JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. B2, PAGES 1897–1899, FEBRUARY 10, 1992

Correction and Addition to "The Solid-State Flow of Polymineralic Rocks" by Mark R. Handy

CORRECTION

In the paper "The Solid-State Flow of Polymineralic Rocks" by Mark R. Handy (*Journal of Geophysical Research, 95* (B6), 8647-8661, 1990), equations (8), (12), and (13) in section 4.2 on p. 8657 are incorrect and should include volume proportion terms. They should read

$$\sum_{i=1}^{N} \phi_i \, \sigma_i \, \dot{\varepsilon}_i = \sigma_{\mathrm{rock}} \, \dot{\varepsilon}_{\mathrm{rock}} \tag{8}$$

where σ_i and $\dot{\varepsilon}_i$ are the stresses and strain rates of the ith constituent phase in a rock of viscous strength σ_{rock} at a bulk strain rate ε_{rock} and where ϕ_i is the volume proportion of the ith phase.

$$\sigma_{\mathrm{rock}} = \frac{\phi_i \, \dot{\varepsilon}_i \left[\dot{\varepsilon}_i F_i^{-1} + \exp n_i^{-1}\right] + \phi_j F_j \sigma_j^{n_j+1}}{\dot{\varepsilon}_{\mathrm{rock}}} \tag{12}$$

$$\sigma_{\mathrm{rock}} = \frac{\phi_i \dot{\varepsilon}_i \left[\dot{\varepsilon}_i F_i^{-1} + \exp n_i^{-1}\right] + \phi_j \dot{\varepsilon}_j \left[\dot{\varepsilon}_j F_j^{-1} + \exp n_j^{-1}\right]}{\dot{\varepsilon}_{\mathrm{rock}}} \tag{13}$$

where n is the creep exponent with differing values in the mineral phases i and j. F is expressed as $A\exp(-Q/RT)$, where T is the absolute temperature, R is the universal gas constant, Q is the activation energy of creep, and A is an empirically determined constant. The values of Q and A are material-dependent and differ for the two phases.

The omission of appropriate volume proportion terms in equations (14) and (15) in section 4.3 on p. 8658 also invalidates the normalized strength versus composition diagram in Figure 9*a*. The stress concentration diagrams presented in Figures 1 and 2 below replace Figure 9*a* and are consistent with the hypothesis in section 4.3 of the original paper regarding the effect of foliation development on viscous rock strength.

ADDITION TO FOLIATION DEVELOPMENT IN ROCKS

Using equation (5) and the data in Figure 7 of the original paper, one can calculate the maximum stress concentration in the quartz matrix for two hypothetical, end-member clast-matrix microstructures as discussed in section 4.3. An ideal, high-strain mylonitic microstructure comprises perfectly planar, uniformly spaced, alternating layers of quartz and feldspar oriented parallel to the shearing plane. The compositional dependence of maximum stress concentration in the quartz matrix of a perfectly foliated greenschist facies mylonite is estimated by equating the distance between the centers of neighboring feldspar clasts in the real mylonite (Figure 7) with the shortest distance between the center planes of adjacent feldspar layers in the hypothetical mylonite. Thus, the volume proportion of quartz ϕ_{quartz} is equal to the clast spacing-size factor α in equation (5). Varying the size of the clasts at constant spacing is like varying the volume proportion and thickness of feldspar in the uniformly spaced layers of the hypothetical mylonite.

The mechanical and geometric opposite of a perfectly planar foliation is an ordered configuration of perfectly spherical clasts. A face-centered cubic configuration of feldspar clasts is chosen here to represent an ideal, unstrained microstructure in which stress concentration in the quartz matrix is maximized for a given volume proportion of feldspar. The compositional dependence of maximum stress concentration in the quartz matrix at the onset of deformation of this unstrained aggregate is obtained by replacing α in equation (5) for the real mylonite with $1-[(4.24/\pi)(1-\phi_{quartz})]^{1/3}$ for the hypothetical unstrained rock.

