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The influence of grain size and grain size distribution on methods for estimating paleostresses from twinning in carbonates

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Abstract—This study examines the relative differential stresses around a minor thrust fault within the Mountain City window, Tennessee, U.S.A. The fault zone developed within dolomite rocks and deformation took place by twinning, fracturing, pressure solution and the development of fine-grained deformation zones. Grain-size reduction is observed from undeformed wall rock to the center of the fault zone, and occurred by dynamic recrystallization. Methods to determine paleostresses in naturally deformed rocks from twinning assume a single, coaxial, strain-inducing event. The recrystallization within the center of the fault zone removed the effects of earlier deformation, so that the twinning more closely reflects a single, coaxial deformation event late in the fault history. Two methods were used to estimate the relative differential stresses across the fault zone and the results show opposite trends towards the center of the fault zone. The different results may be partially explained by the influence of grain size, as only one of these methods considers the influence of grain size. In addition, the grain-size data from this fault zone demonstrate that the tendency for a grain-size class to be twinned depends on the grain size distribution. The grain size distribution may result in grain-to-grain stress concentrations that induce twinning. Thus, grain size distribution should also be considered to achieve more accurate estimates of paleostresses.

INTRODUCTION

THE magnitudes of stresses involved in the formation of faults in ancient mountain belts has been a subject of great interest, and has spurred the development of many methods for determining paleostresses. Attempts to reconstruct paleostresses involved in deformation have been made from recrystallized grain size (e.g. Twiss 1977, White 1979, Schmid 1983), fault striation analyses (e.g. Etchecopar *et al.* 1981), and from twinning in carbonates (e.g. Jamison & Spang 1976, Etchecopar 1984, Rowe & Rutter 1990, Laurent *et al.* 1990). This study estimates the relative magnitudes of paleostresses across a natural fault zone in dolomite rocks using samples ranging from relatively undeformed hanging wall rocks to strongly deformed rocks at the center of the fault zone. Paleostresses were determined using both Jamison & Spang's (1976) and Rowe & Rutter's (1990) methods based on twinning in carbonates. The use of two methods allows a cross-check of the results, and differences in the results might indicate potential problems in one or both methods. This paper focuses on the influence of grain size and grain size distribution on twinning activity, and thus on the paleostress determination methods.

Experimental studies and studies of naturally deformed carbonates have established a relationship between twinning and grain size. Twinning is more difficult within fine-grained rocks than in coarse-grained rocks (Friedman & Heard 1974, Schmid & Paterson 1977, Casey *et al.* 1978, Spiers 1982, Rowe & Rutter 1990). Rowe & Rutter's (1990) method takes this relationship into account, while Jamison & Spang's (1976) does not. As fault zone deformation typically involves progressive grain-size reduction, we also looked at the influence of grain size distribution on twinning activity. Finally, a comparison of paleostress estimates from different studies shows other potential problems with the different methods that are currently being used by various workers. While this study reaches no definite conclusions regarding the magnitude of paleostresses along the fault zone studied, it points to certain serious shortcomings of established paleostress determination methods that use twinning and the need for developing more refined methods for paleostress determination.

PIONEER LANDING FAULT ZONE

The Pioneer Landing fault zone lies within the Blue Ridge province of the Southern Appalachians of Tennessee and North Carolina, U.S.A. (Fig. 1a). In this area, the Blue Ridge sheet (of Precambrian granitic basement rocks) was emplaced by northwestward thrusting over a Cambrian sedimentary sequence. Footwall imbrication produced a hinterland-dipping duplex (Boyer & Elliott 1982) and resulted in folding of the

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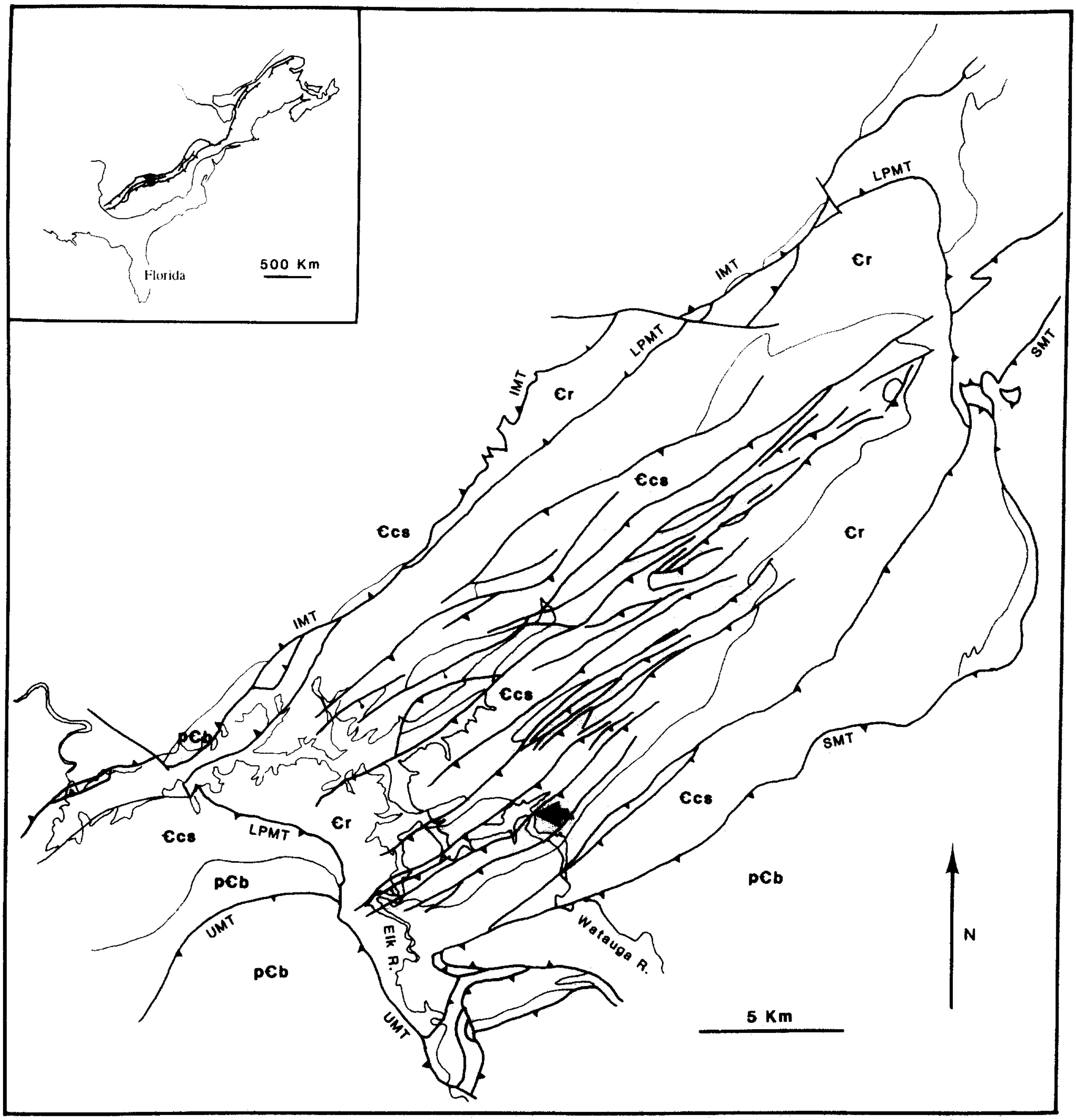

Fig. 1. (a) Location map of the Mountain city window (MCW) (circle) in the southern Blue Ridge, U.S.A. (b) Geologic map of the northern MCW (after Diegel 1988) showing the location of the Pioneer Landing fault zone (arrow). UMT = Unaka Mountain thrust, SMT = Stone Mountain thrust, LPMT = Little Pond Mountain thrust, IMT = Iron Mountain thrust, p-Ꞓb = Precambrian Basement, Ꞓcs = Cambrian Chilhowee Quartzite and Shady Dolomite, Ꞓr = Cambrian Rome Formation.

