Journal of Structural Geology, Vol. 9, No. 2, pp. 195 to 205, 1987
Printed in Great Britain

0191-8141/87 $03.00 + 0.00

Early history and reactivation of the Rand thrust, southern California

CLAY E. POSTLETHWAITE and CARL E. JACOBSON

Department of Earth Sciences, Iowa State University, Ames, IA 50011, U.S.A.

(*Received* 10 *May* 1985; *accepted in revised form* 12 *August* 1986)

Abstract—The Rand thrust of the Rand Mountains in the northwestern Mojave Desert separates an upper plate of quartz monzonite and quartzofeldspathic to amphibolitic gneiss from a lower plate of metagraywacke and mafic schist (Rand Schist). The Rand thrust is considered part of the regionally extensive Vincent/Chocolate Mountain thrust system, which is commonly believed to represent a Late Cretaceous subduction zone. The initial direction of dip and sense of movement along the Vincent/Chocolate Mountain thrust are controversial. Microfabrics of mylonites and quartzites from the Rand Mountains were analyzed in an attempt to determine transport direction for this region, but the results are ambiguous. In addition, the southwestern portion of the Rand thrust was found to have been reactivated as a low-angle normal fault after subduction. Reactivation might have occurred shortly after subduction, in which case it could account for the preservation of high-pressure mineral assemblages in the Rand Schist, or it could be related to mid-Tertiary extension in the western United States. In either event, the reactivation might be responsible for the complicated nature of the microfabrics. The Rand Schist exhibits an inverted metamorphic zonation. Isograds in the schist are not significantly truncated by the reactivated segment of the Rand thrust. This indicates that other segments of the Vincent/Chocolate Mountain thrust should be re-evaluated for the possibility of late movement, even if they show an apparently undisturbed inverted metamorphic zonation.

INTRODUCTION

ONE OF the most enigmatic structural features of southern California is the Vincent/Chocolate Mountain thrust (Fig. 1), which separates an upper plate of igneous and metamorphic rocks of continental affinity from a lower plate composed principally of metagraywacke and metabasite. The rocks of the lower plate are termed the Pelona, Orocopia and Rand Schists, and are thought to have been metamorphosed simultaneously with emplacement of the upper plate (Ehlig 1958, Graham & England 1976, Haxel & Dillon 1978, Jacobson 1980, 1983a,b). This conclusion is based on the parallelism of fold axes, lineations and foliation in the schists to equivalent structures in mylonites at the base of the upper plate; increase of temperature of metamorphism of the schists toward the upper plate (inverted metamorphic zonation); and similar radiometric ages for metamorphism of the schists and mylonites (52–59 Ma, Ehlig 1981; but see Haxel *et al.* 1987 for a reinterpretation of the age of metamorphism).

Since the Vincent/Chocolate Mountain thrust separates units of continental affinity from a lower plate of metasediments and metavolcanics of inferred oceanic derivation, and since the rocks of the lower plate exhibit a relatively high-pressure metamorphism (Graham & England 1976, Graham & Powell 1984, Jacobson & Sorensen 1986), the thrust is generally regarded as a relict subduction zone. However, the fault has been folded and disrupted by Cenozoic deformations, so that the direction of overthrusting is not evident from the present orientation of the thrust surface. Nonetheless, knowledge of this direction is critical for reconstructing the Mesozoic paleogeography of southern California.

Models to explain the origin of the Vincent/Chocolate Mountain thrust and Pelona–Orocopia–Rand schist can be divided into three general categories. (1) The schist is a correlative of the Franciscan Complex that was underthrust beneath the continental crust of western North America in a low-angle E-dipping subduction zone (Yeats 1968, Crowell 1968, 1981, Burchfiel & Davis 1981, Dickinson 1981, Powell 1982). (2) The schist formed in a W-dipping subduction zone between North America and an outboard island arc. The arc could have originated by rifting of North America (Haxel & Dillon 1978, Tosdal *et al.* 1984), or it might have been exotic to the continent (Ehlig 1981, Vedder *et al.* 1982). (3) The

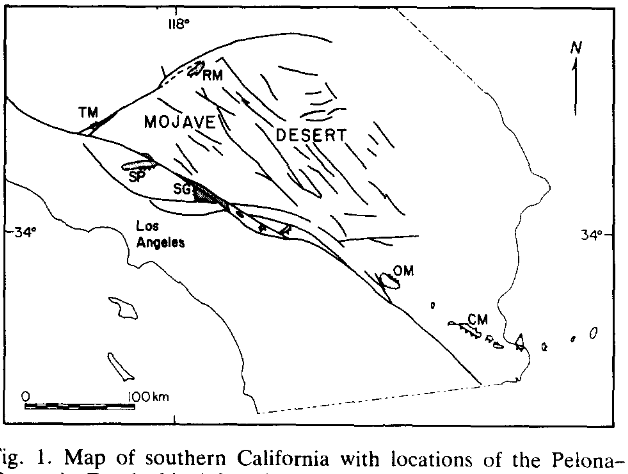

Fig. 1. Map of southern California with locations of the Pelona–Orocopia–Rand schist (after Haxel & Dillon 1978, fig. 2). Faults of the San Andreas and Garlock systems and those of the Mojave Desert are also shown. Locations referred to in the text are as follows: CM, Chocolate Mountains; OM, Orocopia Mountains; RM, Rand Mountains; SG, San Gabriel Mountains; SP, Sierra Pelona; TM, Tehachapi Mountains.

