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By MARY M. DONATO

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A Newly Recognized Ductile Shear Zone in the Northern Klamath Mountains, Oregon—Implications for Nevadan Accretion

By Mary M. Donato

Abstract

An 800-to 1,500-m-thick ductile shear zone in the northernmost Klamath Mountains marks the contact between metasedimentary rocks of the May Creek Schist and structurally underlying amphibolite. The shear zone trends approximately east-west, dips southward, and has been traced about 13 km along strike. Petrographic criteria and quartz petrofabric analyses of semipelitic schists and quartzofeldspathic gneisses of the May Creek Schist in the hanging wall consistently demonstrate a top-to-the-northwest sense of shear, indicating northwestward thrusting (present-day geographic framework) of schist over amphibolite in the footwall. Syntectonic sillimanite in deformed May Creek Schist indicates that amphibolite-facies conditions prevailed during deformation. The tectonic transport direction is perpendicular to the northeast-trending structural grain of the northernmost Klamaths, and in particular to southeast-dipping thrusts related to accretion of Jurassic volcanic rocks which lie to the west. The age of the ductile deformation is inferred to be approximately 145 Ma, based on $^{40}Ar/^{39}Ar$ cooling age determinations of metamorphic hornblende from amphibolite in the footwall. I suggest that the ductile shear zone is a manifestation of Nevadan (144-157 Ma) convergence, during which an incipient back-arc spreading center (the protolith of the amphibolite) and its sedimentary cover (now the May Creek Schist) were shortened by contractive faulting during accretion to North America. Available Nevadan stretching lineations and transport directions from various Klamath Mountain localities are disparate and underscore the apparent structural complexity of the Nevadan orogen.

INTRODUCTION

Purpose of study

One of the most frequently encountered problems in structural analysis of complexly deformed metamorphic terranes is the determination of the sense of movement in sheared rocks. In regions composed of accreted terranes, such as the Klamath Mountains, such information can shed light on the relative motions of large blocks of crust and thus may enhance our understanding of the processes by which accretion takes place.

Only a few previous attempts have been made to relate structures in metamorphic tectonites to the regional accretionary tectonic framework of the Klamath Mountains. Microstructural and mineral-preferred orientation studies were used by Cannat and Boudier (1985) to deduce convergence directions in ophiolitic complexes in the western Paleozoic and Triassic belt and the western Jurassic belt (names of Irwin, 1966) in northern California. Their results indicated northeast-southwest convergence during Mesozoic time, but their interpretations of age relationships, especially for the Josephine ophiolite, are controversial (Harper and Harding, 1986; Cannat and Boudier, 1986). Recent analysis of structural and shear criteria in amphibolite and serpentinite attest to thrusting of the Josephine ophiolite toward the north-northeast during Nevadan time (Grady and others, 1989; Harper and others, 1990). Cashman's (1988) strain analysis of the Galice Formation beneath the Orleans thrust fault at the contact between the western Jurassic belt and the western Paleozoic and Triassic belt revealed northwest-southeast-trending stretching lineations due to Nevadan convergence; shear-sense indicators are compatible with dextral oblique convergence on the fault.

Many useful criteria for determining the sense of shear in mylonitic rocks have been recognized, including mesoscopic and microscopic features such as rotated porphyroblasts, pressure shadows, mica fish, and composite planar (S-C) fabrics (Berthé and others, 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984; Passchier and Simpson, 1986). Quartz crystallographic fabric asymmetry has also been used successfully as a primary tool for investigating kinematics of large-scale folding and thrusting (Behrmann and Platt, 1982; Patrick, 1988; Klaper, 1988). This study uses mesoscopic structural data, petrographic criteria, and quartz petrofabric analysis to deduce the sense of shear in ductilely deformed quartzites and semipelitic schists from a newly discovered mylonitic shear

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zone separating the May Creek Schist and structurally underlying amphibolite in the northernmost Klamath Mountains. The data consistently indicate Nevadan thrusting of the May Creek Schist (usage of Donato, 1991b) over the amphibolite in a present-day northwestward direction. These results provide additional constraints on the geometry of accretion of the May Creek Schist and adjacent metamorphic terranes and thus contribute to the growing body of knowledge about the accretionary history of the region.

Acknowledgments

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GEOLOGIC SETTING

This report focuses on two lithologic units in the northernmost Klamath Mountains (fig. 1): metasedimentary rocks called the May Creek Schist (MCS) and structurally underlying hornblende schist and gneiss derived from basaltic igneous rocks (amphibolite). Although the original nature of the contact between the MCS and the amphibolite, now the locus of intense ductile deformation, is not certain, the contact may have originally been depositional. Metamorphism and deformation of the MCS and amphibolite accompanied the imbrication and collapse of a small back-arc basin during which the basaltic basement was overthrows by its sedimentary cover (Donato, 1987, 1991a).

These units are part of the western Paleozoic and Triassic belt (Irwin, 1966), a collage of Jurassic and older accreted oceanic and island arc terranes. Tertiary volcanic and volcaniclastic rocks of the Western Cascades are in possible depositional contact with the Klamath Mountains in this region, but this contact has been extensively modified by high-angle faults (Donato, 1991b). To the north, amphibolite and metasedimentary rocks of uncertain age are truncated by the Tertiary dextral strike-slip Canyonville fault, which also marks the northern boundary of the Klamath Mountains Province. To the south, the MCS is in probable fault contact with the greenschist-facies oceanic metavolcanic and metasedimentary rocks of the Applegate group (Smith and others, 1982). Rocks belonging to Irwin's (1966) western Jurassic belt lie immediately to the west and include low-grade ophiolitic rocks of the Sexton Mountain area and arc-derived hornblende- and pyroxene-bearing metavolcanic and metavolcaniclastic rocks, including the middle Jurassic Rogue volcanics of Garcia (1979). The western Jurassic belt is cut by numerous northeast-trending, east-dipping thrust faults related to late Jurassic (Nevadan) accretion (fig. 1).