Blue Ridge sheet; later erosion produced a window exposing the footwall imbricate faults. The Pioneer Landing fault is one of the minor imbricate thrusts within the Mountain City window (Fig. 1b). The fault dips steeply southeast and places Cambrian Shady Dolomite over Shady Dolomite. The hanging wall has been displaced approximately 100 m northwest (King & Ferguson 1960, Newman & Mitra in press). The regional geology (Boyer & Elliott 1982) suggests that the fault formed at a depth of ~9 km (270°C at a 30°C km^{-1} geothermal gradient). The zone of deformation related to the faulting extends approximately 14 m into the hanging wall from the center of the fault zone. This study focuses on the hanging wall deformation.

The deformation along the fault zone took place by twinning, fracturing, intracrystalline slip as indicated by minor undulose extinction and a dimensional preferred orientation in some grains, the removal of material by solution along stylolites, and the development of fine-grained deformation zones (Newman 1993, Newman & Mitra in press). Grain-size reduction is observed from the undeformed wall rock to the center of the fault zone, and occurred predominantly by dynamic recrystallization, resulting in the development of a 1–3 m wide

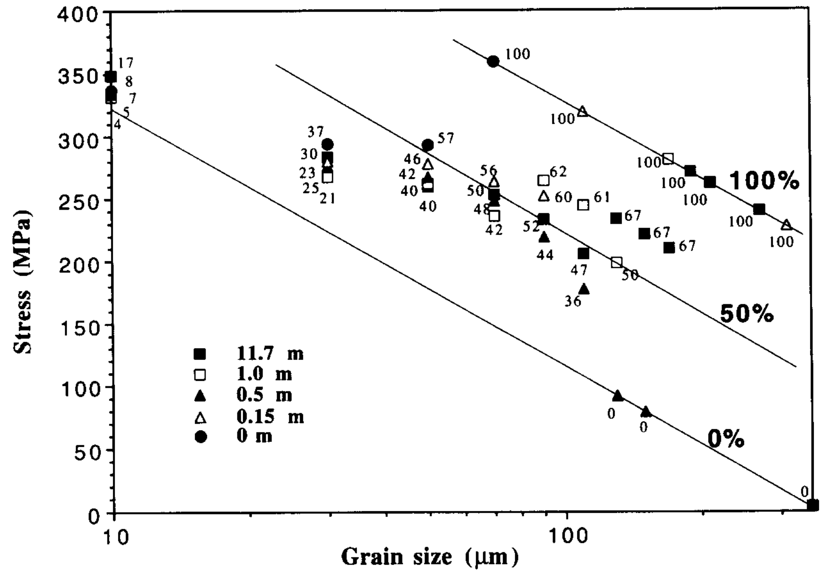

Fig. 2. Differential stress vs log grain size. Numbers adjacent to symbols indicate twinning incidence. Stress for every grain-size class in each sample calculated according to Rowe & Rutter's (1990) twinning incidence method. Lines connect points of equal twinning incidence. Symbols indicate the distance of the sample from the center of the fault zone as specified in bottom left corner of the graph.

mylonite zone. Twinning occurred concurrently with the recrystallization. As a result, the twinning in recrystallized fault zone rocks represents the later increments of deformation along the fault. Twins resulting from prior deformation have been cleared by the recrystallization. Thus these rocks are an ideal material for estimating paleostress from twinning.

STRESS ESTIMATES

Three methods have been described to estimate paleostress magnitudes from twinning in carbonates. This study estimates the variation in paleostresses across the Pioneer Landing fault zone using Rowe & Rutter's (1990) and Jamison & Spang's (1976) methods which are described in more detail below. A third method (the Inverse Method), described first by Etchecopar (1984), establishes a deviatoric stress tensor responsible for the formation of twin lamellae. Many regional studies have been carried out using this method (e.g. Laurent *et al.* 1990, Tourneret & Laurent 1990, Lacombe *et al.* 1990, Lacombe & Laurent 1992). The results of some of these studies are compared with data from this study in a later section.

Rowe & Rutter (1990)

Rowe & Rutter (1990) used the relationship between twinning activity and grain size to develop a method for estimating paleostresses in limestones. They established relationships between differential stress, twinning activity and grain size through high-temperature deformation experiments on polycrystalline calcite. Their method assumes that the deformation resulted from a single, coaxial stress field. They suggest that twinning incidence (I_t), the percentage of grains per grain-size class that contain optically visible twin lamellae, is largely independent of temperature, strain rate, and strain, and dependent on differential stress. Plots of differential stress vs log grain size showed consistent behavior for constant I_t values. Grain-size data from different samples were plotted by grain-size class; data representing different grain-size classes and the same twinning incidence fall on lines of equal slope. Multiple linear regressions describe the best-fit lines of this relationship between log grain size, twinning incidence, and differential stress. The relationships were then applied to naturally deformed rocks to determine paleostresses.

To determine whether it is reasonable to extrapolate the empirical equation of Rowe & Rutter (1990) to dolomite for relative values of paleostresses, the stresses for every grain-size class at each sample locality were determined using Rowe & Rutter's (1990) equation:

$$\sigma = 523 + 2.12 I_t - 204 \log d,$$

where σ is the differential stress in MPa and d is grain size in microns. The results are plotted on a differential stress vs log grain size plot (Fig. 2), similar to the experimentally derived plot of Rowe & Rutter (1990) described above. The plot exhibits consistent behavior for these dolomite samples as it did for calcite in Rowe & Rutter's experimental studies; i.e. data representing different grain-size classes and the same twinning incidence fall on lines of equal slope. As the effective critical resolved shear stress necessary to produce twinning (t_c) is higher for dolomite than for calcite (e.g. Wenk *et al.* 1983), this method cannot be used to obtain absolute magnitudes of paleostresses, but is does allow estimates of relative values of paleostresses across the fault zone.