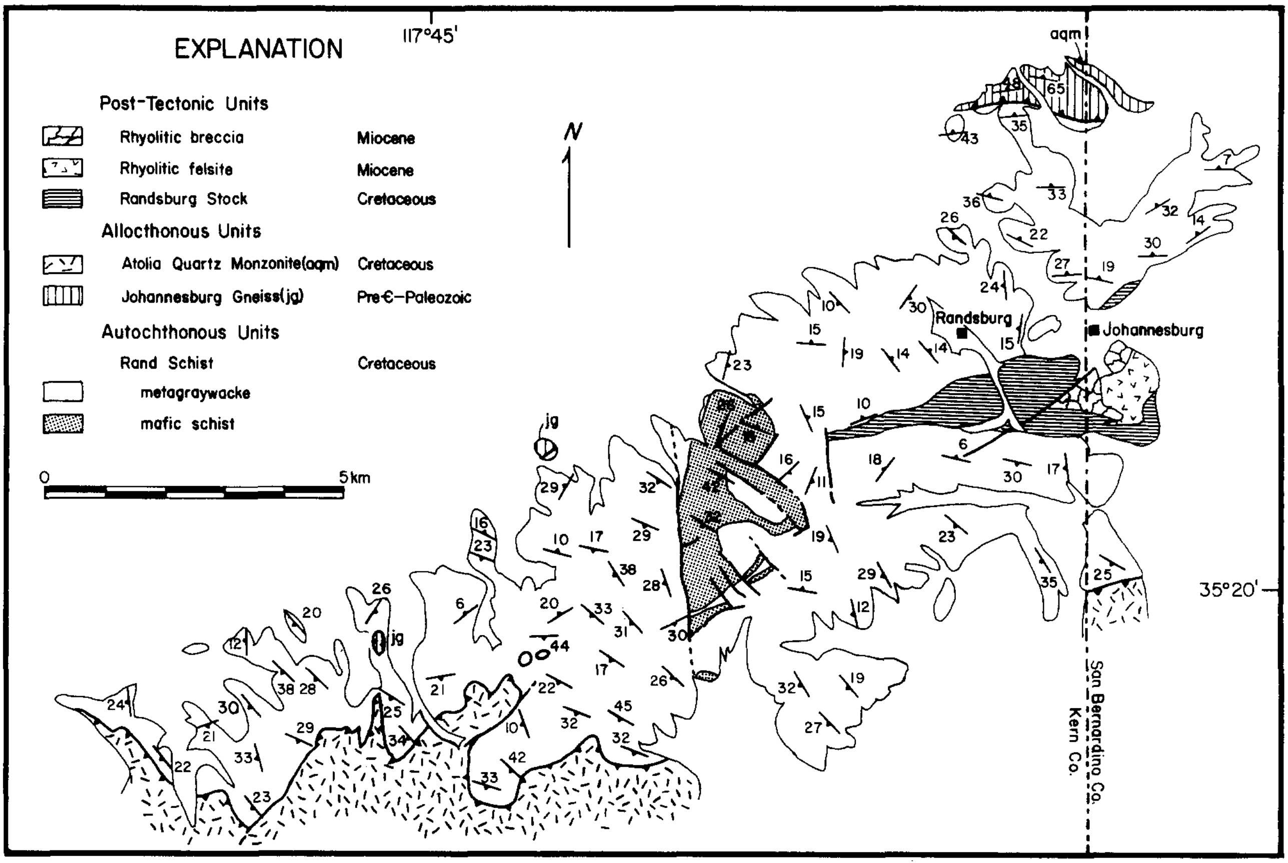

Fig. 2. Generalized geologic map of the Rand Mountains. The northeastern portion of the map is based on the work of Dibblee (1967) and Vargo (1972).

schist is an old metamorphic complex that lay on the eastern side of an exotic terrane that was sutured to North America between 65 and 55 Ma (Vedder *et al.* 1982).

Various arguments have been presented for and against the different models (Haxel & Dillon 1978, Burchfiel & Davis 1981, Crowell 1981, Ehlig 1981, Vedder *et al.* 1982, Jacobson 1983a, Mukasa *et al.* 1984, Tosdal *et al.* 1984). Perhaps the greatest controversy surrounds interpretation of movement direction on the Vincent/Chocolate Mountain thrust. Ehlig (1958, 1981) used the sense of overturning of a macroscopic synform directly beneath the Vincent thrust in the San Gabriel Mountains (Fig. 1) to infer a northeastward direction of overthrusting. This direction is consistent with models 2 and 3, but inconsistent with model 1. Ehlig's interpretation, however, has been criticized by Burchfiel & Davis (1981), who pointed out that the synform is truncated by the thrust and may have been part of a larger structure, the vergence of which is unknown. In addition, Ehlig assumed that thrusting was perpendicular to fold axes and stretching lineations, contrary to many recent interpretations of deep-seated thrust zones (Bryant & Reed 1969, Escher & Watterson 1974, Bell 1984). Furthermore, the Pelona Schist and Vincent thrust of the San Gabriel Mountains are anomalous in that fold axes and lineations in that area trend NW–SE as opposed to the NE–SW orientation found in most other areas.

Northeast transport has also been inferred for the segment of the thrust in the Chocolate Mountains and vicinity (Fig. 1), where Haxel & Dillon (1978) applied the technique of Hansen (1967) to minor folds in both the mylonites and Orocopia Schist. These folds, however, postdate the schistosity, and Burchfiel & Davis (1981) and Crowell (1981) argued that they may have formed after thrusting. On the other hand, Jacobson (1983b, 1984) concluded from petrological evidence that similar folds in the San Gabriel Mountains did form during thrusting.

Because of the importance of determining thrusting direction, and because of the uncertainties associated with the fold analyses, we conducted a microstructural and quartz-fabric analysis of the segment of the Vincent/Chocolate Mountain thrust located in the Rand Mountains of the northwestern Mojave Desert. Both mylonites from the Rand thrust zone and metacherts from the Rand Schist were studied. Since some previous work had been conducted in the eastern portion of the mountains (Vargo 1972), our studies concentrated on the western region. As shown below, the fabrics exhibited by the mylonites and metacherts are complex. Moreover, during the course of the study, we found evidence that the segment of the 'Rand thrust' along the southwestern margin of the range (Fig. 2) may have undergone extensive reactivation after metamorphism of the Rand Schist and, in fact, may be a low-angle normal fault.

