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The interpretation of stretching lineations in multiply deformed terranes: an example from the Hualapai Mountains, Arizona, USA

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Abstract

Stretching lineations are commonly assumed to be genetically related to the foliation plane in which they occur and are generally interpreted to represent the finite elongation direction, or tectonic transport direction in highly strained rocks. In multiply deformed terranes, however, lineations may be reoriented rendering their interpretation less straightforward. This situation could lead to misinterpretation of the kinematics or strain signature of the second event. An example from the Hualapai Mountains, Arizona, shows that, where two discrete deformational events occurred under similar physical conditions, an early L_1 lineation developed on S_1 could be misinterpreted as an L_2 lineation developed on S_2. Here, a gently dipping S_1 fabric was reoriented by folding into a steeply dipping composite S_1/S_2 fabric. In areas of little D_2 overprint, the L_1 lineation is essentially down dip. F_2 folding of L_1 resulted in reorientation of the lineations to very shallow rakes. D_1 fabrics are exposed only in extremely limited areas due to nearly complete overprinting by D_2 structures. Therefore, unless thorough field mapping reveals the local presence of D_1 structures, it would be easy to infer mistakenly that the L_1 lineation seen on the widespread S_2 foliation formed during D_2 thereby leading to an incorrect interpretation of the strain signature and kinematics of the second event.

Keywords: Stretching lineations; Multiply deformed terranes; Foliation plane

1. Introduction

In multiply deformed terranes, early stretching lineations and their associated kinematic indicators may be reoriented, thus complicating interpretation of the kinematics of regional deformation (Goscombe and Trouw, 1999). For example, folding of a pre-existing shear fabric may or may not result in an inversion of shear sense on alternate limbs of folds depending upon the orientation of the early (L_1) lineation relative to the later (F_2) fold axis (Goscombe and Trouw, 1999). As another example of this complexity, open upright folding of an original subhorizontal fabric may result in an apparent change from shortening to extensional geometries (Goscombe and Trouw, 1999; their Fig. 4).

An additional complication is the common assumption that lineations are genetically related to the foliation plane in which they occur. In multiply deformed terranes in which a second event (D_2) largely overprints or obscures structures associated with an earlier (D_1) event, this assumption may be unwarranted and lead to an incorrect interpretation of kinematics (and finite strain signature) of the later, D_2, event. The purpose of this contribution is to show how a lineation (L_1) developed on S_1 could be mistaken for an L_2 lineation developed on S_2, resulting in the incorrect interpretation for the finite elongation direction (= movement direction in the case of strongly deformed tectonites) for the second event. Such a misinterpretation could be made easily in regions where D_1 fabrics are poorly or only locally preserved due to strong overprinting by D_2 fabrics, and particularly where D_2 is characterized by flattening strain in which no new lineations are formed. An example from the northern Hualapai Mountains, Arizona, that illustrates this problem is presented after a brief discussion of the possible geometries of folded lineations.

2. Background

Mineral elongation, or stretching, lineations are generally interpreted to represent the finite elongation direction, or *X*-axis of the strain ellipsoid, in tectonites (e.g. Ramsay

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and Huber, 1983). At high strains in simple shear, stretching lineations are commonly interpreted as approximating the movement direction (within 10° for $\gamma = 5$, within 6° for $\gamma = 10$) (e.g. Berthé et al., 1979; Simpson and Schmid, 1983), although this may not necessarily be the case in transpressional settings (Tikoff and Greene, 1997). Lineations are generally considered to be genetically related to the foliation plane in which they occur. The foliation plane is interpreted as the flattening plane (*XY*), which in simple shear, initiates at about 45° to the shear plane and progressively rotates toward the shear plane with increasing strain (e.g. Passchier and Trouw, 1996).

In multiply deformed terranes, several generations of foliations or cleavages may be present, each of which may or may not possess a genetically related stretching lineation, depending on whether strain is dominantly flattening (no lineation) or whether there is a component of stretching in one direction (lineation). Different generations of foliations or cleavages are commonly distinguished on the basis of crosscutting or overprinting relations, or different synkinematic mineral assemblages; however, it is well known that multiple planar and linear fabrics can form during a progressive or protracted deformational event (e.g. Gray and Mitra, 1999; Potts and Reddy, 1999). A potentially complex situation occurs when two distinct deformational events, separated in time, occur at the same or nearly the same physical conditions (i.e. P, T, a_{H2O}, strain rate). In this case, mineral assemblages may be similar or even identical for each event and there may not be any discrete overprinting fabrics, such as a new foliation. An example is where a subhorizontal planar fabric, for example compositional banding, is folded and rotated into a subvertical fabric, at the same physical conditions, without development of a new axial planar foliation. In this case, the character of the fabric has not changed (i.e. it is still compositional layering) but the orientation has, and thus the strain signature of the

