GEOLOGY AND STRUCTURE OF THE ROCKS ASSOCIATED WITH THE BASAL (MADSTONE) THRUST OF THE JOSEPHINE OPHIOLITE IN SOUTHWESTERN OREGON: EVIDENCE FOR A METAMORPHIC SOLE

A thesis presented to the Faculty

of the State University of New York

at Albany

in partial fulfillment of the requirements

for the degree of

Master of Science

School of Science and Mathematics

Department of Geological Sciences

Kristin A. Grady

1990

University at Albany

School of Science and Mathematics

Department of Geological Sciences

The thesis for the master's degree submitted by

Kristin A. Grady

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Geology and structure of the rocks associated with the basal (Madstone) thrust of the Josephine ophiolite in southwestern Oregon: evidence for a metamorphic sole

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ABSTRACT

Many ophiolites have amphibolite at their base which contains a sharp inverted grade of metamorphism. These metamorphic soles are thought to have formed during the detachment and emplacement of the ophiolite. In addition to the sharp inverted grade of metamorphism, other characteristics of metamorphic soles include 1). a highly strained peridotite unit of the hanging wall which has concordant structures with underlying amphibolite and 2). an underlying melange sequence and continental rocks.

The Madstone thrust displaces the Josephine peridotite (Josephine ophiolite-162 Ma) onto amphibolites and underlying deformed gabbros of the Chetco Intrusive Complex. The rocks associated with the Madstone thrust do not display typical characteristics of other metamorphic soles. Structural data, however, indicates structures above and below the Madstone thrust are concordant, and geochronology, which dates the deformation as Nevadan, indicates that these rocks are associated with the emplacement of the Josephine ophiolite.

In the hanging wall of the Madstone thrust, 20-40 meters of high-T serpentinite mylonite occurs along the base of the Josephine peridotite instead of the typical highly strained peridotite mylonite unit in other soles. These serpentinites have lineations that trend north-northeast and are structurally concordant with the underlying amphibolites. The serpentinite show metasomatism which probably resulted from the interaction with fluids derived from the underlying amphibolite. In the foot wall, the amphibolites are 200-300 meters thick and show two generations of folds having hinges parallel to a north-northeast strectching lineation. The amphibolites display a grain-size reduction and asymmetric fabrics indicative of mylonites formed by progressive simple shear.

The sense-of-shear criteria for the serpentinite mylonite and the amphibolite, which are structurally concordant, indicate thrusting of the Josephine ophiolite toward the north-northeast over the Chetco Intrusive Complex. Thrusting continued in a north-northeast direction during retrograde metamorphism as indicated by sense-of-shear criteria in the phyllonite (retrogressed amphibolite) next to the Madstone thrust. Also, the lower contact of the amphibolite with the Chetco Intrusive complex is intrusive and syntectonically deformed along with the amphibolite.

Various conditions during the emplacement are as follows: 1). preliminary geochemical data suggest that the metamorphic sole is not related to the Josephine ophiolite and may be related to the root rocks of the Chetco Intrusive complex. 2). a geochronological study (Harper and others, 1989) suggests that the metamorphism and deformation occurred during the Nevadan Orogeny and indicates cooling from ~450^{o}C at 153 Ma, intrusion of the pegmatite at 150 Ma, and cooling to ~350 at 153 Ma, intrusion of the pegmatite at 150 Ma, and cooling to ~350^{o}C at 146 Ma. 3). Preliminary geothermometry and geobarmetry indicate relatively low P/T metamorphism compared to other metamorphic soles. 4). Preliminary $\delta^{18}O$ measurements indicate that metamorphic fluids were present during serpentinization.

The metamorphic sole and regional geologic setting of the Josephine ophiolite is distinct from other ophiolites. The sole has no apparent inverted metamorphic gradient, it is lower in overall temperature. The Josephine ophiolite was thrust over an active magmatic arc rather than obducted onto a continental margin. In addition, the ophiolite and overlying Galice Formation were thrust beneath North America along the roof thrust (Orleans fault), which produced regional greenschist metamorphism.