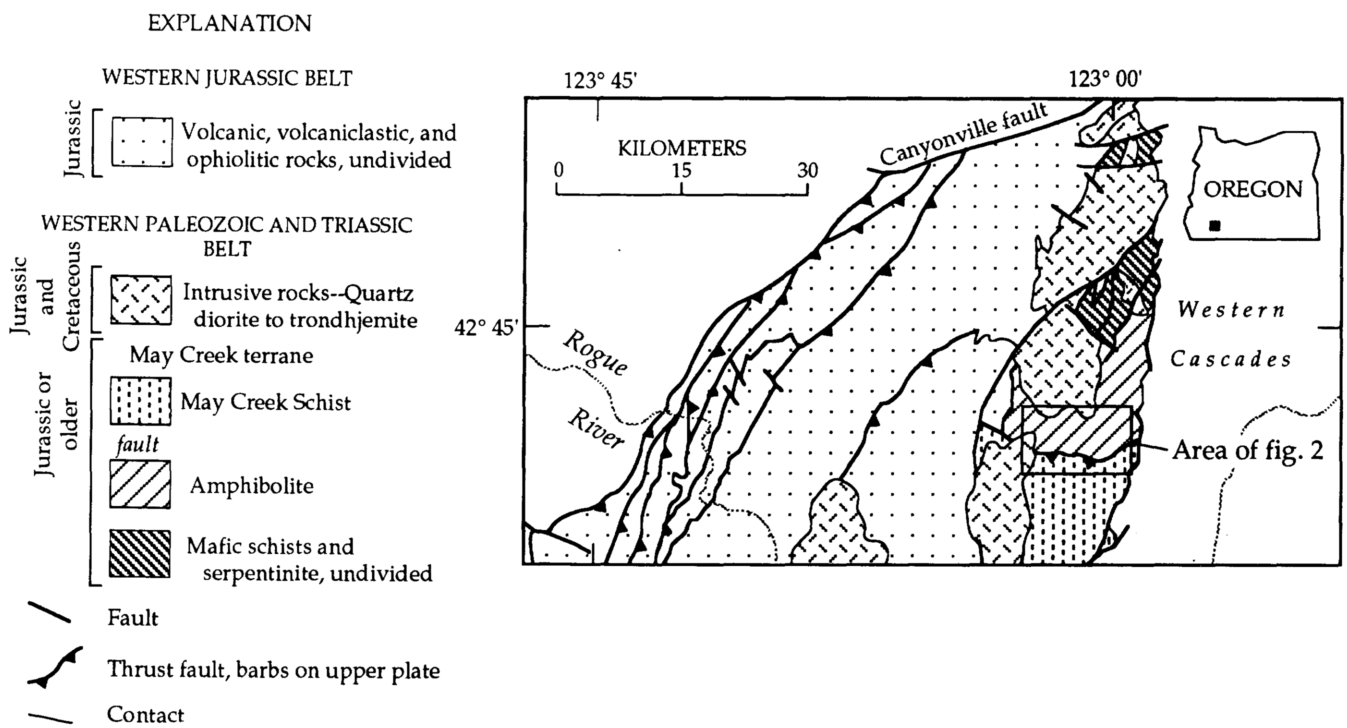


Figure 1. Generalized geologic map of the northern Klamath Mountains, modified from Smith and others (1982), Silberling and others (1987), and Irwin (in press).

Two post-metamorphic plutons intrude the western part of the MCS and underlying amphibolite (fig. 2), but extensive weathering limits exposures in all but a few localities. Contact-metamorphic effects of the White Rock pluton (141 Ma, biotite K/Ar, Hotz, 1971) extend probably no more than 100 meters into surrounding amphibolite. The Wimer pluton intrudes both the May Creek Schist and amphibolite, but isotopic age determinations for this pluton are not available. The Wimer, White Rock, and the nearby Grants Pass pluton (139 Ma, U-PB, Saleeby, 1984) belong to Irwin's (1985) Grants Pass plutonic belt, which he considered Early Cretaceous in age.

Amphibolite

The amphibolite consists chiefly of variably layered hornblende schist and gneiss. In spite of thorough meta-

