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RELATIONSHIP OF DEFORMATION AND METAMORPHISM OF THE PELONA SCHIST TO MOVEMENT ON THE VINCENT THRUST, SAN GABRIEL MOUNTAINS, SOUTHERN CALIFORNIA

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ABSTRACT. A thickness of 4 km of Pelona Schist is exposed beneath the mylonites of the Vincent thrust zone in the San Gabriel Mountains of southern California. The schists have undergone a complex history of folding. Isoclinal folds are present throughout the section and show no variation in abundance or degree of appression with approach to the thrust. Directly beneath the thrust, the isoclinal folds are overprinted by a relatively open macroscopic synform (Narrows Synform). The formation of the Narrows Synform caused schistosity-parallel muscovites in metagraywackes to become crenulated. In many cases, the crenulated muscovites recrystallized to form new, strain-free grains. These recrystallized grains are higher in Paragonite content and lower in Celadonite content than both unrecrystallized muscovites in the same rocks and muscovites in samples far from the thrust, which were not affected by the Narrows Synform. These differences of composition appear to be related to the thrusting event, indicating that the Narrows Synform cannot have formed subsequent to the thrusting.

INTRODUCTION

In studying the structural geology of complexly deformed metamorphic rocks, the major goals typically involve differentiating generations of folds, determining the metamorphic conditions (P/T conditions) at which the different folds formed and, ultimately, determining whether the various folds were produced during a single, polyphase orogenic cycle or during several separate tectonic events that are completely unrelated. Since the work of Zwart (1960a, b), petrographic studies of the relations between folding and mineral growth have been commonly used to help solve these problems. More recently, the electron microprobe has also been used for this purpose. For example, Boulter and Raheim (1974) have described an area in which phengite (celadonitic muscovite, Guidotti and Sassi, 1976) grew during each of three successive phases of folding. Each of the folding events was found to be associated with a phengite of distinct composition. By using the phengite compositions to indicate the conditions at which the three sets of folds were formed, it was possible to determine how closely the different folds were related to each other.

This paper presents the results of a similar study, in which muscovite compositions were used to study the relationship between folding and metamorphism of the Pelona Schist underlying the Vincent thrust in the San Gabriel Mountains of southern California. The metamorphism of the Pelona Schist is considered to have occurred during movement of the Vincent thrust (Ehlig, ms; Graham and England, 1976; Haxel and Dillon, 1978; below). Thus, the relationship between folding and metamorphism gives an indication of the relationship between folding and thrusting. The study is important because of a controversy regarding the implications of certain folds in the Pelona Schist for the sense of movement on the Vincent thrust (Burchfiel and Davis, 1981; Crowell, 1981; Ehlig, 1981; Jacobson, ms and in press). This paper concentrates on the relationship between folding and metamorphic recrystallization. The regional implications are considered elsewhere (Jacobson, ms and in press).

THE VINCENT-CHOCOLATE MOUNTAIN THRUST SYSTEM

The Vincent thrust of the San Gabriel Mountains is part of a regional thrust system of Late Cretaceous-early Tertiary age (Vincent-Chocolate Mountain thrust of Haxel and Dillon, 1978, p. 453) which is exposed in southern California and southwestern Arizona (fig. 1). The upper plate of the thrust system consists of Precambrian, Paleozoic, and Mesozoic igneous and metamorphic rocks which are mylonitized near the contact with the lower plate. The lower plate consists of metamorphic rocks (Pelona, Rand, and Orocopia Schists) derived from graywackes and smaller proportions of shales, basaltic volcanics, ferromanganiferous cherts, limestones, and ultramafic rocks. The metamorphism is pervasive and ranges from greenschist to lower amphibolite facies.

Previous workers have noted systematic metamorphic zonations within the Pelona and related schists that apparently indicate an increase of temperature of metamorphism toward the overlying plate (inverted metamorphic zonation in the schists). This phenomenon was first described by Ehlig (ms), who found that the greenschist facies Pelona Schist of the San Gabriel Mountains shows an increase of grain size with approach to the Vincent thrust. An inverted zonation has also been described for the Sierra Pelona, where there is a progression from lower greenschist facies far from the thrust to lower (oligoclase) amphibolite

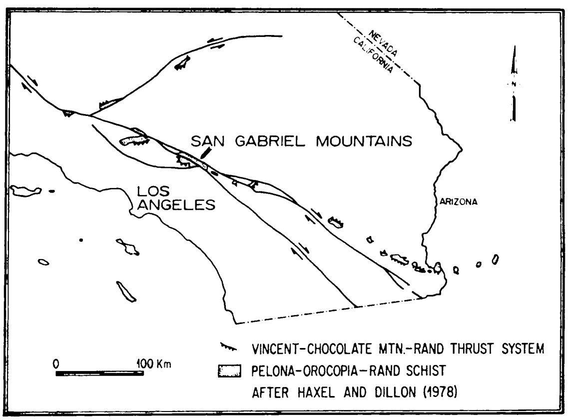

Fig. 1. Distribution of the Pelona, Rand, and Orocopia Schists (Pelona-Orocopia Schist) and Vincent, Chocolate Mountain, and Rand thrusts (Vincent-Chocolate Mountain thrust; after Haxel and Dillon, 1978, fig. 2).

facies at the contact with the upper plate (Graham and England, 1976). A variation from greenschist to lower amphibolite facies has also been described for some of the schists in southeasternmost California (Dillon, ms). Because of compositional heterogeneity and lack of suitable bulk compositions, little study has been made of metamorphic variations within the upper plate.

THE VINCENT THRUST AND PELONA SCHIST OF THE SAN GABRIEL MOUNTAINS

A map of the Pelona Schist and Vincent thrust of the San Gabriel Mountains is shown in figure 2. Thrusting motion was presumably distributed throughout the entire thickness of mylonites developed at the base of the upper plate. The Pelona Schist and mylonites are exposed in the form of a post-metamorphic arch (style 3 arch of fig. 2). A thickness of approx 4 km of Pelona Schist measured perpendicular to the thrust is exposed in the arch. The sinuous outcrop trace of the arched mylonite zone results from the 2000 m of topographic relief in the area.