In applying this empirical equation to naturally deformed rocks, Rowe & Rutter (1990) chose d for which I_t = 100% for each sample they analyzed. Here, d is

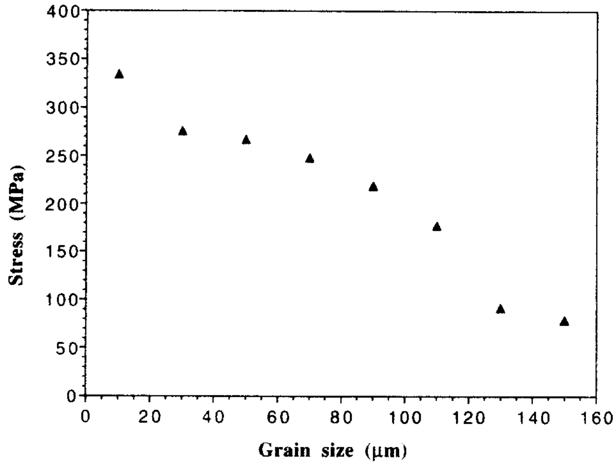

Fig. 3. Differential stress vs log grain size for sample 0.5 m above the center of the fault zone. Stress for each grain-size class calculated according to Rowe & Rutter's (1990) twinning incidence method. Differential stress varies according to grain size.

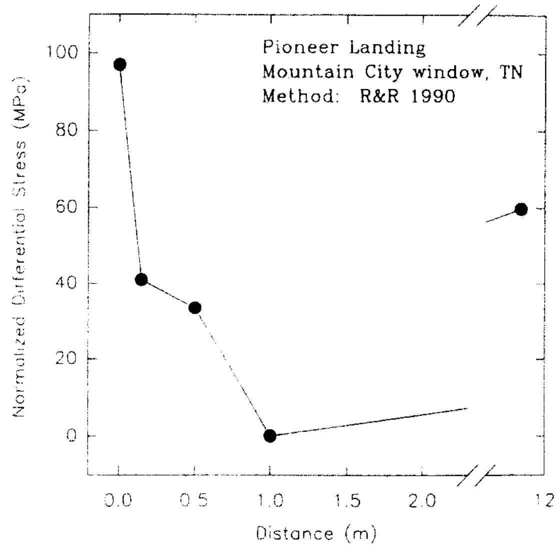

Fig. 4. Paleostress vs distance from the center of the fault zone. Stress calculated by Rowe & Rutter's (1990) twinning incidence method. Stresses normalized relative to lowest estimate.

equal to the center of the grain-size interval with the highest number of grains for each sample for the following reasons:

(1) The differential stress calculated changes significantly according to d chosen (Fig. 3). The differential stress is strongly dependent on the grain size chosen so that large variations in stress are recorded at each sample location.

(2) In the experimental samples of Rowe & Rutter (1990), I_t values rarely attained 100%. This is to be expected, as the samples were subjected to a simple, homogeneous stress field. Only those grains appropriately oriented for twinning are expected to twin.

(3) Rowe & Rutter (1990) point out that when 100% I_t is attained, typically in the largest grain-size classes, it is due to small sample sizes in the large grain-size classes; i.e. very few grains occur in the large grain-size classes. In the samples of naturally deformed rocks from the Pioneer Landing fault, as well, I_t in the large grain-size classes was generally 0% or 100%, and typically represents only one or two grains (out of 700–1500 measured for each sample).

Figure 4 shows the relative paleostresses estimated using this method. Magnitudes are normalized relative to the lowest stress estimate. The data show a trend of increasing stresses toward the center of the fault zone. At 11.6 m, the location within the less deformed hanging wall rocks, the stress is slightly higher than in samples closer to the fault zone, although not as high as within the center of the fault zone.

Jamison & Spang (1976)

Jamison & Spang's (1976) method for determining paleostresses was developed for dolomite as well as calcite, allowing estimates of absolute magnitudes of stress. Their method relates the differential stress ($\Delta\sigma$), to a critical resolved shear stress necessary to produce twin gliding (τ_c), and a resolved shear stress coefficient (S_i) by the equation:

$$\tau_c = \Delta\sigma \cdot S_i.$$

S_i is determined by assuming an infinite number of possible crystal orientations, and determining the percent of twinned grains. This method assumes homogeneous strain, no preferred crystallographic orientation of grains, and that the deformation occurred within a single, irrotational stress field. There is controversy concerning the temperature and strain rate dependence of τ_c for twinning in dolomites (Higgs & Handin 1959, Friedman & Heard 1974, Barber *et al.* 1981, Rowe & Rutter 1990). Experiments to determine a critical resolved shear stress for twinning in dolomite have resulted in a wide range of values; possible reasons for this are discussed in a later section of this paper. Jamison & Spang (1976) suggest 50 MPa based on their application of their method to naturally deformed rocks. If we assume τ_c = 50 MPa for dolomite, after Jamison & Spang (1976), the equation gives estimates of differential stress ranging from 294 MPa at 11.6 m above the center of the fault zone to 147 MPa within the center of the main fault zone. The stress decreases toward the center of the fault zone (Fig. 5); the opposite of the trend indicated by the paleostresses determined using Rowe & Rutter's (1990) method. Note that this method does not consider grain size, and that the geometric mean grain size steadily decreases across this distance (Fig. 6).

INFLUENCE OF GRAIN SIZE

The two paleostress measurement methods show opposite trends for stress variations across the fault zone. Jamison & Spang's (1976) method indicates a decrease in stress while Rowe & Rutter's (1990) method indicates an increase in stress towards the center of the fault zone. But Jamison & Spang's (1976) method does not consider grain size, and the mean grain size of twinned and untwinned grains steadily decreases

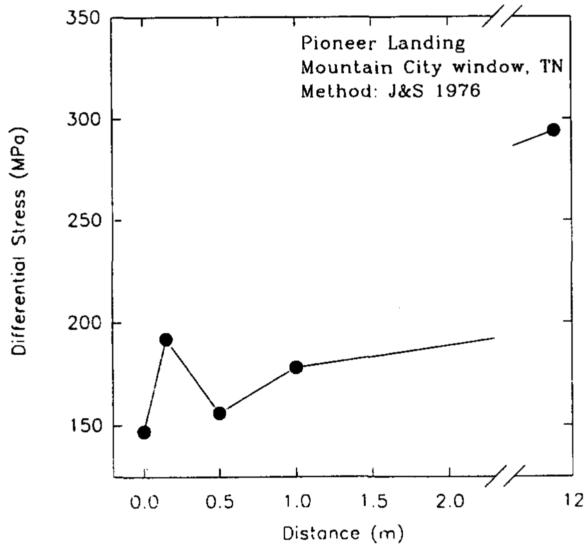

Fig. 5. Paleostress vs distance from the center of the fault zone. Stress calculated by Jamison & Spang's (1976) method.

