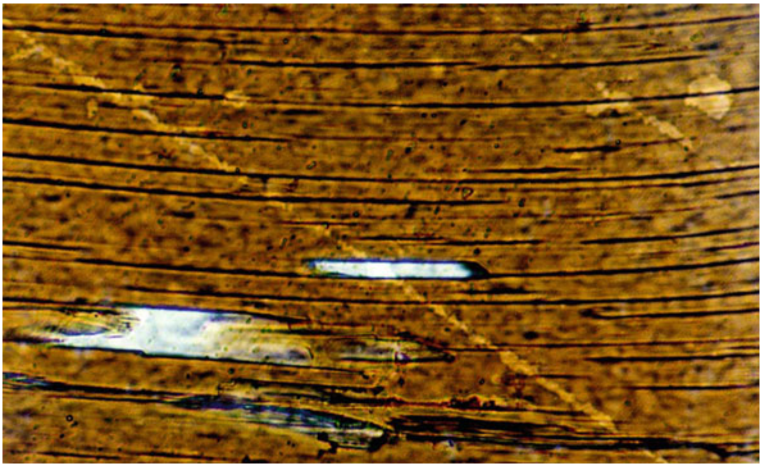

**Fig. 6.1** Nucleated muscovite grains inside a biotite host grain. The long dimension of the inclusion parallels biotite cleavages. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

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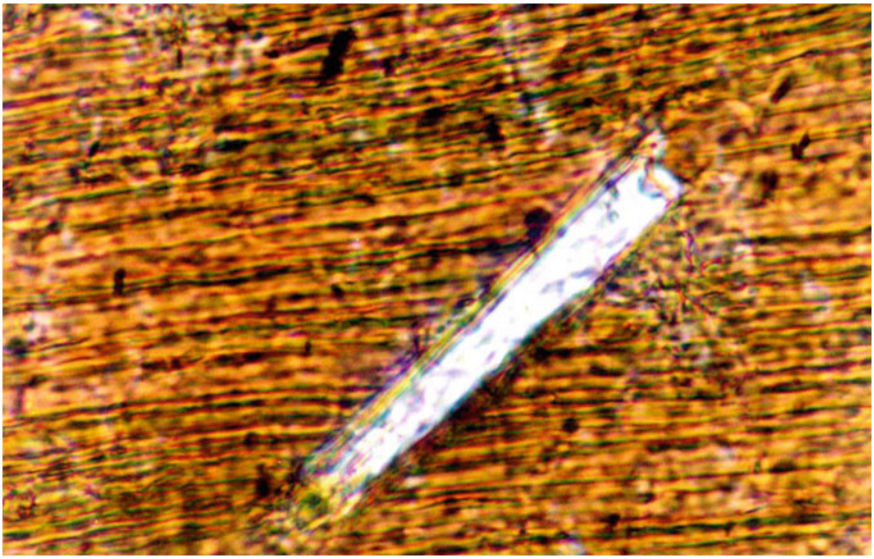

**Fig. 6.2** A near-*rectangular* muscovite inclusion with hazy margins with its long axis oblique to the cleavage of the host biotite grain. Cleavages near the muscovite grain are curved gently. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

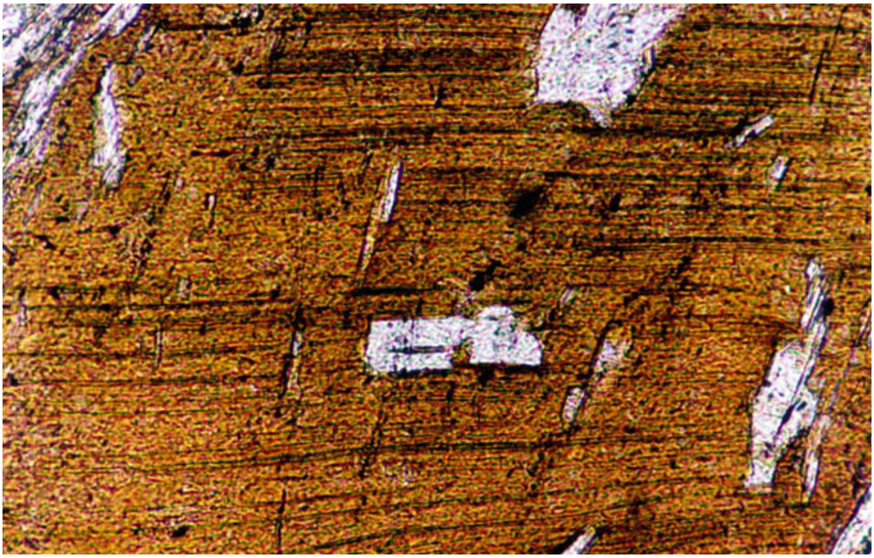

**Fig. 6.3** Muscovite grains nucleated inside a biotite host grain. Long dimensions of few the nucleated grains parallel the cleavages of the host. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

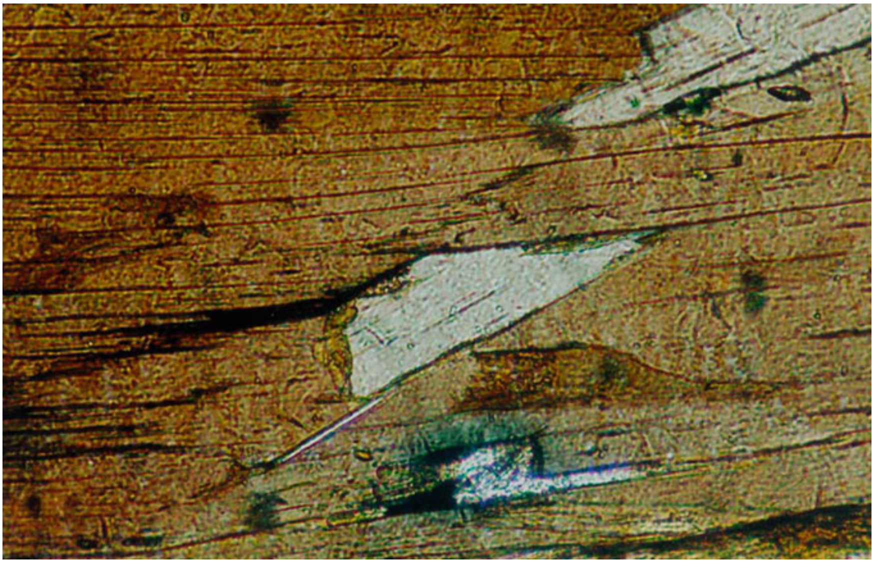

**Fig. 6.4** A nearly *trapezoid-shaped* muscovite inclusion inside a biotite host mineral. Only one of the margins of the inclusions parallels the cleavages of the host biotite. Cleavage planes of the *trapezoid-shaped* grain parallel its longest margin. Plane polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 0.5 mm

**Fig. 6.5** A nearly *parallelogram-shaped* muscovite inclusion inside a biotite host mineral. None of the margins of the inclusions parallel the cleavages of the host biotite. *Location* Higher Himalaya (Himachal Pradesh, India). Plane polarized light. *Width of view* 1 mm

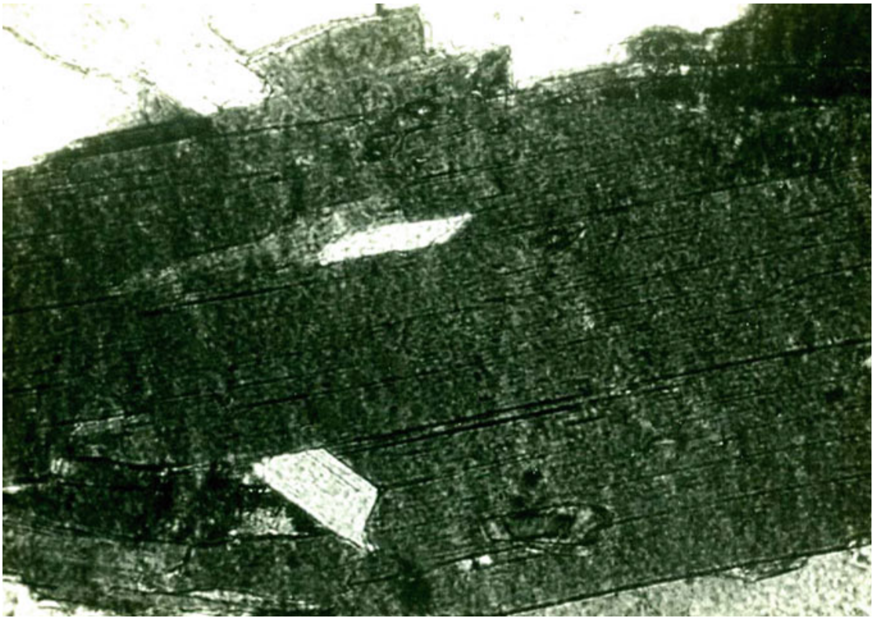

**Fig. 6.6** A *parallelogram* and another *trapezoid* inclusion of muscovite inside a biotite host mineral. Cleavages of the former inclusion parallel that of the host mineral. But this is not the case for the latter inclusion. Shear along the cleavage planes might give rise to *parallelogram shape* of the former from a *rectangular shape*. If so, how did the later acquired a *trapezoid shape*? Cross-polarized light. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 1 mm