Figure 3 is a northeast-southwest cross section (adapted from Ehlig, 1975, fig. 1) through the Narrows area of the East Fork of the San Gabriel River. The macroscopic synform (Narrows Synform) located directly beneath the mylonites has a horizontal, northwest-southeast trending axis. Ehlig (ms and 1981) has concluded that the synform developed during the thrusting event. From the sense of overturning of the upper limb, he infers that the upper plate moved toward the northeast.

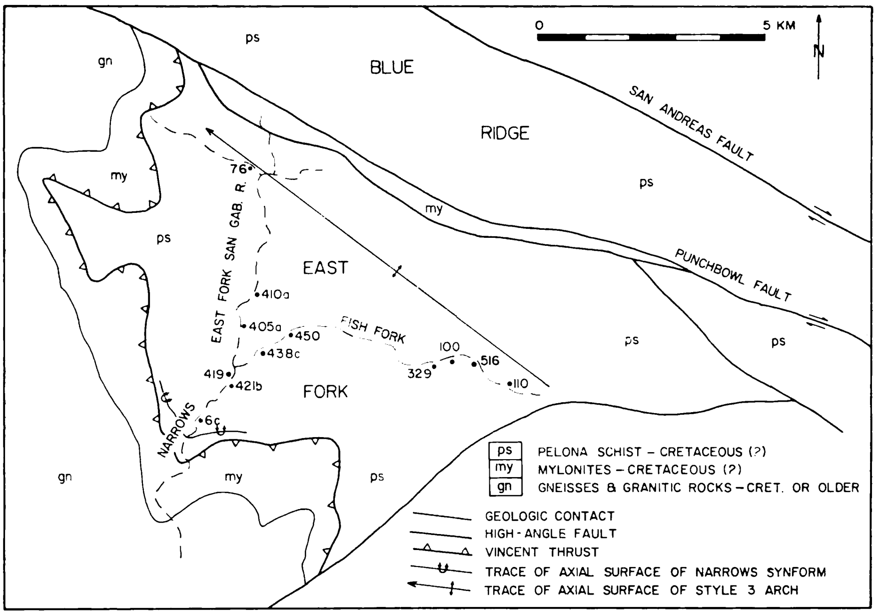

Fig. 2. Geologic map of the Pelona Schist and Vincent thrust in the San Gabriel Mountains (see fig. 1 for location; modified from Jennings and Strand, 1969). Sample localities are indicated, except for specimens closer to the thrust than 6c, which were omitted due to space limitations.

Although a prominent feature of the Pelona Schist, the Narrows Synform is actually a relatively late structure superimposed upon highly flattened isoclinal folds (Jacobson, ms and in press). In some areas the isoclinal folds are found to refold even earlier isoclinal folds. In the following discussion, the Narrows Synform and its associated minor folds are referred to as "style 2" folds. Both early and late isoclinal folds are called "style 1" folds. The isoclinal folds have a pronounced axial-plane schistosity defined principally by muscovite. Style 2 folding has produced a crenulation of that schistosity. The axes of style 1 folds trend northwest-southeast, parallel to the axis of the Narrows Synform, as well as to tight folds in the mylonite zone. Style 1 folds show no variation in abundance or degree of appression with respect to distance from the thrust. In contrast, style 2 deformation dies out approx 700 m structurally below the thrust. On an outcrop scale, style 2 deformation is recognized by the presence of relatively open minor folds and by the crenulation of style 1 schistosity.

The complicated structural history of the Pelona Schist of the San Gabriel Mountains is important for the following reason: In all other areas where the Pelona Schist and its correlatives have been studied, the schists contain isoclinal folds that formed during prograde metamorphism and that apparently are related to the thrusting (Raleigh, ms; Harvill, ms; Vargo, ms; Dillon, ms; Haxel, ms). In many areas, the isoclinal folds are overprinted by open to tight folds which formed during retrograde metamorphism or after metamorphism (refs. cited above). These late folds indicate post-thrusting deformation. Because the Narrows Synform is relatively late and open compared to style 1 folds, this study was conducted to determine if it, too, might be a post-thrusting feature. The approach taken was (1) to determine if there is any regional variation of metamorphism in the Pelona Schist of this particular area that might be thrust related and, if found, (2) to use textural relations to establish its time of formation relative to the development of the Narrows Synform. From previous studies (Ehlig, ms) it was known that the Pelona Schist of this region lies entirely within the greenschist facies. It thus appeared that a detailed microprobe study would be necessary

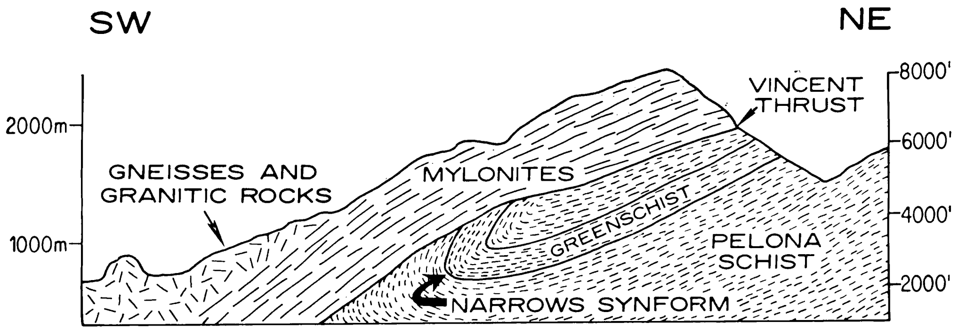

Fig. 3. Cross section through the Narrows area of the East Fork of the San Gabriel River (after Ehlig, 1975, fig. 1).