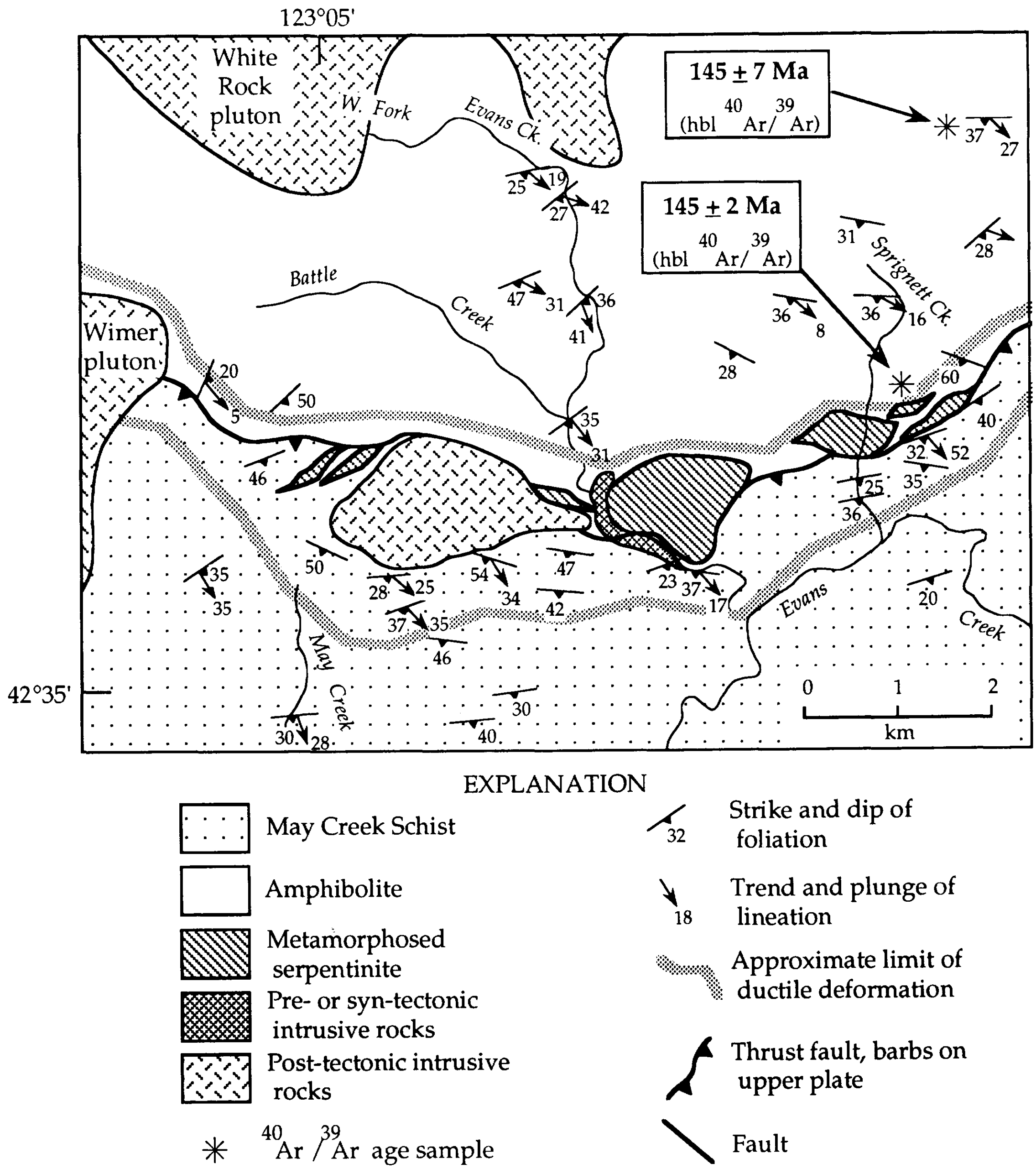


Figure 2. Simplified geologic map of the main part of the contact zone between the May Creek Schist and structurally underlying amphibolite. The shear zone trends approximately east-west and dips moderately southward. Oblique lineations suggest either oblique motion within the zone or post-deformation tilting or rotation of the shear zone.

morphic recrystallization, relict igneous textures such as plagioclase phenocryst pseudomorphs and chilled intrusive contacts are commonly visible in less deformed rocks. These features suggest that the protolith was an igneous complex which included basaltic dikes or sills, shallow diabase intrusions, and gabbro. The chemistry of the amphibolite is homogeneous and strongly resembles some back-arc basin basalts. Based on this geochemical similarity and on regional field relations, the amphibolite is believed to have formed in a back-arc basin, probably in middle Jurassic or earlier time (Donato, 1991a).

The most common metamorphic mineral assemblage in the amphibolite is green hornblende+plagioclase+sphene+opaque oxide, indicating middle amphibolite-facies conditions. New $^{40}Ar/^{39}Ar$ analyses of metamorphic hornblende from two samples of amphibolite (see fig. 2 for sample locations) give isotopic ages of 145 ± 2 and 145 ± 7 Ma (Donato, 1991a). The protolith (igneous) age of the amphibolite is unknown.

The amphibolites are LS-tectonites with a pervasive schistosity or foliation defined by alternating hornblende- and plagioclase-rich layers. The foliation generally strikes northeast and dips southeast, although local and regional broad warping of the foliation has occurred. A strong, consistent southeast-plunging hornblende lineation is also present throughout (fig. 3). In some cases, elongate, recrystallized plagioclase grains or aggregates define a measurable flattening plane, or rarely, a stretching lineation parallel to the hornblende lineation. Foliation and lineation become more pronounced in the amphibolite with proximity to the contact with the overlying MCS, but shear criteria and textural evidence of intense ductile deformation and dynamic recrystallization are best-developed in the basal, quartzose part of the MCS.

Rare outcrop-scale isoclinal reclined folds deform the compositional layering. Available data indicate that the folds generally plunge southeast, parallel to the hornblende lineation and parallel to stretching lineations measured in metasedimentary rocks from the ductile shear zone (see fig. 3 and below); the axial planes of reclined folds are parallel to the measured foliation.

May Creek Schist

The structurally lowest units of the MCS, including the newly discovered ductilely deformed rocks, were described by Diller and Kay (1924) as "highly metamorphosed mica schist and mica slate." They consist of fine-grained and strongly layered metapelite, metapsammite, and quartzofeldspathic gneiss consisting mainly of quartz, plagioclase, biotite, and white mica, with accessory spessartine, tourmaline, and opaque oxides. These rocks grade upward into grayish-green to purplish fine-grained metagraywacke and volcaniclastic metasedimentary rock and impure calcareous units containing rare marble lenses.

