

## Near-Surface in Situ Stress

### 4. Residual Stress in the Tully Limestone Appalachian Plateau, New York

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The direction of maximum expansion during strain relaxation of the Tully Limestone at Ludlowville, New York, is oriented about  $NO4^{\circ}E$  and thus is within a couple of degrees of the strike of both set Ia cross-fold joints and the compression direction indicated by the teeth of tectonic stylolites. These joints and stylolites are members of a suite of structures accommodating approximately 9% layer-parallel shortening during the main phase of the Alleghanian Orogeny within the Appalachian Mountains. Because of the parallelism of the maximum expansion with the main phase Alleghanian compression and because our measurements were made in joint-bounded blocks, we suggest that the expansion represents the relief of a residual stress locked into the Tully Limestone during the Alleghanian Orogeny. The magnitude of the strain relaxation indicates that the residual differential stress was 14 MPa. Using a flow law for pressure solution, we infer that the Tully Limestone deformed at a strain rate of about  $3 \times 10^{-15} \text{ s}^{-1}$ , and thus the layer-parallel shortening observed in the Tully Limestone may have required an aggregate deformation interval of only 1 m.y.

#### INTRODUCTION

The Appalachian Plateau, New York, is an area where the direction of maximum compression associated with the contemporary tectonic stress field [Sbar and Sykes, 1973] is at a high angle to the direction of maximum compression associated with the major orogenic event affecting this region, the late Paleozoic Alleghanian Orogeny [Geiser and Engelder, 1983]. The purpose of this paper is to present an example of near-surface strain relaxation which is not oriented parallel with the contemporary tectonic stress field. This example is in contrast with those in two accompanying papers describing near-surface strain relaxation related to the contemporary tectonic stress, either as a direct measure of that stress [Sbar et al., this issue] or as it aligns with local structures [Plumb et al., this issue].

The Appalachian Plateau in central and western New York was compressed about 9% in a north to NNW direction during the later of two phases of the late Paleozoic Alleghanian Orogeny affecting the plateau [Engelder and Engelder, 1977]. This compression is recorded by deformed fossils, solution cleavage, pencils, and mechanically twinned calcite [Engelder, 1979a; Engelder and Geiser, 1979]. A cross-fold joint set is approximately coaxial with the structures indicative of layer-parallel shortening and is clearly formed contemporaneously with the layer-parallel shortening, as indicated by the crosscutting relationship between solution cleavage and calcite-filled joints (set Ia of Engelder and Geiser [1980]). Strain relaxation of the Middle Devonian Onondaga Limestone [Engelder, 1979b] and Upper Devonian Machias Sandstone [Engelder and Geiser, 1980] also shows a NNW maximum expansion parallel to these Alleghanian tectonic trends (Figure 1). In both cases, strain relaxation was interpreted as the relief of a residual stress of tectonic origin locked within Appalachian Plateau rocks.

#### STRUCTURES OF THE TULLY LIMESTONE

The Tully Limestone is an anomalous limestone that interrupts the thick sequence of detrital rocks constituting the Middle to Upper Devonian clastic wedge known as the Catskill Delta [Heckel, 1973]. The Tully varies in thickness from 1 to 7 m in central New York, overlies a gray shale of the Hamilton Group, and grades upward into black shale of the Genesee Group. Dominant lithologies in the Tully include abraded calcarenites and bedded skeletal calcilutites.

The Tully contains a well-developed, spaced pressure solution cleavage of tectonic origin; these cleavage planes have a stylolitic morphology [Stockdale, 1922] with irregular teeth protruding as much as 5 mm (Figure 2) and are spaced at about 5-cm intervals between stylolite seams. In the vicinity of Ithaca, New York, the stylolite teeth point  $5-10^{\circ}$  east of north, indicating a maximum compression in that direction during the late Paleozoic [Engelder and Geiser, 1979]. In cross section the stylolitic teeth are the shape of irregular triangles rather than columns. This triangular shape makes it difficult to measure the exact direction toward which the teeth of the stylolites point. The compression direction is most easily measured as the normal to the average strike of the total length of the stylolite on the outcrop pavement. This technique is probably accurate to  $\pm 2^{\circ}$ .

