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Lithosphere rheology—a note of caution

E. H. Rutter and K. H. Brodie

Department of Geology, University of Manchester, Manchester M13 9PL, U.K.

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Abstract—It has become common practice to use laboratory-determined, low-temperature frictional sliding data, together with power-law equations for 'steady-state' creep of rocks at high temperatures, to construct inferred profiles of rock strength and mode of failure with depth in the lithosphere. In some cases this may involve unwarranted extrapolation of rock mechanics behaviour beyond the region of its validity. The form of transition from frictional behaviour to intracrystalline plastic flow in the Earth is much more complex than is suggested by the above model. Within the regime of plastic flow, substantial changes in flow-strength and mode of failure (whether flow becomes localized into shear zones) may accompany microstructural changes developed over large strains. When deformation is accompanied by metamorphic changes, existing flow laws for rocks are likely to be wholly inapplicable. Until a clearer understanding has emerged of the full range of expression of the rheological behaviour of rocks, existing models of lithosphere rheology should be treated with caution.

INTRODUCTION

Since the pioneering work of Goetze & Evans (1979), attempts to construct strength profiles with depth in the lithosphere, based on the results of rock mechanics experiments, have become very fashionable (e.g. Meissner & Strehlau 1982, Sibson 1982, Chen & Molnar 1983, Smith & Bruhn 1984, White & Bretan 1985, Dewey *et al*. 1986, Dunbar & Sawyer 1989, and many others). These models have been manipulated by many (but not all) authors in an uncritical way, with a lack of consideration for the limitations of the experimental data and an apparent disregard for what field and microstructural studies tell us about the mechanical properties of the lithosphere. It is the purpose of this note to draw attention to some of these limitations and to urge caution in the construction of models for lithosphere rheology.

SUMMARY OF CURRENT VIEWS

It is generally held that the strength of the upper 15 km or so of the lithosphere is controlled by friction on faults. To a first approximation this is independent of rock type, deformation rate and temperature (e.g. Byerlee 1968, 1978, Carter & Tsenn 1987). On the other hand, frictional strength is very sensitive to effective normal stress across a fault surface, hence the overall strength nominally increases markedly with depth, at a rate dependent upon whether faulting has a thrust, strike-slip or normal character. Local increase in pore fluid pressure at any depth markedly reduces strength, although in model studies the effects of pore pressure have commonly been restricted to the assumption of a hydrostatic rate of increase of fluid pressure with depth.

At greater depths it is inferred that progressively higher temperatures cause the resistance to flow by intracrystalline plasticity to drop to lower levels than the resistance to faulting. Intracrystalline plastic flow is strongly temperature and deformation rate-sensitive, but relatively pressure-insensitive, hence the strength vs depth profiles passes through a maximum, which broadly corresponds to the mechanism transition. The friction to plastic transition is inferred to lie at shallower depths as deformation rate decreases or thermal gradient increases (e.g. Meissner & Strehlau 1982, Sibson 1982, Chen & Molnar 1983, Kusznir & Park 1986), and has been proposed to correspond with the depth limit of shallow seismicity.

This simple picture is essentially that painted by Goetze & Evans (1979), and subsequently elaborated by others. A significant elaboration is the idea that petrological stratification of the lithosphere will lead to stratification of mechanical properties (e.g. Smith & Bruhn 1984, Ranalli & Murphy 1987). Rock mechanics experiments under isomineralic conditions consistently show that for intracrystalline plasticity, quartz-rich rocks are weaker than feldspathic rocks, which are in turn weaker than ultramafic rocks. These observations are qualitatively consistent with what one may infer about the relative strengths of such rocks from their modes of failure in nature when they occur in close proximity to each other. There are also reasons for believing that, to a good approximation, deformation of the continental upper crust is dominated by the flow of quartz-rich rocks, the lower crust by feldspar-rich rocks and the upper mantle by olivine-rich rocks. Hence 'rheological stratification' of the lithosphere is to be expected (Ranalli & Murphy 1987), with strength locally markedly increasing as one passes down from the base of an overlying, weaker stratum to the top of a subjacent, stronger level. Within each stratum, strength decreases with depth as a result of rising temperature. It has also been suggested that the weak intervals at the base of a stratum of given composition may be preferred levels for the localization of sub-horizontal detachment or slip-transfer zones (e.g. White & Bretan 1985). Kusznir &

Park (1986) have pointed out that for large-scale tectonic processes to occur, involving displacements of hundreds or thousands of kilometres, it is necessary for yield conditions over the whole of the strength vs depth profile to be attained (whole-lithosphere failure).

LIMITATIONS OF THE ABOVE GENERALIZATION

The concept of rheological stratification has undoubtedly proved useful in constructing mechanical models of the lithosphere and in helping understand the depth distribution of seismicity. It is important to be aware of the limitations of this approach, however, and to consider conditions under which it may be inapplicable.