Diagnostic metamorphic mineral assemblages are rare, owing to the lack of appropriate bulk compositions, but amphibolite-facies conditions are clearly indicated locally. Sillimanite occurs with quartz, plagioclase, biotite, garnet, and white mica at two known localities. In calcareous tuffaceous rocks higher in the section, the assemblage is diopside+plagioclase+quartz+actinolitic amphibole+calcite±biotite. No direct determination of the metamorphic age of the MCS has been made, but the age is inferred to be 145 Ma, on the basis of apparent synchroneity of metamorphism of the MCS and the amphibolite.

The MCS is everywhere well foliated but strongly lineated only where it has undergone intense ductile deformation near its base. In pelitic, semipelitic, and psammitic varieties, foliation is defined by alternating micaceous and quartzofeldspathic layers, and by flattened lensoidal aggregates of plagioclase or mica. Rocks within the ductile shear zone display a conspicuous lineation caused by elongated quartz, feldspar, and mica grains within the foliation plane. Structural elements in the MCS are generally parallel to those in the amphibolite (fig. 3).

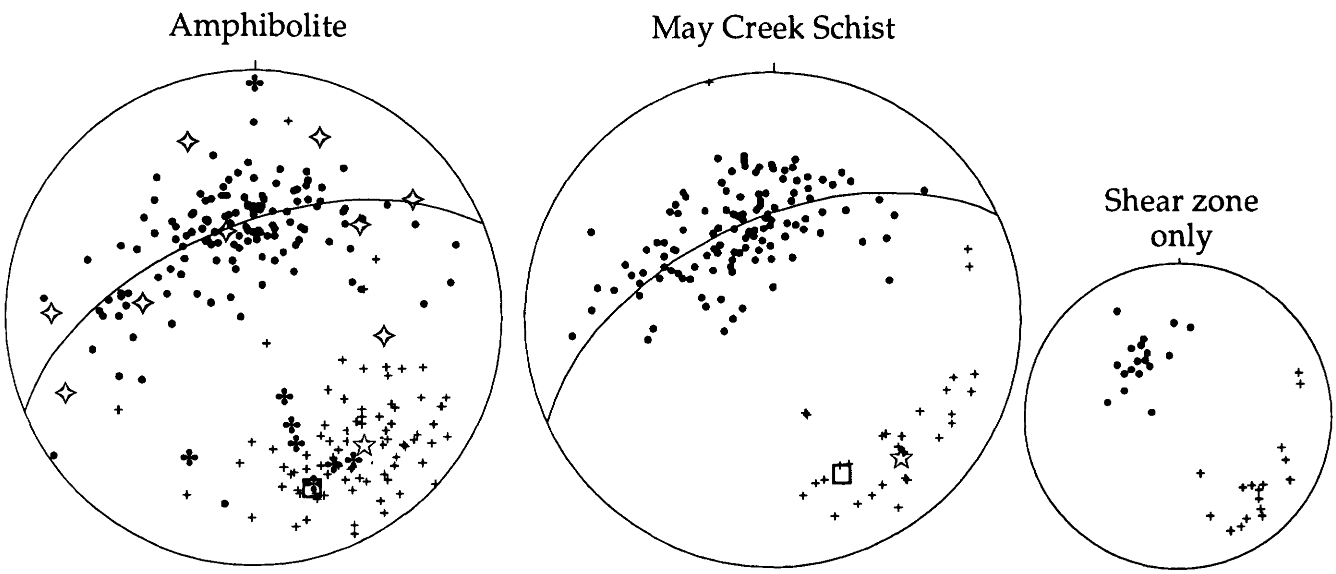
DUCTILE SHEAR ZONE

A zone of ductilely deformed quartz-mica schist and quartzofeldspathic gneiss marks the basal part of the MCS along its contact with the amphibolite (fig. 2). The ductile shear zone trends approximately east-west, is estimated at two localities to be approximately 800 to 1,500 m thick, and is traceable along strike for about 13 km. These rocks are "mylonitic," according to the criteria accepted by Penrose Conference attendees (Tullis and others, 1982): (1) they have undergone grain size reduction, (2) they occur in a relatively narrow planar zone, and (3) they display enhanced foliation and lineation due to strain concentration. Field evidence for mylonitization includes a strong south- to southeast-dipping laminar foliation and a pronounced southeast-plunging lineation defined by aligned mica flakes and stretched quartz and plagioclase feldspar grains. In quartzofeldspathic rocks, comminuted, broken feldspar porphyroclasts are visible on surfaces exposing the X-Z plane of the strain ellipsoid. Thin sections of such rocks cut in this plane commonly display beautiful fluxion structure. Plagioclase grains are blocky or subrounded and occasionally broken, whereas quartz has deformed ductilely, flowing around resistant plagioclase grains and forming elongate ribbons up to 5 mm long.

Mylonitic metasedimentary rocks are only locally in direct contact with the underlying amphibolites. Various highly deformed rocks, including metaserpentinite, metasomatic rocks, and deformed dioritic intrusive rocks, commonly occur between the mylonites and the amphibolite. For example, linked traverses in Evans Creek, traversing down section through the contact zone (fig. 4), lead from mylonitic quartzofeldspathic schist through lenses of sheared metaserpentinite, talc-tremolite schist, thinly layered quartzite, hornblende-biotite schist, hornblende-epidote schist, mylonitic quartzite, gneissic hornblende diorite, and mylonitic amphibolite. The structural thickness of the tectonically disrupted zone at this locality is about 1,500 m. A similar zone of interlayered ultramafic and mafic intrusive rocks separating amphibolite from mylonitic quartzofeldspathic gneisses is exposed in Sprignett Creek (fig. 4). Here the zone is probably only 600 to 800 m thick.