TABLE 1

Mineral assemblages of the analyzed samples

Sample	qtz	mu	ab	ep	sph	chl	cal	act	stp	gar	bi	other
7	20.0	29.9	26.6	2.3	3.4	11.0	0.5	6.1				0.2
69	40.8	27.5	11.9	6.3	2.3	5.8	4.9					0.5
28	45.3	19.4	18.0	2.0	1.8	9.9	0.8	1.9		0.5		0.4
394	36.6	21.8	22.9	6.2	1.7	6.2	4.0					0.6
462b	22.6	32.5	31.2	3.0	1.3	8.0					1.0	0.4
31	31.8	34.9	28.4	2.5	0.7			0.1				1.6
202	28.4	30.2	28.4	2.0	0.9	5.7	2.0		2.2			0.2
6C	29.0	20.2	30.5	8.3	1.6	5.5	3.3					1.6
421b	29.1	22.9	37.7	3.2	1.0	5.4		0.2		0.3		0.2
419	21.4	25.6	32.5	6.7	1.5	8.8	3.2	0.2				0.1
405a	29.5	32.5	24.7	4.0	2.2	6.1				0.4		0.6
438c	28.3	30.2	30.3	4.9	0.3		2.2	0.2	3.5			0.1
410a	28.6	36.5	23.4	4.5	0.7	0.1	0.6		5.1			0.5
450	23.8	35.4	26.0	4.2	1.6	8.8						0.2
76	22.9	26.5	38.3	4.7	1.0	0.3	2.3		2.5			1.5
329	19.6	27.9	38.1	8.7	0.9		0.1	1.8				2.9
100	11.2	45.7	36.2	4.6	0.9			1.3				0.1
516	31.3	11.1	36.2	0.3	2.0	18.8						0.3
110	24.6	23.7	39.0	6.7	1.3	2.2	1.3					1.2

Samples listed in order of increasing distance from the Vincent thrust. Concentrations determined by counting 1000 points. Qtz = quartz, mu = muscovite, ab = albite, ep = epidote, sph = sphene, chl = chlorite, cal = calcite, act = actinolite, stp = stilpnomelane, gar = garnet, bi = biotite. "Other" includes minor accessories (apatite, tourmaline, zircon), alteration minerals (hematite, goethite, limonite), and vein minerals (quartz, calcite, chlorite, potash feldspar). The vein potash feldspar has 2V = 0 to −20 and does not show microcline twinning. Its structural state is unknown. In some veins it occurs together with chlorite. All samples except 6c, 421b, 405a, 438c, 450, 76, and 329 contain a dark, fine-grained disseminated material inferred to be graphite.

to document any variation of metamorphic conditions. Accordingly, a microprobe analysis was conducted on 19 samples of metagraywacke collected at various distances from the thrust. Metagraywacke was used because it is by far the most abundant and widespread of the rock types of the Pelona Schist. Muscovite was found to be the best mineral for showing compositional and textural variations and is thus discussed in greatest detail.

MINERAL ASSEMBLAGES

The mineral assemblages present in the 19 samples studied with the microprobe are indicated in table 1, with the samples listed in order of increasing distance from the thrust. Quartz, muscovite, albite, epidote, and sphene occur in all samples. Chlorite and calcite are present in a majority of cases, whereas actinolite, stilpnomelane, garnet (Ca and Mn rich, fig. 4), and biotite are less common. Abundances of individual minerals vary markedly from sample to sample but show no obvious correlation with distance from the thrust. There is no pronounced relation between mineral assemblage and distance from the thrust, although garnet appears somewhat more common and stilpnomelane less common close to the thrust.

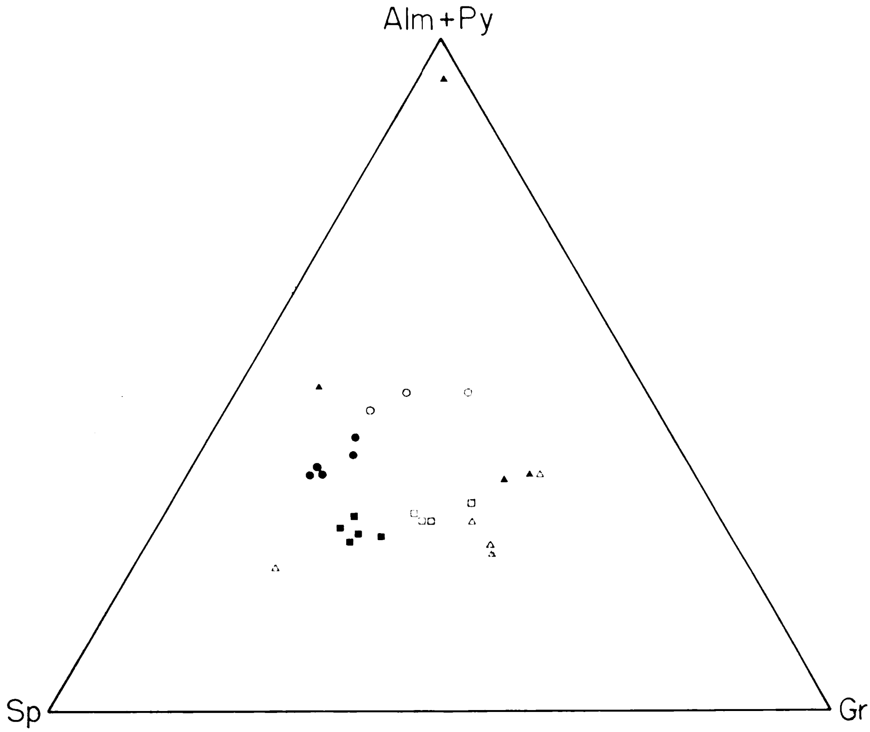

Fig. 4. Composition of garnet in samples 28, 405a, and 421b. Circles — sample 28; squares — sample 405a; triangles — sample 421b. Closed symbols indicate core compositions; open symbols, rim compositions. Alm = Almandine, Py = Pyrope, Sp = Spessartine, Gr = Grossular.

The various assemblages can be represented schematically on AKNa and AKF diagrams (fig. 5) modified to include CO_2 and epidote (actually clinozoisite) as projection points in addition to the usual quartz and H_2O and on a Thompson AFM diagram with albite, epidote, and CO_2 added as projection points (see Brown, 1975, and Harte and Graham, 1975 for several similar projections). The modifications allow phases such as calcite and amphibole to be plotted.

For all three diagrams, projection is made from epidote toward Al_2O_3. Thus, calcite projects in a negative sense, and tie-lines between it and other phases extend to infinity (Greenwood, 1975). Calcite is not present in all samples (table 1). Absence of calcite can be explained either by high Al_2O_3 for the tie-line configurations shown (fig. 5) or by locally low PCO_2, which could cause a change in the tie-lines.