Figure 1 shows the compositional dependence of maximum stress concentration in the quartz matrix of a quartz-feldspar aggregate for both the ideal unstrained (dashed curve) and strained microstructures (solid curve). Stress concentration is expressed as a multiple of the creep stress in a pure quartz layer (equation (4)). Note that because stress concentration in the viscous matrix only becomes significant at very small clast spacings (Figure 2*a*), the maximum stress concentration in Figure 1 only slightly overestimates the average stress concentration in the matrix for ϕ_{quartz} values corresponding to the range of measured z/d ratios (undotted parts of curves in Figure 1). Although the average stress concentration is always less than the maximum stress concentration, the relative position of the two curves in Figure 1 remains the same for any given two-phase composition. Before discussing the mechanical significance of the curves in Figure 1, I emphasize that they are only quantitatively valid for quartz undergoing power law creep under greenschist facies conditions (300-400°C) at a constant bulk natural strain rate. This bulk strain rate is poorly constrained and ranges from about 10^{-11} to 10^{-13} s^{-1}. These estimates are based on the extrapolation of experimental steady state creep laws to flow stresses (about 100 MPa) obtained from dynamically recrystallized grain size piezometry in pure quartz mylonites at the same locality as the quartz-feldspar mylonite used in this study [*Handy*, 1986]. For any volume proportion of quartz less than 1, high bulk strain rates tend to increase the stress concentration in the matrix, whereas low bulk strain rates decrease the stress concentration. Despite these uncertainties in bulk strain rate and temperature, the asymmetrical shape of the curves in Figure 1 probably typifies the compositional dependence of stress concentration in any two-phase material containing a matrix that undergoes dislocation creep between clasts of a rigid phase.

Figure 1 indicates that the development of a foliation is associated with a marked decrease in the stress concentration within the viscous quartz matrix, particularly in rocks with low to moderate volume proportions of quartz. Both pairs of stress concentration curves in Figure 1 are only valid for hypothetical end-member geometrical distributions of feldspar

Paper number 91JB02203.
0148-0227/92/91JB-02203$02.00

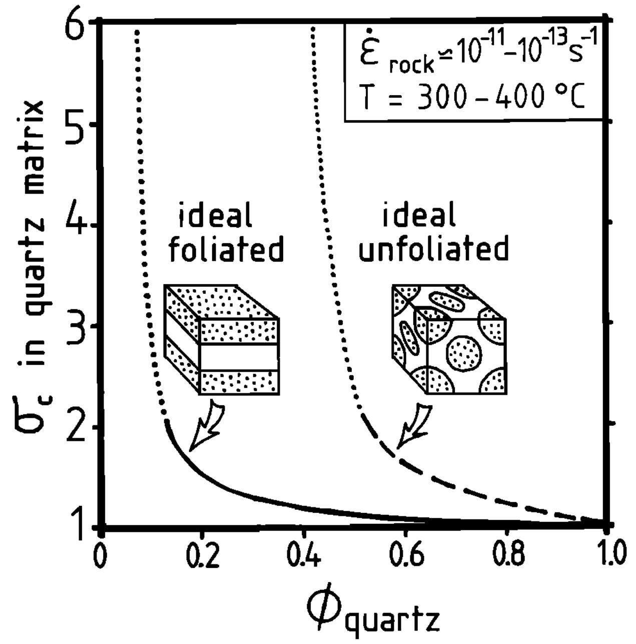

Fig. 1. Maximum stress concentration in quartz matrix versus volume proportion of quartz for two hypothetical, end-member microstructures in a greenschist facies quartz-feldpar rock. Solid line is for perfectly planar foliation parallel to the plane of shear (ideal high strain microstructure), whereas dashed line is for a face-centered cubic configuration of spherical feldspar clasts (ideal unstrained microstructure). Dotted parts of curves correspond to extrapolation of quartz grain size data to clast *z/d* values less than 1.13 and probably significantly overestimate the actual stress concentration in the quartz matrix (see text for further explanation). Curves calculated from modification of equation (5) using a stress-grain size exponent p of 0.71 [*Twiss*, 1977].