Limitations of experimental studies

Although useful, the generalization of Byerlee (1978) that rock friction is independent of rock type is an approximation established almost entirely at room temperature. At low effective pressures (up to 50 MPa) the variability is very wide and few data are available at normal stress levels above 1000 MPa. Most data are for normal stress levels up to ~250 MPa, within which range friction can vary by a factor of up to 2. Most laboratory friction data are collected over only a few mm of fault displacement, but it is presently unclear whether friction over large (metres) displacements will be significantly different (Blanpied *et al.* 1988, Tullis & Weeks 1989, Tullis *et al.* 1989) as fault-rock fabric and thickness develops.

Although temperature and deformation rate have relatively little effect on friction, the effect is not negligible. At elevated temperatures and in the presence of chemically agressive pore fluid (i.e. water), sub-critical crack growth, solution and diffusive effects may favour fault creep by processes other than intracrystalline plasticity (e.g. Rutter & Mainprice 1978, Angevine *et al.* 1982, Atkinson & Meredith 1987, Scholz 1988). Conversely, dehydration reactions in clay minerals or cementation by hydrothermal minerals may cause hardening under quiescent conditions (e.g. Rutter & Mainprice 1978, Angevine *et al.* 1982). Low-temperature studies of fault-rock friction (e.g. Dieterich 1978, Ruina 1983) have shown that under some environmental conditions friction decreases during a slip velocity increase, and vice versa under other conditions. The former (velocity-weakening) condition favours seismogenic instability, whilst the latter (velocity-strengthening) favours stable fault slippage. The region of transition from shallow-crustal, brittle faulting to deeper-crustal plastic flow is therefore a complex and probably wide zone. It is an oversimplification to attempt to correlate a deformation *mechanism* transition (defined by extrapolation of strength vs depth behaviour expected at shallower and deeper levels respectively to an intersection point) with the depth limit of shallow seismicity (Rutter 1986, Scholz 1988).

Fits to experimental data for rocks deforming by intracrystalline plastic flow have generally been made using the Dorn (1956) power-law creep equation, assuming true steady-state flow at constant microstructure. Most experimental studies have been carried out on monomineralic rocks, and few attempts have yet been made to assess the effects of the addition of a second crystalline phase with different rheological behaviour (e.g. Jordan 1988, Handy 1990). Mechanical experiments are generally performed over strain increments of only about 20%. It is generally not well established: (a) whether the Dorn law is a good basis for the fitting operation even within the limits of the experimental data (Walker *et al.* in press); and (b) over what range of strain the flow remains 'steady'.

Leaving aside the question of the suitability of the Dorn law as a descriptor of the behaviour of rocks at low strain rates, there may be only a limited range of geological conditions for which an extrapolation might be valid, i.e. over a strain range of a few tens of per cent. Such small strain events may be of importance in the initiation of continental collision or extension events, provided strain is fairly homogeneous through the thickness of plastically deforming lithosphere. It is also important to realize that the experimental data are for plastic flow under isomineralic conditions (i.e. without accompanying metamorphic transformation or metasomatism).

Studies of naturally deformed rocks commonly show that at high strains intense crystallographic preferred orientations develop, and/or flow localization into shear zones occurs. Little is known yet about the role of preferred orientation development in the evolution of rheology over large strain increments. However, viscoplastic self-consistent modelling (Molinari *et al.* 1987) and the Taylor model (Taylor 1938) can be used to simulate fabric development and to infer polycrystal rheology over large strains, but the results obtained depend upon the quality of the input data on the properties of single crystals. The commonly noted tendency for 'soft' slip vectors to parallel the shear direction in sheared rocks has been used to infer geometric or 'fabric' softening in shear zones (e.g. Schmid & Casey 1986). Based on self-consistent modelling, Wenk *et al.* (1989) pointed out that such an interpretation may be oversimplified, and Takeshita & Wenk (1988) showed that whether fabric production causes softening or hardening depends sensitively on the strain pathway.

The rocks in 'plastic' shear zones are almost always characterized by intense grain-size reduction (e.g. White 1976, Kirby 1985). Such high-strain microstructural modifications are thought likely to reduce the flow strength, hence stabilizing the localization of the flow. We would contend that flow in localized plastic high-strain zones, passing upwards into frictional faults, represents the most important way in which the very large displacements required by plate tectonics are accommodated at all levels within the lithosphere (Sibson 1977, Coward 1984, Daly 1986, Rutter & Brodie 1988a). Hence the rheology of highly strained rocks in localized zones is more relevant to large-scale tectonics than the low-strain flow which has so far (quite properly) been the object of mechanical experiments on rocks.

