Chapter 2
Folds

Ductile shear related folds have been studied by many (e.g. Bell 2010 but many others). Alsop and Holdsworth (2004) classified folds in relation to shear of two main types: (1) those with low inter-limb angles and curved hinge lines formed before shear; and (2) flow perturbed syn-shear overturned intrafolial folds. Vergences of intrafolial folds reveal shear sense in meso- (Figs. 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 2.10, 2.11, 2.12, 2.13, 2.14, 2.15, 2.16, 2.17, 2.18, 2.19, 2.20, 2.21, 2.22, 2.23, and 2.28; Mukherjee et al. 2013) and micro-scales (Mukherjee 2013a). Intrafolial folds with axial traces sub-parallel to the shear planes (Fig. 2.24) are not useful in shear sense determination. Folds that are not bound by a pair of ductile shear planes (Figs. 2.25, 2.26, 2.27, 2.28, 2.29, 2.30, 2.31, 2.32 and 2.33) are not intrafolial, and do not indicate any ductile shear. In terms of tectonics, intrafolial folds from the Greater Himalayan Crystallines indicate a top-to-S/SW fore-shear (see Mukherjee and Koyi 2010a, b; Mukherjee 2013a, b etc.). Additionally, from the South Tibetan Detachment, a top-to-N/NE extensional shear is also reported, which has recently been explained by a combination of crustal channel flow and critical taper mechanisms (Beaumont and Jamieson 2010; recent review by Mukherjee and Ghosh 2013).

S. Mukherjee, *Atlas of Shear Zone Structures in Meso-scale*, Springer Geology,
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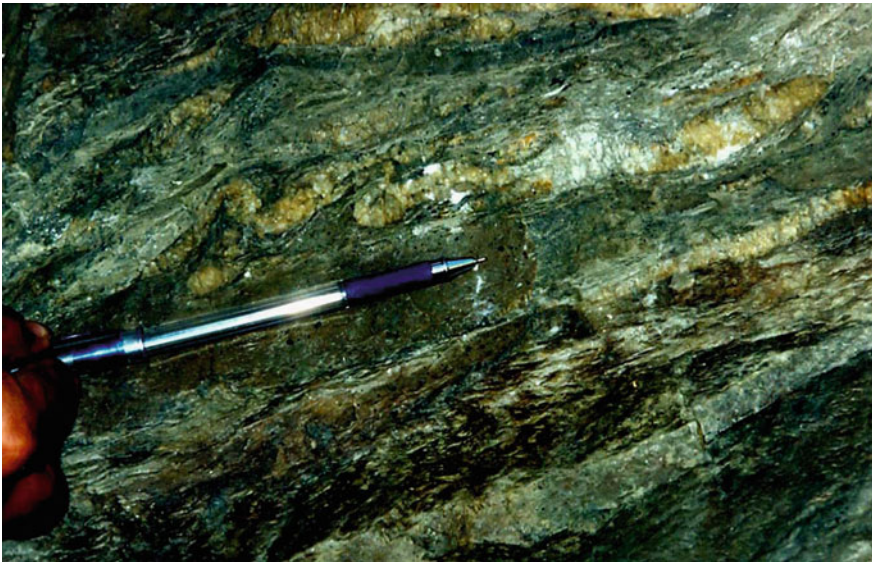

Fig. 2.1 A train of intrafolial folds of quartz (*left*) merges to a sigmoidal bulge (*right*). Dip of axial planes of the folds and the asymmetry of the sigmoid indicate consistently a *top-to-right* (*up*) shear sense. *Location* Greater Himalayan Crystallines from Sutlej section, Himachal Pradesh, India

Fig. 2.2 An overturned intrafolial fold of quartzose layer. *Top-to-left* (*up*) ductile sheared. At Jeori, Sutlej section of Greater Himalayan Crystallines, Himachal Pradesh, India. Reproduced from Fig. 4c of Mukherjee and Koyi (2010a, b)