LITHOLOGIES

The Rand thrust crops out on the limbs of a NW–SE trending post-metamorphic anticline (Figs. 2 and 3a). Over 3000 m of Rand Schist is exposed in the core of the anticline. The dominant lithology is a gray albite–quartz–muscovite schist, derived from graywacke. Of lesser abundance is a mafic schist that generally contains albite, epidote, calcic and/or sodic amphibole, and chlorite. Quartzite is found throughout the Rand Schist, although it is not abundant. Various sized pods of serpentine, talc, actinolite, and fuchsite are rare but distinctive components.

Schistosity and compositional layering in the Rand Schist are parallel, except in the hinges of the isoclinal folds. A lineation is defined by streakings of muscovite on the foliation surfaces, quartz-filled pressure shadows and oriented mineral grains. The lineation is not everywhere well developed, but is better defined in the metagraywackes and quartzites than in the mafic schists. Figure 3(b) shows the orientations of lineations from the southwest limb of the anticline. The NNE–SSW trend is parallel to that observed by Vargo on the northeast limb of the anticline (Fig. 3c) and also to the general trend of lineations in most bodies of Pelona–Orocopia schist (Raleigh 1958, Haxel & Dillon 1978).

Isoclinal folds (style 1 folds) with axial-planar schistosity are present throughout the schist. In all cases the fold axes are parallel to the local lineation. Data from the southwest limb are plotted in Fig. 3(d). Relatively open folds (style 2) that postdate the isoclinal ones are also present. These folds are typically disharmonic and noncylindrical. They have a wide range of orientations (Fig. 3e). No consistent sense of asymmetry was noted for either style of fold.

Hulin (1925) recognized that the Rand Schist north of the town of Johannesburg is overlain by the Johannesburg Gneiss along a low angle fault (Fig. 2) termed the Rand thrust by Vargo (1972). The contact is poorly exposed and generally can be located only to within 8–10 m. The Johannesburg Gneiss is a multiply deformed suite of amphibolite-facies, quartzofeldspathic to amphibolitic gneisses, marble and quartzite. The mafic and most felsic of the gneisses contain almandine garnet. Vargo (1972) suggested that the Johannesburg Gneiss has been retrograded from granulite facies. Due to the multiply deformed nature of the gneiss, it is somewhat difficult to determine the effects on the unit of deformation related to the Rand thrust. Although Vargo (1972) described only an 8–10 m mylonite zone at the base, zones of mylonite parallel to the Rand thrust are present throughout the 900 m of exposed gneiss.

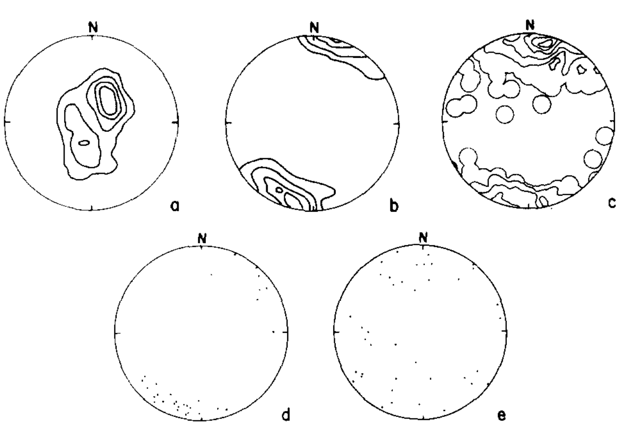

Fig. 3. Structural data for the Rand Schist. All figures are lower-hemisphere, equal-area projections. (a) Poles to foliations. 206 pts. Contour interval 3 sigma. (b) Lineations from the southwestern Rand Mountains. 167 pts. Contour interval 4 sigma. (c) Lineations from the northeastern Rand Mountains (from Vargo 1972). 200 pts. Contours = 0.5, 2, 4, 6, 8 and 10% per 1% area. (d) Style 1 fold axes, southwestern Rand Mountains. 30 pts. (e) Style 2 fold axes, southwestern Rand Mountains. 39 pts.

At the southwest end of the Rand Mountains the Rand Schist is overlain by the Atolia Quartz Monzonite (Fig. 2). The contact was described by Hulin (1925) and Dibblee (1952, 1967) as intrusive, but by Ehlig (1968), Haxel & Dillon (1978), and Dibblee (1980) as a portion of the Rand thrust. The schist and the quartz monzonite are not in direct contact but are separated by a 3–10 m zone of quartzofeldspathic and marble mylonite with lenses of hornblende–plagioclase gneiss. The quartzofeldspathic mylonite and hornblende–plagioclase gneisses locally contain abundant garnet. Compositionally and mineralogically the mylonites show little resemblance to either the Atolia Quartz Monzonite or the Rand Schist. Instead, they appear to be derived from the Johannesburg Gneiss. The Atolia Quartz Monzonite is locally mylonitized within 1–2 m of the marble and quartzofeldspathic mylonite. Elsewhere it is essentially undeformed.

MICROFABRICS

Mylonites overlying the Rand Schist and quartzites from within the Rand Schist were examined to determine if any indication of the direction of motion on the Rand thrust was recorded in their fabric. No shear indicators were found in the mylonites from the Johannesburg Gneiss at the northeast end of the range. The quartz in these samples appears to have annealed, masking any indication of sense of shear (Fig. 4a). Good shear indicators were found in the mylonites from the southwest end of the range.

The most common shear-related fabric in the mylonites is an 'obliquity of elongate recrystallized grains' (Simpson & Schmid 1983, p. 1285, Lister & Snoke 1984). An example is shown in Fig. 4(b). The main foliation (horizontal in Fig. 4b) is parallel to the mylonite zone and presumably to the plane of shear during thrusting. The long axes of the elongate grains define the late-stage direction of maximum extension. The angular relations indicate left-lateral shear, although as emphasized by Brunel (1980) and Simpson & Schmid (1983), this applies only to the last phase of movement. In one sample, the elongate grains were axial planar to a microscopic 'S' fold with the same sense of shear.