Biotite is relatively uncommon in the Pelona Schist of this region (table 1; Jacobson, ms). That present in sample 462b plots at the location labeled bi in figure 5C. In the other samples it is apparently replaced in projection by chlorite + calcite + stilpnomelane. Thus, the presence of biotite and absence of calcite in sample 462b is evidence that PCO_2 does vary locally. The only sample besides 462b that is incompatible with the tie-line configurations of figure 5 is sample 438c, which contains calcite + actinolite + stilpnomelane.

Potash feldspar, which plots at the location of the $KAlO_2$ component in standard AKNa and AKF diagrams, is not present as a primary phase in any of the samples and is apparently replaced in projection by calcite + muscovite.

The treatment of Fe and Mg as a single component in the AKF diagram means that four phases can be present in the projection without violating the phase rule. In fact, either stilpnomelane or amphibole is commonly present with the three-phase assemblage of muscovite + calcite + chlorite (see table 1). Tie lines are drawn to chlorite in the AKF diagram simply because it is more widespread than either stilpnomelane or actinolite.

Garnet is not shown on either the AKF or the AFM diagrams since its occurrence is presumably due to the presence of manganese.

The variation of muscovite composition shown in the AKNa projection (fig. 5A) is due to solid-solution with a Paragonite component[1] ($NaAl_2AlSi_3O_{10}(OH)_2$, indicated by Pg in fig. 5A). The figure suggests that muscovite coexisting with albite and calcite (plus the projecting phases) will have a fixed Paragonite (Na) content at given P, T, and Pfluid. This could be responsible for the systematic behavior of muscovite Na-content described below.

The variation of muscovite composition in the AKF projection (fig. 5B) is due to solid-solution with Celadonite ($K(MgFe)AlSi_4O_{10}(OH)_2$, indicated by Cd in fig. 5B). The extent of this substitution would appear to be fixed where calcite and chlorite are present and at fixed P,

[1] Chemical components will be distinguished from mineral phases by capitalization of the first letter of the former.

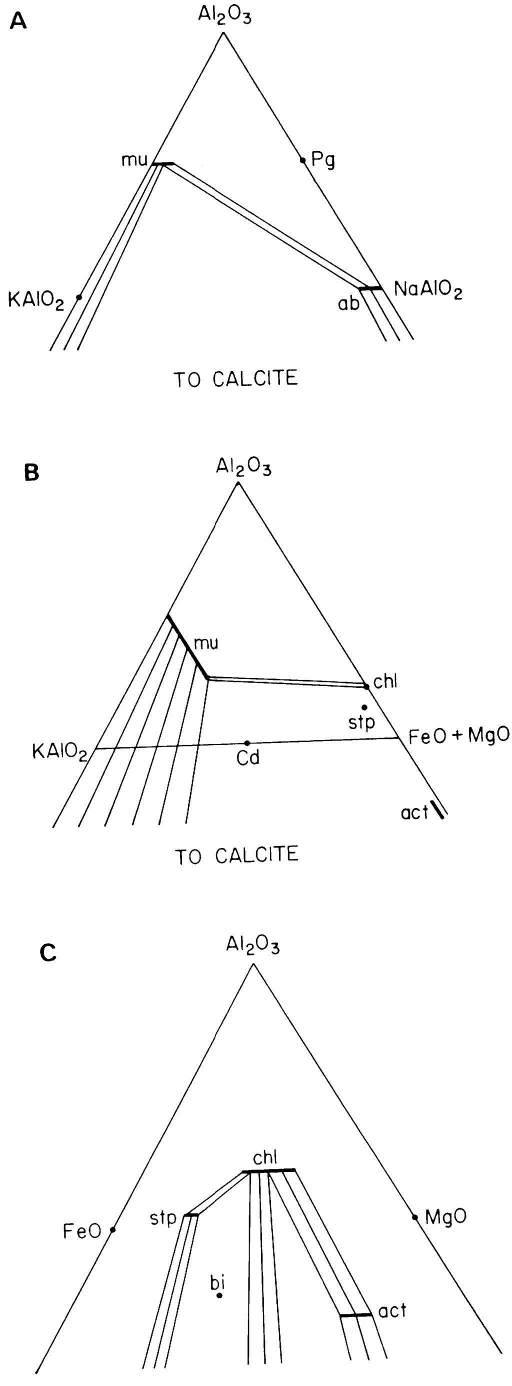

Fig. 5. Modified AKNa (A), AKF (B), and AFM (C) diagrams. Modifications are explained in the text. Mineral phases are indicated by a lowercase first letter: ab = albite, act = actinolite, bi = biotite, chl = chlorite, mu = muscovite, stp = stilpnomelane. Cd and Pg represent the idealized chemical components Celadonite and Paragonite.

T, and Pfluid. As with Paragonite, Celadonite content of muscovite varies systematically throughout the area (below).

No information is provided by these rocks regarding the phase relations of aluminous minerals such as pyrophyllite, paragonite, and margarite, and they have thus been omitted from the projections.

ELECTRON MICROPROBE TECHNIQUE

Electron microprobe analysis of polished thin sections was conducted at UCLA using an ARL–EMX microprobe with automated crystal spectrometers. An accelerating voltage of 15 kV was used for all minerals. Specimen current was varied from 15 to 20 nAmps depending on alkali and H_2O content. A finely focused beam (approximate diameter of 1 micron) was used in analyzing garnet and amphibole. A defocused beam (approximate diameter of 5 microns) was used for analyzing muscovite, albite, chlorite, biotite, and stilpnomelane. To insure that only inclusion-free portions of grains would be analyzed, probe sections were studied before analysis, and appropriate grains were circled and photographed. Standards were chemically analyzed natural silicates and oxides and synthetic silicate glasses from the UCLA standards collection. Standards were rechecked every 2 to 3 hrs. Corrections were made for background and dead time. Analyses were calculated using the correction procedures of Albee and Ray (1970).