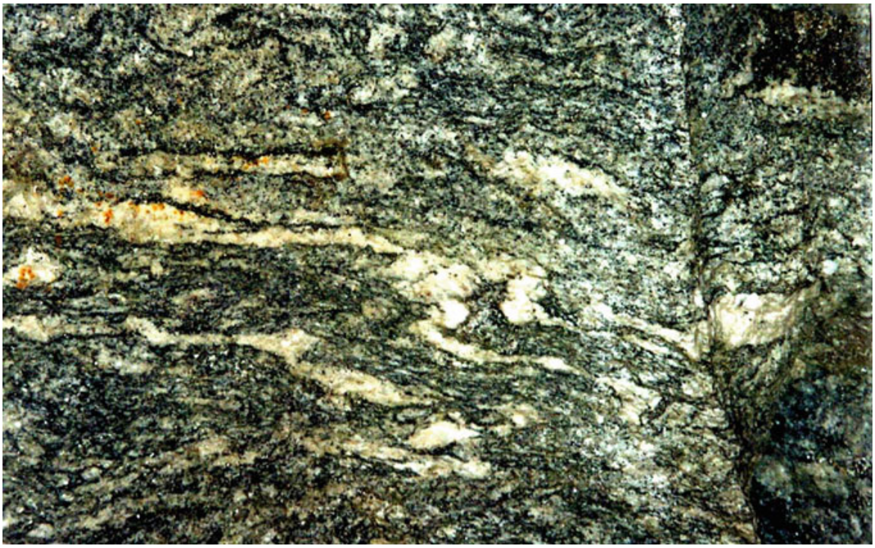

Fig. 2.3 Irregular inconsistent folds inside a mylonitized gneiss. The two fold closures near the *central part* of the photo have left dipping axial traces. *Location* Greater Himalayan Crystallines from Sutlej section, Himachal Pradesh, India

Fig. 2.4 Intrafolial folds of quartz veins with hinges thicker than the limbs. Since their axial traces sub-parallel the bounding nearly straight quartz veins defining primary shear C-planes, these folds cannot indicate any clear cut shear sense. Greater Himalayan Crystallines from Sutlej section, Himachal Pradesh, India

Fig. 2.5 *Hook-shaped round* hinged folds of quartz veins. Axial traces of these folds sub-parallel the mylonitic foliations. Shear sense is not convincing. Ductile sheared migmatitic gneiss near an unnamed iron bridge at Karcham, Greater Himalayan Crystallines, Sutlej section, Himachal Pradesh, India

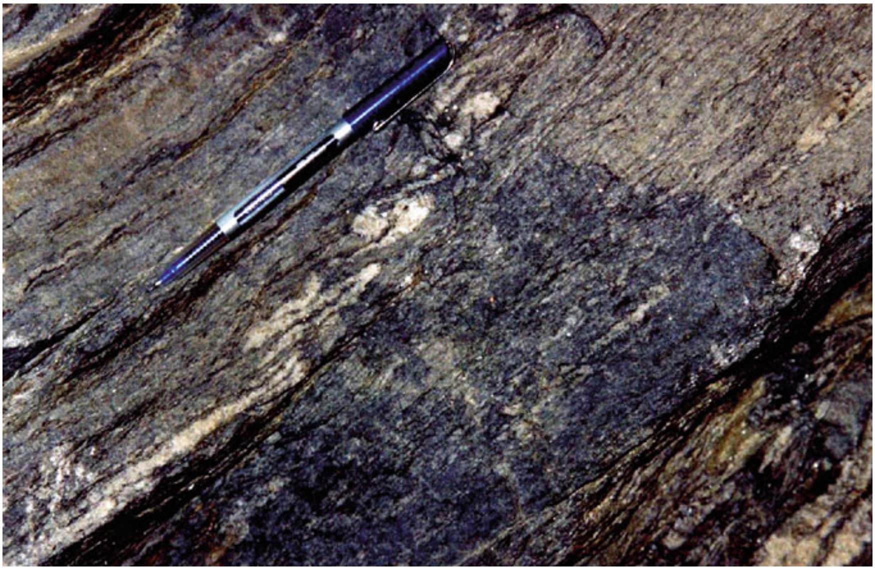

Fig. 2.6 *Round-hinged* overturned intrafolial folds of quartz veins indicate a *top-to-left* (*down*) ductile shear. Near Karcham hydropower plant, Sutlej section of Greater Himalayan Crystallines, Himachal Pradesh, India

Fig. 2.7 Same description and location as the previous caption. A few folds have nearly *straight* hinge zones produced by ductile shear

Fig. 2.8 An overturned intrafolial fold of quartz vein follows nearly the same geometry of folding of gneissic foliation. *Top-to-right* (*up*) shear. At *right*, the folded vein merges with an irregular bulge of quartz. *Location* Karchham, near an unnamed iron bridge, Greater Himalayan Crystallines, Sutlej section, Himachal Pradesh, India