Another common fabric in the mylonites is the asymmetric deflection of foliation around porphyroclasts. In

Fig. 4(c), the foliation is compressed against the upper right and lower left margins of the porphyroclasts. This indicates that the flattening direction during this strain was oriented from upper right to lower left and suggests a left-lateral component of shear on the foliation plane.

Two mylonites contain shear bands (White *et al.* 1980, Simpson & Schmid 1983, Lister & Snoke 1984) inclined at low angles to the main foliation (Fig. 4d). These are secondary shear surfaces (the C'-surfaces described by Berthé *et al.* 1979) that formed at a late stage of deformation after the rock has developed a strong planar anisotropy. The sense of shear in these shear bands is the same as that of the main shear zone. All of the fabrics in the mylonites beneath the Atolia Quartz Monzonite suggest the upper plate moved to the southwest. Nourse & Silver (1986) found the same sense of shear.

Figure 5 is a series of optically determined c-axis fabrics from quartzites in the Rand Schist. The samples were divided into two domains based on their location. Samples of domain I are from the northeast portion of the range where dips are to the north at angles generally less than 35°. Samples in domain II were collected from the southwest portion of the range where dips are generally toward the southwest. An effort was made to collect samples from lineated quartzites located as close to the thrust as possible. The sample locations are shown in Fig. 6(a).

In general, the fabrics consist of a single strong girdle oriented obliquely to the lineation and foliation with or without minor secondary girdles. Simpson & Schmid (1983) suggested that this type of fabric results from a simple shear deformation where the basal and rhombohedral glides are the most active slip systems. These are the systems expected to be active during deformation at relatively low temperatures or high rates of strain. The subsidiary girdles, best developed in samples 9a, 9c and 40 (Fig. 5), might arise from a greater amount of flattening strain (Behrmann & Platt 1982).

Van Roermund *et al.* (1979) and Simpson & Schmid (1983) state that the stronger girdle should lean in the shear direction relative to the foliation. On this basis, it is clear that the fabrics from the two domains give opposing senses of shear. The fabrics from the northeastern area (domain I) generally suggest displacement of the upper layers to the south. With the exception of sample 9a, all of the fabrics from the southwest region (domain II) indicate shear of the upper layers to the northeast.

METAMORPHIC ZONATION

A distinctive feature of many bodies of Pelona–Orocopia schist is an upward increase in temperature of metamorphism toward the overthrust plate. Such a zonation was first described by Ehlig (1958), who noted an increase of grain size with approach to the Vincent thrust in the greenschist facies Pelona Schist of the eastern San Gabriel Mountains. A more pronounced variation is present in the Sierra Pelona, where metamorphism varies from lower greenschist facies deep in the structural section to amphibolite facies adjacent to the mylonites at the base of the upper plate (Graham & England 1976, Graham & Powell 1984). Similar zonations have also been noted in the Orocopia Schist of southeasternmost California (Haxel & Dillon 1978).

An inverted metamorphic zonation is present in the Rand Schist and is evident in both the mafic and quartzofeldspathic rocks. Mafic schists deepest in the structural section contain albite + epidote + chlorite + subcalcic actinolite to winchite + magnesioriebeckite to crossite as the principal constituents. This assemblage indicates metamorphic conditions transitional between those of the blueschist and greenschist facies (Brown 1974). We will refer to such rocks as glaucophanic greenschists. The minerals in the glaucophanic greenschists define a schistosity which is axial-planar to the isoclinal folds in the Rand Schist.

Further up-section are mafic schists that differ from the glaucophanic greenschists only by the absence of sodic amphibole. These rocks belong to the greenschist facies, although the subcalcic nature of the actinolite in them also indicates relatively high pressures of metamorphism (Jacobson & Sorensen 1986). As with the glaucophanic greenschists, minerals in the greenschists lie parallel to the axial planes of isoclinal folds.

Highest in the structural section, the calcic amphibole in the mafic schists is hornblende instead of actinolite, chlorite is diminished in abundance, and epidote is relatively low in ferric iron. These features indicate metamorphism in epidote–amphibolite facies. Textural relations of minerals are similar to those observed in the greenschists and glaucophanic greenschists.

The locations of 16 glaucophanic greenschists, greenschists and epidote amphibolites studied petrographically are shown in Fig. 6(b). Complete mineral assemblages and detailed microprobe data for 10 of these samples are described by Jacobson & Sorensen (1986). Figure 6(b) illustrates the general increase in grade of the mafic rocks with approach to the thrust, although the number of samples is insufficient to locate metamorphic isograds precisely. An approximate idea of their distribution, however, can be inferred from the field relations. Variation of metamorphic grade causes a distinct change in color of the mafic rocks: glaucophanic greenschists are blue, greenschists pale green and epidote amphibolites dark green to black. In all cases, from both the north and south sides of the range, mafic schists near the Rand thrust appear in the field to be epidote amphibolites. Thus the metamorphic isograds must be at least approximately parallel to the Rand thrust.

Quartzofeldspathic rocks from the Rand Schist are composed predominantly of quartz, albite and muscovite in subequal proportions. Virtually all samples also contain a few percent each of epidote and chlorite. In addition, many quartzofeldspathic rocks contain garnet, biotite, and/or calcic amphibole. Studies of quartzofeldspathic rocks from the Pelona Schist of the San Gabriel Mountains indicate that the latter three minerals (garnet in particular) are relatively rare in the green-