MUSCOVITE DATA

Textures.—As noted above, isoclinal folds (style 1 folds) are distributed throughout the Pelona Schist, whereas the more open folds related to the Narrows Synform (style 2 folds) were found only within 700 m of the thrust. In areas affected only by style 1 folding, muscovite occurs as straight, optically strain-free grains oriented parallel to the axial-plane schistosity of the isoclinal folds. These muscovites presumably underwent recrystallization during the formation of the isoclinal folds. Schists within the 700 m zone affected by style 2 folding (Narrows area) have a crenulated appearance in hand sample. Muscovites in these samples can be divided into two categories on the basis of petrographic observations. Muscovites of the first type are bent and show relatively little evidence of recrystallization (pl. 1-A). They lie in a schistosity that is folded around style 2 hinges and are considered to be crenulated equivalents of the axial-plane muscovites associated with style 1 folds. Muscovites of the second type are relatively undeformed and must have recrystallized during or after style 2 folding (pl. 1-B,-C). In five of the samples from the Narrows area (6c, 7, 69, 202, 394) the strain-free, recrystallized muscovites predominate and only these were analyzed. In three samples (28, 31, and 462b) large populations of both types are present and were analyzed.

Regional variation of muscovite composition.—Figure 6 shows the compositional variability of muscovite as a function of distance from the Vincent thrust. All compositions are plotted as moles per formula unit normalized to 11 oxygens and assuming all iron as FeO. For the samples within the Narrows area, only values determined from the recrystal-

PLATE 1

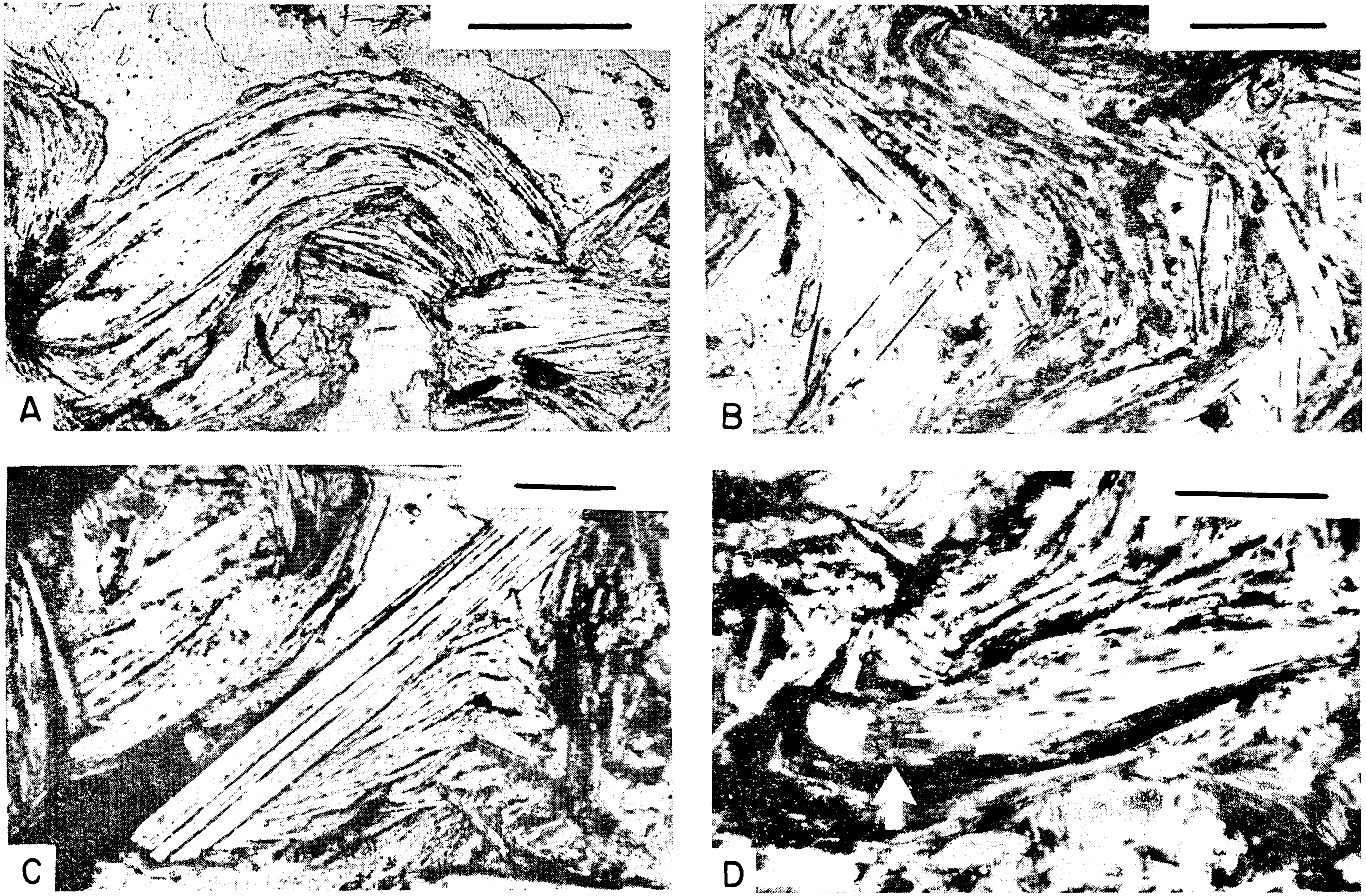

TABLE 2

Major-element contents of old and new muscovites in samples 28, 31, and 462b

Sample		Na	K	Si	Al	Mg	Fe
28	Old (17)	0.028±.004	0.880±.005	3.419±.019	2.125±.032	0.340±.014	0.161±.003
	New (13)	0.042±.005	0.876±.008	3.383±.015	2.185±.021	0.301±.007	0.175±.006
31	Old (15)	0.025±.002	0.926±.006	3.417±.007	2.085±.008	0.301±.003	0.247±.010
	New (14)	0.032±.001	0.932±.003	3.421±.005	2.077±.007	0.305±.002	0.240±.005
462b	Old (9)	0.019±.001	0.905±.005	3.442±.014	2.042±.018	0.344±.008	0.223±.008
	New (14)	0.044±.003	0.908±.004	3.374±.008	2.177±.009	0.287±.003	0.208±.008

Concentrations are in moles per 11 oxygens. Number of analyses indicated in parentheses. Errors are one standard deviation of the mean.

lized grains were plotted. Pronounced systematic variations are evident for Na, Al, and Si. Much weaker trends occur for K and Fe, and data for Mg are highly scattered. The variations of Na and K reflect increased Paragonite content near the thrust. The variation of Si indicates that increase of Paragonite is accompanied by decrease of Celadonite. The trends of Al and Fe must be due at least partly to variation of Celadonite content but might also be related to Ferrimuscovite substitution. Presence of some ferric iron is strongly suggested by the fact that all samples contain more total iron and magnesium than necessary to explain the high silicon contents.