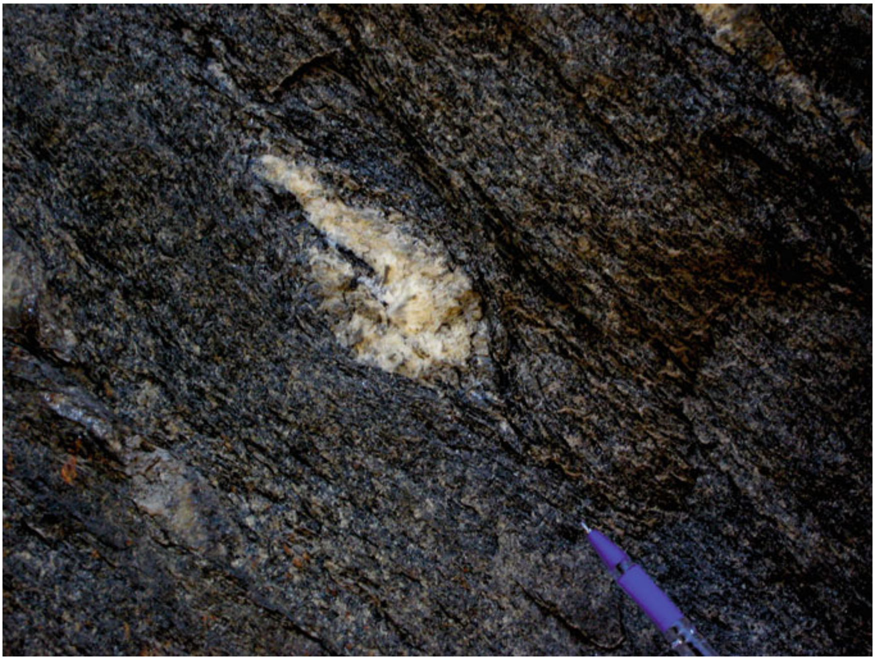

Fig. 2.9 A rootless fold of quartz with a hinge zone much thicker than the limbs. The axial trace sub-parallels the main foliation, and is therefore not a shear sense indicator. *Location* Greater Himalayan Crystallines, Bhagirathi section in India

Fig. 2.10 Overturned intrafolial folds of quartz veins with round hinges much thicker than the limbs. No clear-cut shear sense is revealed since the axial traces are at very low angles to the primary shear planes. From mylonitized gneiss/migmatite of Greater Himalayan Crystallines, Sutlej section, Himachal Pradesh, India. Reproduced from Fig. 17b of Mukherjee (2010). See Figs. 14.29 and 14.30 of Klein and Philpotts (2013) for similar cases

Fig. 2.11 *Top-to-right* sheared overturned intrafolial fold of quartz with round hinge. *Left* to it is an asymmetric quartz pod with mouth/notch at *right*. From mylonitized gneiss/migmatite of Greater Himalayan Crystallines, Sutlej section, Himachal Pradesh, India

Fig. 2.12 *Top-to-left* (*down*) ductile sheared thicker intrafolially folded leucosome layers. The *central part* of this photograph was published as Fig. 2.16d in Mukherjee (2010). Near Karcham, Greater Himalayan Crystallines, Sutlej section, Himachal Pradesh, India

Fig. 2.13 *Top-to-right* (*up*) ductile sheared migmatitic foliations. At places brittle rupture in the same shear sense took place. Greater Himalayan Crystallines, Sutlej section, Himachal Pradesh, India. Reproduced from Fig. 15d in Mukherjee (2010)