Two cross-fold joint sets appear in the Tully Limestone: set Ia and set Ib of Engelder and Geiser [1980]. Set Ia is commonly filled with calcite (Figure 3) and strikes within a few degrees of the compression direction indicated by the teeth of the stylolites, whereas set Ib strikes some  $15^{\circ}-20^{\circ}$  west of set Ia and is only rarely filled with calcite. Crosscutting relationships indicates the contemporaneity between the set Ia joints and cleavage and the set Ib joints developed before the cleavage. The cleavage within the Tully Limestone is Permian or younger and associated with a tectonic compression identified by Geiser and Engelder [1983] as the Main Phase of the Alleghanian Orogeny. Set Ib joints formed during the earlier Lackawanna phase of the Alleghanian Orogeny [Geiser and Engelder, 1983]. Although two phases of the Alleghanian Oro-

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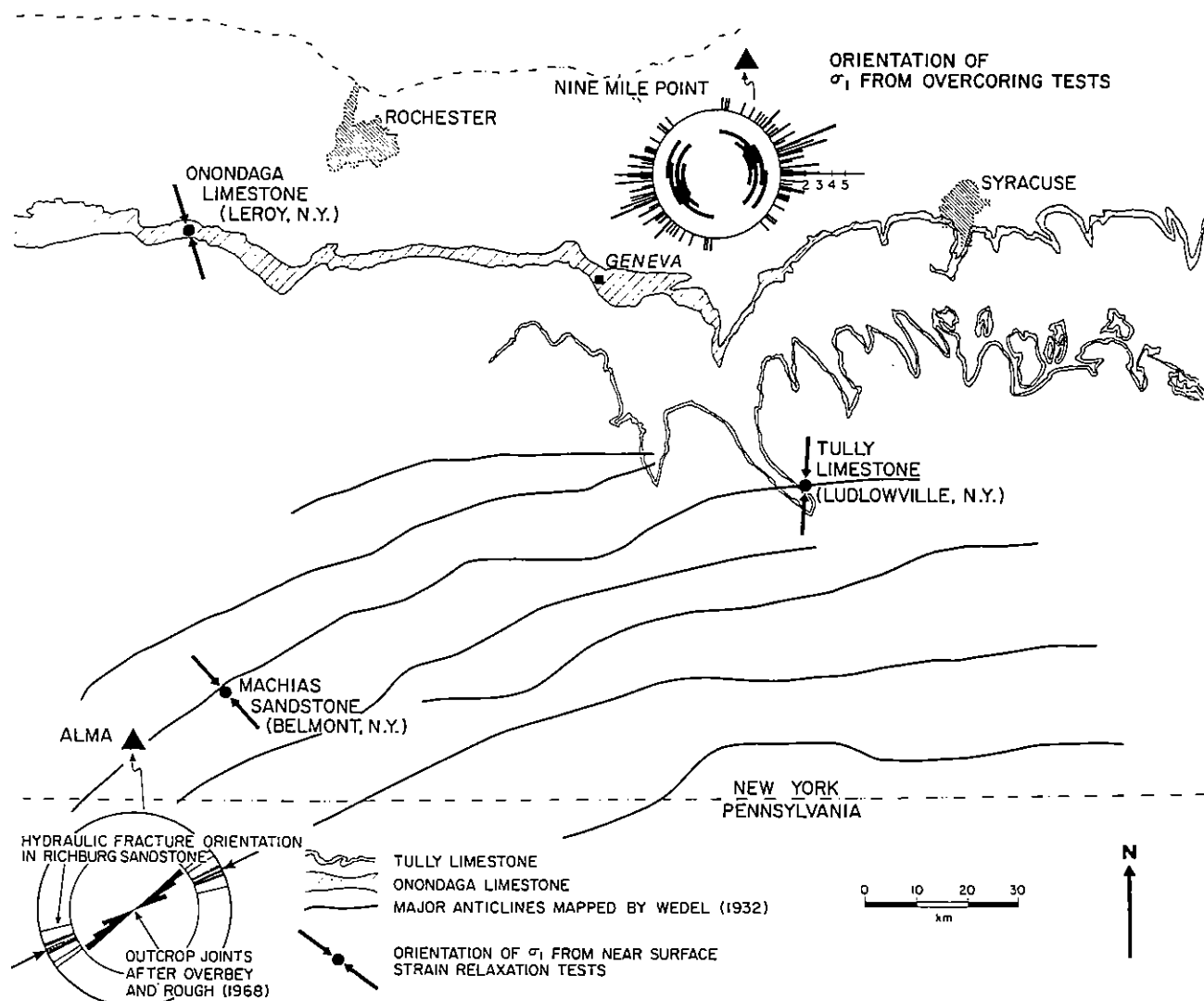