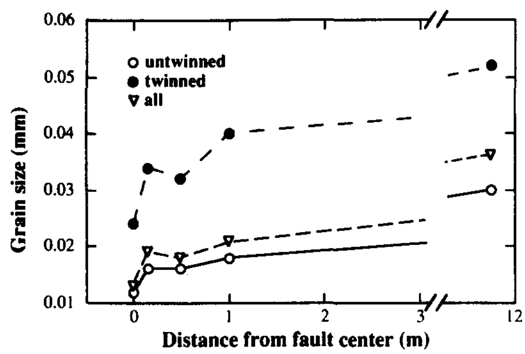

Fig. 6. Geometric mean grain size across the fault zone. Geometric mean is used because the grain size distributions are log normal (see Fig. 8). The horizontal axis indicates distance from the center of the fault zone.

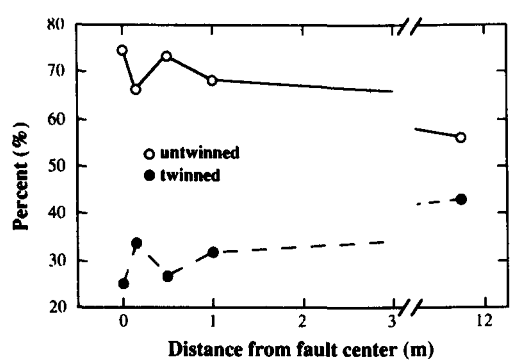

Fig. 7. Percent of rock consisting of twinned and untwinned grains across the fault zone. The horizontal axis indicates distance from the center of the fault zone.

towards the center of the fault zone (Fig. 6), where the finest grained rocks occur and the fewest twinned grains are observed (Fig. 7); the mean grain size of twinned grains is coarser than of untwinned grains at every location. The ratio of twinned to untwinned grains is always <1, and decreases from 0.78 at 11.6 m from the main fault zone to 0.33 within the center of the main fault zone. As twinning is more difficult within finer-grained rocks, it is possible that the decreasing trend in stresses suggested by Jamison & Spang's (1976) method reflects a higher effective critical resolved shear stress for twinning in finer-grained rocks, rather than a decrease in stress.

While the rocks within the center of the fault zone are recrystallized, those far from the center (11.6 m) are not. The increase in the percentage of recrystallized grains toward the center of the fault zone may be partly responsible for the decreasing trend in stress indicated by Jamison & Spang's (1976) method. Rowe & Rutter's (1990) method shows a pattern of increasing stress within rocks within 1 m of the center of the fault zone. If recrystallization cleared twins in the rocks in the center of the fault zone, Rowe & Rutter's (1990) method suggests even higher stresses prevailed than the data indicate. The high stress indicated for the sample at 11.6 m may reflect a higher percentage of twinned grains due to previous deformation.

GRAIN SIZE DISTRIBUTION

Natural fault zones are complex systems that show progressive grain-size reduction during deformation. A result of progressive grain-size reduction is that a heterogeneous grain size distribution is often present in fault rocks (Schmid 1983). Therefore, the effects of grain size distribution on twinning activity need to be considered in addition to the role of grain size to see how it affects twinning.

Grain size was determined by a lineal analysis using an integrating stage. Chord lengths were measured in two traverses across each thin section; one parallel and one perpendicular to the orientation of the main fault zone. The grain size distributions were determined using Spektor's chord analysis for a polydispersed system of spheres (Underwood 1970, p. 126).

Grain size distributions for samples from all locations analyzed are log normal and unimodal (Fig. 8). The trends in grain size distribution across the hanging wall can best be seen using a grain size interval of 20 μm. The highest frequency of untwinned grains falls within the finest grain-size class (<20 μm) for all samples analyzed, but this frequency increases as the center of the fault zone is approached. The grain size distribution curve of twinned grains at 11.6 m from the main fault zone is low and broad and skewed toward larger grain sizes; the highest frequency, 32% of twinned grains, falls between 20 μm and 40 μm. The distribution curve becomes less skewed and the highest frequency shifts gradually to finer grain sizes as the main fault zone is approached, and finally, a more symmetrical distribution is reached, with 88% of twinned grains <20 μm. The low, broad distribution shown by samples farther from the main fault zone indicates a wider range of grain sizes, a heterogeneous grain size distribution skewed toward larger grain sizes.