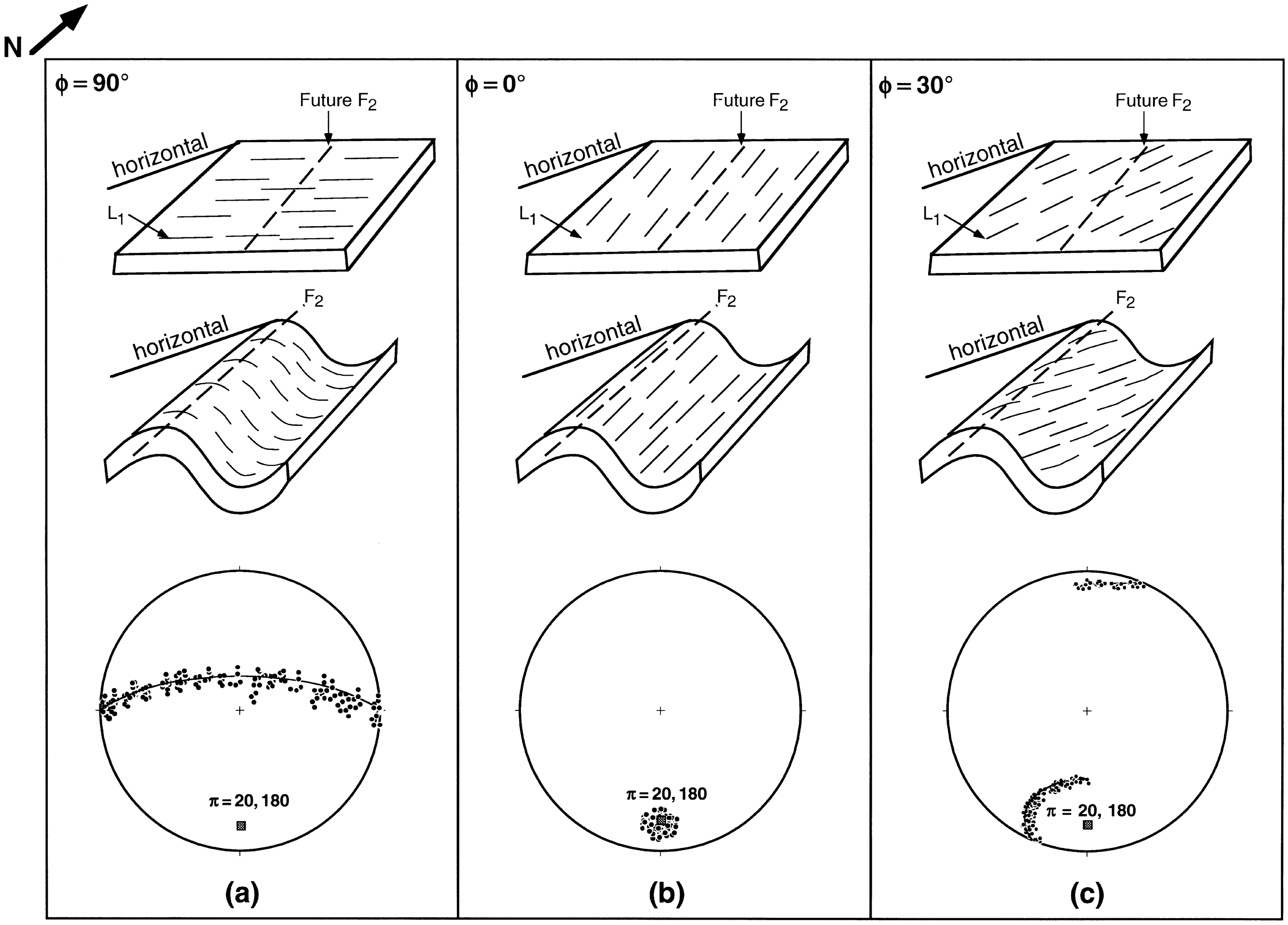

Fig. 1. Geometric relations between early (L_1) lineation and later fold axis (F_2); ϕ = original angle between L_1 and F_2 (after Goscombe and Trouw, 1999). For (a)–(c), top figures show S_1 foliation and associated L_1 lineation prior to folding. North is parallel to sides of blocks; S_1 foliation strikes east and dips 20°S. Middle figures show relation between L_1 and F_2 after folding. The bottom figures are stereograms showing orientations of L_1 (dots) after folding. In (a), where $\phi = 90°$, folding produces a great circle distribution of L_1 with π (= fold axis) as its pole. In (b), where $\phi = 0°$, L_1 forms a cluster of points centered on π. In (c), where $0° < \phi < 90°$, folding produces a small circle distribution of L_1 (adapted from Marshak and Mitra, 1988).

fabric has changed markedly. In these situations, a common notation for the younger, subvertical fabric is S_1/S_2.