Dioritic intrusive rocks which display textural evidence of ductile deformation occur at several localities within the contact zone between amphibolite and the May Creek Schist. A striking example occurs in Evans Creek, where foliated hornblende quartz diorite is exposed (sec. 23, T. 34 S., R. 3 W.). The foliation of the quartz diorite, the attitude of which is variable, is defined by 1- to 5-mm-thick bands or layers of alternating mafic and felsic material, which impart a gneissic appearance to the outcrop. The foliation is crosscut at a high angle by discrete 1 to 2 cm wide shear bands spaced 1 to 2 m apart. These shear bands strike N. 75°-90° W. and dip moderately to steeply southward, subparallel to the local orientation of the metasedimentary rocks-amphibolite contact zone. Within these narrow shear bands, the foliation in the quartz diorite is drawn into parallelism with the shear band, and grain size diminishes. The foliation becomes mylonitic and is composed of finely laminated hornblende, plagioclase porphyroclasts, and quartz ribbons.

In thin section, hornblende is brown with dark-green rims and is ovate or lenticular in shape. Plagioclase is also lenticular, crudely aligned, and commonly displays bent twin lamellae, recrystallized grain margins, and undulatory extinction. A fine-grained mosaic of recrystallized feldspar



EXPLANATION

	Amphibolite	May Creek Schist	Shear zone
	Number of measurements		
• Pole to foliation	134	123	18
+ Lineation	92	31	17
✚ Fold axis	9		
✧ Pole to axial plane	9		
	Azimuth and plunge		
□ Pole to best-fit great circle	158, 31	155, 32	
☆ Mean lineation vector	142, 31	135, 26	

Figure 3. Lower-hemisphere, equal-area stereonets comparing structural features measured throughout the amphibolite and the May Creek Schist. Lineations measured in amphibolite are hornblende lineations; those in the May Creek Schist are $S_1 \times S_2$ intersection lineations or quartz or feldspar stretching lineations measured in mylonitic rocks.

and quartz surrounds lensoidal quartz and feldspar grains in the felsic laminae.

These mesoscopic and microscopic features are characteristic of solid-state ductile deformation in granitic rocks (Paterson and others, 1989), but the alignment of plagioclase (particularly albite twin lamellae) suggests that ductile deformation may have been superimposed on a pre-existing magmatic foliation. Brown hornblende cores suggest locally higher temperatures compared with the adjacent amphibolite. Although there is no direct petrographic evidence of magmatic-state deformation, it is possible that the diorite was intruded during early phases of deformation and cooled below its solidus as deformation proceeded.

SHEAR SENSE CRITERIA

Petrographic Criteria

Oriented thin sections of mylonitic rocks from localities along the length of the shear zone were examined to determine the sense of shear. All thin sections were cut parallel to the lineation and perpendicular to the foliation (that is, in the X-Z plane of the strain ellipsoid) and oriented so that apparent dextral shear in the thin section indicates top-to-the-northwest sense of motion.

Excellent examples of σ-type tourmaline porphyroblasts (Passchier and Simpson, 1986) indicating dextral shear were observed. In one sample, which also contains

