[AMERICAN JOURNAL OF SCIENCE, VOL. 274, JUNE, 1974, P. 662-665]

A MECHANISM FOR "LOCKING-IN" OROGENIC STRESS

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ABSTRACT. The dissipation of fluid pressure is shown to provide a mechanism for "locking in" orogenic stresses in superjacent rock. These stresses can be measured presumably by existing in-situ stress measurement procedures; the measurements may thus be used presumably to evaluate alternative models of orogenesis.

To cite merely one example, Kehle (1970, p. 1650) has shown that for a given constitutive idealization, model geometry, and assumed velocity, an estimate of orogenic stress may be obtained. The equations may be difficult to evaluate if deformable plates, buckling instabilities, décollement zone "shifts", fluid pressure discontinuities, and other complexities are assumed to have been involved, but in principle results can be obtained by employment of numerical methods. *In any case, it seems clear that measurement of orogenic stress, if this were possible, could be used to provide tests of model idealization* (compare Voight and Taylor, 1969).

Significant Appalachian orogenic stresses are known to have extended well into Ohio, for example, as based on evaluation of regional joint patterns (Nickelsen and Van Hough, 1967). The long-distance transmission of such stresses was undoubtedly related to the development of décollement as suggested by Rich (1934), Woodward (1959), Rodgers (1963), Gwinn (1964), and others. If these décollement were characterized by a condition whereby the interstitial fluid pressure was of a magnitude approximately equal to overburden pressure, as suggested by the Hubbert-Rubey (1959) "resolution" of the overthrust "paradox",[1] then a suitable mechanism would be available for "locking in" such stresses; *once fluid pressure dissipated, the frictional strength imposed in the décollement zone by effective overburden pressure would prevent regional relaxation of the orogenic stress existing at that point in space and time* (fig. 1). A conversion is thus implied within the décollement zone, from a low effective stress Coulomb state or a quasi-viscous fluid state (depending on choice of idealization) to a Coulomb state involving moderate to high effective stresses normal to the décollement[2]; this conversion "freezes" lateral stresses existing in superjacent rock. Décollement should thus be expected to represent a discontinuity with respect to existing stress fields. Certain changes in stress would be expected as a consequence of denu-

[1] The existence of clastic dike-like bodies projecting from certain Appalachian décollement argues in favor of an enhanced fluid pressure mechanism (Voight, 1973).

[2] A conversion from a low to high viscosity state would provide an analogous mechanism for "freezing-in" orogenic stresses; the viscosity change could be related to a change in fluid pressure, temperature, or other deformation factors; this phenomenon need not be restricted to décollement but could occur generally within large volumes in orogenic belts.

dation and/or subsequent orogenic events[3]; under numerous conditions, however, the remnant tectonic components would remain significant.

The local and regional program of stress measurement by rock mechanics specialists thus could take on added meaning to tectonic geologists. A suitable and perhaps typical example is provided by stress measurements by the U.S. Bureau of Mines in eastern Ohio (Obert, 1962; Voight, 1967, p. 341-342; compare Hooker and Johnson, 1967, 1969; Voight, 1969, 1971; Rough and Lambert, 1971; Sbar and Sykes, 1973); these measurements, in limestone at a depth of about 700 m, suggest an orogenic stress component on the order of 300 bars. That stress is the pressure in excess of the horizontal pressure accounted for by existing overburden. The direction is in the east-west plane, and although it cannot be presumed *a priori* that existing stress should bear a symmetrical geometric relationship to previously developed (Paleozoic) structures, that assumption seems plausible in this instance.[4] If this stress could be assumed to be uniformly distributed in a thrust plate (this seems unlikely in detail), assuming, for purposes of example only, the adequacy of the simple model treated by Kehle (1970, p. 1649-1650), and further assuming a velocity of 10 km/m.y. (equivalent to the reported sea-floor spreading rate in the North Atlantic), a décollement zone 0.1 km thick should possess a (Newtonian) viscosity of about 4×10^{-2} m.y.-b[5]. For a décollement zone 0.01 km thick the predicted viscosity is one order of magnitude less; both values fall into the range (10^{-1}—10^{-3} m.y.-b) considered reasonable by Kehle for shale under orogenic conditions.