Cylindrical, flexural-slip folding of an early lineation produces predictable patterns on stereograms. These patterns are dependent upon the original orientation of the L_1 lineation relative to the F_2 fold axis. Following Goscombe and Trouw (1999), ϕ is defined as the acute angle between the lineation and the fold axis. Where ϕ is 90°, the folded lineations will define a great circle, the pole to which is the fold axis (Fig. 1a). Where ϕ is 0°, the folded lineations will coincide with (or be centered on) the fold axis (Fig. 1b). Where lineations are oblique to the fold axis ($0° < \phi < 90°$), a small-circle distribution of lineations centered on the fold axis will occur (Fig. 1c). Deviations from either of these ideal situations will occur where (1) original lineation orientations are variable due to heterogeneous strain, (2) a later folding or warping event has occurred, (3) folding has been relatively gentle (interlimb angles >120°). In the latter case, only a partial great or small circle distribution will be seen, and this may be difficult to distinguish from a diffuse scatter of lineation orientations (Fig. 2). As discussed below, a particularly confusing situation occurs where ϕ is small (<25°), the folding is gentle, and the F_2 folding event took place at similar physical conditions to those that prevailed during development of S_1.

3. Hualapai Mountains—a field example

3.1. Regional deformation

The Hualapai Mountains, northwestern Arizona (Fig. 3), are composed largely of Paleoproterozoic quartzofeldspathic paragneiss and pelitic schist that have been intruded by both Paleoproterozoic and Mesoproterozoic granitoids. Two Paleoproterozoic penetrative deformational events have been identified throughout central and northwestern Arizona (Karlstrom and Bowring, 1988; many others). The early deformational event produced a northwest-striking, gently dipping regional foliation (S_1) that is *only very locally preserved* (<10% of Proterozoic exposures in northwestern Arizona) due to widespread overprinting by the subvertical, northeast-striking S_2 foliation. Where not overprinted by D_2 fabrics, the S_1 foliation contains a down-dip mineral elongation lineation (rakes = 70–90°). The D_1 event is characterized by recumbent folds and has been interpreted as representing a collisional event between the Mojave and Yavapai Paleoproterozoic provinces in Arizona (Duebendorfer et al., 2001). D_1 was accompanied by granulite-facies metamorphism (sillimanite-K feldspar zone in pelitic rocks, ca. 700 °C and 6 kbar; Jones et al., 1998; James et al., 2001) and is constrained, by crosscutting relations with dated plutons (U–Pb zircon), to be older than 1720 Ma (Duebendorfer et al., 2001). In support of this

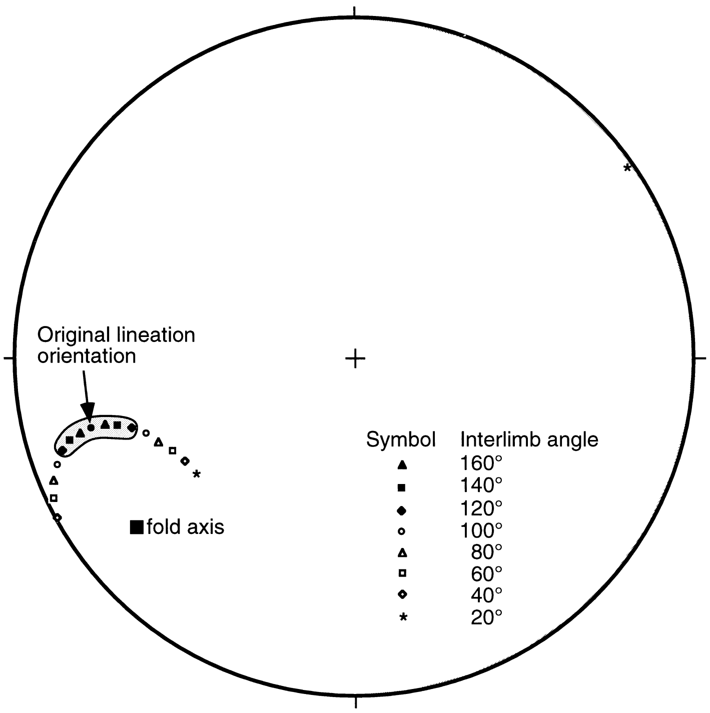

Fig. 2. Synthetic stereogram showing the result of folding of a lineation plunging 21° toward 255° about a fold axis oriented 20° toward 232°. These are the mean orientations of the lineations and fold axes from the Walnut Canyon area. Different symbols correspond to different intensities of folding expressed as fold interlimb angle. Shaded area represents distribution of folded lineations for gently folded foliation (interlimb angles >120°). It may be difficult to distinguish a small circle distribution about the fold axis for gentle or open folds from a natural scatter in lineation orientations. Rotations were done using the computer program Stereonet PPC 6.0.2 by Richard Allmendinger (2001).