clasts in a quartz-feldspar aggregate and so are likely to bracket stress concentration versus composition curves for naturally deformed quartz-feldspar rock at similar strain rates and temperatures. In natural mylonite, the clasts in the foliational layers are often irregularly shaped (Figures 2*b*, 2*c*, and 6 in the original paper). Such geometrical irregularities probably increase the stress concentration in the matrix to levels somewhat above those predicted for a perfectly planar foliation in Figure 1. Similarly, feldspar clasts in undeformed granitic rock are nonspherically shaped and their distribution is not as ordered as in the ideal face-centered cubic configuration assumed here. The stress concentration in the matrix of a rock undergoing incipient deformation is therefore somewhat less than that predicted by the curve for ideal, unfoliated rock in Figure 1. The important point made in the original paper and reiterated here is that strain-dependent development of a foliation decreases the stress in the weak viscous matrix and so also decreases the amount of deformational energy expended on the entire rock for a given increment of strain. This in turn leads to a weakening of rock deforming at a given bulk strain rate, a phenomenon termed "foliation weakening" in experimentally deformed two-phase aggregates [*Le Hazif*, 1978; *Jordan*, 1988].

What factors influence foliation development during shearing? Some insight into this question is gained by observing how stress concentration varies locally within the microstructure of deformed rocks. Figure 2*a* is a plot of equation (5) showing that stress concentration in the dynamically recrystallized quartz matrix varies nonlinearly with distance between the feldspar clasts and with clast size. Three clast spacing-size intervals are distinguished in Figure 2*a* on the basis of microstructural observations: (1) at