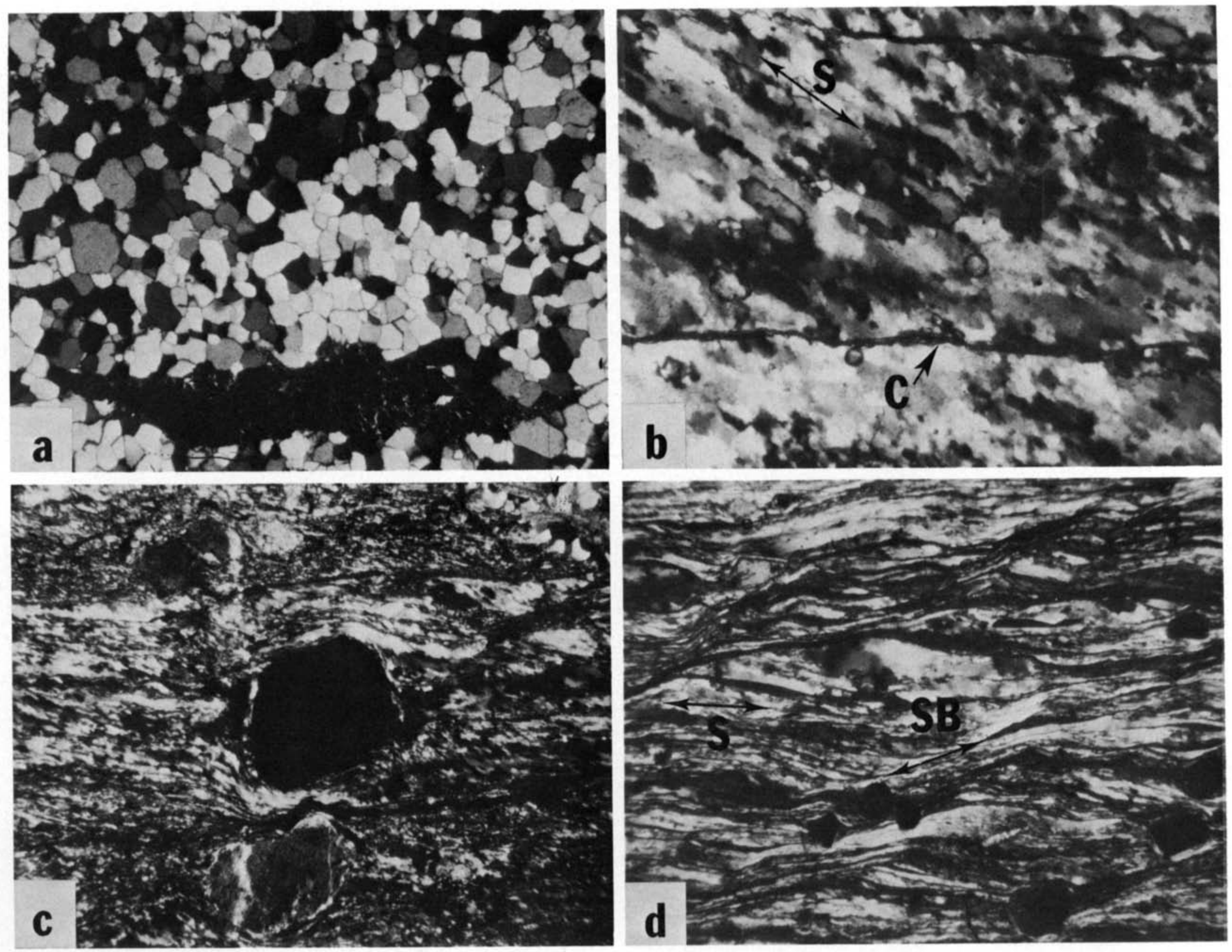

Fig. 4. Microfabrics from the Rand thrust mylonites. (a) Mylonite from the northeast end of the range showing annealed textures. Crossed polars. Width of view is 2.6 mm. (b) Recrystallized quartz grains exhibiting a grain shape asymmetry. Elongate quartz grains are parallel to the late-stage flattening plane (*S*). The shear planes (*C*) are the macroscopic foliation planes of the mylonite zone. The obliquity of the two planes indicates left-lateral shear on the foliation surface. Crossed polars. Width of view is 0.65 mm. (c) Foliation deflected around porphyroclasts. Note the flattened quartz grains on the upper right and lower left sides of the porphyroclasts which indicate flattening oblique to the foliation and left-lateral shear. Crossed polars. Width of view is 2.6 mm. (d) Two intersecting planar fabrics. Schistosity (*S*) and inclined shear bands (*SB*) intersect to suggest left-lateral shear. Crossed polars. Width of view is 2.6 mm.

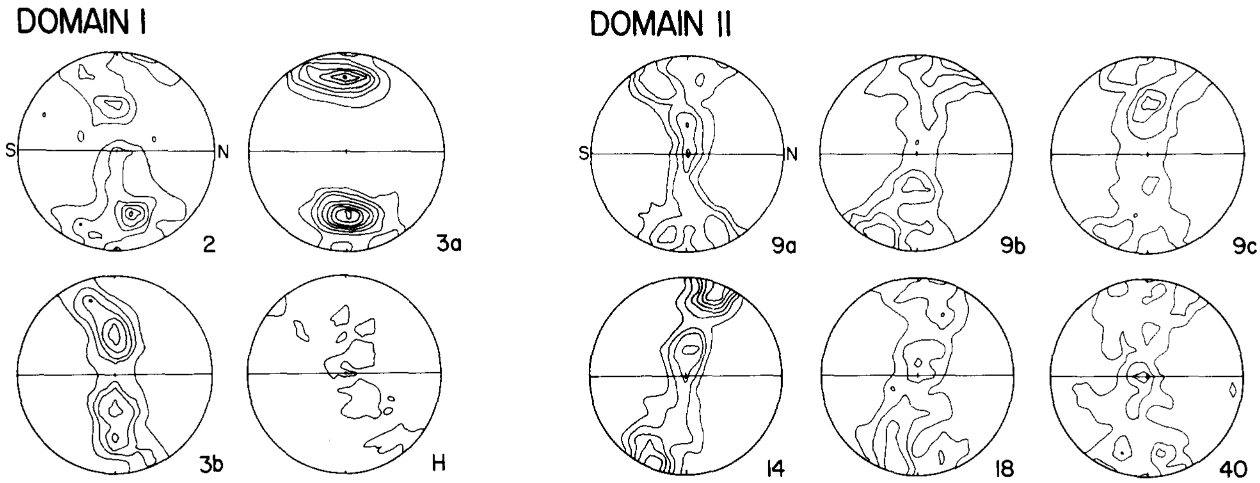

Fig. 5. C-axis fabrics of quartzites from the Rand Schist. The foliation and lineation are horizontal. The lineation is parallel to the projection plane with the NNE end (marked N on figure) on the right side of the diagrams. 200 grains were measured from each sample. Contouring is by the Kamb method. Contour interval is 2 sigma. Sample H is from Vargo (1972). The 2% contour from his plot has been rotated to coincide with our data.