**Fig. 6.7** Two *parallelogram-shaped* biotite grains inclined oppositely nucleated over an aggregate of biotites. Do the nucleated grains indicate opposite shear senses (i.e. *left* inclusion: *top-to-right* shear; *right* inclusion: *top-to-left* shear)? Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

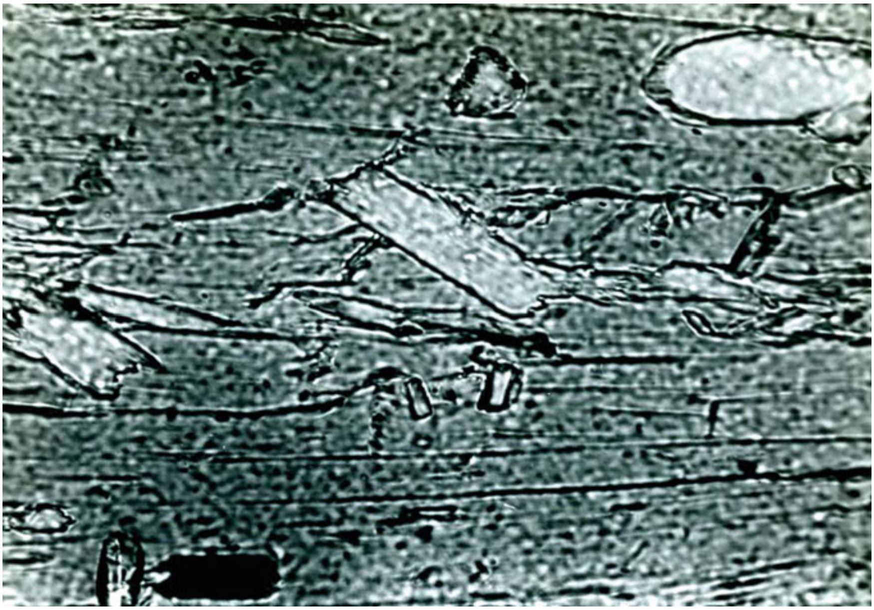

**Fig. 6.8** A train of inclusions of micas, nearly *parallelogram-shaped*, inside a mica host mineral. Possibly *top-to-left* sheared. Some of the smaller inclusions sub-parallel the cleavages of the host mineral. The largest inclusion near the *center* of the photo is inclined to the cleavages. *Location* Higher Himalaya (Himachal Pradesh, India). *Width of view* 0.5 mm

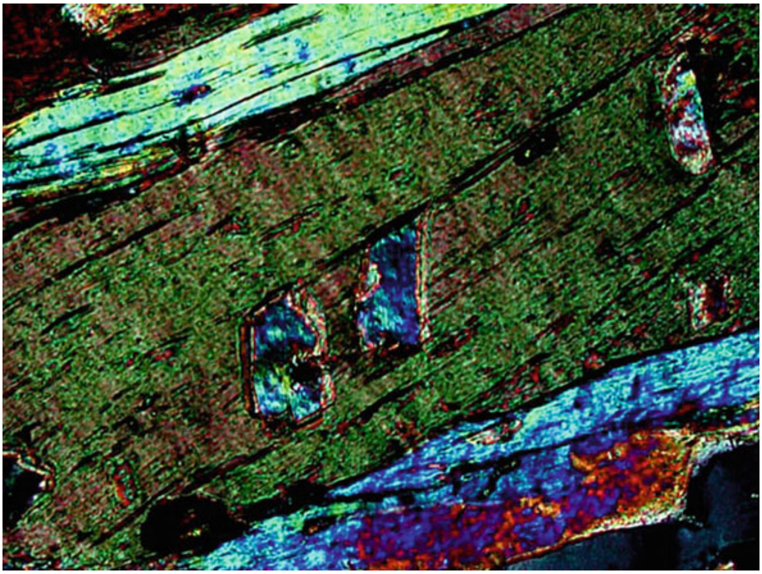

**Fig. 6.9** Two nearly *parallelogram-shaped* mica inclusions inside a mica host mineral. Possibly *top-to-right-up* sheared. A pair of margins of these inclusions parallel cleavages of the host grain. Reproduced from Fig. 7c of Mukherjee (2011). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

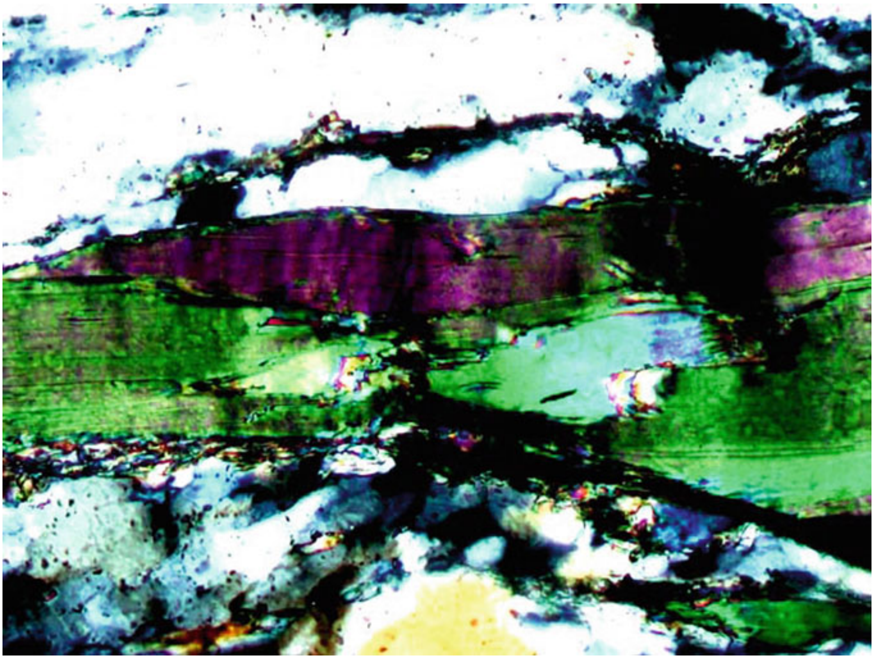

**Fig. 6.10** Two unequal mica inclusions with notches inside a mica host mineral. Are they boudins? Reproduced from Fig. 19 of Mukherjee (2009). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

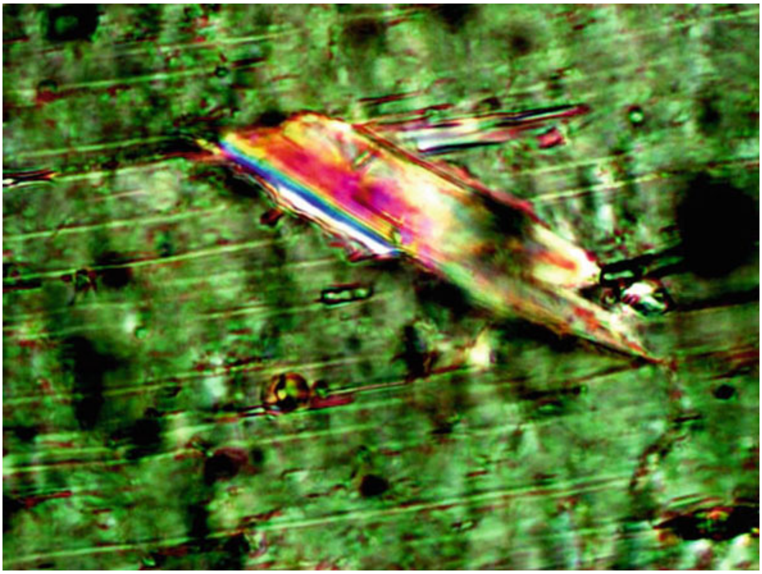

**Fig. 6.11** A nearly *parallelogram-shaped* muscovite nucleation within a biotite host. *Top-to-left* sheared (along cleavages of the host mineral?). Reproduced from Fig. 10c of Mukherjee (2010). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