Fig. 1. The location of strain relaxation experiments in the Tully Limestone, Machias Sandstone, and Onondaga Limestone. Overcoring data from Nine Mile Point represent the orientation of maximum horizontal compressive stress for 74 measurements [Dames and Moore, 1978]. The azimuths are plotted at 1° intervals with the range of azimuths from each of six test holes shown inside the rose diagram. The orientations of nine hydraulic fractures from Alma are shown, with the average azimuth located by the inward pointing arrows [Overbey and Rough, 1968].

geny affected the Tully Limestone, the major strain was absorbed during the later phase.

#### STRAIN RELAXATION MEASUREMENTS

The site for the Tully Limestone study was the bed of Salmon Creek at Ludlowville, New York (Figure 1). At Ludlowville, Salmon Creek flows over a 25 m water fall about 50 m downstream from our drilling site; thus the Tully has an E-W striking free face 50 m to the south. Cross-fold joints (set Ia) and strike joints (set II) are spaced greater than 5 m apart at the drill site. At other locations in the streambed these joints are more closely spaced. The upper member of the Tully Limestone, a calcilitite exposed in the creek bed, was used for the relaxation measurements.

We used the doorstopper technique [Sbar *et al.*, 1979] in four 1-m-deep holes drilled at the corners of a square 1 m on a side. Two to three strain relaxation measurements were made per hole to a maximum depth of 1 m. The four holes were located so that no vertical joint came between any single hole and the other three. Hence all of the measurements were made

in a single mass of rock bounded set Ia and set II by joints. Care also was taken to install the doorstoppers away from vertical solution cleavage planes. A fifth hole was drilled in the same rock mass for a U.S. Bureau of Mines (USBM) gauge measurement [Sbar *et al.*, this issue].

Repeated strain relaxation measurements show a tight cluster for the orientation of maximum expansion equivalent to that from the Algeria granite [Engelder, 1984] and tighter than has been gathered by us to date at the nine other sites with five or more successful doorstopper measurements. For all but one of nine measurements, maximum expansion of the Tully was within 6° of N04°E (Table 1). The anomalous measurement, the shallowest one, also had an anomalously low maximum expansion. The four deepest measurements in the Tully contracted normal to the direction of maximum expansion; this contraction is noteworthy because strain relaxation measurements usually involve expansion along both principal axes.

We performed compressibility tests to determine the static elastic properties for stress calculations and ultrasonic *p* wave

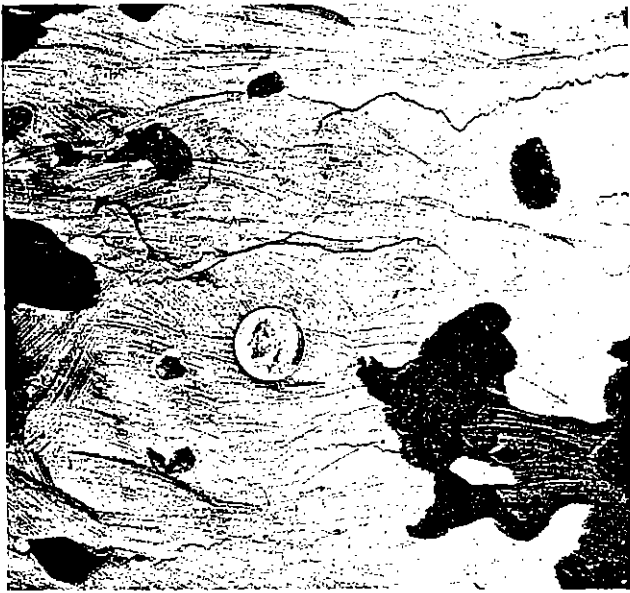


Fig. 2. Photograph of stylolites within the Tully Limestone. The teeth of the stylolites indicate a compression  $5^{\circ}$ - $10^{\circ}$  east of north.