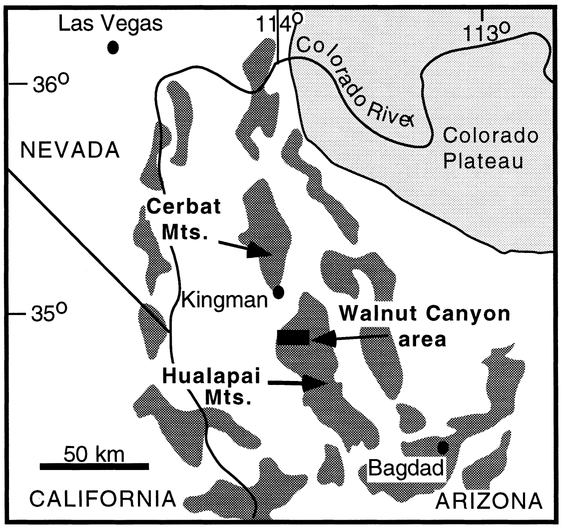

Fig. 3. Index map of northwestern Arizona and neighboring states showing principal mountain ranges (dominantly Paleoproterozoic metamorphic and plutonic rocks, dark stipple) and location of the Walnut Canyon area within the Hualapai Mountains. White areas denote regions of dominantly Cenozoic rocks. The Colorado Plateau is characterized by flat lying Paleozoic and Mesozoic rocks that have been little deformed by regional Mesozoic and Cenozoic deformational events.

interpretation, metamorphic zircons sampled from the Cerbat Mountains, directly north of the Hualapai Mountains, yield U–Pb dates of ca. 1720 Ma (K. Chamberlain, personal communication, 2002).

The second deformational event, which produced the pervasive, subvertical northeast-striking foliation throughout central and northwestern Arizona, is locally characterized by a subvertical elongation lineation; however, large areas of flattening fabrics devoid of lineations are present. This event records northwest–southeast shortening associated with the accretion of the composite Mojave/Yavapai province to the growing Laurentian craton during the Yavapai orogeny at 1700–1685 Ma (Karlstrom and Bowring, 1988, 1993; Hawkins et al., 1996; Duebendorfer et al., 2001). This event occurred at low-pressure granulite-facies conditions (sillimanite + K feldspar + cordierite) (Spear, 1993), but at somewhat lower temperature and pressure (650 °C and 4 kbar) than D1. The marked difference in orientation and timing strongly suggests two distinct deformation events rather than a single progressive deformation. The observation that regional D_1 and D_2 fabrics are consistently oriented throughout central and northwestern Arizona, an area in excess of 75,000 km^2, suggests little or no tilting or rotation of individual blocks and that present-day fabric orientations are probably close to their original orientations.