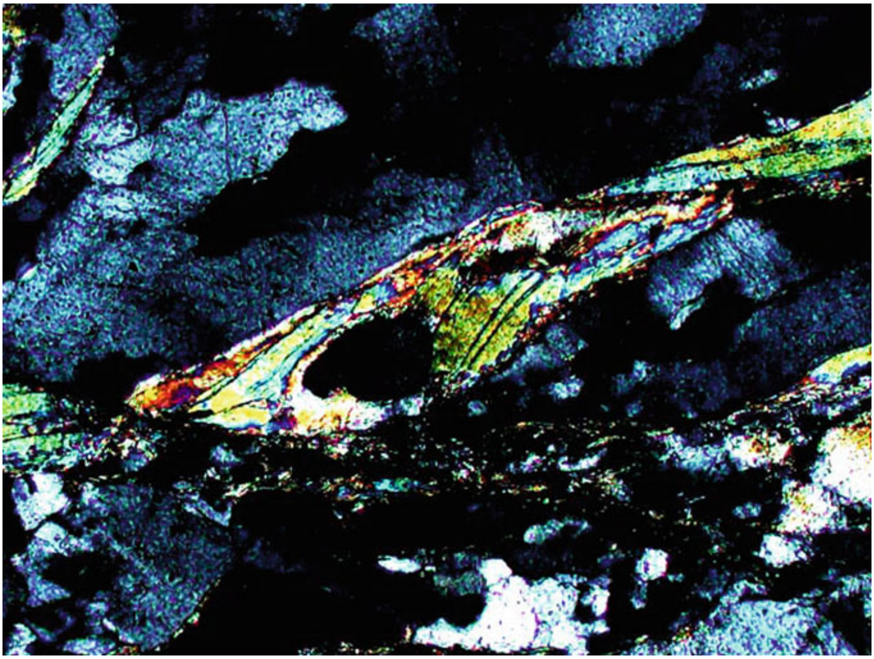

**Fig. 6.12** An alkali feldspar inclusion within a mica fish. The fish shows a *top-to-right* ductile shear. Cleavages of the fish are *curved* significantly near the feldspar grain. Reproduced from Fig. 3a of Mukherjee (2011). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2 mm

**Fig. 6.13** Inclusions inside a garnet porphyroblast restricted mainly in its core. These inclusions do not have any preferred orientation. The *rim* area consists of very few inclusions. Biotites dragged prominently near the garnet. Plane polarized light. *Location* Karcham, Higher Himalaya (Himachal Pradesh, India). *Width of view* 2 mm

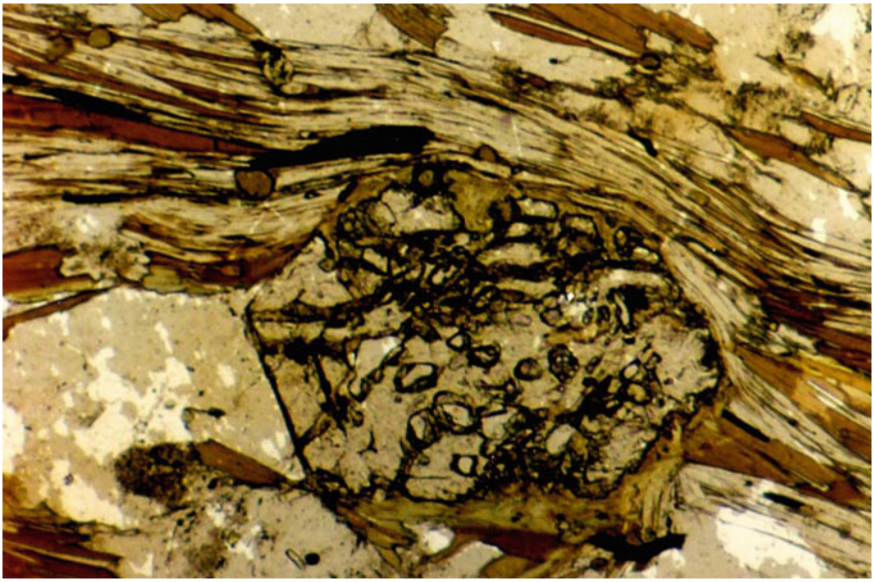

**Fig. 6.14** A garnet porphyroblast with apatite inclusions of no decipherable orientations. Biotite foliations in contact with the garnet have the same sense of curvature (*concave up*). Plane polarized light. *Location* Karcham, Higher Himalaya (Himachal Pradesh, India). *Width of view* 2 mm

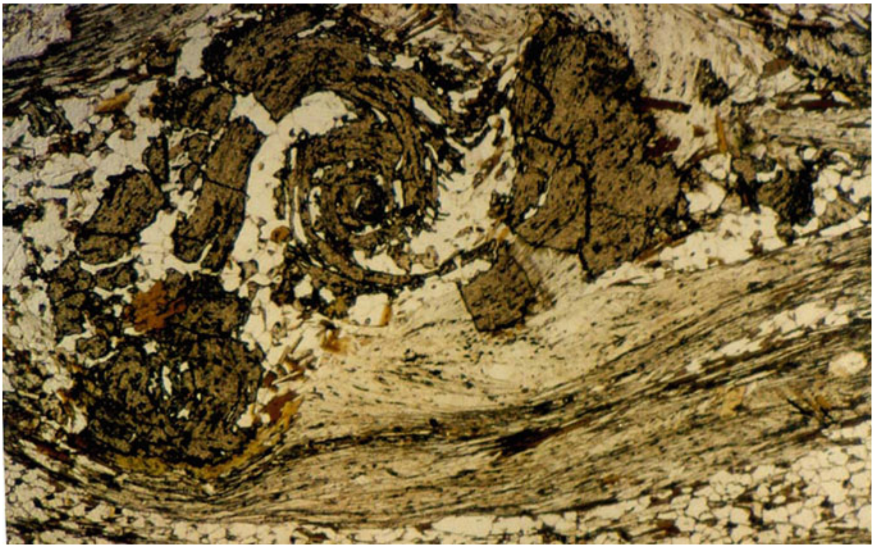

**Fig. 6.15** A typical spiral inclusion pattern inside a garnet porphyroblast. Foliation micas are warped significantly near the *opened up* portion of the garnet grain. Plane polarized light. *Location* Karcham, Higher Himalaya (Himachal Pradesh, India). *Width of view* 2 mm

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# Chapter 7
# Pull-Aparts, Boudins and Brittle Faults

Brittle deformation of mineral grains may slip (= fault), separate along either a parallel opening (parallel-pull-apart) or along a v-opening (V-pull-apart: Hippertt 1993; Mukherjee 2010a etc.). The V-openings could be curved. Minerals can stretch and separate partially (pinch and swell structures) or completely (boudins) (Figs. 7.16, 7.17, 7.18). Brittle slip may or may not be associated with drag of the faulted mineral fragments (Figs. 7.20, 7.21, 7.22, 7.23, 7.24, 7.25, 7.26). The V-pull aparts from the Himalayan shear zones indicate usually a top-to-S/SW brittle shear (Figs. 7.6, 7.8, 7.9, 7.10, 7.11). This shear sense matches with duplexes observed from the same field areas (see Mukherjee and Koyi 2010a, 2010b for discussions). Thus, these pull-aparts are the micro-scale manifestations of foreland vergent forethrusting of the northern portion of the Indian plate. (Figs. 7.1, 7.2, 7.3, 7.4, 7.5, 7.7, 7.12, 7.13, 7.14, 7.15, 7.19)

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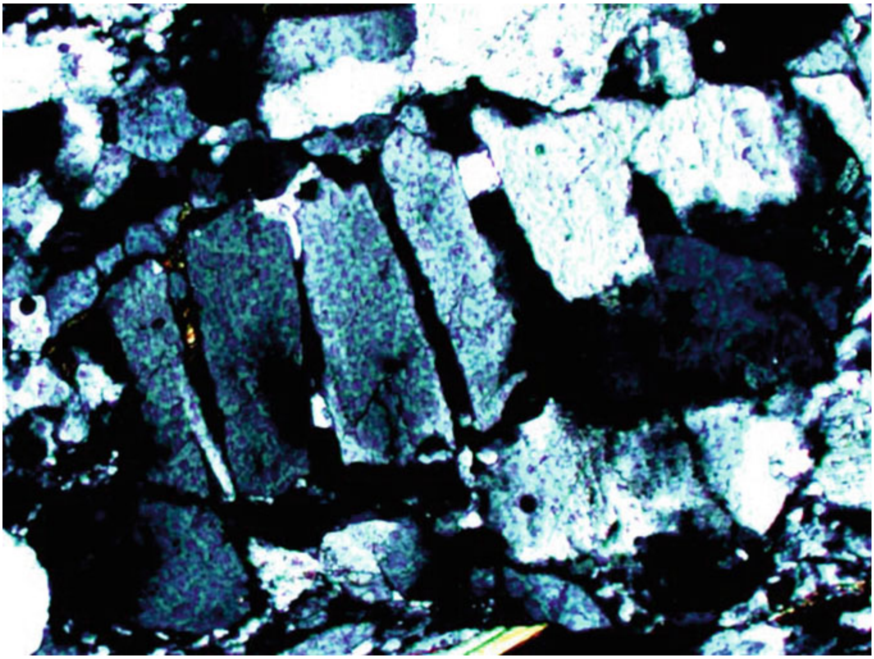