schist facies, but common in the epidote–amphibolite facies (Jacobson 1980, 1983b). Figure 6(c) shows that, in the current study area, garnet, biotite and calcic amphibole are most common in quartzofeldspathic schists relatively close to the Rand thrust. The relationship is striking and consistent with the upward increase of metamorphic grade indicated by the mafic rocks.

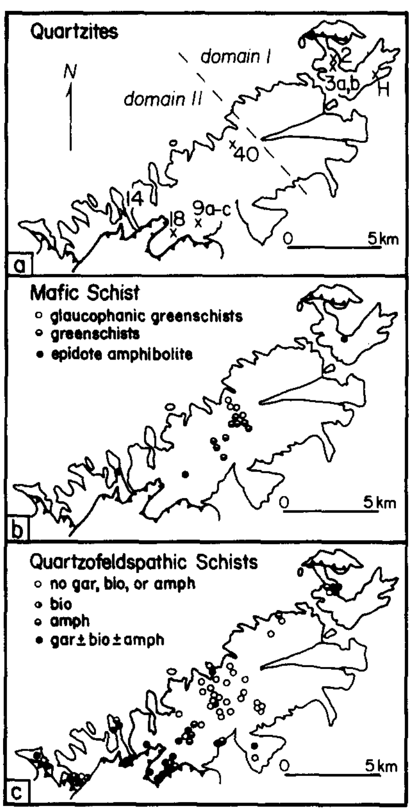

Fig. 6. (a) Locations of quartzites analyzed for c-axis fabrics. Domain I includes samples 2, 3a–b and H. Domain II includes samples 9a–c, 14, 18 and 40. (b) Distribution of mafic glaucophanic greenschists, greenschists, and epidote amphibolites in the Rand Schist. (c) Distribution of garnet, biotite, and calcic amphibole in Rand quartzofeldspathic schists. All samples contain quartz, albite, muscovite, epidote and chlorite.

DISCUSSION

As noted previously, a major controversy exists regarding the initial direction of dip of the Vincent/Chocolate Mountain thrust and the sense of movement along it. Unfortunately, our structural studies have not yielded an unambiguous solution to this problem. The microstructural features other than the c-axis fabrics indicate transport of the upper plate toward the SSW. The quartz c-axis fabrics from the northeast portion of the range (domain I) indicate SSW transport, whereas those from the southwest area (domain II) yield a NNE direction of movement. These opposing senses of asymmetry might be considered as evidence that the c-axis fabrics were developed by flexural flow folding during uplift of the Rand Mountains antiform. However, the foliation does not dip steeply on either limb of the antiform (Fig. 2) and it is difficult to imagine that strains during this event were sufficient to produce the strong crystallographic preferred orientations observed in Fig. 5.

To some degree, the inconsistency among the c-axis fabrics is not surprising. We have analyzed 17 quartzites from the Pelona Schist of the San Gabriel Mountains and found no consistent sense of asymmetry in that area (unpublished data). The fact that c-axis fabrics may yield ambiguous results has also been suggested by Passchier (1983). Simpson & Schmid (1983) cautioned that this technique should not be the sole basis for the interpretation of shear sense. Nonetheless, a striking feature of the fabrics illustrated in Fig. 5 is the good agreement of samples within the individual domains.

The schists of domains I and II differ not only in apparent vergence, but also in the nature of the rocks that overlie them. The Rand Schist of domain I is overlain by a thick section of Johannesburg Gneiss which contains widely distributed mylonites. The quartz in these mylonites shows mosaic texture. In domain II, the schist is overlain by the Atolia Quartz Monzonite with only thin intervening lenses of Johannesburg

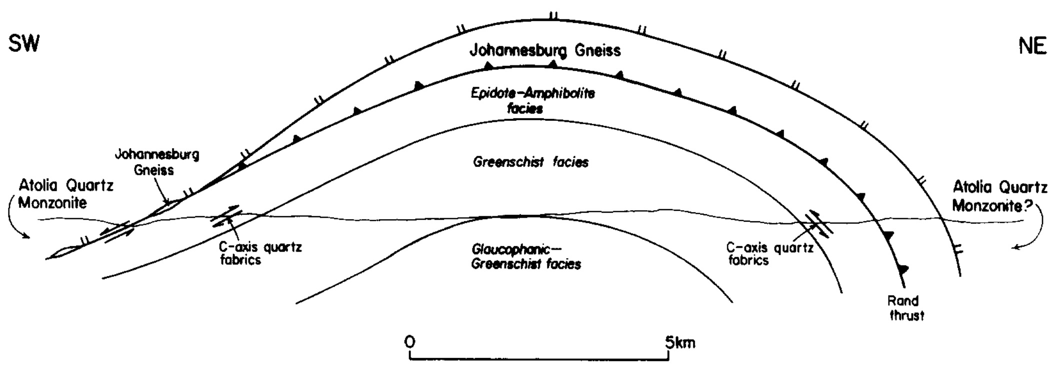

Fig. 7. NE–SW cross-section showing the relations of the major structures in the Rand Mountains and the metamorphic zonation of the underlying Rand Schist. Tentative correlation of a small exposure of granitic rock at the extreme northeast end of the range with the Atolia Quartz Monzonite allows us to project the low-angle normal fault across the range and to show this fault cutting structurally downward to the southwest.