Variation of muscovite composition within individual samples.— Muscovite compositions are presented in table 2 for the three samples for which both bent (old) and recrystallized (new) grains were analyzed. For all three samples, the new muscovites are higher in Na, though the differences are not large (table 2). Interestingly, the three samples show no significant difference of K content between old and new grains. In addition to the difference in Na content, two of the samples, 28 and 462b, show an increase of Al and a decrease of Si and Mg + Fe in the new grains; that is, the new grains are lower in Celadonite than the old grains. This difference in composition between old and new grains is much greater for sample 462b than for sample 28. For sample 31 there is no significant difference between old and new grains for any element other than Na.

In conducting this analysis it was in some cases difficult to distinguish petrographically between old and new grains. For example, three exceptionally high Na-values were obtained from a grain in sample 28 that had been classified as old based on its bent appearance. Upon reexamination it was found that this apparently bent grain is actually

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← Muscovite textures in rocks affected by style 2 folding.

A. Bent grain of muscovite. Plane-polarized light. Scale bar = 0.2 mm.

B. Recrystallized muscovites in a crenulation hinge. Plane-polarized light. Scale bar = 0.1 mm.

C. Recrystallized grain of muscovite. Plane-polarized light. Scale bar = 0.1 mm.

D. Bent grain of muscovite that has undergone annealing. The left portion of the grain consists of several "subgrains" each of which is slightly rotated with respect to the others. The arrow points to one such "subgrain" which is nearly at extinction. Cross-polarized light. Scale bar = 0.1 mm.

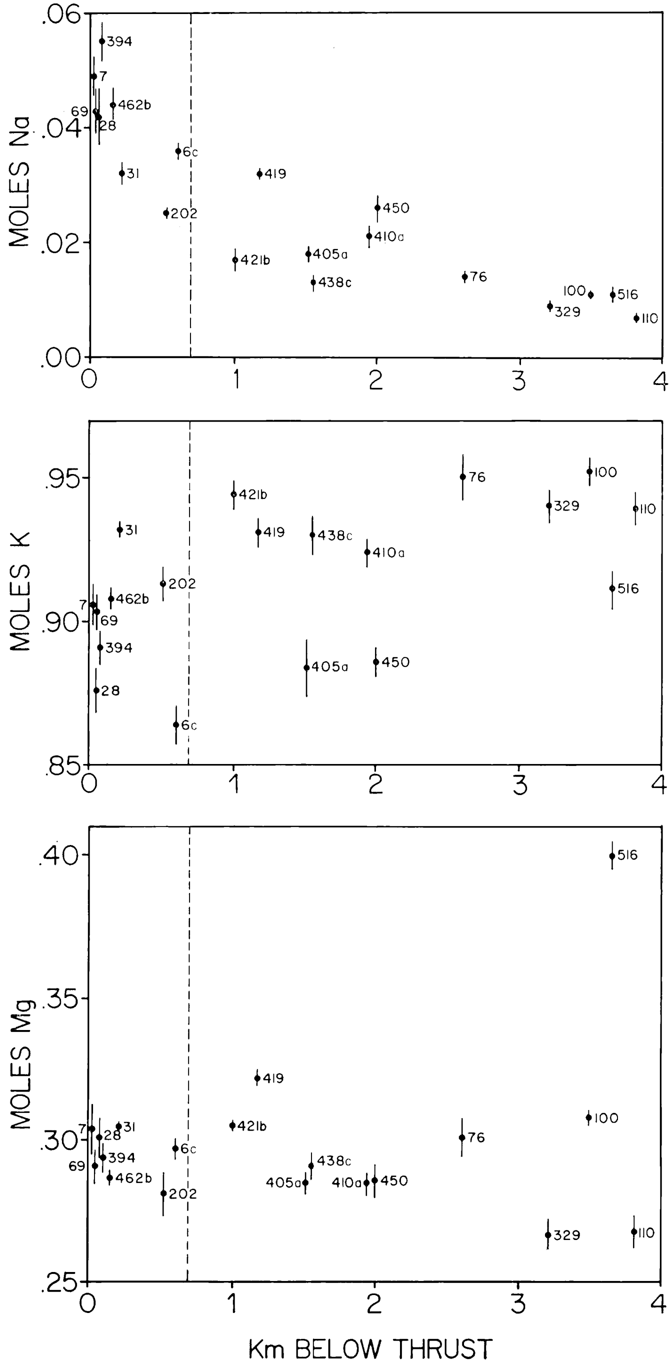
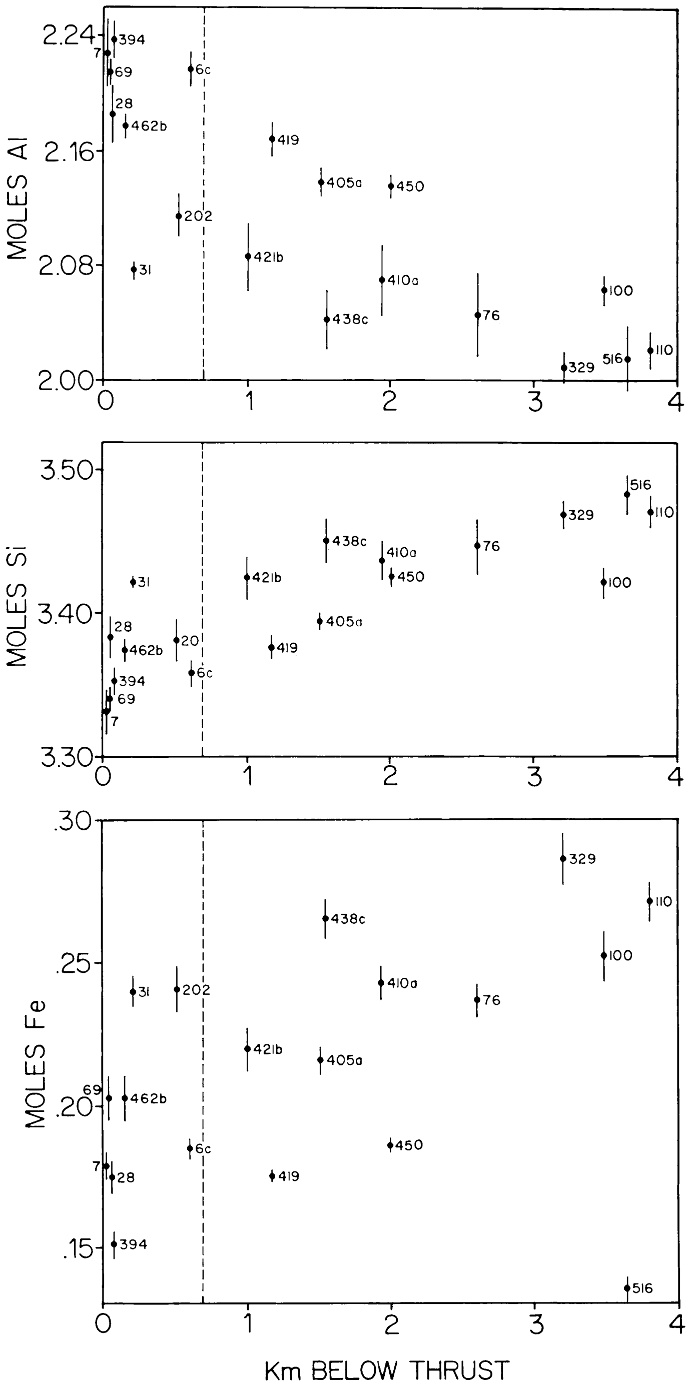