**Fig. 7.1** Sub-parallel pull-aparts of alkali feldspar. Before it was pulled apart, the feldspar grain was elliptical fish shaped. Reproduced from Fig. 12d of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2.5 mm

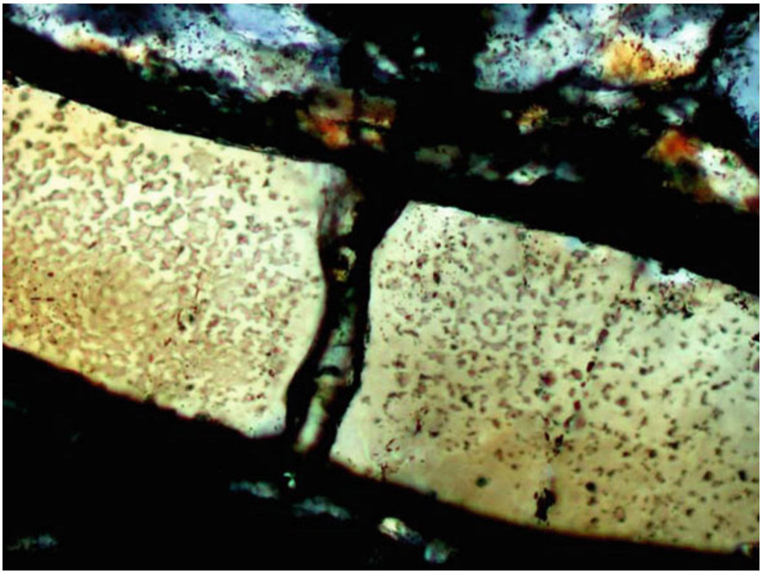

**Fig. 7.2** A parallel pull-apart at high magnification reveals curved brittle planes. Reproduced from Fig. 11b of Mukherjee (2010b). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

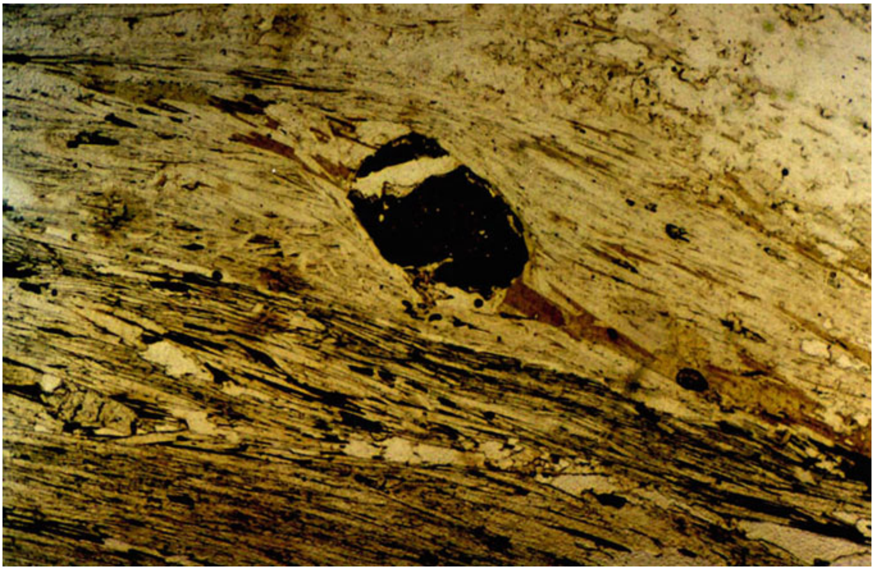

**Fig. 7.3** A lenticular garnet fish with tails of biotites at opposite sides defines an overall sigmoid shape. *Top-to-left* shear. The garnet grain underwent a sub-parallel. A pull-apart of garnet. Nearly of V-type. Plane polarized light. *Location* Shyok Suture Zone (India). *Width of view* 4 mm

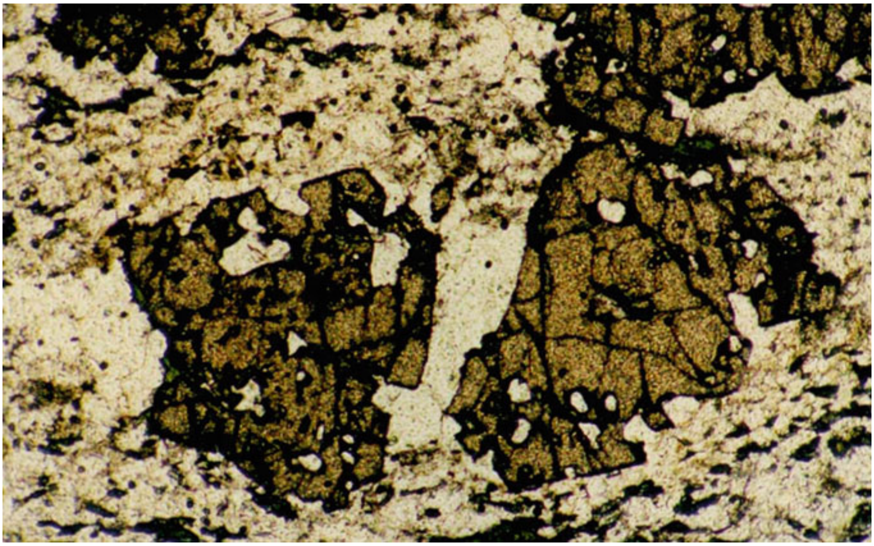

**Fig. 7.4** A pull-apart of garnet. Neither parallel nor V-geometry. Foliation in the matrix scar/ passive folded inside the open space created by the pull-apart. The open space and also the surrounding of the garnet is 'filled up' (?) by quartz. Plane polarized light. *Location* Shyok Suture Zone (India). *Width of view* 1 mm

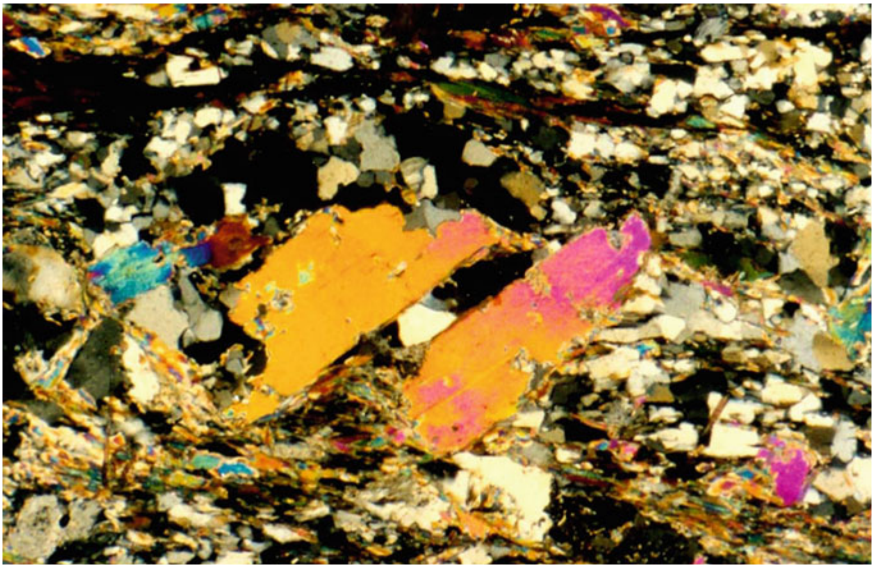

**Fig. 7.5** A pulled-apart mica grain. Neither parallel nor V-geometry. Prominent scar folding of mica foliations in the matrix developed near the opening between the separated fragments. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

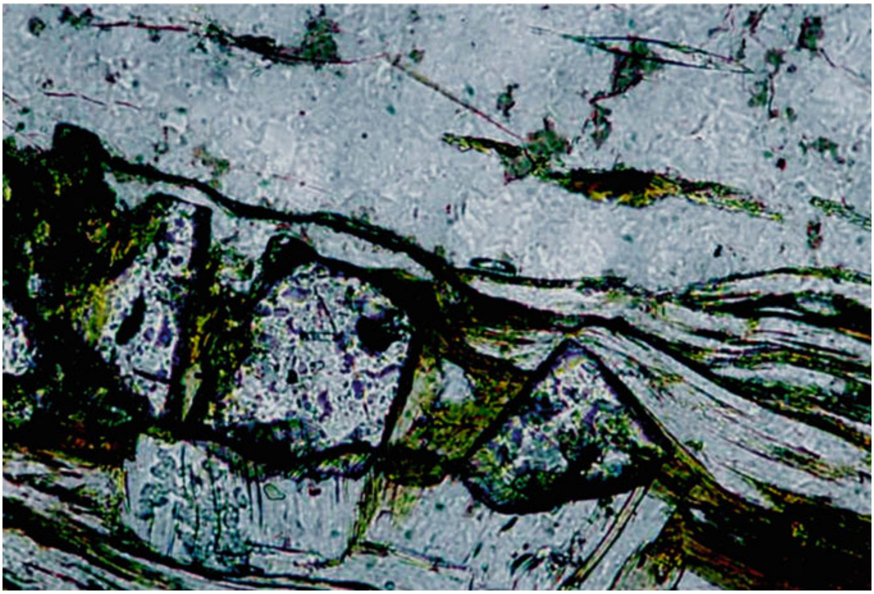

**Fig. 7.6** V-pull-aparts of garnet. Muscovites and chlorites scar/passive folded inside the opening. Reproduced from Fig. 12a of Mukherjee and Koyi (2010a). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 5 mm