Gneiss. Mylonites in this area show well defined grain shape asymmetries and are excellent examples of the type II mylonites of Lister & Snoke (1984), which they believed to be generally formed during uplift.

Particularly striking is the relative thinness of the mylonite zone at the base of the Atolia Quartz Monzonite. Deformation of the quartz monzonite is generally restricted to a zone less than a few meters in thickness. In contrast, the Rand Schist, which has an exposed thickness of 3000 m, shows isoclinal folding and development of schistosity throughout (this study and Jacobson 1983c). The schist was undergoing prograde metamorphism and dewatering at the time of its deformation. Water liberated from the schist should have allowed extensive deformation of the quartz monzonite, if it actually was emplaced over the schist during metamorphism. In fact, some portions of the Vincent/Chocolate Mountain thrust do show pronounced deformation and retrogression of the upper plate, apparently due to emplacement over the Pelona–Orocopia schist (Jacobson 1983b).

The fact that the Rand Schist is overlain in the northeast by the Johannesburg Gneiss, but in the southwest by the Atolia Quartz Monzonite bears further consideration. The rock types present in the Rand Schist, and in the Pelona–Orocopia schist in general, are eugeoclinal in nature and similar to the lithologies found in many terranes inferred to represent relict subduction complexes (Dickinson 1971, Blake *et al.* 1974, Ernst 1975, 1977). In addition, the glaucophanic greenschists found in the lowest structural portions of the Rand Schist indicate relatively high pressures of metamorphism, providing further evidence for an origin by subduction. Nonetheless, certain observations make it difficult to accept that the contact between the Rand Schist and the Atolia Quartz Monzonite is the original contact between the hangingwall and footwall of a subduction zone. Specifically, the Atolia Quartz Monzonite is structureless, except near the contact with the Rand Schist (this report, Hulin 1925, Dibblee 1952); it is not associated with migmatites; and, in general, it does not show any characteristics of a deep crustal intrusion. In other words, the Atolia Quartz Monzonite and Rand Schist do not appear to have formed at similar depths.

The above features suggest that the Rand thrust in domain II is not the original fault beneath which the Rand Schist was subducted and metamorphosed (a similar conclusion was reached by Silver *et al.* 1984, and Nourse & Silver 1986). In fact, they seem to imply that the Rand thrust is actually a low-angle normal fault along which the high-pressure, highly deformed Rand Schist has been brought into contact with igneous rocks typical of a mid-crustal level of intrusion. Our model of the Rand Mountains is shown on the cross section in Fig. 7. Recently, there has been a great deal of interest in mid-Tertiary extensional tectonics and detachment faulting in the southwestern United States (Crittenden *et al.* 1980, Frost & Martin 1982). In particular, Frost *et al.* (1981) and Frost & Martin (1983), have argued that the Chocolate Mountain thrust in south-easternmost California may have been reactivated in the mid Tertiary by detachment faulting. Thus, one possible explanation for the anomalous features just described is that the Rand 'thrust' in domain II is actually a mid-Tertiary detachment fault.

Although mid-Tertiary extensional faulting may well have affected certain segments of the Vincent/Chocolate Mountain thrust, it is possible that the postulated reactivation of the Rand thrust occurred at an even earlier date. Haxel *et al.* (1985) recently described a low-angle fault (Sortan fault) in south-easternmost California along which the Orocopia Schist is overlain by dacite, quartz arenite, argillitic siltstone and conglomerate of the Jurassic(?) Winterhaven Formation. The Orocopia Schist is highly deformed and metamorphosed, like the Rand Schist. In contrast, the Winterhaven Formation is only incipiently recrystallized, shows no penetrative deformation, and could never have been buried to the 20–30 km depths inferred for the Pelona-Orocopia schist (Haxel *et al.* 1985). From these relations, Haxel *et al.* (1985) concluded that the Sortan fault is a normal fault that has caused the removal of about 10 km of crustal rocks. The Sortan fault is intruded by the granite of Marcus Wash, which has a K–Ar minimum age of approximately 60 Ma (Frost & Martin 1983). Thus, although the Sortan fault is similar to the mid-Tertiary detachment faults in that it juxtaposes deep and shallow crustal rocks, it is significantly older.

It is not known whether late Mesozoic to early Tertiary uplift of the Orocopia Schist indicated by the Sortan fault is only a local phenomenon, or whether it is due to an event that affected the entire Pelona–Orocopia schist, and which included the postulated reactivation of the Rand thrust. A widespread event would have bearing on the metamorphic evolution of the Pelona–Orocopia schist. Relatively high pressures of metamorphism are indicated in the Rand Mountains by the presence of glaucophanic greenschists, and for most other bodies of Pelona–Orocopia schist by high celadonite contents in muscovite, the presence of subcalcic actinolite and hornblende in greenschists and epidote amphibolites, occurrence of magnesioriebeckite to crossite in metachert and as a rare relict grains in metabasites, presence of slightly jadeitic aegirine–augite in metachert, and local abundance of stilpnomelane (Ehlig 1958, Graham 1975, Graham & England 1976, Jacobson 1980, Sharry 1981, Graham & Powell 1984, Jacobson & Sorensen 1986). Jacobson & Sorensen (1986) have emphasized that the minerals indicative of high-pressure metamorphism are synkinematic and show relatively little overprinting by low-pressure assemblages. Recent studies show that the preservation of high-pressure mineral assemblages requires either rapid uplift (England & Richardson 1977, Draper & Bone 1981) or prolonged subduction to cause extensive cooling of the overthrust plate (Peacock 1986). The reactivation of the Vincent/Chocolate Mountain/Rand thrust system postulated here may indicate that the former is important. Testing of this hypothesis, however, requires better knowledge of the timing of metamorphism and faulting than is currently available.