velocity tests to measure elastic anisotropy in the horizontal plane. These tests indicated that the Tully is isotropic parallel to bedding and that  $P$  wave velocities increase slightly with depth [Engelder and Plumb, 1984]. Stress was calculated for three of the doorstopper samples plus the USBM sample. In static compression one shallow sample (East-15) appears anisotropic, whereas the deeper samples (East-64 and West-79) are nearly isotropic. The anisotropy shown in the static test for East-15 is not apparent in the dynamic tests. As was the case for the dynamic tests, the shallow sample (East-15) has a greater compressibility than the deeper samples. The greatest compressibility was in the direction of the greatest strain relaxation, a behavior which is attributed to slight weathering within 30 cm of the surface of the Salmon Creek bedrock. The weathering may preferentially attack the stylolitic clay seams and thereby weaken the Tully and cause strain relaxation normal to the clay seams. Sample East-15, which is believed most affected by near-surface weathering, also shows an anomalous orientation for strain relaxation. For the other samples, taken at 33-79 cm, the direction of maximum principal stress is parallel to the maximum expansion on overcoring. Two deeper doorstopper samples show  $\sigma_1$  to exceed 10 MPa, whereas  $\sigma_3$  is tensile and in excess of 1 MPa.

#### DISCUSSION

##### *Significance of Stress Orientation*

The average direction of maximum expansion on overcoring is oriented within  $3^{\circ}$ - $4^{\circ}$  to the compression direction indicated by the stylolites in the Tully Limestone but more than  $60^{\circ}$  from the compression direction of contemporary tectonic stress (Figures 1 and 4). On the basis of our previous experience with strain relaxation, we can say that the orientation of strain relaxation within the Tully Limestone is remarkably consistent from sample to sample, and the lack of exact parallelism of the maximum expansion with the compression indicated by the stylolites is not significant. Unlike examples described by Engelder and Sbar [1977] and Engelder and Geiser [1980] where strain relaxation appears related to joints spaced less than 2 m, joint spacing within the Tully Limestone

at the drill site exceeds 5 m, and a direct genetic relationship between jointing and in situ stress seems less likely. Because of this strong correlation in orientation between maximum expansion and the teeth of stylolites it seems likely that the orientation of strain relaxation was sensitive to some rock property that correlates with the direction of compression during the Main Phase of the Alleghanian Orogeny.

The question raised by this correlation concerns what mechanism is responsible for the strain relaxation. One possibility is that the Paleozoic compression was preserved for 225 m.y. as a residual stress in the form of a composite of interlocking and loaded elastic or viscoelastic "springs." Another possibility is that recent stresses activated a 225-m.y.-old rock fabric to give a strain relaxation coaxial with the Paleozoic compression. More than one mechanism may be responsible for the latter process. One possibility is that moisture and temperature changes accompanying overcoring cause a fabric element such as microcracks or cleavage to open. This process was minimized by coring below the water table, using water near the temperature of the groundwater. Strain relaxation was measured in the in situ environment. A second mechanism for fabric activation may be visualized for an elastically anisotropic rock in which the compliant direction was parallel to the late Paleozoic compression. If such a rock were loaded uniformly in all directions, then it would strain the most in the compliant direction. If such a rock were then overcored, strain relaxation would be greatest in the most compliant direction. Either a closely spaced cleavage or preferentially oriented microfractures would contribute to a high compliance normal to their strike. In this regard, thin section observation shows that the stylolitic cleavage was too widely spaced to be of consequence and preferentially oriented microfractures are not visible. On this basis we reject the activated rock fabric hypothesis.

Further support for rejection comes from both dynamic and static measurements which also show that the Tully Limestone is not appreciably anisotropic after relaxation. There was a change in acoustic properties upon overcoring, but the



Fig. 3. A calcite-filled joint within the Tully Limestone. Note that the joint consists of several subveins of calcite each representing a separate event of cracking and filling. A fossil has been cut by the joint and calcite has grown in crystallographic continuity with the fractured fossil.

TABLE 1. Strain Relaxation Data

Hole	Depth, cm	Strain			Pseudolinear Compressibility			Stress		
		$\epsilon_1$ , $\times 10^{-6}$	$\epsilon_2$ , $\times 10^{-6}$	Azimuth of $\epsilon_1$	Maximum, $\times 10^{-5}$ MPa $^{-1}$	Minimum, $\times 10^{-5}$ MPa $^{-1}$	Azimuth of Maximum	$\sigma_1$ , MPa	$\sigma_2$ , MPa	Azimuth of $\sigma_1$
South	12	28	-26	N23°E						
East	15	260	173	N04°E	2.08	1.20	N15°W	15.9	10.9	N51°E
USBM gauge	33							8.0	4.2	N01°E
West	33	112	16	N10°E						
North	46	60	40	N01°W						
South	58	235	172	N04°W						
East	64	101	-9	N02°E	1.09	0.84	N90°E	12.0	-1.6	N02°E
North	74	105	-9	N02°W						
West	79	111	-27	N01°E	1.00	0.88	N30°E	11.4	-2.7	N01°E
South	86	86	-20	N05°E						