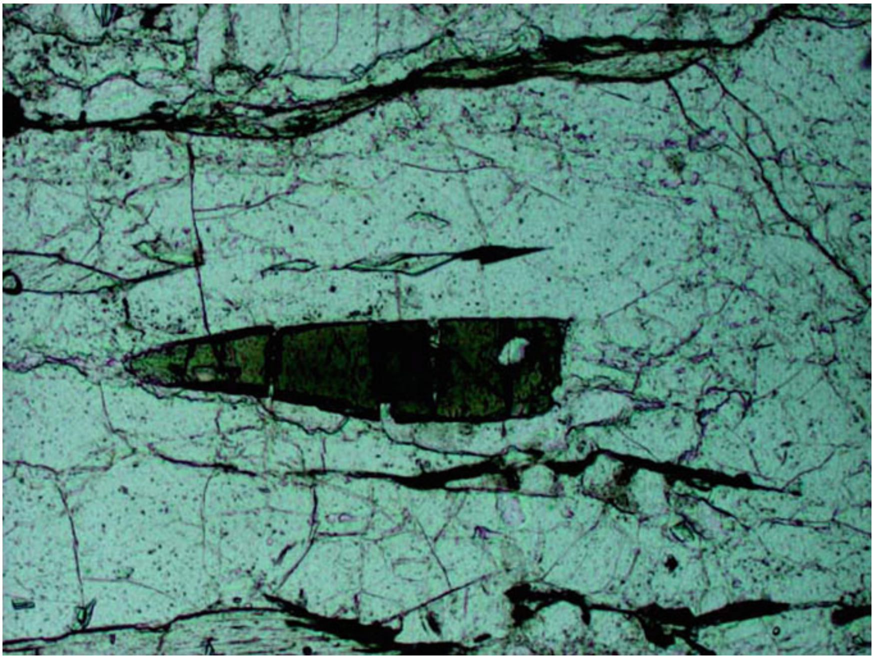

**Fig. 7.7** A tourmaline grain within quartzofeldspathic matrix underwent a number of sub-parallel pull-aparts. Reproduced from Fig. 5b of Mukherjee (2010b). Plane polarized light. *Width of view* 0.5 mm

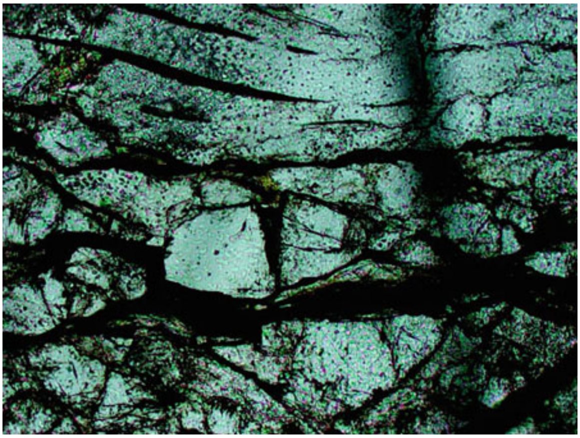

**Fig. 7.8** A V-pull-apart of lenticular and symmetric muscovite fish. *Top-to- right* brittle sheared? Reproduced from Fig. 12c of Mukherjee and Koyi (2010a). Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view*

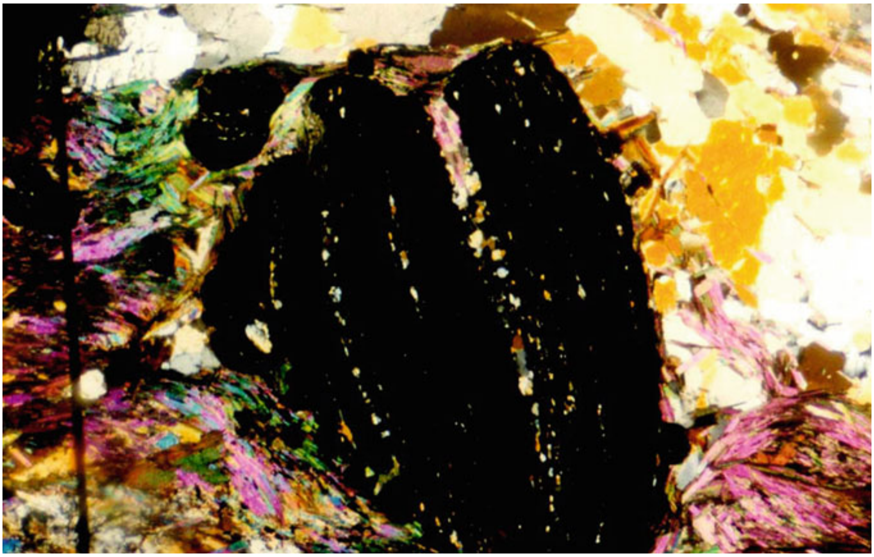

**Fig. 7.9** The garnet porphyroblast underwent V-pull-apart deformation. The V opening is curved. Mica foliations are scar folded near the opening. Quartzofeldspathic minerals of smaller size than that at matrix fill up the opening. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

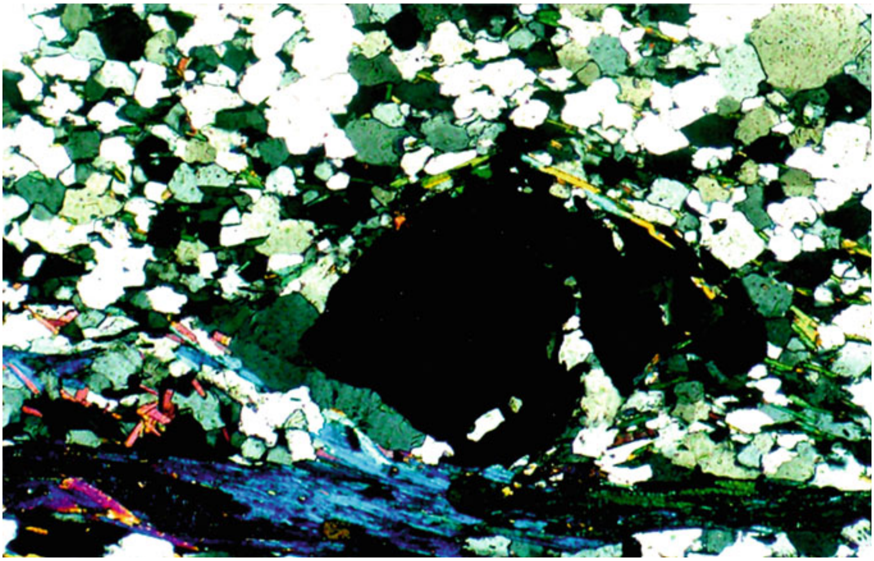

**Fig. 7.10** A V-pull-apart of garnet porphyroblast. *Top-to-left* brittle sheared? Reproduced from Fig. 9c of Mukherjee (2010b). Cross-polarized light. *Location* Karcham, Higher Himalaya (Himachal Pradesh, India). *Width of view* 4 mm

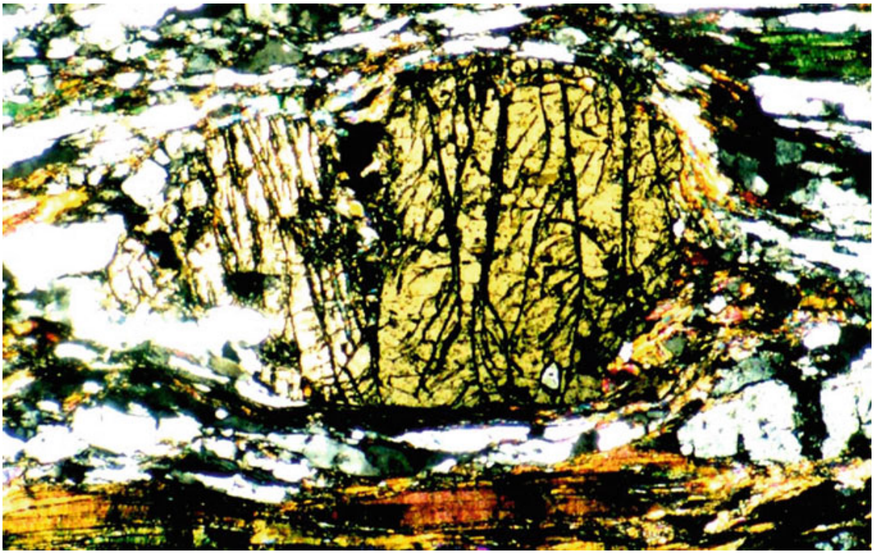

**Fig. 7.11** A lenticular staurolite fish got V-pulled apart. The lenticle is mantled by much finer grained minerals- possibly micas. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