Reactivation of the Rand thrust in domain II was inferred partly from the lack of extensive deformation in the Atolia Quartz Monzonite. In contrast, the Johannesburg Gneiss in domain I is highly deformed throughout. In this area, the Rand thrust dips northward toward the Garlock fault. If the Tertiary strike–slip movement on the Garlock is removed, the Rand Schist lies adjacent to the Pelona Schist of the Tehachapi Mountains (Fig. 1). There, the thrust also dips northward. The upper plate in the Tehachapi Mountains is a complex of amphibolite to lower granulite facies gneisses and plutonic rocks that Sharry (1981) and Ross (1985) suggest are the root-zone of the Sierra Nevada batholith. Geobarometry by Sharry (1981) on the gneisses indicates depths of metamorphism on the order of 25–30 km. Similar depths of metamorphism were also calculated for the underlying schist. All of the lithologies in the Johannesburg Gneiss can be correlated to units in the Tehachapi Mountains complex. This suggests that the Rand thrust in domain I could be a portion of the original fault along which the Pelona Schist was subducted. Similarly, in the San Gabriel Mountains, the Pelona Schist is overlain by a zone of mylonites up to 1000 m in thickness. This may be another area in which an original segment of the Vincent/Chocolate Mountain thrust is preserved.

Of particular importance is the fact that the Rand Schist all along the contact with the Atolia Quartz Monzonite is of epidote–amphibolite facies, and that this is the same grade of metamorphism as the Rand Schist adjacent to the Johannesburg Gneiss. This indicates that if the Rand thrust in domain II was reactivated as a normal fault, it caused little excision of the underlying schist, at least at presently exposed levels. This is a very important conclusion, because parallelism of isograds to the Vincent/Chocolate Mountain thrust has commonly been cited as evidence that metamorphism of the Pelona Schist occurred during emplacement beneath the current upper plate. This is probably a valid conclusion in the areas where there is extensive synkinematic recrystallization of the upper plate and where the recrystallized assemblages are of the same metamorphic grade as the directly underlying schist (e.g. San Gabriel Mountains). However, where such is not the case, as along the southwest margin of the Rand Mountains (similar relations seem to exist also in the Orocopia Mountains), significant post-subduction deformation can probably be easily overlooked.

The structural history inferred here for the Rand thrust appears similar to that undergone by the Coast Range thrust of western California. The latter feature separates an upper plate of unmetamorphosed to barely metamorphosed sediments of the Great Valley fore-arc basin from the underlying high-pressure metamorphic rocks of the Franciscan subduction complex (Blake *et al.* 1974). The Coast Range thrust is commonly thought of as the zone along which the Franciscan complex was subducted. Nonetheless, consideration of the contrast in pressure of metamorphism between the upper and lower plates indicates that the latest phase of movement must have been in a normal sense to allow uplift of the subducted rocks (Ernst 1977, Cowan & Silling 1978, Cloos 1982). This is exactly the case argued for the Rand thrust. Another similarity with the Rand Mountains is that the Franciscan complex, too, exhibits an inverted metamorphic zonation that is not truncated by the upper plate (Ernst 1975, 1977), although the zonation in the Franciscan is on a much larger scale than in the Rand Schist.

As recently summarized by Haxel *et al.* (1985), some workers have suggested that the Rand Schist might actually be somewhat older than the Pelona and Orocopia Schists. Nonetheless, we are struck by the impressive similarity of lithologies, metamorphism, and structural history between the units, and the fact that all consist of oceanic lithologies that currently underlie sheets of continental basement rock. Even if the units differ in age, they must have formed in virtually identical tectonic environments. It is for this reason that we have assumed that all the units can be considered together.

CONCLUSIONS

The Vincent/Chocolate Mountain thrust is commonly considered to be the primary fault along which the oceanic protolith of the Pelona–Orocopia schist was underthrust (subducted) beneath continental crust.

Much work on the fault has emphasized the determination of movement direction, because of the constraints that direction would place on plate-tectonic models. Nonetheless, several recent studies indicate that some portions of the thrust may have undergone significant reactivation since the metamorphism of the Pelona–Orocopia schist (this study, Frost & Martin 1983, Silver *et al.* 1984, Nourse & Silver 1986). Furthermore, the lack of truncation of metamorphic isograds along a reactivated segment of the Rand thrust implies that other superficially intact segments of the thrust system could also have undergone late movement.

Much additional work is necessary to establish the extensiveness of late movement on the Vincent thrust system. The presence in some regions of apparently intact mylonite sequences, as in domain I of the Rand Mountains and in the San Gabriel Mountains, may indicate that reactivation occurred only locally. Late faults in the latter areas could simply be present at higher structural levels, rather than right at the original upper plate–Pelona Schist boundary.

Also unclear is the age of reactivation. The Sortan fault in south-easternmost California appears to be no younger than 60 Ma, which indicates that uplift of the Pelona–Orocopia schist may be only slightly younger than the metamorphism of the Pelona–Orocopia schist (Haxel *et al.* 1985). If so, the uplift event might be responsible for preservation of the high-pressure mineral assemblages. On the other hand, reactivation could be due to mid-Tertiary extensional faulting, in which case it would not be genetically related to the initial metamorphism of the Pelona–Orocopia schist. In either event, polyphase deformation might be an explanation for the ambiguous results obtained in the microfabric analyses conducted for this study, and the possibility of such complexity must be carefully considered in any studies of folds or microfabrics used to determine movement direction on the Vincent/Chocolate Mountain thrust.

Acknowledgements—Funding was provided by the Iowa State University Research Foundation, a Research Corporation Cottrell Research Grant, and NSF grants EAR-8121210 and EAR-8319125. Our understanding and interpretations of the Pelona Schist problem have benefited greatly from discussions or written communication with John Crowell, Perry Ehlig, Gordon Haxel, Dan May, Jeff Morehouse and Carol Simpson. This manuscript was greatly improved by reviews from Gordon Lister and an anonymous reviewer. The program used in contouring quartz-fabric diagrams was provided courtesy of Dave Miller.

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