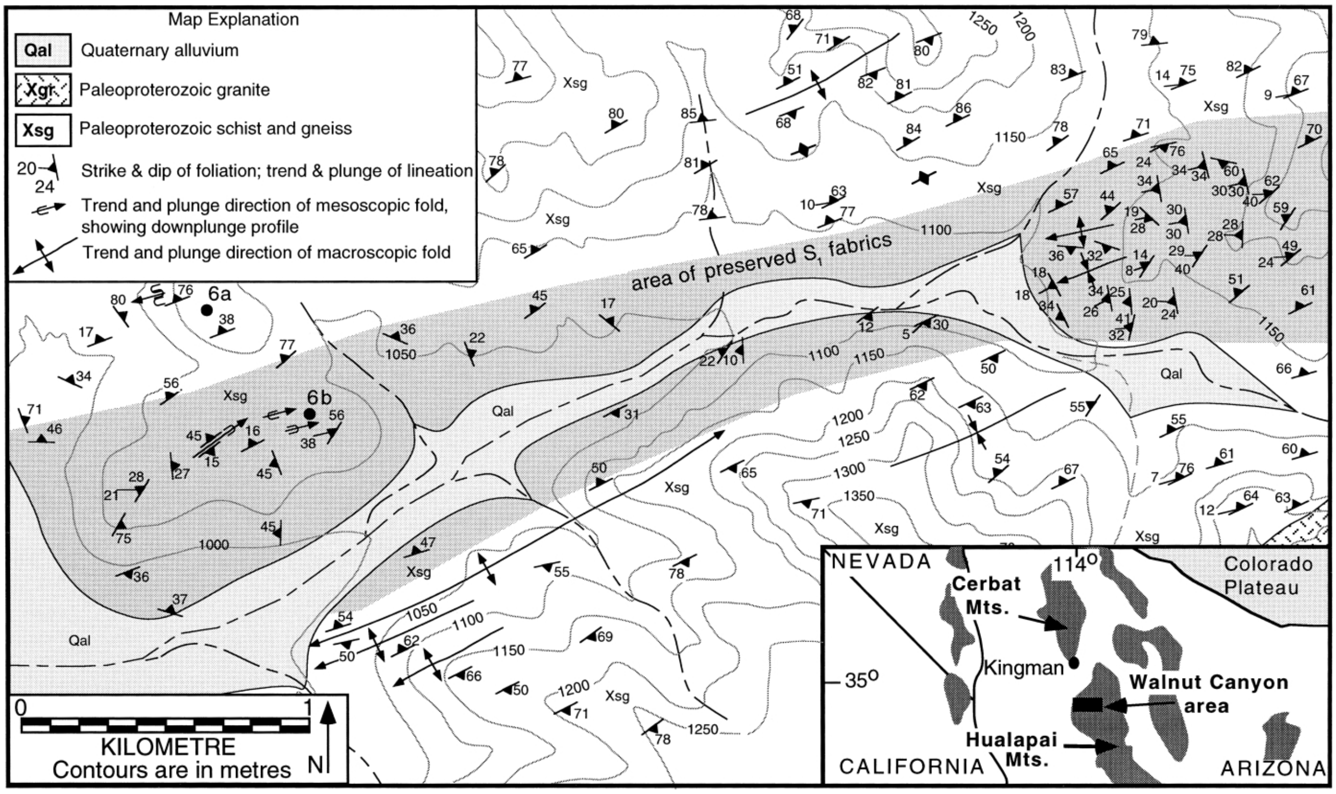

Fig. 4. Structure map of a part of the Walnut Canyon area that preserves the S_1 foliation (area delineated by darker stipple). For several kilometers north and south of Walnut Canyon, the S_1 foliation has been completely reoriented into the northeast-striking, subvertical S_2 orientation, which appears to be the only foliation in those areas. Locations of Fig. 6a and b are shown on the map. Inset shows location of Fig. 4 in northwest Arizona.

3.2. Walnut Canyon area

Because of the complete transposition of the S_1 fabric by S_2 throughout most of northwestern Arizona, S_2 *appears* to be the only penetrative fabric in much of the area. Only small pockets of the S_1 fabric are preserved. One such place is a 3 km^2 area in Walnut Canyon, northern Hualapai Mountains (Fig. 4). Nowhere in this area does S_2 sharply truncate S_1; S_1 is simply folded into the regional northeast-striking S_2 orientation. Examination of microstructures and mineral assemblages reveals no differences in conditions of deformation between rocks from gently dipping domains (i.e. S_1) and steeply dipping domains (i.e. S_2).

In the parts of Walnut Canyon largely devoid of F_2 folds, the average orientation of S_1 is strike = 000°, and dip = 15–30° west (Fig. 4, east part of map; Fig. 5). A mineral elongation lineation, defined by recrystallized quartz and feldspar aggregates (*X*:*Z* ratios range from 5:1 to >10:1), generally plunges 15–30° toward 70–80° or 250–260° indicating a dominant dip-slip component of motion (rakes = 70–90°). Towards the margins of the area of well-preserved S_1 fabric, S_1 becomes gently warped by mesoscopic F_2 folds that plunge 0–35° toward 30–50° and 210–230°, that is, oblique to L_1 (Figs. 5 and 6). The divergence in plunge (to both the northeast and southwest) is a result of a late folding event (F_3), apparently restricted to the Walnut Canyon area, that produced broad, northwest-trending warps at wavelengths of 10s to 100s of meters. Most mesoscopic F_2 folds are gentle, with interlimb angles greater than 120° (Fig. 5, note concentrations of poles to foliation near the center of the stereogram). In this part of Walnut Canyon, the relation between L_1 and F_2 is obvious; i.e. L_1 is clearly folded by F_2 (Fig. 6). The regional π axis plunges 20° toward 232° similar to the orientation of mesoscopic F_2 folds (Fig. 5).

North and south of Walnut Creek, however, transposition of the originally gently dipping S_1 fabric into the northeast-striking, subvertical S_2 orientation is complete, and there is no evidence for the earlier S_1 fabric. As a result of F_2 folding, the folded L_1 lineations contained within the composite S_1/S_2 foliation plunge gently to the northeast or southwest (rakes = 0–30°and 150–180°) (Fig. 7). A geologist working in the large area dominated by D_2 structures could easily conclude that L_1 was genetically related to S_2 (and therefore interpret it as L_2), leading to the incorrect interpretation that D_2 was characterized by subhorizontal extension, perhaps due to strike-slip motion. Where present, the regionally subvertical mineral lineations that characterize the D_2 event indicate that motion was predominantly dip slip (discussed above).

3.3. Geometric relations between F_2 folds and L_1 lineations

Because of the obliquity of F_2 and L_1, a small-circle distribution of L_1 about F_2 would be expected on a stereogram. This is obviously not the case (Fig. 5), due