The tendency for the coarser fraction of grains to be

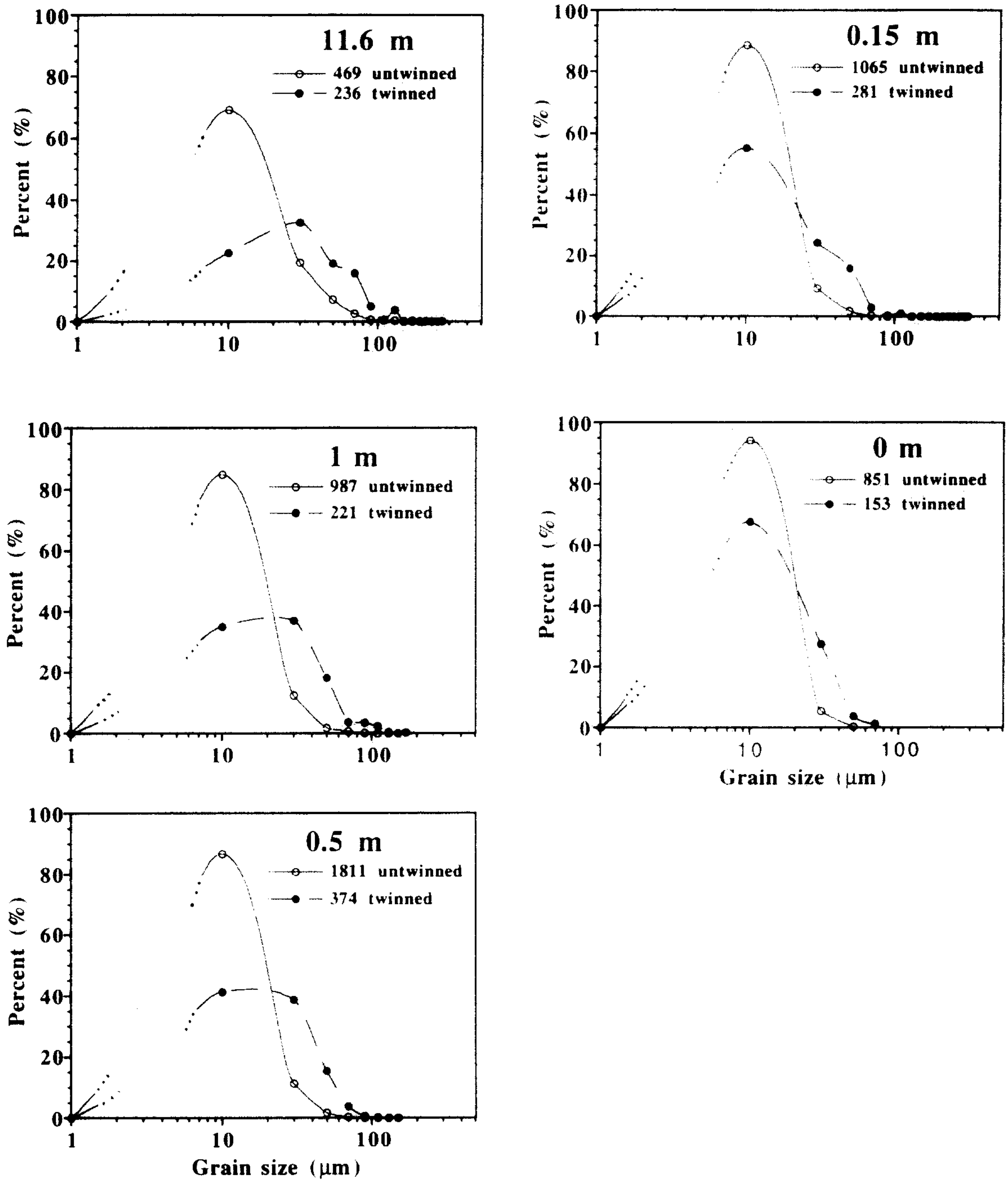

Fig. 8. Grain size distribution data. Grain size interval is 20 μm. Each graph shows the frequency of grains within each grain-size class vs logarithmic grain size. Twinned and untwinned grains are considered as separate populations. Distance from the main fault zone is indicated at the top of each graph. The numbers of twinned and untwinned grains measured are also indicated at the top of each graph. The grain size distribution for samples from all locations are log normal and unimodal.

twinned is implicitly shown by the grain size distribution of twinned vs untwinned grains in Fig. 8; but this tendency can be best seen by looking at the twinning incidence (I_t) (Rowe & Rutter 1990), the percentage of grains per grain-size class that contain optically visible twin lamellae. At most locations sampled, there is a generally monotonically increasing relationship between I_t and grain size; I_t increases as grain size increases (Fig. 9). This is especially clear at the location farthest from the main fault zone (11.6 m), and within the center of the main fault zone. As the grain size distribution changes from a wide range of grain sizes at locations farthest from the main fault zone, to a homogeneous, fine-grained distribution at locations closest to and within the center of the fault zone (Fig. 8) the relationship between I_t and grain size remains (Fig. 9). However, the slope of the line of this relationship increases in samples closer to and within the main fault zone where the coarser size fractions are no longer present. In the center of the main fault zone, a monotonically increasing relationship between I_t and grain size can be seen in grains all finer than 100 μm.

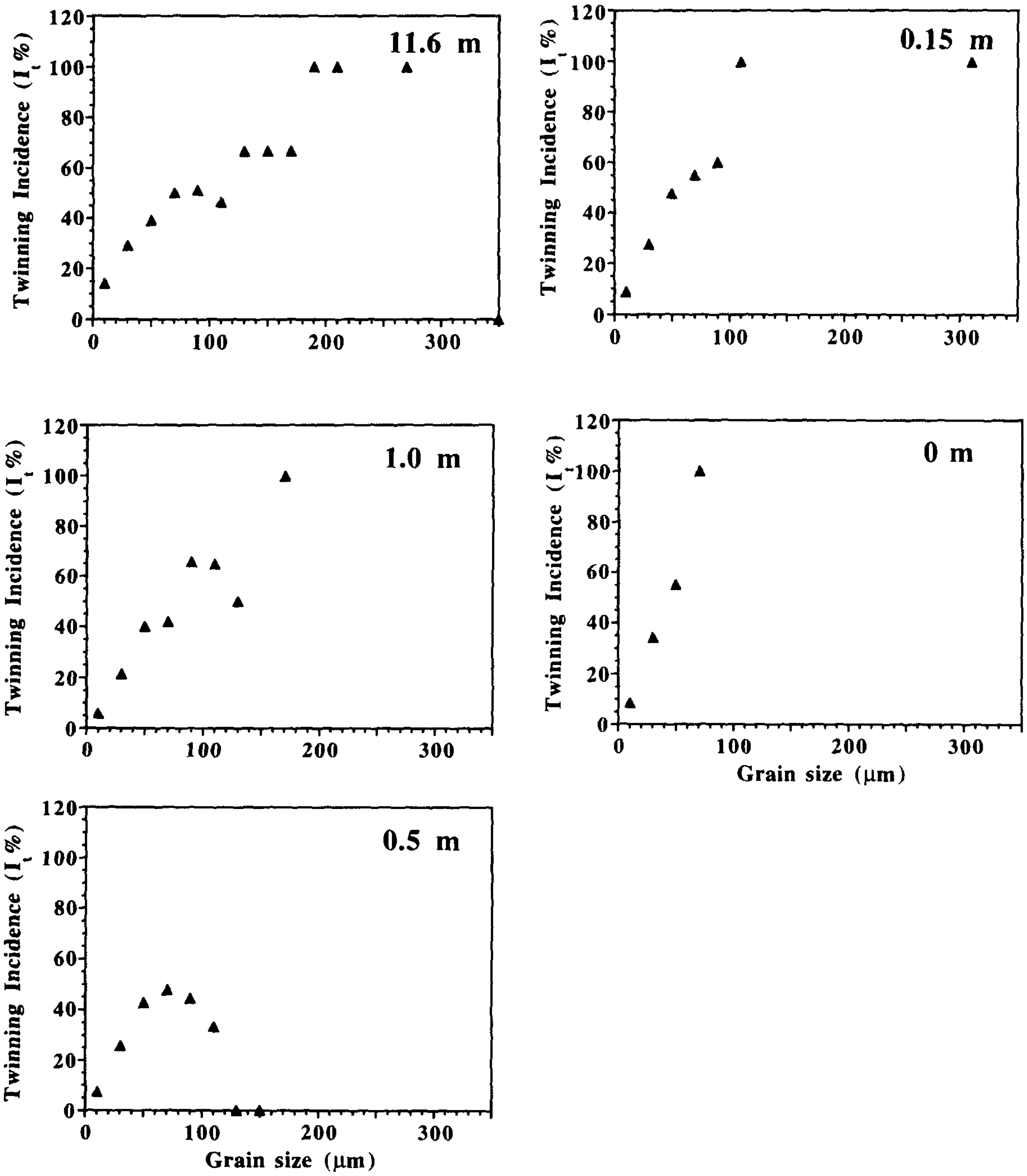

Fig. 9. Twinning Incidence (I_t) data. I_t is the percentage of twinned grains per grain-size class. Distance from the main fault zone is indicated at the top of each graph.

THE INFLUENCE OF GRAIN SIZE DISTRIBUTION

The grain-size distribution data and twinning incidence data suggest that twinning is dependent on grain size distribution in addition to grain size. Although the percentage of twinned grains decreases as the geometric mean grain size decreases (Figs. 6 and 7), the grain size distribution plays a role in the twinning incidence of grains within a given grain-size class. Where a wide range of grain sizes are present, at 11.6 m above the fault zone, a grain that is 70 μm has a twinning incidence of 50%. In the center of the fault zone, where the rock is composed of fine-grained, homogeneous material, a grain that is 70 μm has a twinning incidence of 100%. While higher stresses may have prevailed in the center of the fault zone, the grain size distribution data and twinning incidence data suggest that the relationship between grains, at grain-to-grain contacts, is an important variable in twinning activity and may have influenced the stress estimates.