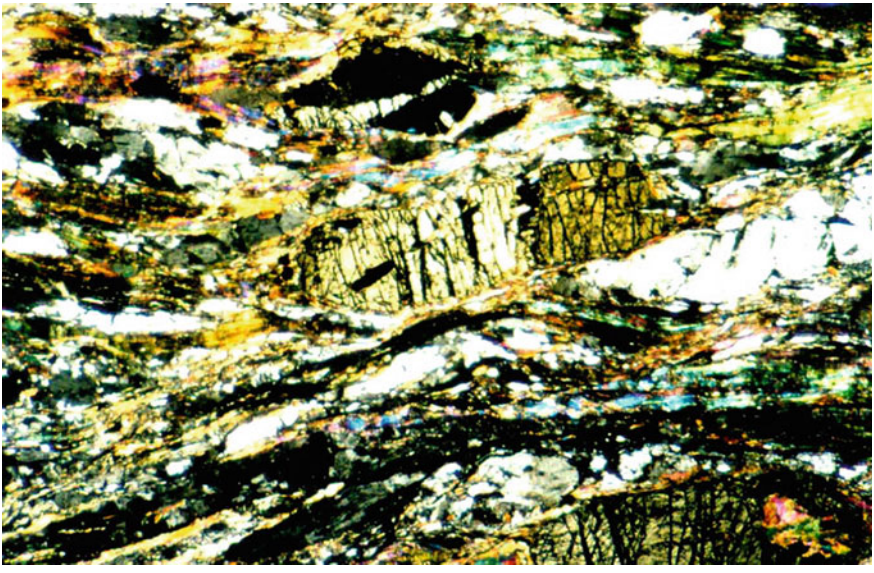

**Fig. 7.12** Sets of sub-parallel pull-aparts within staurolite. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

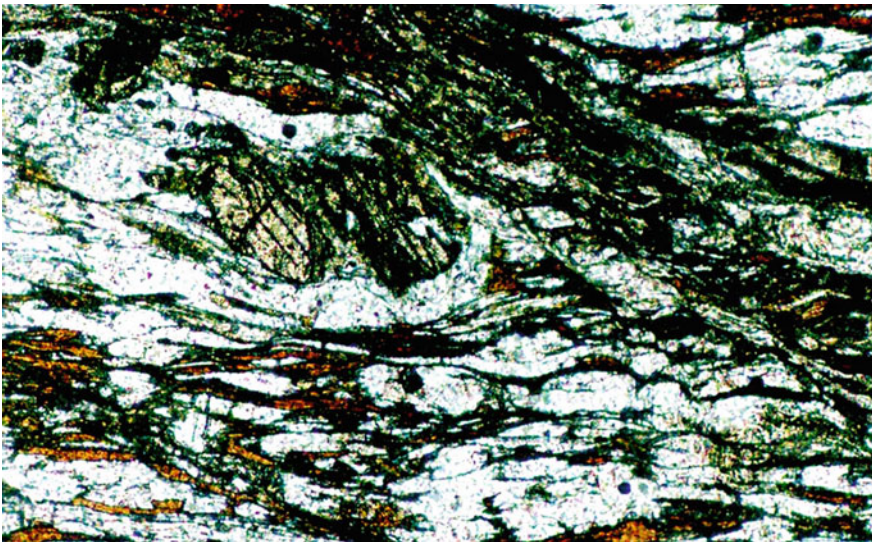

**Fig. 7.13** A pull-apart of garnet. Neither parallel- nor V-type. Plane polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 4 mm

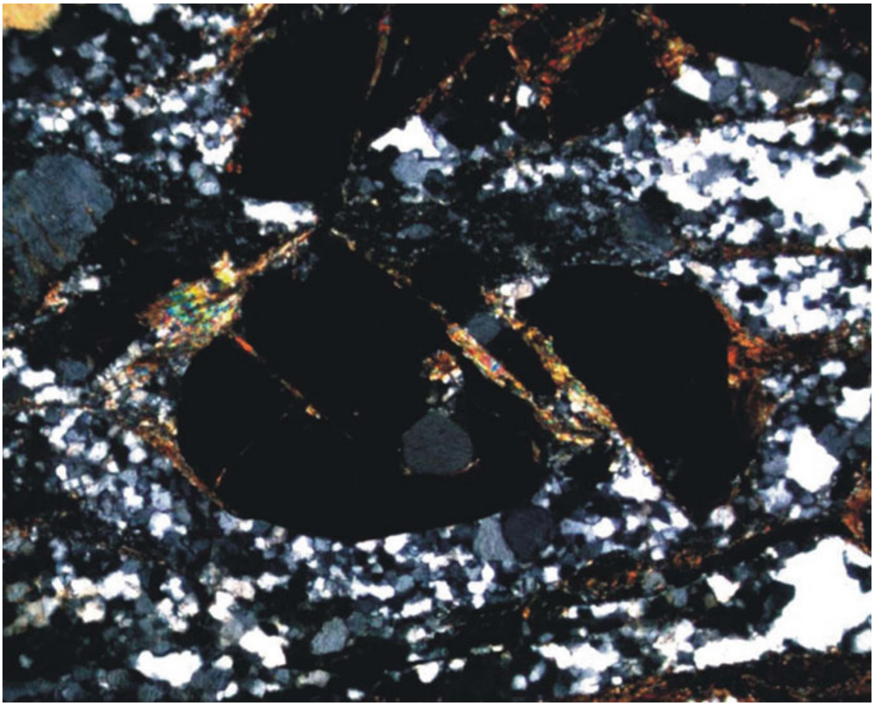

**Fig. 7.14** Parallel pull-aparts of a garnet. Cross-polarized light. *Sample location* Ghora, Near Ambaji, Gujrat (India). Reproduced from Mukherjee (2011c). *Width of view* 1.5 mm

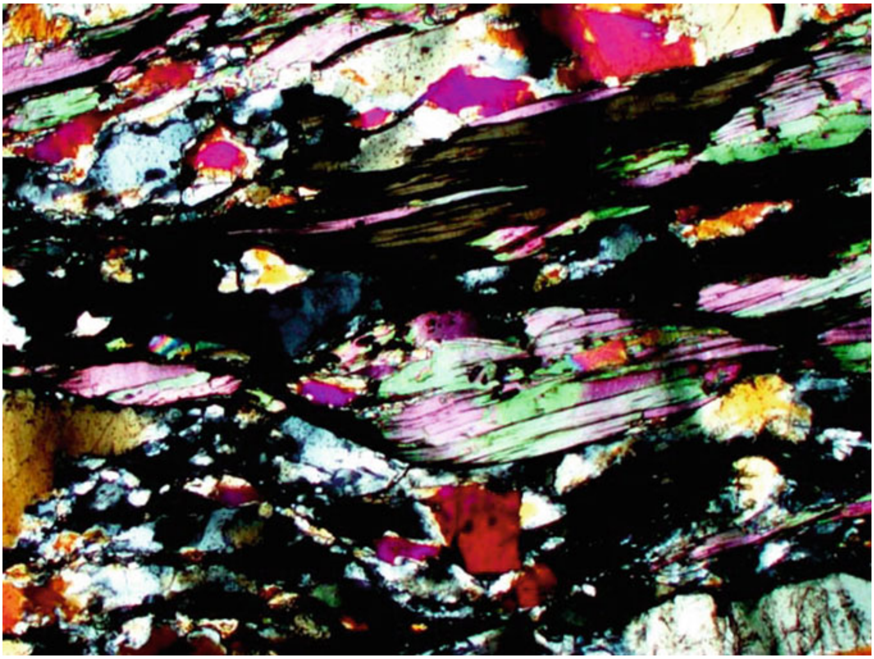

**Fig. 7.15** A lenticular foliation fish of muscovite grains. The two bulges are of quite dissimilar shape. Reproduced from Fig. 15d of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 2.5 mm