change was uniform and not a function of direction [Engelder and Plumb, 1984]. For ultrasonic tests, both in situ and core, the ray path of the ultrasonic pulse traversed spaced solution cleaved planes. The presence of these solution cleavage planes, particularly in situ, seemed to have no effect on ultrasonic travel times. The decrease in velocity on overcoring indicates that the opening of cracks accompanied relaxation, but the uniform change indicates that the cracks were not preferentially oriented either to accommodate the expansion in the high-stress direction or contraction in the low-stress direction. Therefore we interpret the microcrack fabric to be axially symmetric, and the relatively small size of these cracks is indicated by their obscurity in thin section.

Since we could detect no fabric responsible for the strain relaxation, a residual stress model must be considered for the mechanism driving strain relaxation in the Tully limestone. Two aspects of residual stress to consider are the mechanism of locking residual stress into the Tully Limestone and the role of joints in relaxing the residual stress.

How might we picture residual strain in the Tully Limestone, a calcilutite originally composed of clasts of shell fragments floating in a mud matrix? Residual strain might come about by the interlocking of a combination of high-

compliance (either intragrain or grain boundary) cracks, intermediate-compliance grain boundaries filled with a clay matrix, and low-compliance grains. This multiple-compliance model is similar to that described by Gallagher *et al.* [1974] and Voight and St. Pierre [1974]. We infer from the age of the limestone (Late Devonian) relative to the age of the deformation (probably Permian or younger) that compression took place after the aggregate was lithified. Compaction and lithification removed most pore space, leaving little room for the introduction of cement after tectonic compaction as visualized by the Voight and St. Pierre [1974] model. Rather than introducing cement after an aggregate of large clasts was compressed, as in the Voight and St. Pierre [1974] model, we suggest that the matrix and clasts of the Tully Limestone deformed together in such a manner that the matrix prevented the aggregate from relaxing after the tectonic stress was removed. This might be accomplished by tectonic deformation during late-stage diagenesis which, as described by Dunoyer de Segonzac [1970], consists of the disappearance of montmorillonites and mixed-layer clays and the recrystallization of kaolinite. Likewise, it might be that intragranular deformation of the matrix accompanied by pressure solution and recrystallization could have locked in the stress. Yet the exact mechanisms by which residual stress became unlocked during overcoring is well beyond present understanding.

We further hypothesize that the stresses present in the near-surface outcrops of Tully Limestone are residual because the measurements were made in joint-bounded blocks close to a 25-m vertical face. The effect of the joints and vertical face is to unload the contemporary stress field from the Tully Limestone. Unloading from the contemporary stress field is supported by the correlation between the orientation of the maximum expansion on overcoring and the direction of Paleozoic compression. The joints, however, were not open in the sense that we could slide a knife blade between the joint faces, so it is conceivable that minor tractions existed across the joints.

A further difficulty with our understanding of the process of locking and releasing residual stress concerns the affect of joint formation. Overcoring serves to isolate a cylinder of rock in much the same manner that jointing isolates blocks of rock. Because overcoring releases residual stress, there is no apparent reason why jointing should not release residual stress in the same manner. Yet residual stress is present in blocks of rock isolated by jointing and appears not to be released by jointing. An explanation may be that the release of residual stress may depend to a very large extent on the size of the block that is isolated where the magnitude of the strain released is inversely proportional to the volume of rock isolated.

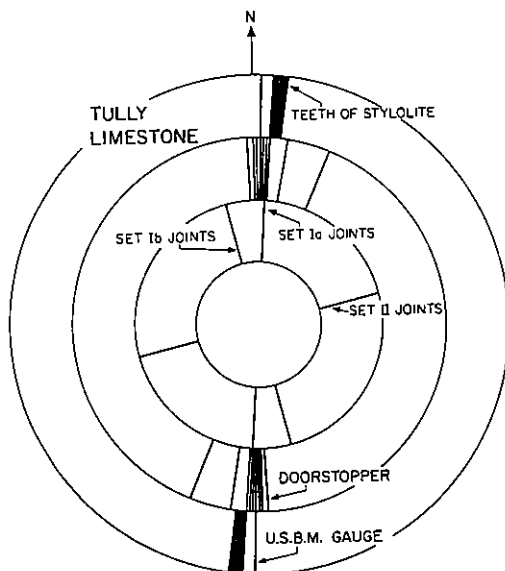


Fig. 4. A rose diagram showing the orientation of joints and the teeth of stylolites within the Tully Limestone relative to the orientation of maximum expansion on overcoring of the Tully Limestone as monitored by doorstopper and the USBM gauge.