Stress concentrations occur at grain-to-grain contacts (e.g. Means 1976), suggesting two mechanisms by which grain size distribution may influence twinning activity:

(1) A stress concentration must be in an appropriate orientation to induce a twin within a grain. The higher the number of grains surrounding any given grain (center grain), the higher the likelihood that one of

those grains will produce a stress concentration (at a grain-to-grain contact) in an appropriate orientation to nucleate a twin within the center grain.

(2) Experimental studies and studies of naturally deformed carbonates indicate that twinning is more difficult within finer grains than in coarser grains. Therefore, given two adjacent grains of different grain sizes, with a stress concentration along the grain boundary, the coarser grain is more likely to accommodate the strain by twinning than the finer grain. This would indicate that relative grain size is important in twinning activity.

Evidence for these two processes can be found in microstructural observations of the fault rocks in this study. Figures 10(a) & (b) show isolated twins occurring at the contact with a smaller protruding grain, suggesting the importance of stress concentrations between grains of different relative grain sizes. A twin is also seen at the contact with a grain inclusion (Fig. 10b), a source of stress concentration. Figures 11(a) & (b) demonstrate the influence of relative grain size and the influence of the number of surrounding grains. Relatively large twinned grains are observed surrounded by many smaller adjacent untwinned grains. Note that the scale on Figs. 11(a) & (b) are the same. Grains of the same grain size can be seen on both photographs, but they show different behavior depending on the relative size of surrounding grains—i.e. the grain size distribution.

These relationships can be seen quantitatively by plotting grain size (measured as longest grain diameter) vs number of adjacent grains (Fig. 12). While there is a tendency for coarser grains to be twinned, there is also a tendency for grains with a higher number of adjacent grains to be twinned. A grain that is 20 μm and surrounded by five other grains is generally untwinned. A grain that is 20 μm and surrounded by 10 or more other grains generally is twinned. These data and the observations from the microstructures indicate that grain-to-grain stresses and relative grain size are important variables that influence twinning, and suggest that grain size distribution should be considered by the methods for determining paleostresses.

NATURAL FAULT ZONES AND ASSUMPTIONS FOR PALEOSTRESS METHODS

Natural faults are zones of concentrated and typically complex deformation, and many of the assumptions necessary for the methods for determining paleostresses are not met. Rotation of blocks often occurs during fault zone deformation, and this will increase the percentage of twinned grains. At each increment of rotation, grains will be reoriented with respect to the stress field and new twins will form. Also, faulting involves progressive deformation, so that the proportion of twinned grains does not necessarily represent one deformation event, nor one stress field, due to reorientation during progressive displacement. Reorientation of grains also occurs during grain boundary sliding, a process that may often occur during deformation of fine-grained rocks (Schmid 1983). These processes will result in non-coaxial, or rotational strain, while coaxial and irrotational strain are necessary conditions for the paleostress determination methods.

While Rowe & Rutter's (1990) data suggest that strain rate does not influence twinning incidence, Friedman & Heard (1974) suggest that duration of application of stress will increase the percentage of twinned grains. It is possible that during deformation, each increment of deformation, as small as the formation of a single twin, will cause a change in the local stress field, and in stresses around individual grains, producing new stress concentrations, and thus new twins. As a result a higher number of twins will be recorded, which would indicate higher than actual stresses if we use current stress determination methods based on the percentage of twinned grains.

The deformation along this fault zone is interesting in that although the rocks show evidence of dynamic recrystallization, this did not occur as a result of high temperatures during deformation. The deformation was influenced by fluids along the fault zone which enhanced diffusion, resulting in dynamic recrystallization at low temperatures (Newman 1993, Newman & Mitra in press); geologic strain rates may have also contributed to recrystallization at lower temperatures than expected from laboratory data (Handin & Fairbairn 1955, Higgs & Handin 1959). As a result, recrystallization and twinning operated concurrently in these rocks. The grain size distribution and twinning incidence data indicate that grains of progressively finer grain size twin as grain-size reduction occurs, suggesting that the finer, recrystallized grains twinned. If during the deformation, the rocks continually recrystallize (i.e. the strain is removed from the grains), the twins that are present would represent the last increment of deformation. Twins resulting from prior deformation, during rotation of blocks or grains, or from earlier episodes of deformation, would have been removed. Thus, the twins would represent a single, coaxial or irrotational deformation event, and the assumptions necessary for the paleostress measurement methods would be met.

It is important to note that Jamison & Spang's (1976) method for estimating paleostresses from twinning assumes the existence of a critical resolved shear stress for twinning, while the influence of grain size and stress concentrations on twinning activity imply that it may be difficult to establish a single critical resolved shear stress for twinning for a population of grains. Experiments on the stress necessary for twinning in metals indicate that there is no critical resolved shear stress for twinning. Nucleation and propagation of twins involve stress concentrations (Cahn 1964, Mahajan & Williams 1973). Studies of whisker (highly perfect crystals) and quasi-whisker crystals showed no twinning, or, twinning only at very high stresses (Cahn 1964). Furthermore, the twins that did form formed at re-entrant corners, etch pits, or adjacent to the grips—i.e. at possible stress concentrators. Imperfections in natural crystals act as stress concentrators, lowering the effective critical resolved shear stress for twinning. Because of the importance of stress concentrations, experiments to