Fig. 6. Major-element composition of muscovite in metagraywackes of the Pelona Schist versus distance below the Vincent thrust. All concentrations are in moles per 11 oxygens. Analyses were calculated assuming all iron as FeO. Each data point represents the average of generally nine analyses from a single rock. Error bars indicate one stan-



dard deviation of the mean. Samples located to the left of the vertical dashed line are from the Narrows area and have been affected by style 1 and style 2 folding. Samples to the right of the line have been affected only by style 1 folding. Ca, Mn, and Ti were also determined, but their concentrations are very small and have been neglected.

composed of several small "subgrains" of similar orientation (pl. 1-D), indicating recrystallization. Thus, the difference in Na content of old and new grains in sample 28 would have been even greater if these three high-Na values had been included with the new grains. Overall, difficulty of distinguishing between old and new grains was a problem in sample 28 but was not felt to be important for samples 462b and 31.

ALBITE DATA

Albite was analyzed in all the samples, and the relative proportions of Ab, An, and Or are plotted in figure 7. The samples closest to the thrust (the ones affected by style 2 folding) are indicated by open circles. Most samples lie in a cluster very close to the Ab corner of the diagram. Four samples are distinguished by slightly higher An than the rest. These happen to be the four samples closest to the thrust (7, 69, 28, and 394), and among these four samples An content decreases uniformly away from the thrust. There is no significant variation of Or content between the samples.

DISCUSSION

Origin of the metamorphic zonation.—The muscovites analyzed in this study show an increase of Paragonite content and a decrease of Celadonite content with approach to the Vincent thrust. These changes, by analogy with variations of muscovite composition noted in other low-grade terranes (compare Guidotti and Sassi, 1976), would appear to indicate an increase of temperature near the thrust, confirming the previous conclusions of Ehlig (ms and 1981), Graham and England (1976), and

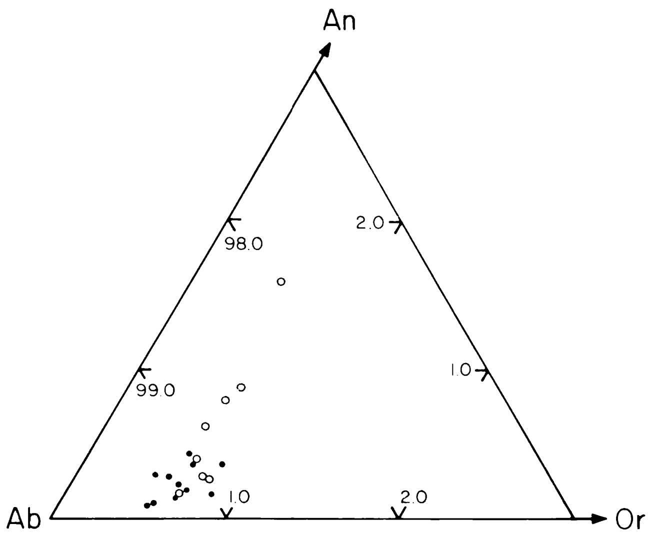


Fig. 7. Composition of albite in the 19 samples for which muscovite has been analyzed. Dots indicate samples from the area affected only by style 1 folding. Open circles indicate samples within the Narrows area (area of style 2 folding). Each data point represents the average of generally nine analyses from a single rock.

Haxel and Dillon (1978). However, consideration of several idealized metamorphic reactions that might be relevant to these rocks indicates that the situation is, in fact, complicated. Figure 5A implies that a continuous variation in Na content of muscovite can be brought about by a reaction involving quartz, albite, epidote, calcite, CO_2, and H_2O. This assemblage occurs in 12 of the 19 analyzed samples. Figure 5B indicates that if chlorite is included in the reaction then variations of Celadonite content can also be explained. Solving a system of simultaneous equations for mass balance yields the following reaction:

$$\begin{aligned} 1.0\,\text{mu(OLD)} + 0.053\,\text{ab} + 0.106\,\text{ep} + 0.212\,CO_2 + 0.072\,H_2O &\rightleftharpoons \\ 1.053\,\text{mu(NEW)} + 0.009\,\text{chl} + 0.212\,\text{cal} + 0.354\,\text{qtz}. \end{aligned} \quad (1)$$

Mineral formulas used in the calculations are indicated in table 3. The "old" muscovite represents an idealized composition for a sample far from the thrust; the "new" muscovite a sample close to the thrust. The chlorite composition is an average value determined from unpublished microprobe data. Iron and magnesium are assumed to be present in the same proportion in all samples. Ferric iron is ignored, despite its obvious presence in epidote and its almost certain presence in muscovite.