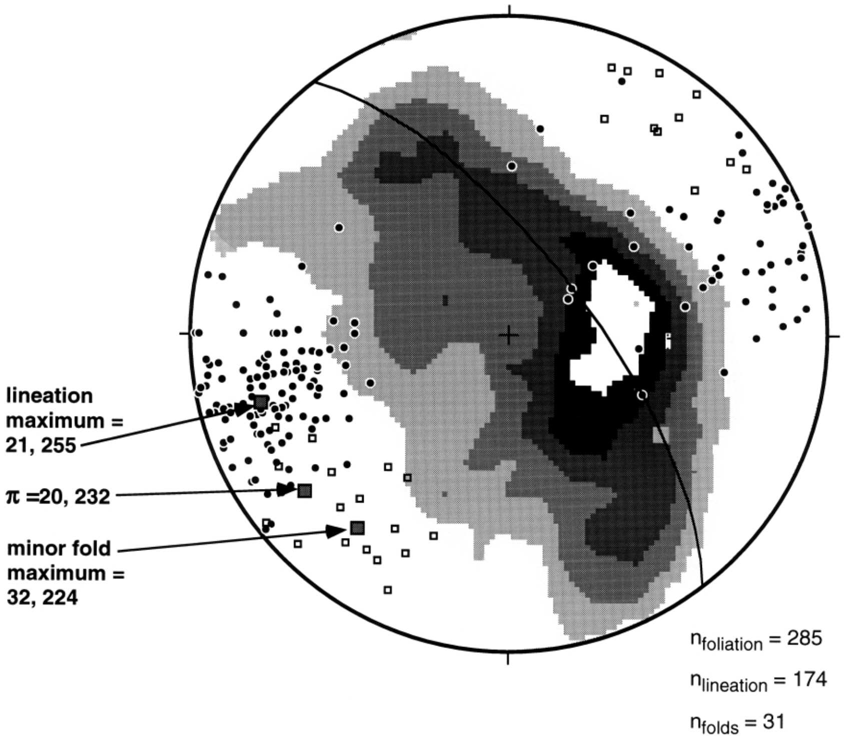

Fig. 5. Structural data from the Walnut Creek area (Fig. 4). Lower-hemisphere, equal-area plot of poles to S_1/S_2 foliation (Kamb contour interval = 2σ), L_1 lineations (dots), and mesoscopic F_2 folds (open boxes). Best-fit great circle defines a π axis of 20°, 232° that represents F_2 fold axis.

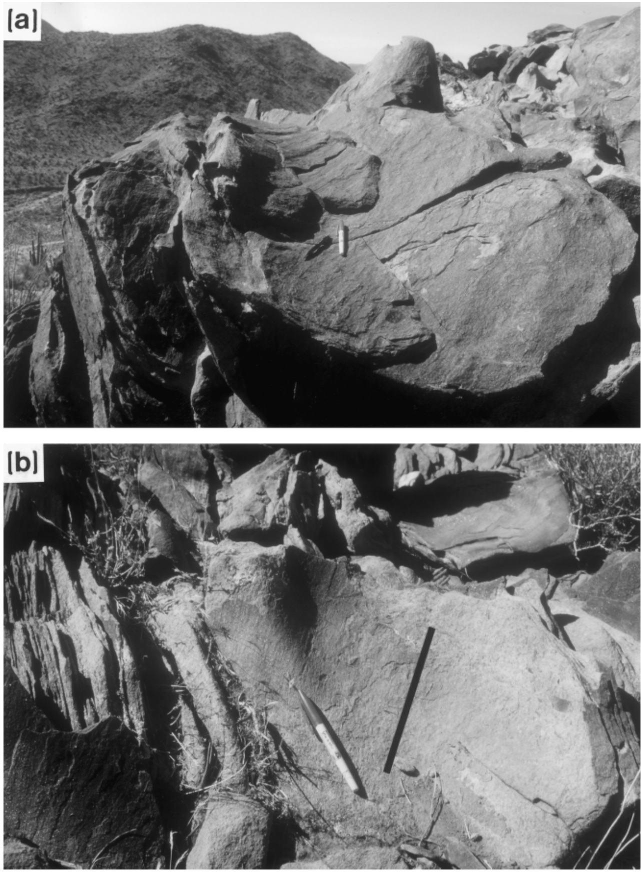

Fig. 6. (a) Up-plunge view of mesoscopic F_2 synform showing folded L_1 lineation (parallel to pencil). Marking pen approximates trend of the F_2 fold hinge. Marking pen is 14 cm long. Erosion follows the folded S_1 foliation. (b) View looking down at mesoscopic F_2 antiform showing folded L_1 lineation (parallel to black line). Marking pen approximates trend of the F_2 fold hinge. Marking pen is 14 cm long. Erosion follows the folded S_1 foliation.

largely to the gentle character of F_2 folds (see Fig. 2), complications introduced by the later, northwest-trending F_3 warps (described above), and probable original natural scatter in L_1 lineation orientation. Thus, analysis of fabric element orientations on the stereonet would not necessarily reveal the presence of folded lineations that are clearly present in the field, but *only in a very small area* (Fig. 4).