Geochronologic and structural studies indicate that the basal Madstone thrust and the roof thrust were both active at 150±1 Ma, but the thrusting direction along the roof thrust appears to have been west or northwest. The north-northeast thrusting direction along the basal thrust is nearly parallel to the inferred paleogeographic trends and almost 90^{o} to northwest thrusting directions along the roof thrust. On possible interpretation is that the lineations formed perpendicular to the thrusting directions. Another more plausible interpretation is that the back arc basin in which the Josephine ophiolite formed was imbricated due to oblique subduction. In this interpretation, then, the north-northeast directed thrusting would be related to a flattened strike-slip intra-arc wrench fault.

ACKNOWLEGMENTS

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Susan Delay assisted the author in the field during the summer of 1987 when conditions were not always ideal. Phil Hicks and Marsha Haines provided support during the summer field work offering their home, laughter, meals, and a hot shower. In addition, I would like to express my thanks to Susan, Phil Marsha, and Jutta Strebe for hauling over 250 pounds of rock from the Kalmiopsis Wilderness area.

Dr. Gregory Harper introduced the subject of metamorphic soles to the author; I thank him for his interest and support especially towards the end of this thesis project. Also, I would like to thank the other members of my thesis committee, Drs. Win Means and Bill Kidd, whose discussions and comments on the manuscript were very helpful. Also discussions with Matt Heizler improved the geochronology section of Chapter 3. David O'Hanley provided suggestions and comments on the interpretations of the serpentinite.

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CHAPTER 1: INTRODUCTION

1.1. DEFINITION, DESCRIPTION, AND TECTONIC SIGNIFICANCE OF "METAMORPHIC SOLE"

Amphibolite below the Madstone thrust, in southwestern Oregon, has been described by Cannat and Boudier (1985) as a metamorphic sole of the Josephine ophiolite (Figure 1.1 for location). They interpreted north-northeast emplacement of the ophiolite by sense of shear in quartz stringers in metaquartzites and amphibolites. Before an interpretation such as this can be made, however, typical features observed in most metamorphic soles should be documented. In order to compare the amphibolites with other soles, this section will define the term metamorphic sole, describe the "typical" features of the basal portions of other ophiolites, and briefly discuss these implications on models for emplacement of ophiolites. These findings are compared to the results of this study in Chapter 4.

1.1.1 HISTORICAL

Prior to 1970, ophiolites were thought to be mafic magma intruded into the upper crust. At the contact with these intrusions were rocks over a short distance that displayed an inverted grade of metamorphism and were often very deformed. For this interpretation, the inverted grade of metamorphism was thought to form due to the contact of the hot mafic body with the cold country rock (Tuke, 1968). The observed high strained structures were more difficult to interpret since the slow cooling of an intrusion would not produce these high strain features. Stevens and Church (1970) ascribed the structures in these rocks to a deformation event before metamorphism. However, in 1973, as ophiolitic rocks began to be described as oceanic rock sequences, Williams and Smyth interpreted the occurrence of the structures and metamorphism of the rocks below the Bay of Islands ophiolite as related to thrusting of the ophiolite. According to Williams and Smyth, the proper terminology was dynamothermal aureole because their metamorphism and deformation were not only formed by contact metamorphism but also related to the detachment of the ophiolite, probably three to six