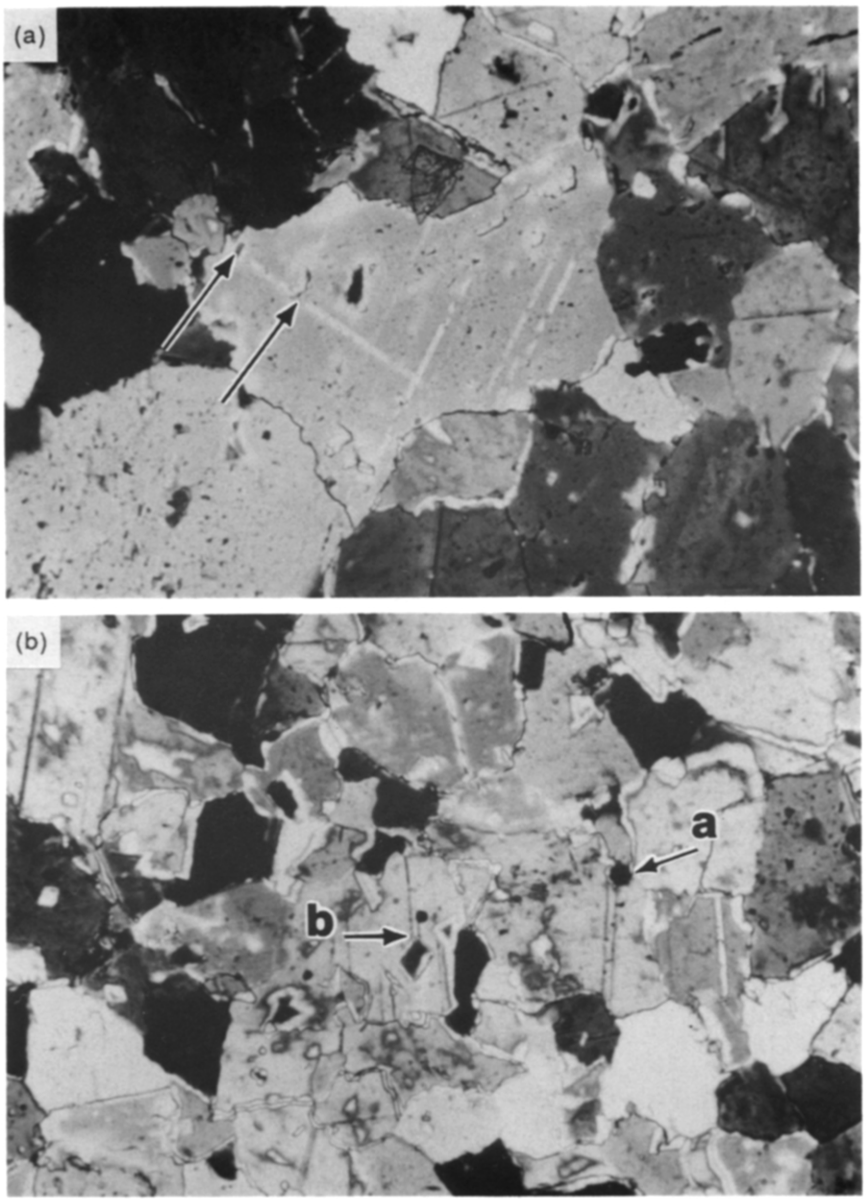

Fig. 10. (a) An isolated twin occurs at the contact with a small protruding grain. The width of the photograph is 0.3 mm. (b) An isolated twin occurs at the contact with a small protruding grain (arrow a). There is also a twin occurring at the contact with a grain inclusion (arrow b). The width of the photograph is 0.24 mm.

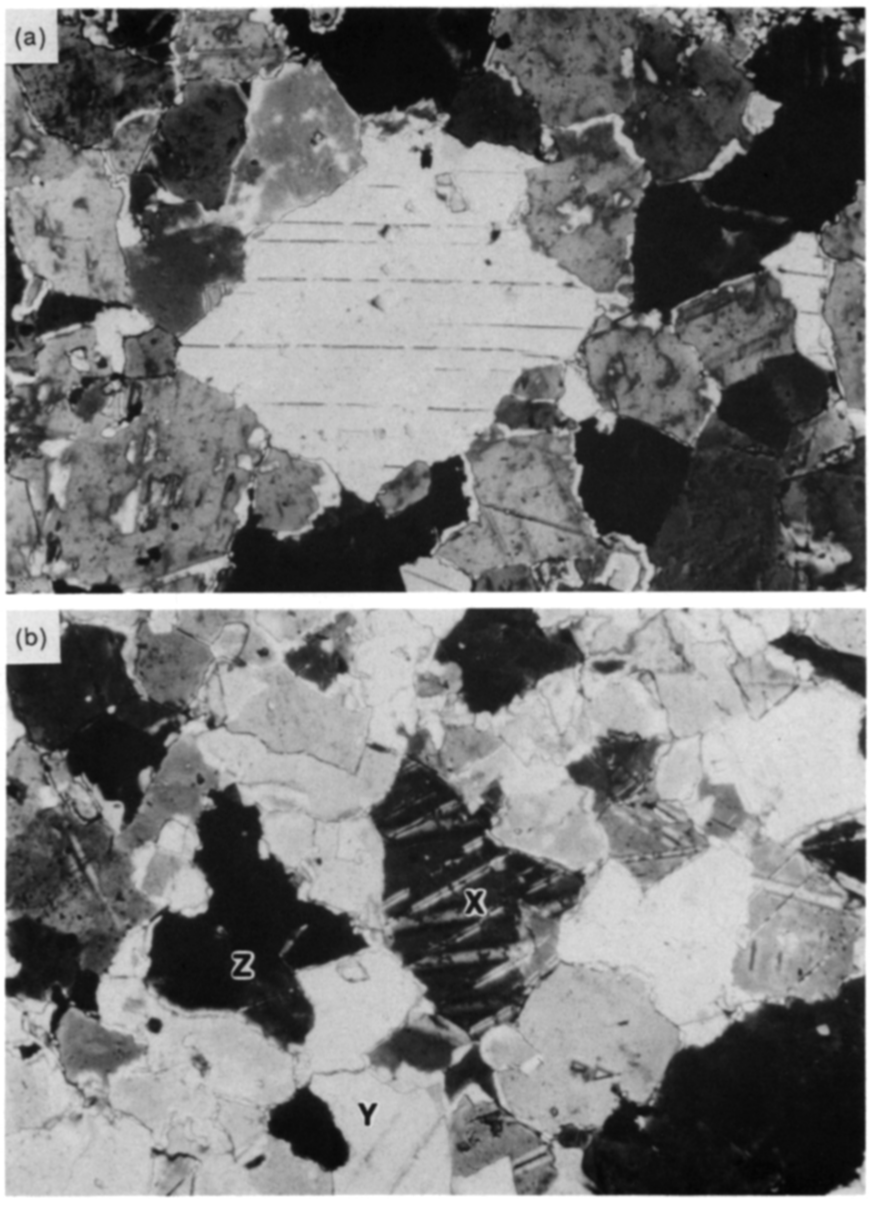

Fig. 11. (a) Relatively large twinned grain surrounded by many smaller, generally untwinned grains. Sample is from 0.5 m from the center of the fault zone. (b) Relatively large twinned grains (x, y, z) surrounded by many smaller, generally untwinned grains. Sample is from 0.15 m from the center of the fault zone. Also note that the scale on (a) & (b) are the same. While grain x is relatively large in (b) it would be considered relatively small in (a). Untwinned grains of the same general grain size as (x) can be seen in (a). The width of the photographs is 0.3 mm.