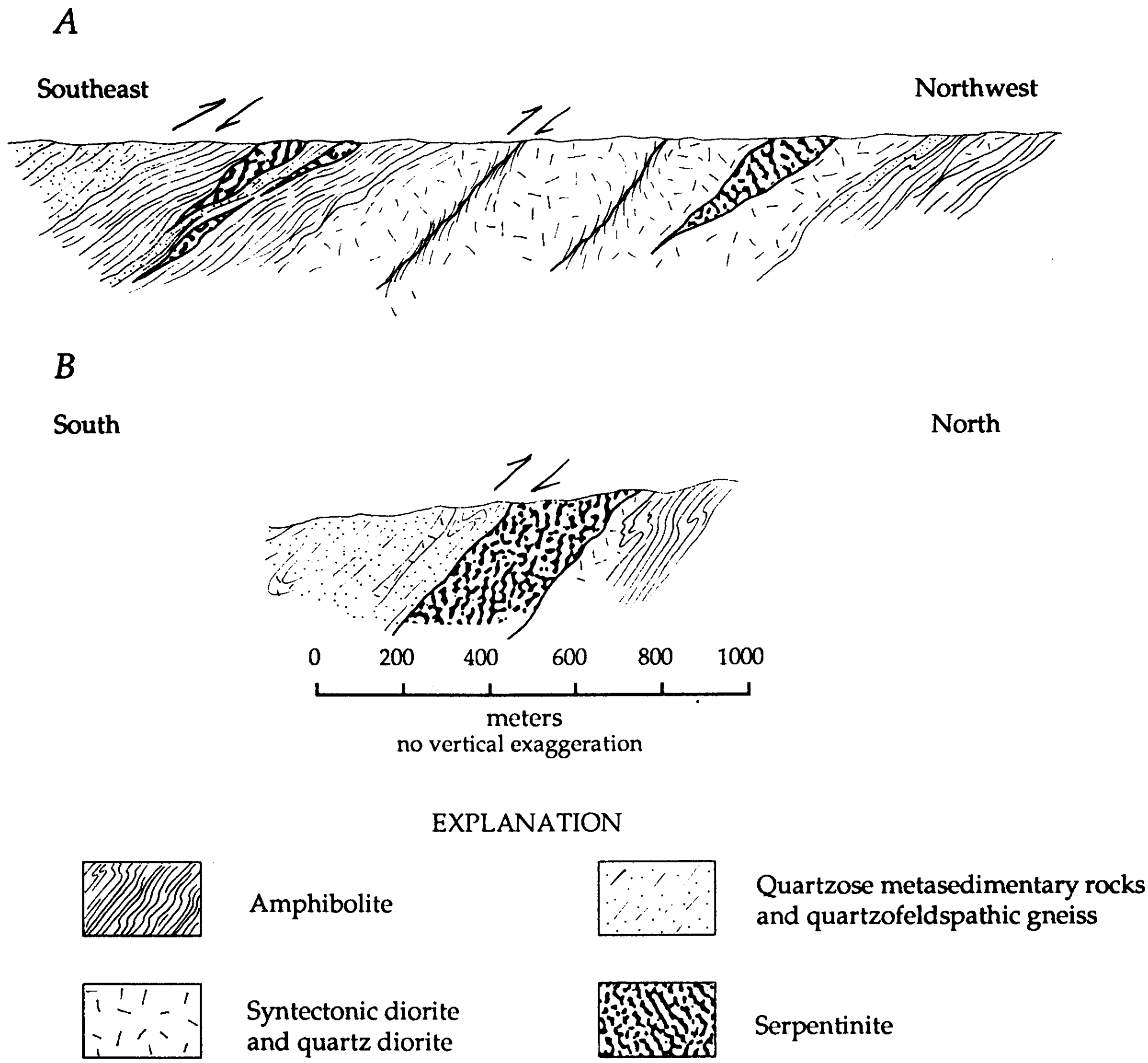


Figure 4. Schematic cross sections of the ductile shear zone based on traverses in Evans Creek (*A*) and Sprignett Creek (*B*).

biotite and garnet, curved syntectonic sillimanite fibers in the tails of a rotated tourmaline porphyroblast demonstrate that amphibolite-facies metamorphic conditions prevailed during mylonitization (fig. 5*A*). Well-developed S-C fabrics (fig. 5*B*) and sigmoidal mica "fish," all indicating dextral shear, are also commonly found in the more micaceous lithologies.

Quartz Fabrics

Quartz petrofabric studies of 12 oriented thin sections of quartz-rich metasedimentary rocks from localities along the shear zone were performed in order to confirm the sense of shear in the mylonites. Sections were cut parallel to the lineation and perpendicular to the foliation. No lineation was measurable in the field for 5 of the 12 samples, so the sections were cut parallel to the local lineation, measured either elsewhere at that outcrop, or at a nearby outcrop. The orientations of [c]-axes were measured with a standard four-axis Universal Stage and plotted on lower-hemisphere, equal-area stereographic projections. The contoured results are shown in figure 6.

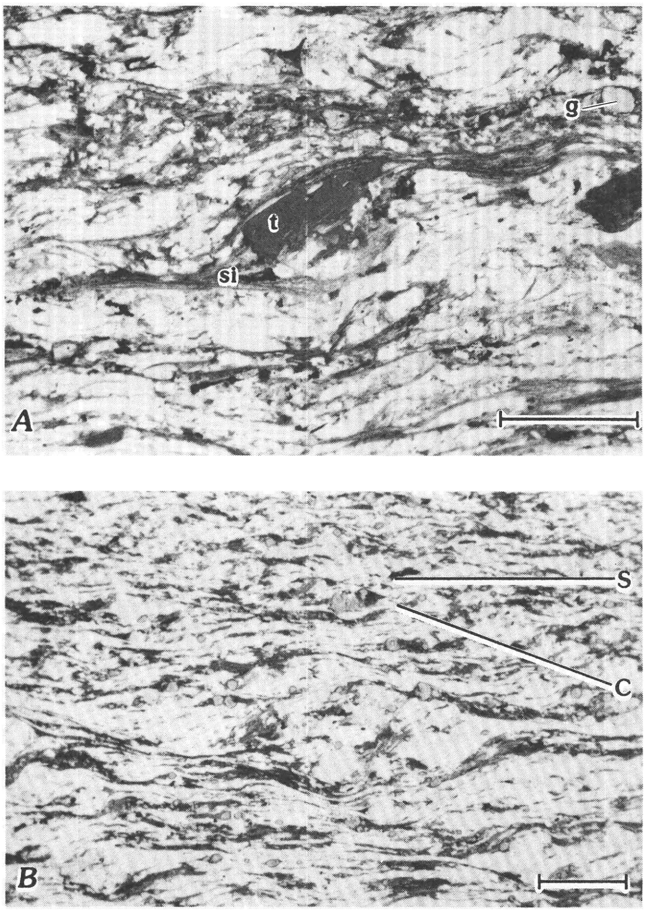


Figure 5. *A*, Asymmetric tourmaline porphyroblast (t) with sillimanite (si) tails indicating dextral shear in sample 156. Garnet (g), ribbon-like quartz, plagioclase, and opaque oxide are also present. Scale bar represents 1 mm. *B*, Quartzofeldspathic schist with micaceous S-C surfaces indicating dextral shear (sample 258-A1). Small, round, high-relief grains are garnet. Scale bar represents 1 mm.

Dextral shear is displayed by the clockwise rotation of the girdles with respect to the foliation plane in eight samples ("leading edge asymmetry"; Ralser, 1990), indicating a thrust sense of movement between the MCS and amphibolite. The remaining four samples displayed strong lattice preferred orientation of quartz, but did not yield shear sense information. No samples indicated sinistral sense of shear. The [c]-axis patterns shown are typical of those described in major shear zones where dextral shear is independently verified by other criteria (see Bouchez and Pècher, 1981; Behrmann and Platt, 1982; Schmid and Casey, 1986). Such independent verification is important, because experimental results show that for a single sense of shear the [c]-axis asymmetry with respect to the shape fabric may be either "leading edge" or "trailing edge," depending on pre-existing fabric (Ralser, 1990).