As noted above, in areas devoid of F_2 folds, the rake of the L_1 lineation is generally 70–90° indicating dominantly dip-slip motion for D_1. Because of the relatively small angle ($\phi = 20–30°$) between L_1 and F_2, the L_1 lineation is reoriented toward increasingly lower rakes on the limbs of mesoscopic F_2 folds. Fig. 7, a plot of S_1 and S_1/S_2 foliation strike vs. lineation rake, shows that rakes vary systematically with the strike of foliation. Where foliation strike is approximately orthogonal to S_2, i.e. the regional S_1 orientation (150–180°), rakes are high. Where S_1 has been rotated, by F_2 folding, into the steep northeasterly strikes typical of the regional S_2 foliation, rakes are low. This type of plot may be useful in testing for folded lineations in areas where folding of an earlier lineation may be suspected but is not directly observable in the field.

4. Discussion

Multiphase deformation is the rule in most orogenic belts; however, it is common that fabrics and structures formed during early deformation events become strongly or completely overprinted by subsequent deformational events. In areas where evidence of polyphase deformation is obvious, for example where mesoscopic overprinting structures can be seen in the field or where fold interference patterns are evident at the map scale, it is generally straightforward to define which fabric elements correspond to which phase of deformation. In areas where early fabrics are completely overprinted except for small windows that have escaped later deformation, it is possible to miss, in the field, evidence for that early event. With the increasing focus in structural geology on detailed analysis of mesoscopic and microscopic structures, sometimes at the expense of field mapping of large areas, the potential for missing evidence for an earlier event becomes greater. In some cases, as described above, even stereonet analysis may fail to reveal evidence for polyphase deformation. As seen in the example from the Hualapai Mountains, failure to recognize that L_1 lineations have been folded by F_2 folds may lead to a misinterpretation of the kinematics and strain signature of the D_2 event. This possibility underscores the need for detailed mapping of large areas, in concert with mesoscopic and microscopic analysis of structures, to fully understand the structural evolution of an orogen.

5. Conclusion

Elongation lineations, generally interpreted to represent the finite elongation direction, or tectonic transport direction in highly strained rocks, are commonly assumed to be genetically related to the foliation plane in which they occur. Reorientation of a lineation by later folding, if not recognized, may lead to misinterpretation of the kinematics or strain signature of the second event, as seen in the example from the Hualapai Mountains, Arizona. In the case where the angle between the early lineation and the later fold axis is small (<25°), the expected small circle distribution of folded lineations on stereograms may be difficult to distinguish from a diffuse, natural scatter of lineation orientations, such that folding of the lineations may not be recognized. In such cases, plots of foliation strike vs. lineation rake may aid in the recognition of folded lineations.