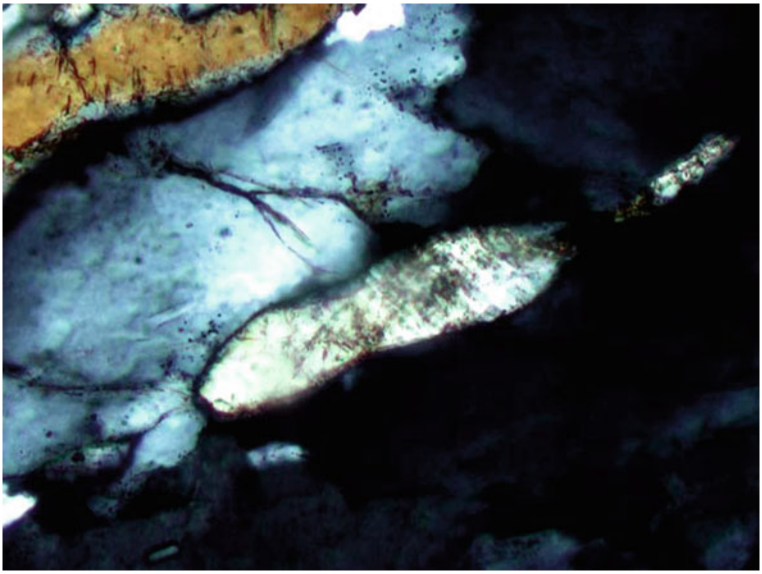

**Fig. 7.16** A pinched and swelled alkali feldspar grain. May not indicate a regional extension (as per Schmalholz and Maeder 2012). Reproduced from Fig. 15a of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

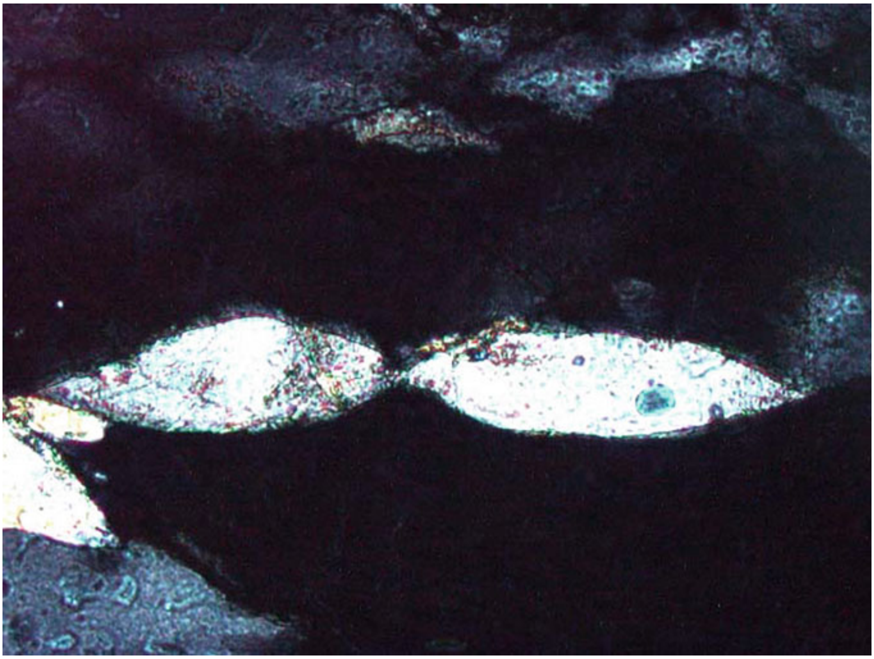

**Fig. 7.17** Lenticular boudin of alkali feldspar. Same as Fig. 15b of Mukherjee and Koyi (2010a) but is in a different position of the stage of the microscope. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

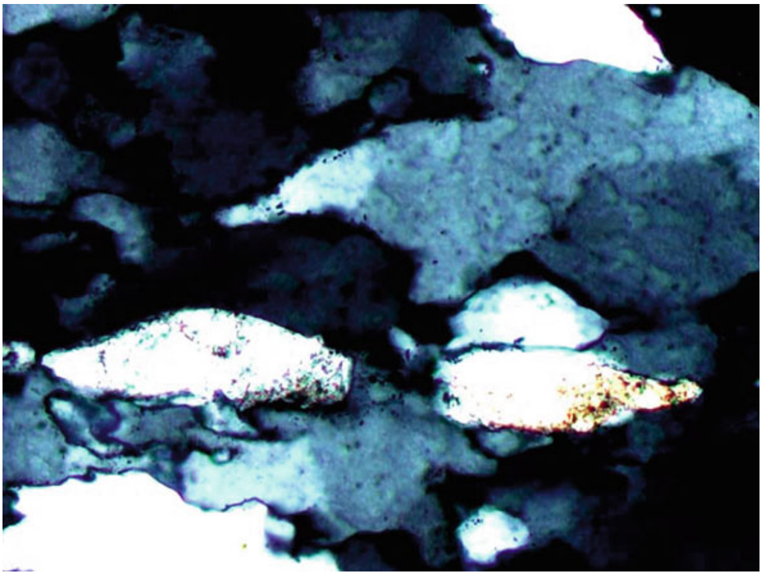

**Fig. 7.18** Lenticular boudin of alkali feldspar. The boudinaged clasts are separated from each other. Reproduced from Fig. 15c of Mukherjee (2010b). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

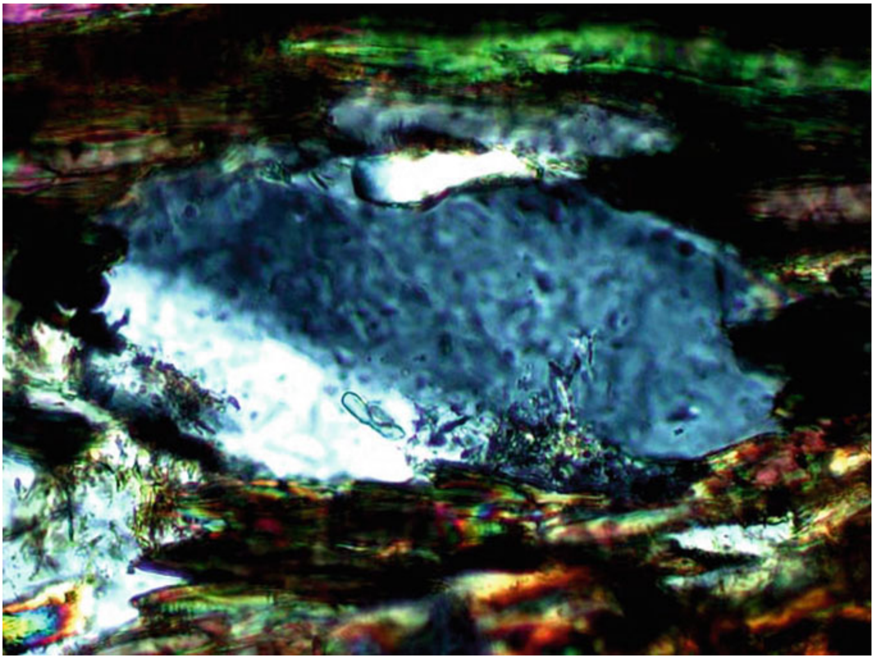

**Fig. 7.19** A pinch and swelled quartz grain. Notches at opposite sides. Reproduced from Fig. 5c of Mukherjee (2010c). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

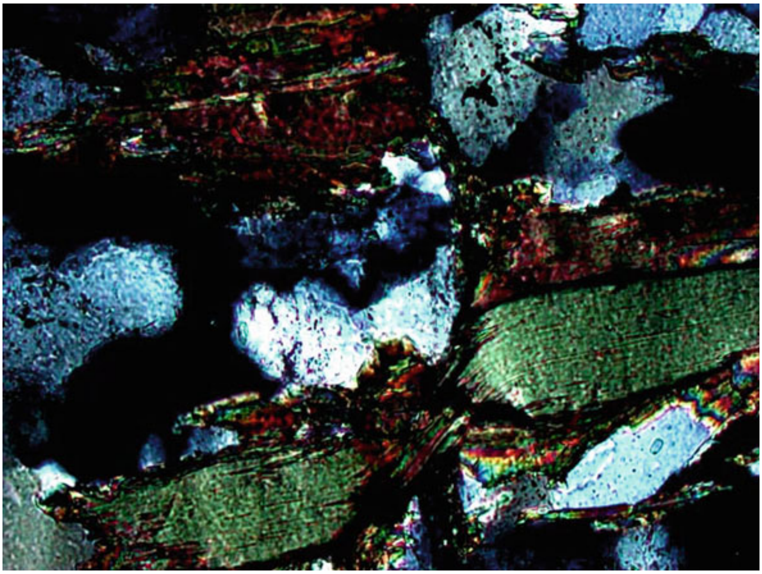

**Fig. 7.20** Brittle-ductile deformation of mica grains across a fault plane. The fault plane dips towards left. Curving of grain margins and cleavages near the fault is of 'normal drag' type. Reproduced from Fig. 8c of Mukherjee (2010c). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