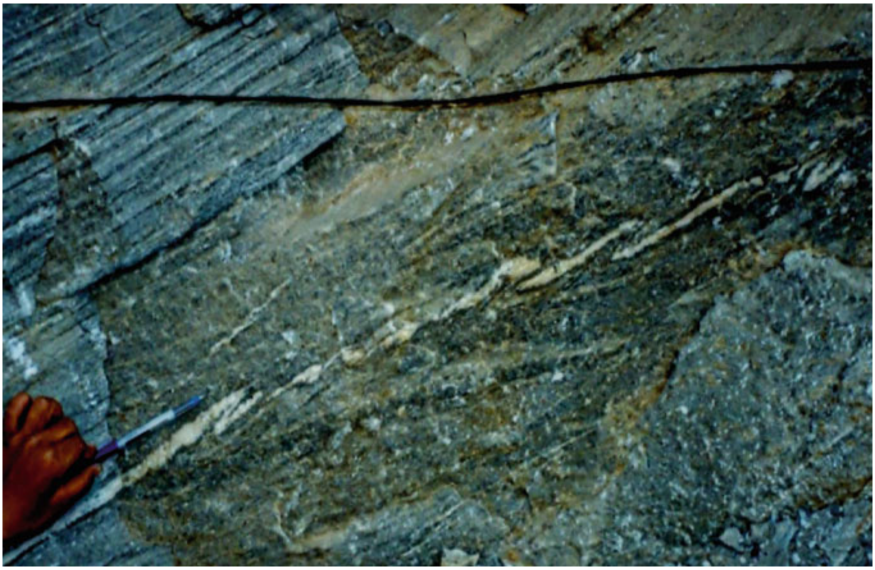

Fig. 2.14 Overturned intrafolial fold of quartz vein. *Top-to-right* (*up*) sheared. Pronounced shear led to boudinage. From mylonitized gneiss/migmatite of Greater Himalayan Crystallines, Sutlej section, India

Fig. 2.15 Isoclinally folded round hinged quartz vein. A few are *hook-shaped*. Notice at *bottom*, the fold cuts across the *left* dipping foliation. Hence these are not intrafolial folds, and are not to be considered as ductile shear sense indicators. From mylonitized gneiss/migmatite of Greater Himalayan Crystallines, Sutlej section, India

Fig. 2.16 Quartz vein folded with a vergence towards right. Shear sense is ambiguous since these folds are not bound by (nearly) *straight* shear C-planes. *Location* Greater Himalayan Crystallines from Sutlej section, Himachal Pradesh, India

Fig. 2.17 A tight polyclinally folded quartz vein cuts across foliations of mylonitized gneiss/ migmatite. Since this fold is not bound by foliations, it is not to be considered an 'intrafolial fold', and therefore is not to be used as a shear sense indicator. Greater Himalayan Crystallines, Sutlej section, India. Reproduced from Fig. 15c of Mukherjee (2010)

Fig. 2.18 Quartz-rich foliations at places show hook-fabric [see Wennberg (1996) for modeled—and Mukherjee and Koyi (2010b) for micro-scale examples]. Hook-fabrics are produced from pro- and retro- shear along the same primary shear C-planes. One can also work out the relative timing of the two shear sense from them. However, in the present case, the hook fabrics is seen to cut across the C-planes (= main foliations dipping towards right). So its origin might be different. From mylonitized gneiss/migmatite of Greater Himalayan Crystallines, Sutlej section, India. Reproduced from Fig. 14c of Mukherjee (2010)

Fig. 2.19 An isoclinally folded quartz vein resembling a 'hook' with hinge much thicker than the limbs. Since its axial trace parallels the main foliation, it cannot be used for ductile shear sense determination. Such parallel nature may be achieved if the fold underwent a protracted ductile shear. From mylonitized gneiss/migmatite of Greater Himalayan Crystallines, Sutlej section, India

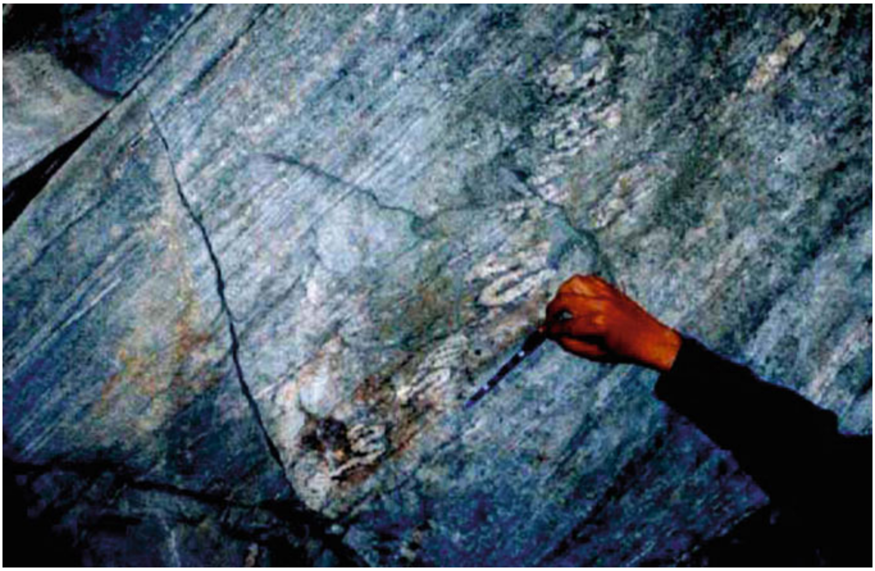

Fig. 2.20 Folded quartz vein cuts across gneissic foliation, and is not bound by the later. Therefore these folds are not intrafolial and are to be avoided to determine shear sense. *Location* Karchham, near an unnamed iron bridge, Greater Himalayan Crystallines, Sutlej section, India