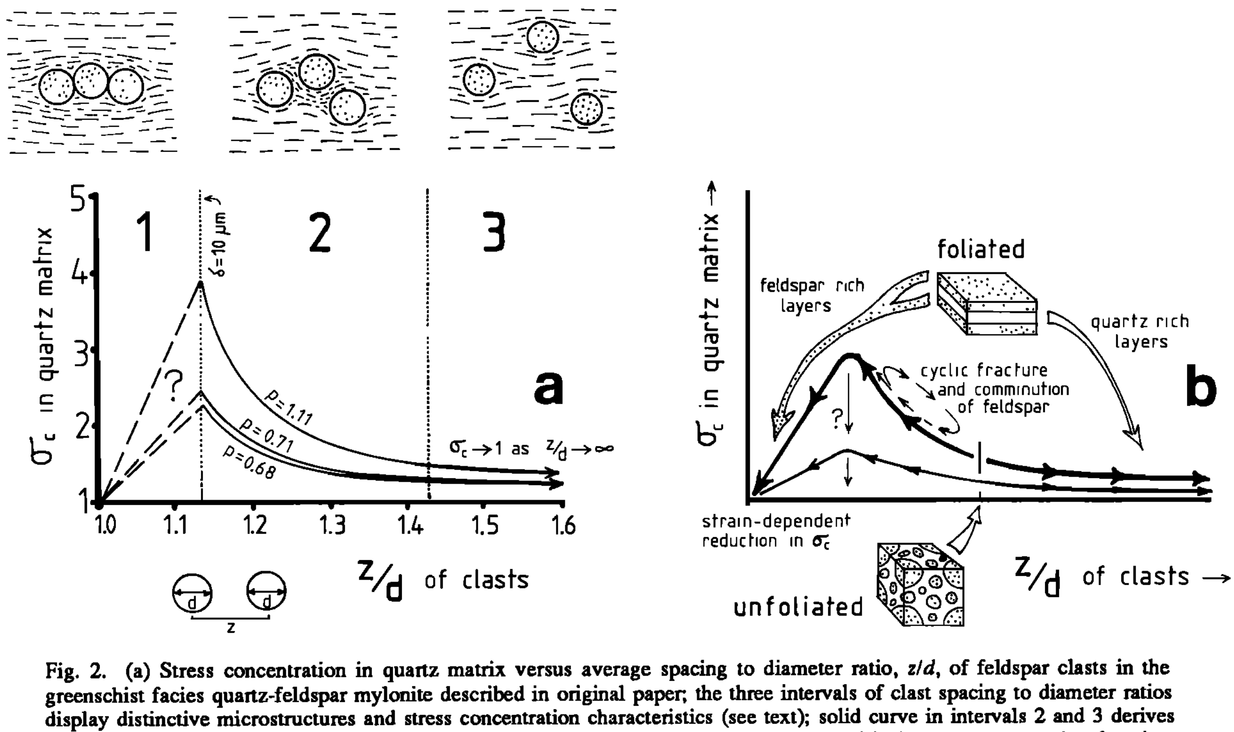

Fig. 2. (a) Stress concentration in quartz matrix versus average spacing to diameter ratio, *z/d*, of feldspar clasts in the greenschist facies quartz-feldspar mylonite described in original paper; the three intervals of clast spacing to diameter ratios display distinctive microstructures and stress concentration characteristics (see text); solid curve in intervals 2 and 3 derives from a best fit of grain size and spacing measurements in the natural mylonite to an empirical stress concentration function (equations (3) and (5) in original paper); dotted curves in interval 1 are inferred from microstructures discussed in the text; stress-grain size exponents p for hydrous quartzite used in equation (5): 0.68 [*Mercier et al.*, 1977], 0.71 [*Twiss*, 1977] and 1.11 [*Christie et al.*, 1980]. (b) Schematic plot of stress concentration versus spacing to diameter ratio of clasts showing the inferred change in localized stress concentration in the matrix (arrows) during the evolution of feldspathic and quartzose layers from an initially undeformed granitic rock with an isotropic distribution of feldspar grains (see text for explanation).

moderate to high clast spacing to size ratios ($1.43 < z/d < \infty$, interval 3 in Figure 2*a*), there is no significant stress concentration in the quartz matrix except in the immediate vicinity of feldspar clasts [*Prior et al.*, 1990]. To the extent that it is observed, localized stress rise in the matrix appears to be controlled by viscous drag around the rigid clasts rather than by the far field effects of neighboring feldspar clasts [*Masuda and Ando*, 1988]; (2) at small to moderate clast spacing to size ratios ($1.13 < z/d < 1.43$, interval 2 in Figure 2*a*), stress concentration in the quartz matrix varies strongly with the relative spacing of feldspar clasts; (3) at extremely low clast spacing to size ratios ($1 < z/d < 1.13$, interval 1 in Figure 2*a*), stress concentration in the viscous matrix is inferred to decrease from a maximum between intervals 1 to 2 to either a lesser finite value or to unity as the z/d ratio approaches unity. This inference comes from the observation that feldspar clasts within foliational layers are often in mutual contact (Figure 2*b* in original paper), suggesting that hydrodynamic lubrication forces in the viscous quartz matrix breakdown at very small clast spacings. The maximum stress concentration in the quartz matrix at the boundary between intervals 1 and 2 is limited by one or more factors: High localized stress concentration in the matrix can induce either fracturing [*Mitra*, 1978] or yielding of the feldspar grains, depending on the ambient temperature and local strain rate. Alternatively, the local stress-dependent dynamically recrystallized grain size of the quartz matrix becomes small enough ($\delta = 10$ mm or less) to induce a mechanism switch from dislocation creep to grain size sensitive diffusion creep in the matrix. The boundary between intervals 2 and 3 coincides with clast spacing to size ratios for which quartz matrix grain sizes fall within the range of quartz grain sizes in pure quartzite mylonites ($\alpha > 0.3$ in Figure 7*b* of original paper).