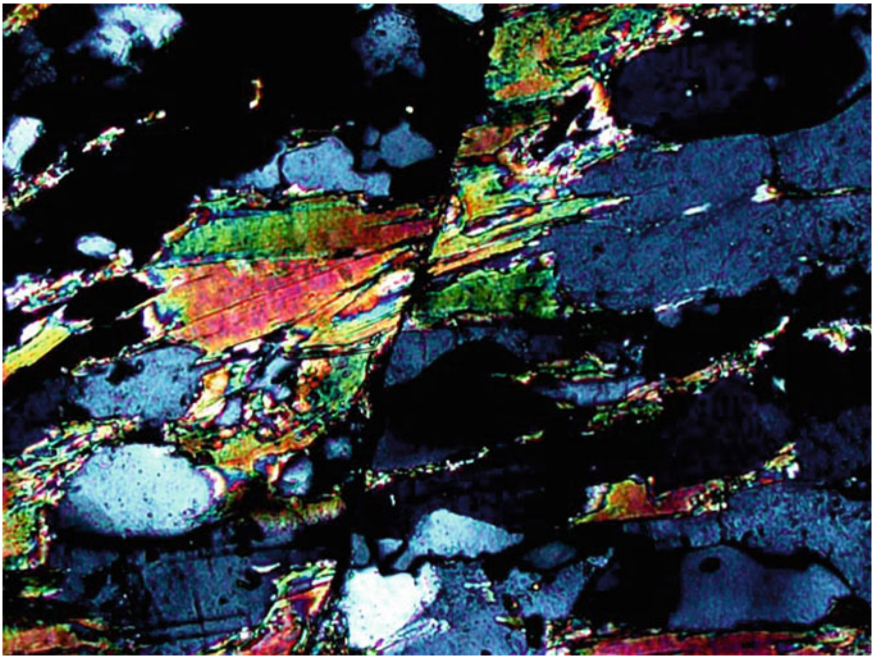

**Fig. 7.21** Across a brittle fault plane, micas prominently slipped and weakly dragged. Reproduced from Fig. 13a of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 5 mm. (The figure is similar to Fig. 1.1 of Passchier and Trouw 2005)

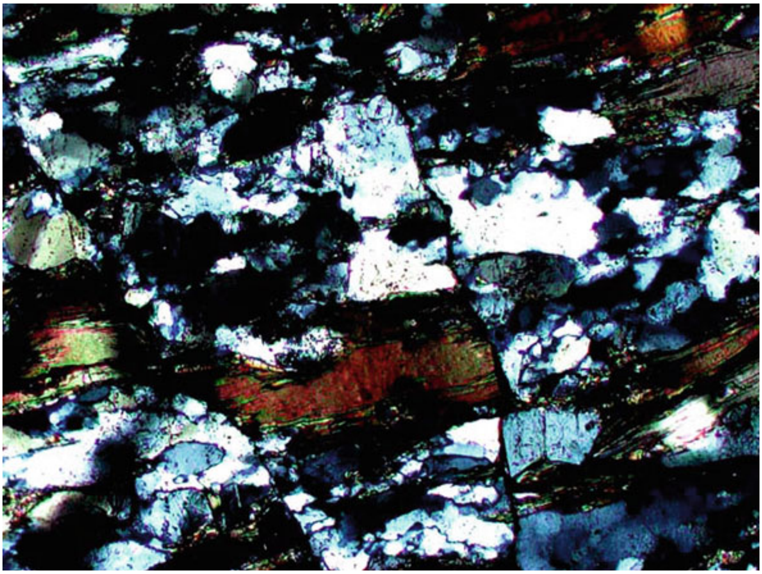

**Fig. 7.22** Across two non-parallel fault planes, micas prominently dragged and slipped. Reproduced from Fig. 13b of Mukherjee and Koyi (2010a). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 5 mm

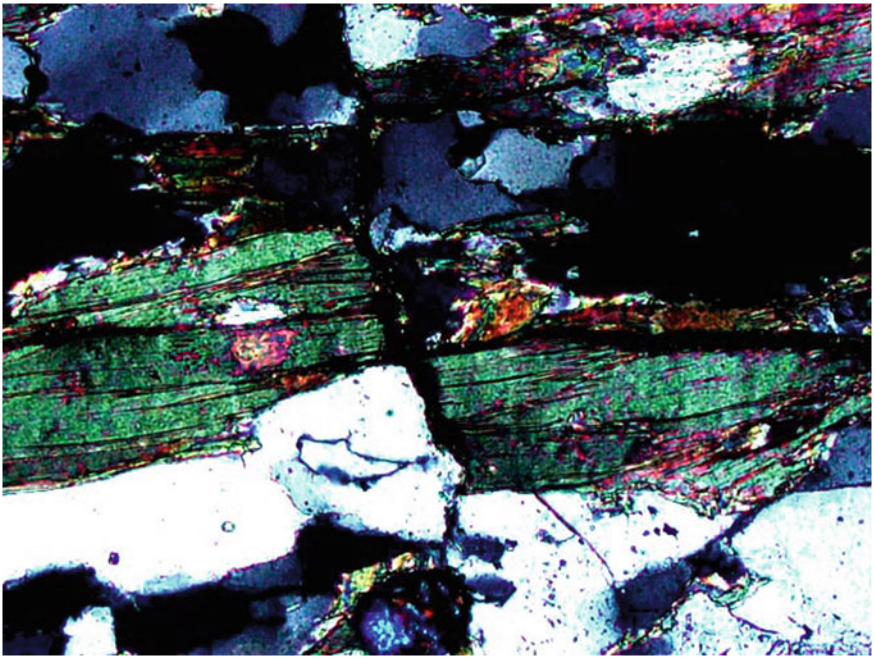

**Fig. 7.23** Across a brittle fault plane, micas prominently slipped without significant drag. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

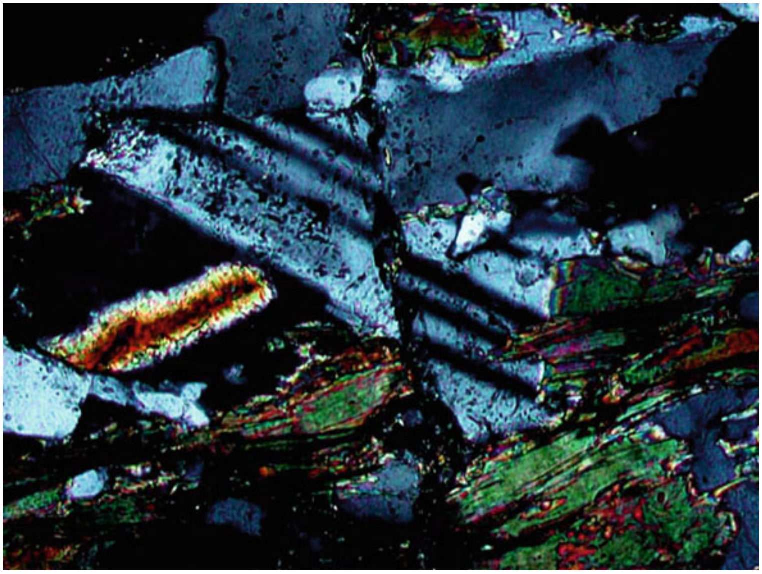

**Fig. 7.24** Across a brittle fault plane, a plagioclase grain slipped prominently. Reproduced from Fig. 9a of Mukherjee (2010c). Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 0.5 mm

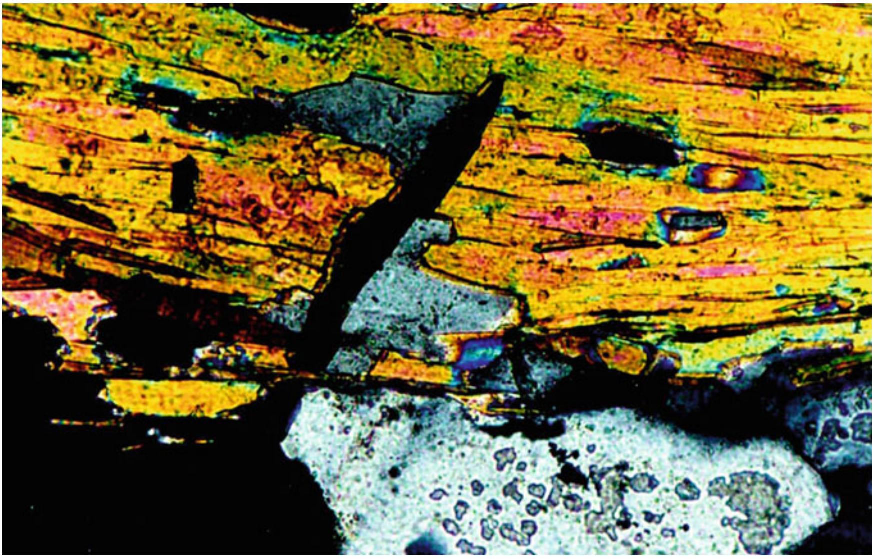

**Fig. 7.25** Across a nucleated muscovite grain (in extinction position), an alkali feldspar probably got brittle faulted. Cross-polarized light. *Location* Zanskar Shear Zone (India). *Width of view* 1 mm

**Fig. 7.26** Listric brittle faulting of originally a single muscovite grain. Cross-polarized light. *Location* Tso Morari dome (India). *Width of view* 4 mm

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