Fig. 2.21 A zone of folded gneissic foliation bound by nearly *straight sub-parallel* foliations. Axial traces of these folds sub-parallel those bounding foliations. Parasitic folds are also present. For these complicacies, these folds are to be avoided in shear sense determination. *Location* Karchham, near an unnamed iron bridge, Greater Himalayan Crystallines, Sutlej section, India

Fig. 2.22 *Left* verging folded quartz veins with hinge zones much thicker than the limbs. *Location* Greater Himalayan Crystallines, Bhagirathi section, India

Fig. 2.23 *Left* verging folded quartz veins with hinge zones much thicker than the limbs. Its axial trace sub-parallels the foliation, therefore the vergence cannot be used reliably as a shear sense indicator. Instead, a train of quartz vein with sheared sigmoid bulges at right gives a *top-to-left* (*up*) shear sense. *Location* Greater Himalayan Crystallines, Bhagirathi section, India

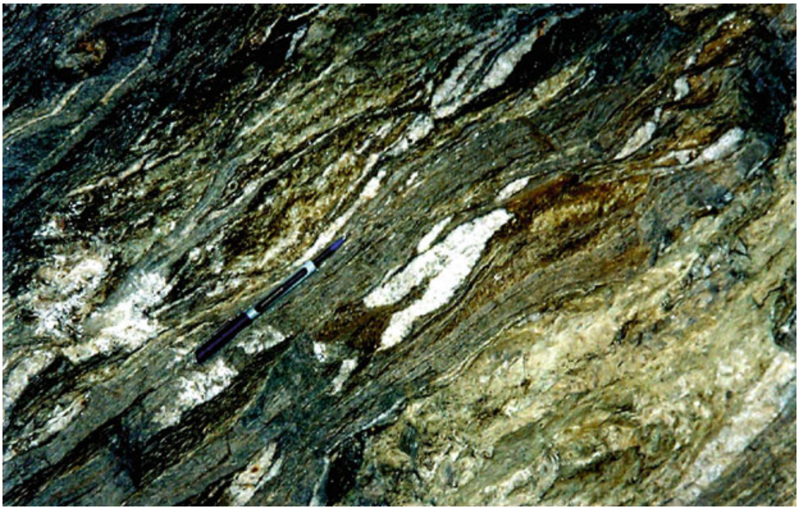

Fig. 2.24 *Right* to the *marker* (*pen*), a rootless flame fold of quartz with axial trace parallel to the *left* dipping mylonitic foliation. The fold does not indicate any shear sense. However, a few sigmoid quartz pods interconnected by secondary synthetic ductile shear C′ planes indicate reliably a *top-to-right* (*up*) shear, at top right portion of the photo. From mylonitized gneiss/migmatite of Greater Himalayan Crystallines, Sutlej section, India