Samples 258-C2 and 323A show atypical double-maximum patterns occurring at 45° to 55° to the foliation plane, and cannot be used to deduce sense of shear. The patterns may reflect previously existing fabrics, lower strain, or the effects of feldspar or mica on quartz deformation. Two other samples from east of Sprignett Creek (no lineations available) have strong fabrics but do not indicate sense of shear (fig. 6). Rotating the data in attempts to compensate for incorrectly estimated lineation directions did not improve the results.

DISCUSSION AND CONCLUSIONS

From the combined petrographic and petrofabric data, I conclude that the ductile shear zone was the locus of northwest-directed overthrusting of the MCS. Although the isotopic age of the ductile deformation is not directly known, a Nevadan age (approximately 153-144 Ma; Harper and Wright, 1984; Harper and others, 1986) is inferred on the basis of metamorphic and structural continuity between the ductilely deformed rocks and the underlying amphibolite, which has a cooling age of 145 Ma (Donato, 1991a). Although there is some uncertainty that the ductile deformation was synchronous with metamorphism, this is a reasonable assumption given that there is no petrographic evidence for multiple metamorphic events, and given the structural and metamorphic continuity across the shear zone.

The N. 38°-45° W. transport direction is approximately perpendicular to the structural grain of the northernmost Klamath Mountains, which is defined primarily by the trend of major southeastward-dipping thrust faults which bound and displace terranes of the western Jurassic belt (fig. 1; Smith and others, 1982). These faults are probably related to the Nevadan accretion of this material to North America. The geometric relation between the trend of the faults and the transport direction suggests that the ductile shear zone is a smaller thrust inboard of the locus of accretion and reflects imbrication of the hanging wall of a larger thrust system. Convergence, therefore, was probably northwest-southeast in a present-day geographic framework.

The significance of this ductile shear zone with regard to large-scale tectonic plate motions is not clear. The Nevadan continental margin was undoubtedly complex. The angular relationship between stretching lineations and relative plate motion is not simple and may depend on subduction angle and finite strain (Ellis and Watkinson, 1987). Early stretching lineations formed in the footwall may develop subparallel to the trend of the orogen and may reflect relative plate motion. However, later lineations formed during or after the peak of metamorphism may not reflect relative convergence and are more likely related to imbrication and isostatic emergence of the hanging wall normal to the orogen (Ellis and Watkinson, 1987). The observed stretching lineations probably correspond to the latter type, because they developed during the metamorphic peak, and therefore may have formed perpendicular to the trend of the orogen.

Figure 7 summarizes existing data for Nevadan tectonic transport directions and stretching directions in the northern Klamath Mountains. Two pre-Nevadan transport directions are also shown. It should be noted that none of the data represented have been corrected for post-Nevadan tectonic rotation (for example, up to 60° of clockwise rotation is postulated for the Josephine ophiolite; Harper and others, 1990). The amount of post-Nevadan rotation of the MCS, if any, is unknown.