Although it is known that dynamic recrystallization and preferred orientation development over large strain increments in metals can cause strain-softening (e.g. Sellars 1978), understanding of strain-softening processes in rocks based on experimental observations is much less clear. Part of the problem resides in the difficulty of inducing large (generally heterogeneous) strains whilst retaining the ability to make meaningful measurements of mechanical properties. Nevertheless, there is some experimental evidence that dynamic grain refinement can lead to weakening and a tendency to localize flow, e.g. in clinopyroxenite (Kirby & Kronenberg 1984), olivine (Post 1977) and feldspar (Tullis & Yund 1985). Equally, it is clear that dynamic recrystallization of some rocks does not necessarily lead to perceptible change in mechanical properties as Schmid *et al.* (1980) have shown for marble. Recently, however, Karato *et al.* (1986) have described weakening of olivine rocks as grain-size is reduced, and we have demonstrated the characteristics of grain-size sensitive flow (in which strength decreases markedly with decreasing grain-size) of synthetic calcite rocks of controlled fine grain-size (Walker *et al.* in press). There is therefore sufficient basis in experimental studies to support the view that grain refinement at large strains can cause weakening and a change in rheological characteristics, but it is not yet clear how such rheological changes depend upon physical environmental conditions and their history.

As mentioned above, it has been suggested that in a lithosphere characterized by 'rheological stratification', weak intervals in the strength vs depth profile (for strains of a few tens of per cent) might be expected to form preferred zones of sub-horizontal detachment. It should be considered, however, that it is in the initially *strong* intervals that tectonic grain-size reduction (and hence strain-dependent weakening) may be most extreme. This may lead to sub-horizontal detachments forming in the initially stronger intervals instead (Rutter & Brodie 1988a). The common occurrence of 'mid-crustal detachments' (e.g. Davis *et al.* 1986) may be an example of this effect. This hypothesis of detachment faulting being controlled by a strain-dependent rheology is amenable to testing by analog or numerical modelling.

Flow to small strains, when microstructure is still evolving, is also of geological importance. The flexural response of the lithosphere to lateral variations in vertical load involves time-dependent relaxation of the elastic fibre strains induced below the neutral surface of the flexure. Attempts to incorporate this into models of lithospheric flexure have used the Dorn law for 'steady-state' flow (e.g. Goetze & Evans 1979, Willett *et al.* 1985), when a transient or state-dependent rheology would be more appropriate (Kirby 1983). Relatively little effort has yet been made to understand the transient rheology of rocks.

Implications of natural rock microstructure

The crucial test of the applicability of high-temperature experimental rock mechanics results to nature is the comparison of experimentally induced deformation microstructures with natural ones. There can be no doubt that good correspondence is sometimes found, but this is usually in the case of monomineralic rocks like quartzites, marbles or dunites, or where polymineralic rocks are deformed under conditions which do not favour metamorphic transformations, for example during cooling of high-grade rocks into which there is no readmission of water.

It is commonly observed in piles of metamorphic rocks that geometrically simple thermal structures are imprinted on rocks showing great internal structural complexity, such as folding and thrusting on a wide range of scales. This is also reflected in the common development of metamorphic microstructures indicative of crystallization and growth under hydrostatic stress (or very low deviatoric stress) conditions. Much of the commonly observed deformed state of rocks is attained during temperature rise towards the metamorphic peak, and this is largely because tectonic displacement is the agency which stacks rock units in such a way that thermal diffusion (and hence metamorphism) occurs.

There are several ways in which syntectonic metamorphism can facilitate deformability of rocks (e.g. Brodie & Rutter 1985, Murrell 1985). Although some relevant experimental studies have been carried out (e.g. Raleigh & Paterson 1965, Vaughan & Coe 1981, Rutter & Brodie 1988b), we know little of the rheology of rocks under such conditions. Certainly the flow laws which have been obtained from laboratory studies on rocks under isomineralic conditions are inapplicable. It is therefore essential in tectonic modelling that a clear distinction be made between situations in which experimental data can be realistically applied and those when it cannot. Equally, in field- and microstructure-based studies of metamorphic tectonites it is vital to report the mechanistic relationships between deformation and metamorphism more carefully than has been usual. For example, it must always be made clear whether a foliation is overprinted by metamorphic equilibration on the grain-scale, or whether it is related to grain-scale deformation features such as plastic grain-flattening and intracrystalline creep features. For the latter instance laboratory-determined flow laws might be applicable; in the former case they would not.

CONCLUSION

Based on currently available constitutive laws for friction and intracrystalline plastic flow of rocks it is possible to construct simple models for the variation of strength and mode of failure of rocks with depth in the lithosphere. Even discounting the question of the validity of extrapolation to low strain-rates, such models can only be valid for isomineralic deformation over the strain ranges observed in the experiments. Possible strain-dependent changes in rheology and hence of failure mode, and the effects of syntectonic metamorphism, mean that lithosphere rheology can be much more variable than is commonly assumed.

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