The volume of rock isolated by jointing is considerably larger than that isolated by overcoring. This hypothesis is compatible with our observation that the magnitude of strain relaxation was smaller in outcrops with closer joint spacing [Engelder and Sbar, 1977].

#### Significance of Stress Magnitude

Is it reasonable to expect that the magnitude of the residual stress found in the Tully Limestone today has anything to do with the stress magnitude that deformed the rock more than 225 m.y. ago?

This question may be partially answered by considering whether a differential stress of 14 MPa is compatible with flow laws for rocks equivalent to the Tully Limestone. The deformation mechanism accounting for the most layer-parallel shortening on the Appalachian Plateau is pressure solution [Engelder, 1979a]. Equations modeling deformation by pressure solution are Newtonian viscous in form [Rutter, 1976; Groshong, 1975]. Because pressure solution is a viscous deformation mechanism, the Tully Limestone should have relaxed and not been able to carry a differential stress of 14 MPa for 225 m.y. In order to preserve residual stress for 225 m.y. we must hypothesize that the mechanisms favoring pressure solution turn off prior to relaxation of the tectonic stresses. Possible ways of "turning off" pressure solution may be to stop massive pore fluid migration or to saturate the pore fluid with the solute, which, in the case of the Tully Limestone, is primarily calcite and quartz. Pore fluid migration may slow or stop with the decrease of topography accompanying erosion. With the driving mechanisms for pressure solution slowed or stopped, the Tully Limestone may have failed to relax. Frictional slip on joints and fractures seems not to have aided in the relaxation of the 14-MPa differential stress.

Assuming that 14 MPa was the differential stress on the Tully Limestone at the time the pressure solution was active, a flow law for pressure solution of calcite [Rutter, 1976] suggests that the Tully Limestone deformed at a strain rate of about  $3 \times 10^{-15} \text{ s}^{-1}$  (Figure 5). At this strain rate the aggregate time necessary to achieve 9% layer-parallel shortening of the Appalachian Plateau is of the order of 1 m.y. The length of time required for the deformation of the Appalachian Plateau cannot be evaluated independently except to say that the Main Phase of the Alleghanian Orogeny lasted at least 65 m.y., the length of the Permian. For a continuous deformation lasting 65 m.y. and producing 9% layer-parallel shortening, the stress required for pressure solution flow must not exceed 0.3 MPa (Figure 5).

Whether or not the 9% layer-parallel shortening occurred during one deformation pulse is debatable. Set Ia joints within the Tully are calcite filled and often formed by the "crack-seal" mechanism of Ramsay [1980], as shown in Figure 3. The presence of multiple cracking of calcite-filled joints might suggest that the layer-parallel shortening took place in several pulses. If this were the case, the Main Phase of the Alleghanian Orogeny could have lasted considerably longer than 1 m.y. Likewise with small deformational pulses punctuating periods of quiescence the 1 m.y. calculated from Rutter's flow law for pressure solution represents the aggregate time for all deformational pulses during the Main Phase of the Alleghanian Orogeny, as indicated by residual stress within the Tully Limestone. The migration of the Alleghanian Orogeny across the foreland could have taken much longer than the deformation at one point within the Tully Limestone.