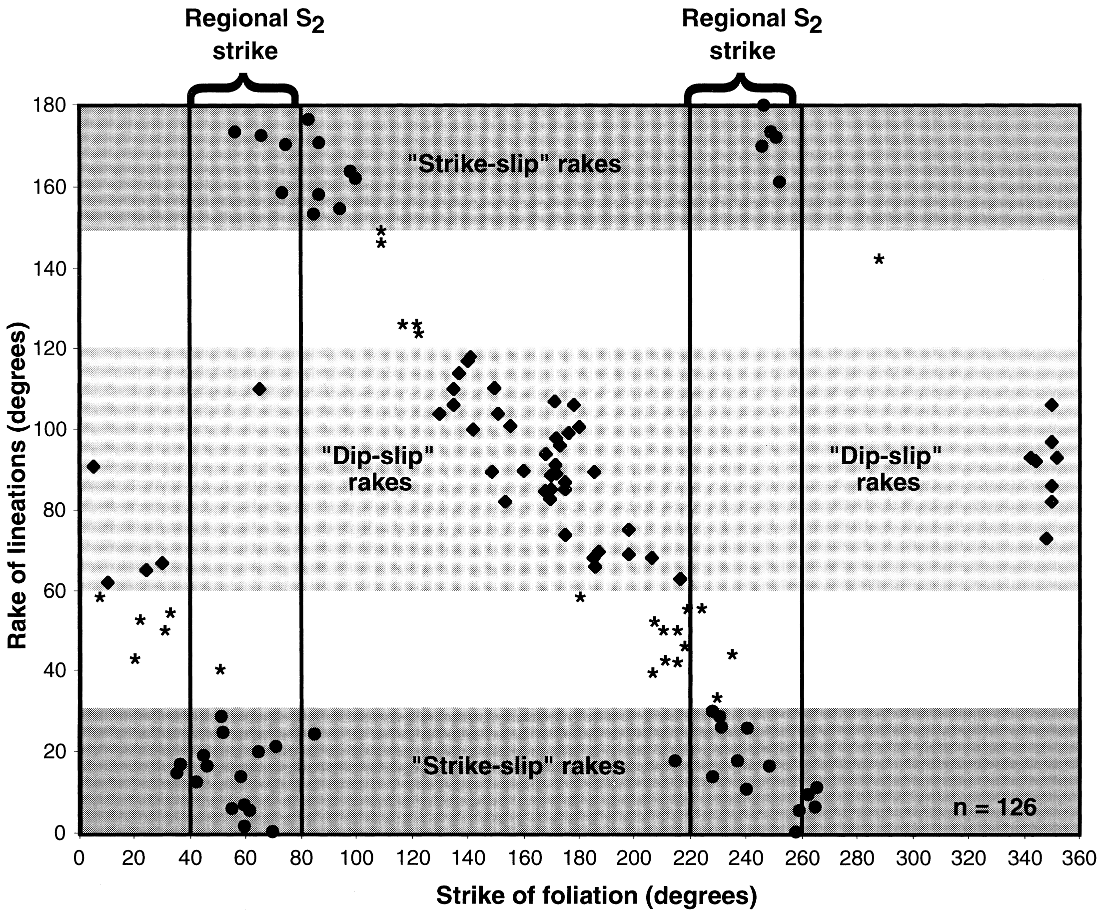

Fig. 7. Plot of strike of S_1 and S_1/S_2 foliation vs. rake of folded L_1 lineation using right-hand rule (e.g. for north-striking, east-dipping foliation, lineations with northerly rakes plot between 0° and 89°; lineations with southerly rakes plot between 91° and 180°). Note systematic variation in rake relative to foliation strike. Strikes corresponding to regional S_2 (040–080° and 220–260°) are delineated by bold rectangles. For these strikes, nearly all rakes are less than 30° or more that 150°, suggesting (erroneously) subhorizontal elongation. For S_1 orientations (160–200° and 340–020°), rakes are 60–120°, representing dominantly dip-slip movement. Dots = lineations with 'strike-slip' rakes, diamonds = lineations with 'dip-slip' rakes, stars = lineations with 'oblique-slip' rakes. Number of foliations and lineations shown on this plot are less than those on Fig. 5 because some foliations lack lineations and some lineations were not developed on foliation surfaces (L tectonites).

Acknowledgements

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References

Berthé, D., Choukroune, P., Jegouzo, P., 1979. Orthogneiss, mylonite and noncoaxial deformation of granites: the example of the South Armorican Shear Zone. Journal of Structural Geology 1, 31–42.

Duebendorfer, E.M., Chamberlain, K.R., Jones, C.S., 2001. Paleoproterozoic tectonic history of the Mojave–Yavapai boundary zone: perspective from the Cerbat Mountains, northwestern Arizona. Geological Society of America Bulletin 113, 575–590.

Goscombe, B., Trouw, R., 1999. The geometry of folded tectonic shear sense indicators. Journal of Structural Geology 21, 123–127.

Gray, M.B., Mitra, G., 1999. Ramifications of four-dimensional progressive deformation in contractional mountain belts. Journal of Structural Geology 8/9, 1151–1160.

Hawkins, D.P., Bowring, S.A., Ilg, B.R., Karlstrom, K.E., Williams, M.L., 1996. U–Pb geochronologic constraints on the Paleoproterozoic crustal evolution of the Upper Granite Gorge, Grand Canyon, Arizona. Geological Society of America Bulletin 108, 1167–1181.

James, S.C., Duebendorfer, E.M., Hoisch, T.D., 2001. Location of the granulite–amphibolite facies transition in northwestern Arizona. Geological Society of America Abstracts with Programs 33, 24.

Jones, C.S., Duebendorfer, E.M., Hoisch, T.D., 1998. Structure and metamorphism of the Vock Canyon area, Cerbat Mountains, Arizona: implications for amalgamation and accretion of the Mojave and Yavapai Proterozoic crustal provinces. Geological Society of America Abstracts with Programs 30, 12.

Karlstrom, K.E., Bowring, S.A., 1988. Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America. Journal of Geology 96, 561–576.

Karlstrom, K.E., Bowring, S.A., 1993. Proterozoic orogenic history of Arizona. In: Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., Van Schmus, W.R. (Eds.), Precambrian Conterminous. U.S. Geological Society of America, The Geology of North America C-2, pp. 188–211.

Marshak, S., Mitra, G., 1988. Basic Methods of Structural Geology, Prentice-Hall, Englewood Cliffs, New Jersey.

Passchier, C.W., Trouw, R., 1996. Microtectonics, Springer-Verlag, Berlin.

Potts, G.J., Reddy, S.M., 1999. Construction and systematic assessment of relative deformation histories. Journal of Structural Geology 8/9, 1245–1254.

Ramsay, J.G., Huber, M., 1983. The Techniques of Modern Structural Geology. Volume 1: Strain Analysis, Academic Press, London.

Simpson, C., Schmid, S.M., 1983. An evaluation of the criteria to deduce the sense of movement in sheared rocks. Geological Society of America Bulletin 94, 1281–1288.

Spear, F.S., 1993. Metamorphic Phase Equilibria and Pressure–Temperature–Time Paths, Mineralogical Society of America Monograph, Washington, DC.

Tikoff, B., Greene, D., 1997. Stretching lineations in transpressional shear zones: an example from the Sierra Nevada Batholith, California. Journal of Structural Geology 19, 29–39.