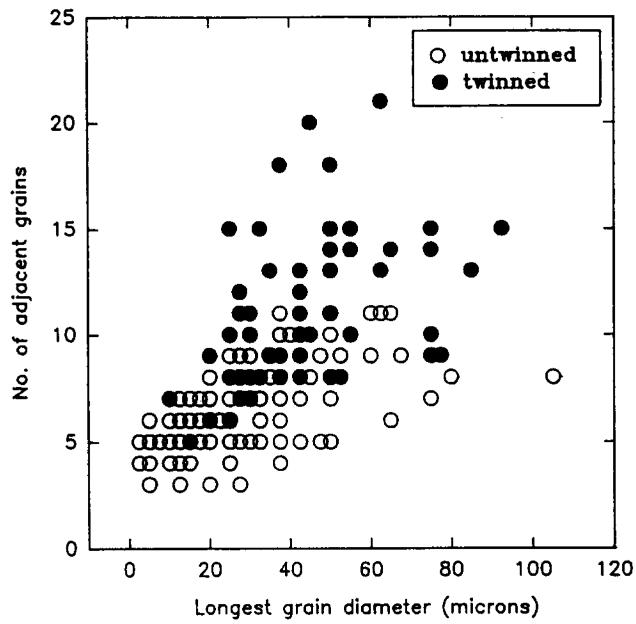

Fig. 12. Number of adjacent grains vs grain size (measured as longest grain diameter) vs number of adjacent grains. Two hundred and seven grains measured.

determine a critical resolved shear stress for twinning in metals have resulted in a very wide range of values (Mahajan & Williams 1973). Tullis (1980) suggested that despite these findings, experiments on minerals in which no special precautions are taken to use highly perfect crystals result in relatively uniform values for a critical resolved shear stress. These values would represent the stress necessary for propagation of twins, as stress concentrators are plentiful in natural rocks, in the form of fractures, dislocation pile-ups and pre-existing twins. But the data from this study suggest that stress concentrators external to the grain, at grain-to-grain contacts can influence the nucleation and propagation of twins, so that Tullis' assumption may not be entirely valid. As in metals, experimental studies to determine the critical resolved shear stress for twinning in dolomite have resulted in a wide range of values, ranging from 200 MPa (Higgs & Handin 1959) to 95 MPa (Heard *et al.* 1978) for single crystal dolomite. Jamison & Spang's (1976) application of their method to naturally deformed polycrystalline rocks suggests that both of these estimates are high, and they suggest a critical resolved shear stress of 50 MPa.

It is clear that grain size influences twinning activity, and the relationship between twinning and grain size is the basis for Rowe & Rutter's (1990) paleostress estimate method. But natural fault zones show progressive grain-size reduction, which typically results in the development of heterogeneous grain size distributions. As stress concentrations at grain-to-grain contacts and relative grain size also influence twinning activity, grain size distribution should be considered to achieve more accurate estimates of paleostresses. The data presented here suggest that a heterogeneous grain size distribution will increase the percentage of twinned grains, but experimental studies on rocks with heterogeneous grain size distributions are necessary to quantify this effect.

COMPARISONS OF STRESS ESTIMATES

Comparisons of paleostress estimates from twinning in carbonates from different studies show some trends. Figure 13 lists paleostress estimates from different studies according to the general locations of the studies from the hinterland to the foreland of various fold and thrust belts. The first four studies concern upper crustal deformation. The estimates of Lacombe & Laurent (1992) and Lacombe *et al.* (1990) were carried out in the Burgundy platform of eastern France using Etchecopar's (1984) Inverse Method. The second two studies, Laurent *et al.* (1990) and Tourneret & Laurent (1990), also carried out using the Inverse Method, are from the Quercy region of France, ~200 km north of the Pyrenean chain. The next three estimates were carried out using Jamison & Spang's (1976) method for estimating paleostresses (including this study). Jamison & Spang (1976) estimated the paleostresses within the McConnell thrust of the Canadian Rockies. House & Gray (1982) estimated paleostresses along the Saltville thrust of the Southern Appalachians, and this study looks at the

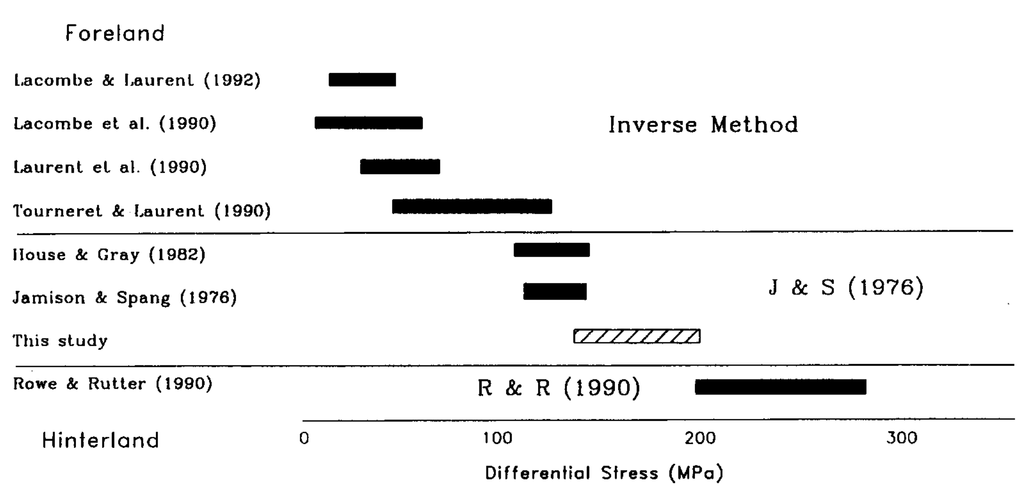

Fig. 13. Comparison of paleostress estimates from twinning in carbonates from different studies.

Pioneer Landing fault zone, approximately 60 km southeast of the Saltville thrust. Rowe & Rutter (1990) estimated paleostresses along a minor fault within the Cantabrian zone of the Hercynian chain in northern Spain.

The estimates show a trend of increasing stresses toward the hinterland of mountain belts. However, the estimates are also grouped according to the method used: the lowest estimates were obtained using the inverse method, the next three using Jamison & Spang's (1976) method, and the highest estimate using Rowe & Rutter's (1990) method. While the trend of increasing stresses toward the hinterland may be real, it may be an artifact of the methods used. The estimates also group according to regional studies (first four) vs fault zone studies (last four). Again, higher stresses may occur along fault zones, but the results may be method dependent. The methods need to be cross-checked by carrying out estimates on naturally deformed samples from a single location using more than one method.

CONCLUSIONS

Two paleostress measurement methods based on twinning in carbonates indicate opposite trends for stress variations across the Pioneer Landing fault zone. Jamison and Spang's (1976) method indicates a decrease in stress towards the center of the fault zone, while Rowe and Rutter's (1990) method indicates an increase in stress.

The different trends may reflect the influence of grain size, as Rowe and Rutter's (1990) method considers grain size and Jamison and Spang's (1976) does not. In addition, grain-to-grain stresses and relative grain size influence twinning activity, suggesting that grain size distribution should also be considered by methods for determining paleostresses. Furthermore, while Jamison and Spang's (1976) method assumes an effective critical resolved shear stress for twinning, the grain size distribution and twinning incidence data indicate that there is no effective critical resolved shear stress for twinning in these naturally deformed dolomite rocks.

Other assumptions necessary for Rowe & Rutter's (1990) and Jamison & Spang's (1976) methods, including homogeneous strain, and a single non-coaxial or irrotational stress field, are also unlikely to be met in most natural fault zones. In addition, changes in mean grain size and the development of a heterogeneous grain size distribution are likely to occur during fault zone deformation. The complex nature of fault zone deformation may explain the higher paleostress estimates reported for fault zone studies than for regional studies, and suggests that these methods for determining paleostresses are not appropriate for fault zone studies. Paleostress estimates from different studies group according to the method used. The methods should be cross-checked by carrying out studies on naturally deformed rocks using more than one method on a single sample.

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