Reaction 1 implies that the increase of Paragonite content and decrease of Celadonite content near the thrust could be due to a systematic regional variation of fluid composition. Alternatively, if fluid composition is assumed to be invariant, then the presence of two volatile phases on the left side of the reaction suggests that the reaction should proceed to the right with falling temperature. This would indicate lower temperatures near the thrust and is surprising because it contradicts the conclusions of previous workers (Ehlig, ms and 1981; Graham and England, 1976; Haxel and Dillon, 1978).

A limitation to the above reaction is that it assumes a closed system other than for H_2O and CO_2. In fact, there is evidence that this assumption may not be valid. The upper plate of the Vincent thrust contains a large proportion of gneisses and plutonic rocks which range in composition from quartz monzonite to quartz diorite. It has previously been noted (Jacobson, ms and in press) that, where these rocks are mylonitized, plagioclase feldspar is largely altered to muscovite or fine sericite. Potash feldspar in the same rocks shows little or no sign of alteration. These relations imply that potassium has been added to the rocks of the mylonite zone, and a likely source would be the underlying schists. Thus, reaction 1 was recalculated to take into account an arbitrary loss of 0.1

TABLE 3

Mineral compositions used for calculating reactions (1) to (3)

mu(old)	=	$K_{1.0}(Mg,Fe)_{0.4}Al_{2.2}Si_{3.4}O_{10}(OH)_2$
mu(new)	=	$K_{0.95}Na_{0.05}(Mg,Fe)_{0.3}Al_{2.4}Si_{3.3}O_{10}(OH)_2$
ab	=	$NaAlSi_3O_8$
ep	=	$Ca_2Al_3Si_3O_{12}(OH)$
chl	=	$(Fe,Mg)_{9.55}Al_{5.09}Si_{5.46}O_{20}(OH)_{16}$
act	=	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$

Abbreviations of mineral names are same as for table 1.

mole of K_2O per 1 mole of low-Paragonite, high-Celadonite muscovite consumed:

$$1.0\,\text{mu(OLD)} + 0.042\,\text{ab} + 0.095\,\text{cal} \leftrightharpoons 0.84\,\text{mu(NEW)} + 0.015\,\text{chl} + 0.048\,\text{ep} + 0.52\,\text{qtz} + 0.095\,CO_2 + 0.014\,H_2O + 0.1\,K_2O. \quad (2)$$

In this case, the production of high-Na, low Celadonite muscovite results in the expulsion of CO_2 and minor H_2O and should occur with increased temperature. This mechanism, although speculative and generalized, can explain the sericitization of plagioclase in the mylonites and is consistent with a temperature inversion during thrusting as postulated by previous workers for other segments of the Vincent thrust.

In the above two reactions, muscovite, quartz, albite, epidote, calcite, and chlorite were considered because they form the most common mineral assemblage found in the analyzed samples. However, a third reaction can be written utilizing actinolite instead of calcite:

$$1.0\,\text{mu(OLD)} + 0.053\,\text{ab} + 0.056\,\text{ep} + 0.021\,\text{chl} + 0.084\,\text{qtz} \leftrightharpoons 1.053\,\text{mu(NEW)} + 0.056\,\text{act} + 0.087\,H_2O. \quad (3)$$

Reaction (3) is a dehydration reaction and should proceed to the right with increasing temperature. The reaction can explain the observed compositional variation of muscovite in amphibole-bearing assemblages and would be consistent with the presence of an inverted thermal gradient beneath the thrust.

The above reactions provide a number of explanations for the variation of muscovite composition illustrated by figure 6. Nonetheless, whatever detailed reaction is occurring, the strong correlation between composition and distance from the thrust is strong evidence that the compositional trends formed during the thrusting. This is further supported by the presence of systematic, thrust-related metamorphic zonations in other bodies of Pelona Schist (Graham and England, 1976; Haxel and Dillon, 1978).

Relationship between metamorphism and folding.—If the observed regional variation of muscovite composition developed during the thrusting, then it can be used to indicate the time of formation of the Narrows Synform. Specifically, in figure 6, the compositions plotted for samples within the Narrows area were obtained from muscovites that recrystallized during or after the formation of the Narrows Synform (above). This indicates that the metamorphic zonation is superimposed upon the synform and therefore must have developed largely after the formation of the fold. Thus, the Narrows Synform cannot be a post-thrusting structure, despite its relatively open shape.

This conclusion is further supported by the limited data indicating a difference in composition between old and new muscovites in samples 28, 31, and 462b. Old muscovites in these three samples are generally similar in composition to muscovites in samples located relatively far from the thrust; new muscovites are more sodic and generally less celadonitic. By analogy with the regional variation of muscovite composition, the increase of Paragonite and decrease of Celadonite in the new muscovites would apparently be related to the thrusting. Since the new muscovites are synkinematic to postkinematic relative to the Narrows Synform, they provide additional evidence that the Narrows Synform is closely related to the thrusting event.

The variation of muscovite composition, both between samples and within samples, though statistically significant, is not large. This, together with the similar orientations of style 1 and 2 folds (Jacobson, ms and in press), may indicate that all the observed recrystallization and folding in the Pelona Schist occurred during a single protracted tectonic event rather than during several separate events.

The conclusion that the Narrows Synform is closely related to thrusting has implications for interpretation of regional paleogeography that are discussed elsewhere (Jacobson, in press). The important point here is that detailed petrologic considerations can be used to solve problems of interest to structural geologists.

CONCLUSIONS

Muscovite in metagraywackes of the Pelona Schist of the San Gabriel Mountains displays a regular increase of paragonitic substitution and decrease of celadonitic substitution with approach to the Vincent thrust. The exact cause of this metamorphic zonation is not clear, although the zonation most likely developed during movement of the Vincent thrust. Relations between the metamorphic zonation and the Narrows Synform suggest that the synform is related to the thrusting event.

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