In order to establish the credibility of a strain rate for the

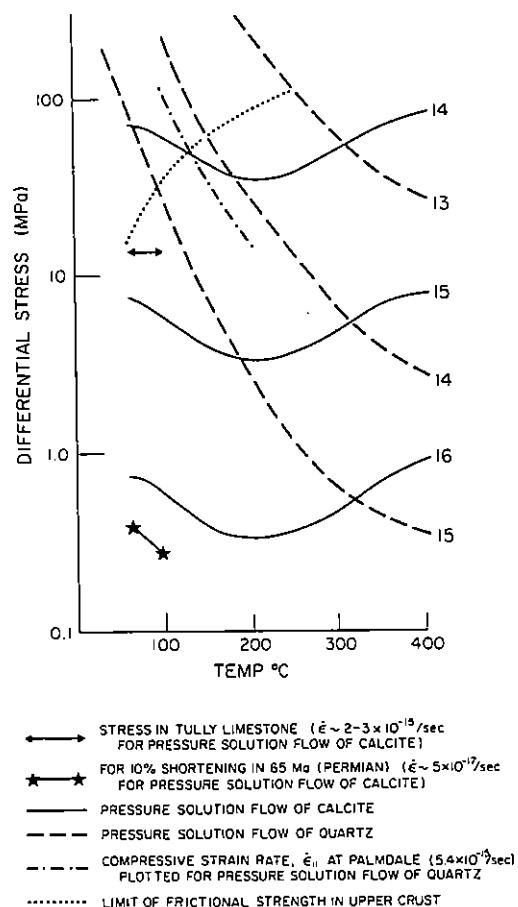


Fig. 5. Strain rate  $\epsilon_{11}$  plotted as a function of temperature and differential stress for deformation of quartz and calcite by pressure solution [Rutter, 1976].

Tully Limestone, strain rate data from southeastern California are presented. A strain rate of  $3 \times 10^{-15} \text{ s}^{-1}$  for the Appalachian Plateau is about half the rate measured by trilateration networks for compressive strain  $\epsilon_{11}$  in the vicinity of Palmdale, California [Savage et al., 1981]. An  $\epsilon_{11}$  of  $5.4 \times 10^{-15}$  from Savage et al. [1981] is plotted on Figure 5 along a curve of the pressure solution flow of quartz (a significant component of the southern California batholith). For this strain rate and depths of less than 3 km the differential stress necessary to drive pressure solution flow in quartz exceeds the theoretical frictional limit for the upper crust in the vicinity of the San Andreas fault, assuming stress magnitudes measured by Zoback et al. [1980]. This assumes that Rutter's [1976] flow law for the pressure solution of quartz is representative of conditions at depth near the San Andreas fault. Using assumptions for the validity of pressure solution flow laws, pressure solution flow of quartz would not be a significant deformation mechanism in the vicinity of Palmdale at depths where the pressure solution flow of the Tully Limestone occurred. For pressure solution flow of Tully Limestone at strain rates of  $5.4 \times 10^{-15} \text{ s}^{-1}$ , large enough stresses would be generated to cause frictional slip at depths less than 2 km, assuming stress magnitudes given in McGarr's [1980] compilation for sedimentary rock. Because frictional slip is not a common deformation mechanism within the Tully Limestone, we infer that the strain rate of  $5.4 \times 10^{-15} \text{ s}^{-1}$  observed in the vicinity of Palmdale is too high for the Appalachian Plateau, in agreement with our previous estimate of  $3 \times 10^{-15} \text{ s}^{-1}$ .

The calcite of the Tully Limestone was also mechanically twinned during layer-parallel shortening. Laboratory tests suggest that the critical resolved shear stress for twinning of calcite is of the order of 10 MPa and independent of normal stress but is time dependent [Turner et al., 1954; Friedman and Heard, 1974]. Using the technique of Jamison and Spang [1976] to estimate the differential stress responsible for twinning the calcite in the Tully, we find that it should have been well in excess of 20 MPa. Either the Tully Limestone did relax from stresses above 20 MPa or, at a strain rate of  $3 \times 10^{-15} \text{ s}^{-1}$ , the critical resolved shear stress for twinning of calcite is lower.

The component of stress ( $\sigma_3$ ) normal to the direction of tectonic compression of the Tully Limestone was tensile. The relief of tensile stresses on strain relaxation made the behavior of the Tully Limestone unusual. Normally, the least horizontal stress is compressive in near-surface rocks. It is possible, however, that on removal of overburden the least horizontal stress may become tensile [Haxby and Turcotte, 1976], in which case the tensile stresses are relieved by jointing. It is not possible to discern whether the tensile stresses in the Tully were once higher and then relieved by jointing during removal of overburden or whether the present tensile stress is the maximum to which the rock was subjected during its denudation process. If the former is true, then our estimate of differential stress from overcoring measurements is low. Certainly, effective stress at the time of the propagation of the "crack seal" joints (set Ia) in the Tully was similar to the in situ stress in the limestone today. That is, the effective least principal stress was tensile in order to overcome the tensile strength of the Tully Limestone.

#### CONCLUSION

The Tully Limestone contains a residual stress developed during the Alleghanian Orogeny.

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