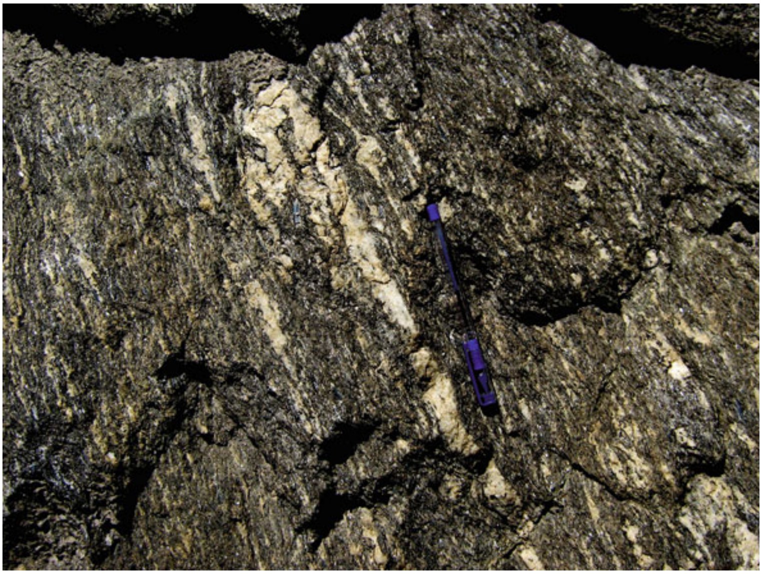

Fig. 2.25 A thicker quartz vein of irregular margins is folded isoclinally and is bound by migmatitic/gneissic foliations. The axial trace of this intrafolial fold sub-parallels the foliation. *Location* Greater Himalayan Crystallines, Bhagirathi section, India

Fig. 2.26 A sheath fold from migmatized gneiss from Greater Himalayan Crystallines, Bhagirathi section (India). These folds were considered by previous workers as indicators of high strain. See Reber et al. (2013) as a latest work on sheath folds

Fig. 2.27 A sheath fold from migmatized gneiss from Greater Himalayan Crystallines, Bhagirathi section (India). Curvature/closure of limb is seen especially at *top left* corner of the fold. Does asymmetry of sheath folds also indicate (here a *top-to-left*) shear sense? Interestingly, Dell et al. (2013) analogue modeled development of sheath fold during progressive shear

Fig. 2.28 An overturned intrafolial fold of gneissic foliation with a rightward vergence. *Top-to-right* (*up*) shear. The fold is bound at *top* by nearly *straight* foliations. *Location* Greater Himalayan Crystallines, Sutlej section (India)

Fig. 2.29 Neutral folded psamitic schist with M-geometry in the hinge zone. *Location* Tethyan Himalaya, near Jangi check post. Sutlej section (India)

Fig. 2.30 Zeolite vesicles within Deccan basalt at Malsejghat, Maharashtra. In first appearance, a single vesicle appears to get isoclinally folded. Hinge thicker than the limbs. However, these structures are produced due to escape of gas bubble upwards when the lava (now the country rock) was hot, and subsequent coalescence of the bubbles. Zeolite later filled up the vesicles

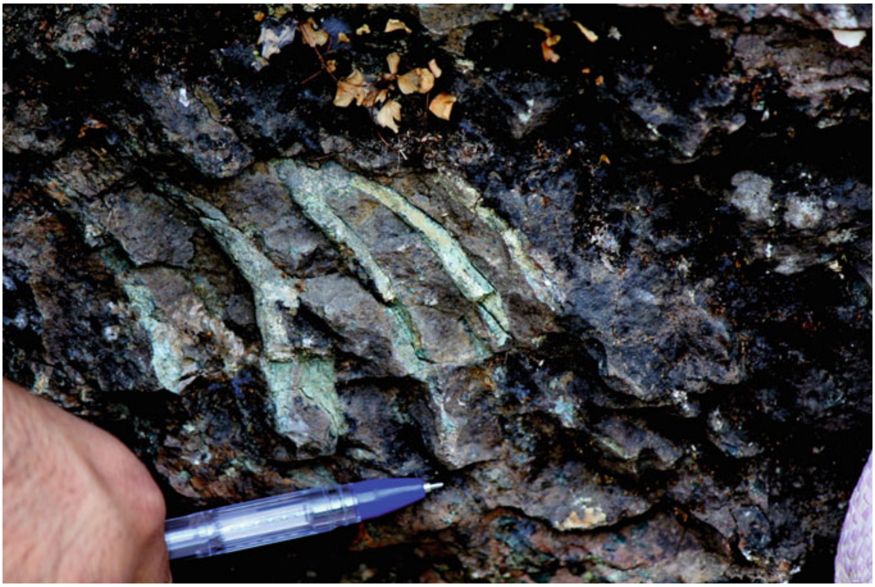

Fig. 2.31 Same interpretation as the previous Fig. 2.30. Deccan trap basalt at Malsejghat, Maharashtra

Fig. 2.32 Elongated zeolite vesicles plunging towards *right*. A few appear folded. Same interpretation as that for Fig. 2.30. Deccan trap basalt at Malsejghat. Maharashtra

Fig. 2.33 A train of isoclinal round hinge folds of granitic material that came out from the margin of a dyke. These folds are *not* ductile shear sense indicators. Ambaji, Gujarat, India

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