Whether this model is even crudely appropriate remains to be tested adequately, for indeed, within that portion of the Appalachians, movement may have been largely restricted to a thin décollement horizon; the Hubbert-Rubey idealization (with inclusion of a residual cohesive term) or some alternative may be in fact more appropos at that locality. However, the proposed "locking" mechanism seems sufficiently

[3] It should be noted that the subsequent imposition of regional strains may change the entire stress field, that is, changes may occur in stresses both above and below existing décollement. In such an instance the actual value of stresses at the conclusion of the overthrust event would not be preserved; however, consideration of the *difference* in stress fields determined above and below décollement horizons, as well as the absolute magnitude of stresses within individual thrust plates, may lead to useful interpretations of the mechanics of deformation.

[4] *Note added in press*: The observed westward inclination of trajectories of maximum compression does seem in accord with inferred Paleozoic stress patterns in contrast to a previously expressed opinion (Voight, 1967, p. 342) now considered to be erroneous. If the measured stresses do in fact reflect, in part, Paleozoic deformation, these stress components can be regarded as *residual*, of type II (Voight, 1967, p. 343), that is, stresses that reflect structural inhomogeneity.

For a recent review of the complex subject of residual stress on a smaller scale the reader is referred to a paper by M. Friedman (1972); the concept of *locked-in versus locking strains* (or corresponding stresses) as discussed by Friedman seems particularly relevant to the fluid pressure mechanism presented herein.

[5] The viscosity unit "million year-bars" (m.y.-b) is used herein to permit direct comparison with Kehle's (1970) paper. Kehle has argued that this unit is more convenient than poise for geologic problems, inasmuch as time is typically measured in millions of years rather than seconds, and stress is measured in bars rather than dynes per square centimeter; 1 m.y.-b is approximately 10^{19} poise.

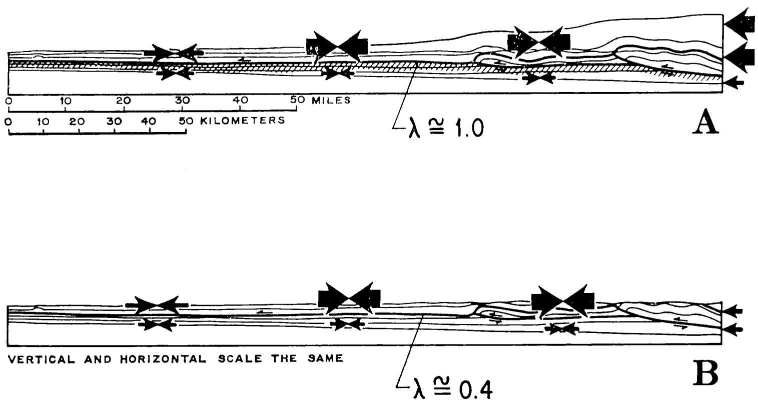

Fig. 1. Cross section of Appalachian Plateau Province in West Virginia (modified from Rodgers, 1963) to illustrate the "locking-in" mechanism for orogenic stress fields. The term λ refers to the ratio of fluid pressure to total overburden pressure. Allegheny orogenic forces are transferred within a plate lying on a low friction décollement characterized by high λ (A). The décollement represent discontinuities in regional stress fields. Dissipation of λ occurs prior to release of significant orogenic boundary forces, "locking-in" upper plate stresses; subsequent denudation produces changes in surface topography and some change in subsurface stress field, but significant stresses remain to the present day (B).

plausible to warrant further examination of the question of locked-in orogenic stress fields and its possible relationship to mechanics of décollement evolution and underlines the tectonophysical potential of rock stress measurements.

ACKNOWLEDGMENT

I am particularly grateful to Professor Jean Goguel, who pointed out the significance of the *difference* in stress fields between a tectonic "basement" and its superjacent thrust sheet.

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