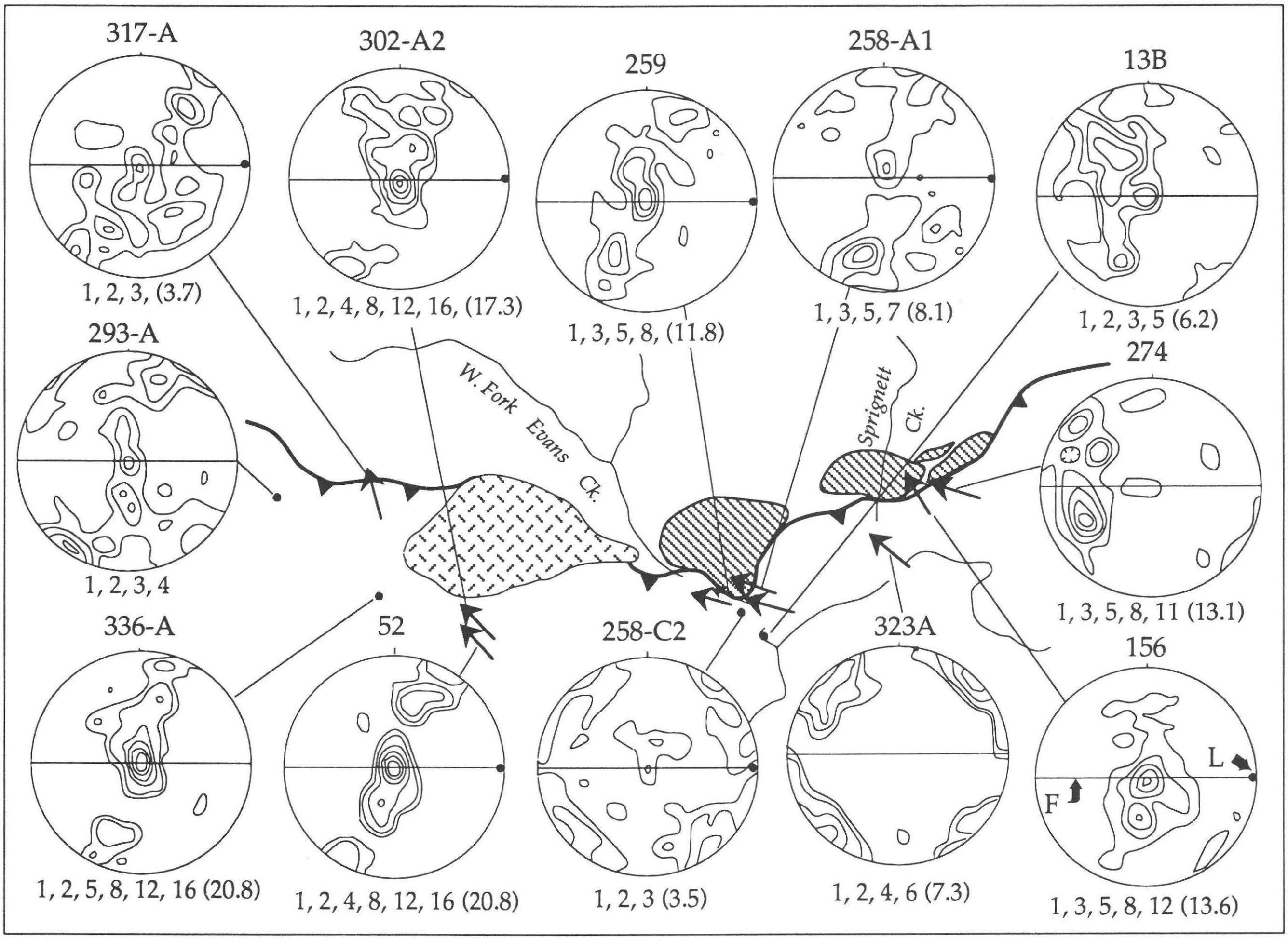


Figure 6. Equal-area, lower-hemisphere stereographic projections of quartz [c]-axes in 12 oriented thin sections of ductilely deformed May Creek Schist. To facilitate comparison among samples, all data have been rotated so that the foliation is vertical and strikes east-west, and the lineation (where known) is horizontal and trends east-west. The number of measurements is 200 for samples 293-A, 258-C2, and 317-A; all others are 100. F = foliation plane and L = lineation (shown only where measured on the sample). Contour intervals beneath each plot are in percent per 1 percent counting area, with the maximum in parentheses. Arrows indicate stretching lineations measured at sample localities. Patterns are same as those used in figure 2.

The MCS transport directions concur with those of Cashman (1988), who reported northwest-southeast dextral oblique convergence on the Orleans fault, about 135 km to the southwest, during Nevadan time. Conversely, Harper and others (1990) found north-northeast-directed Nevadan obduction of the Josephine ophiolite (fig. 7). Two possible explanations for this difference are (1) the Josephine Ophiolite and the MCS were in different stress regimes in the Nevadan orogen and were transported in approximately perpendicular directions and (2) one or both terranes were affected by post-Nevadan rotation and the indicated transport directions do not represent original transport directions. Clearly, a comprehensive tectonic model for Nevadan plate motions and accretion requires a better understanding of chronology, structure, and large-scale block rotations, particularly in the western Jurassic belt. The disparity among the available Nevadan lineations alone underscores the apparent complexity of the Nevadan and younger continental margin.

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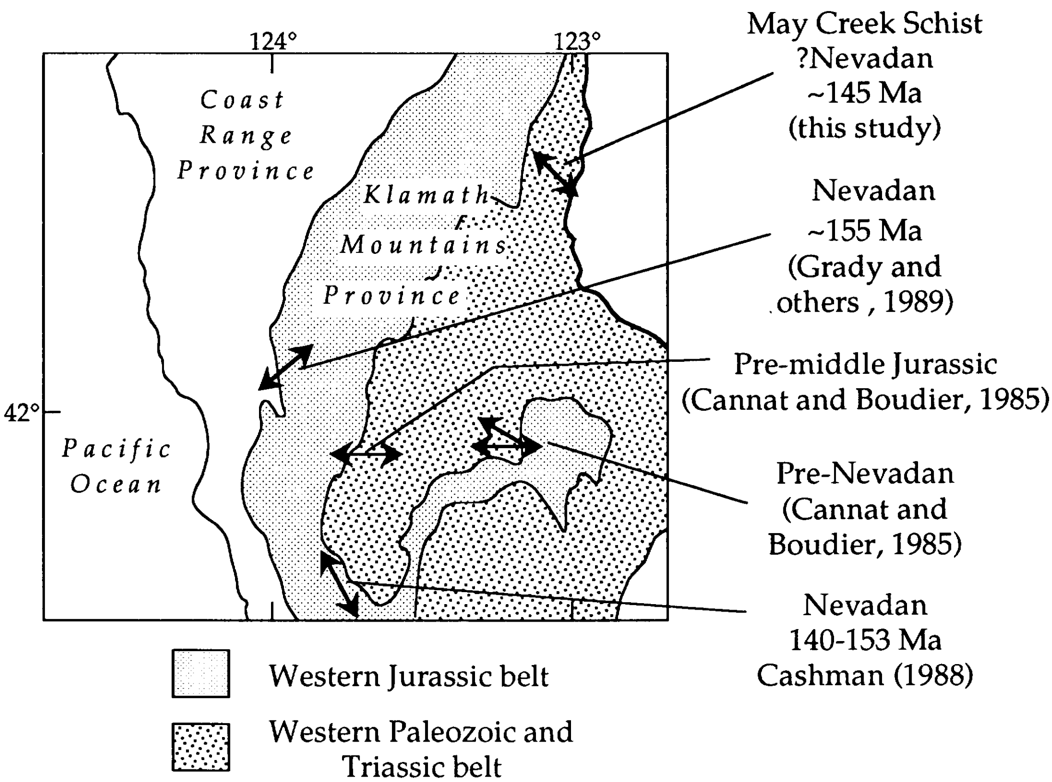

Figure 7. Stretching lineations and transport directions for Nevadan and older deformation in the northern Klamath Mountains. Data are from Cannat and Boudier (1985), Cashman (1988), Grady and others (1989), and this study.

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