An interesting, albeit indirect consequence of Figure 2*a* is that the evolution of a mylonitic foliation is associated with complex stress histories on the scale of individual grains within the aggregate. This is shown schematically in Figure 2*b* for granite with initially homogeneous spatial and size distributions of feldspar and quartz. The formation of feldspar rich foliational layers may involve an initial localized increase in stress concentration followed by a reduction in stress concentration as feldspar clasts are pushed or grow together (leftward shift along the curve in Figure 2*b*). Even more complicated, cyclic stress histories are conceivable if the initial stress rise in the matrix leads to repeated fracturing and comminution of the feldspar grains before they finally impinge. In contrast, the formation of contiguous quartz rich layers appears to involve a progressive reduction of stress concentration in the quartz matrix as feldspar clasts are pushed apart (rightward shift along the curve in Figure 2*b*). What is still poorly understood is how these different localized stresses within the aggregate act in concert to segregate material with contrasting mechanical properties into layers parallel to the shearing plane (see discussion at end of section 4.3). Possibly, a progressive change of the dominant deformation mechanism in the fine grained quartz matrix from dislocation creep to diffusion creep reduces the repellant forces between approaching feldspar clasts. Alternatively, fracturing of the clasts may proceed until the clast size is approximately the same size as the dynamically recrystallized matrix grains and the rigid feldspar grains can no longer concentrate stress into the viscous quartz matrix. Both processes are associated with a decrease in the spacing to size ratio of these clasts that may be sufficiently large to allow the mutual overgrowth and cementation of the clasts in the presence of a sytectonic, metamorphic fluid. *Toriumi* [1986] presents evidence in mylonitic metapelitic rock of elongate aggregates comprising syntectonically overgrown garnet clasts that are oriented length-parallel to the mylonitic foliation. Feldspar clasts may continue to cluster in this way during shearing until a sufficient volume of weak quartz forms contiguous layers for the volume-specific rate of strain energy dissipated in the aggregate (equation (8)) to reach a mimimum value at the ambient temperature and bulk strain rate. Detailed microstructural and mineralogical analyses of grain boundaries in the feldspar rich layers may help to determine whether these or other mechanisms are associated with foliation development in mylonite.

Acknowledgments. I would like to thank Martin Casey for voicing suspicions that lead me to discover my mistake and to Dave Olgaard and Holger Stuenitz for subsequent discussions. I should also mention that Steven Kirby, a reviewer of the original paper, was from the outset skeptical of sections 4.2 and 4.3. Finally, my sincere apologies to anyone who wasted time trying to test the validity of equation (8) in my paper.

REFERENCES

Christie, J.M., A. Ord, and P.S. Koch, Relationship between recrystallized grainsize and flow stress in experimentally deformed quartzite (abstract), *Eos Trans. AGU, 61*(17), 377, 1980.

Handy, M.R., The structure and rheological evolution of the Pogallo fault zone: A deep crustal dislocation in the southern Alps of northwestern Italy, Ph.D. thesis, 327 pp., Univ. of Basel, Switzerland, June 1986.

Jordan, P., The rheology of polymineralic rocks- An approach, *Geol. Rundsch., 77*(1), 285-294, 1988.

Le Hazif, R., Deformation plastique du system biphase Fe-Ag, *Acta Metall., 36*, 247-257, 1978.

Masuda, T., and S. Ando, Viscous flow around a rigid spherical body: A hydrodynamical approach, *Tectonophysics, 148*, 337-346, 1988.

Mercier, J.C., D.A. Anderson, and N.L. Carter, Stress in the lithosphere: Inferences from steady-state flow of rocks, *Pure Appl. Geophys., 115*, 199-226, 1977.

Mitra, G., Ductile deformation zones and mylonites: The mechanical processes involved in the deformation of crystalline basement rocks, *Am. J. Sci., 278*, 1057-1084, 1978.

Prior, D.J., R.J. Knipe, and M.R. Handy, Estimates of the rates of microstructural changes in mylonites, in Deformation Mechanisms, Rheology and Tectonics, edited by R.J. Knipe and E.H. Rutter, *Geol. Soc. Spec. Publ. London, 54*, 309-319, 1990.

Toriumi, M., Mechanical segregation of garnet in synmetamorphic flow of pelitic schists, *J. Pet., 27*, 6, 1395-1408, 1986.

Twiss, R.J., Theory and applicability of a recrystallized grainsize paleopiezometer, *Pure Appl. Geophys., 115*, 227-244, 1977.

Mark R. Handy, Geologisches Institut, Universität Bern, 3012 Bern, Switzerland.

(Received May 31, 1991;
accepted August 19, 1991.)