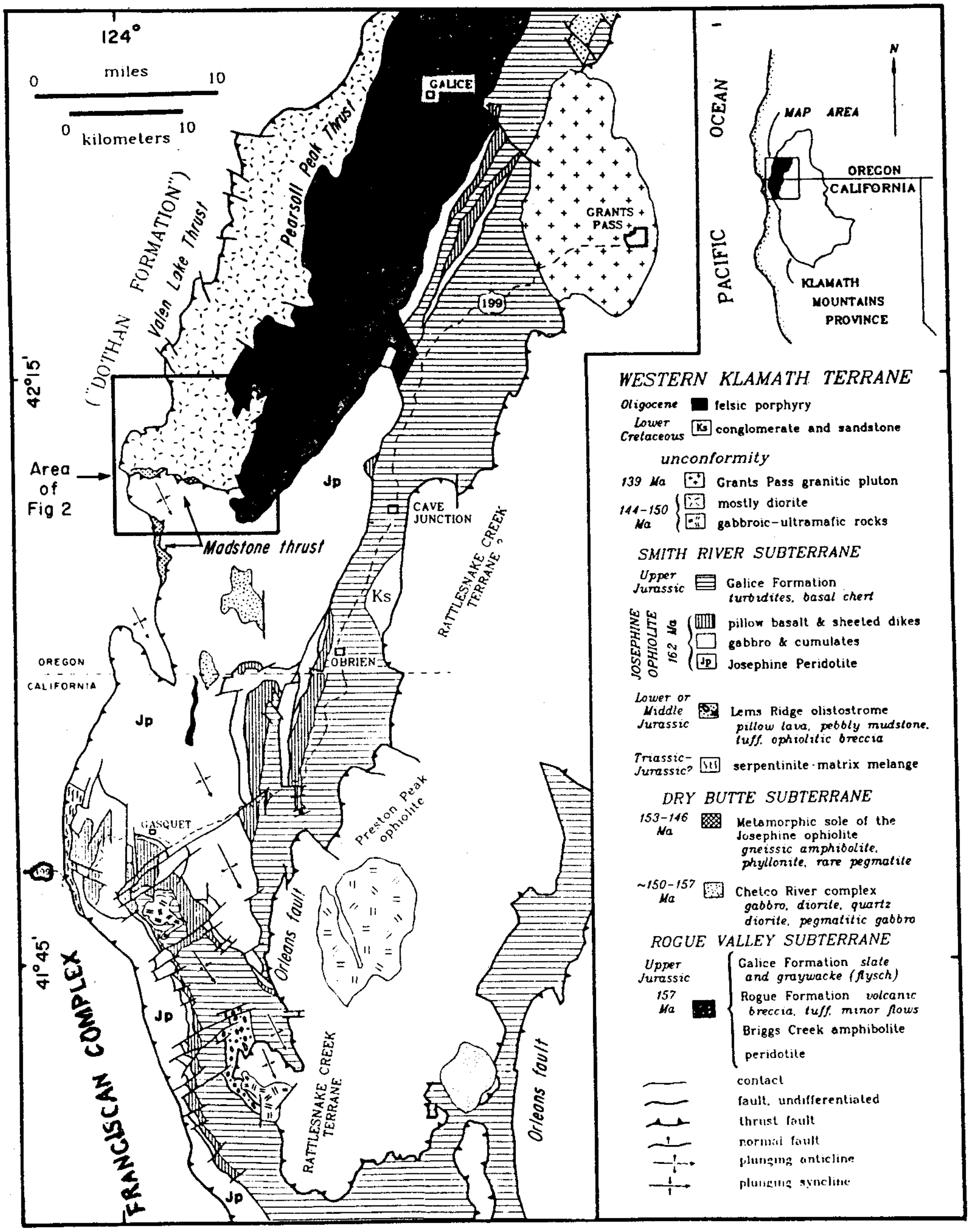


Fig. 1.1 Generalized geologic map of the western Klamath terrane modified from Harper (1989)

kilometers deep in the upper mantle. In other words, some contact metamorphism must have occurred but the thrusting itself caused the deformation and probably some additional heat to produce the metamorphism. This interpretation contained one flaw, namely the explanation of the high pressure assemblages, which are commonly observed in metamorphic soles. Williams and Smyth (1973) first described such metamorphic rocks below the Bay of Islands ophiolite which contained rocks that had undergone a much different metamorphic and structural history than the ophiolite itself. Since this time, metamorphic rocks beneath many ophiolites around the world have been studied as a key to understanding the mechanics of displacement and/or emplacement of ophiolites (see Spray, 1984).

1.1.2 TYPICAL FEATURES

Well developed metamorphic soles have the following characteristics (Spray, 1984; Nicolas, 1989; see Fig. 1.2):

1. They display a sharp inverted grade of metamorphism. Often over only a few hundred meters (500 meters typically), the rocks beneath the peridotites of the ophiolite grade downwards from amphibolite (or sometimes granulite) to greenschist facies rocks, to prehnite-pumpellyite grade metamorphic facies rocks at the base. The associated rock types, although they vary somewhat depending on the degree of metamorphism, are garnet, clinopyroxene amphibolite, plagioclase amphibolite, epidote amphibolite, micaecous schists, pillow basalts and metacherts. This decrease in metamorphism is the single most important characteristic of metamorphic soles.

2. Analogous to the sharp inverted grade of metamorphism, the intensity of the deformation of these rocks decreases away from the peridotites. The structural foliations generally are gneissose and schistose in the amphibolites closest to the peridotites and grade downward to phyllitic and relatively undeformed rocks in the greenschist facies metamorphic rocks.

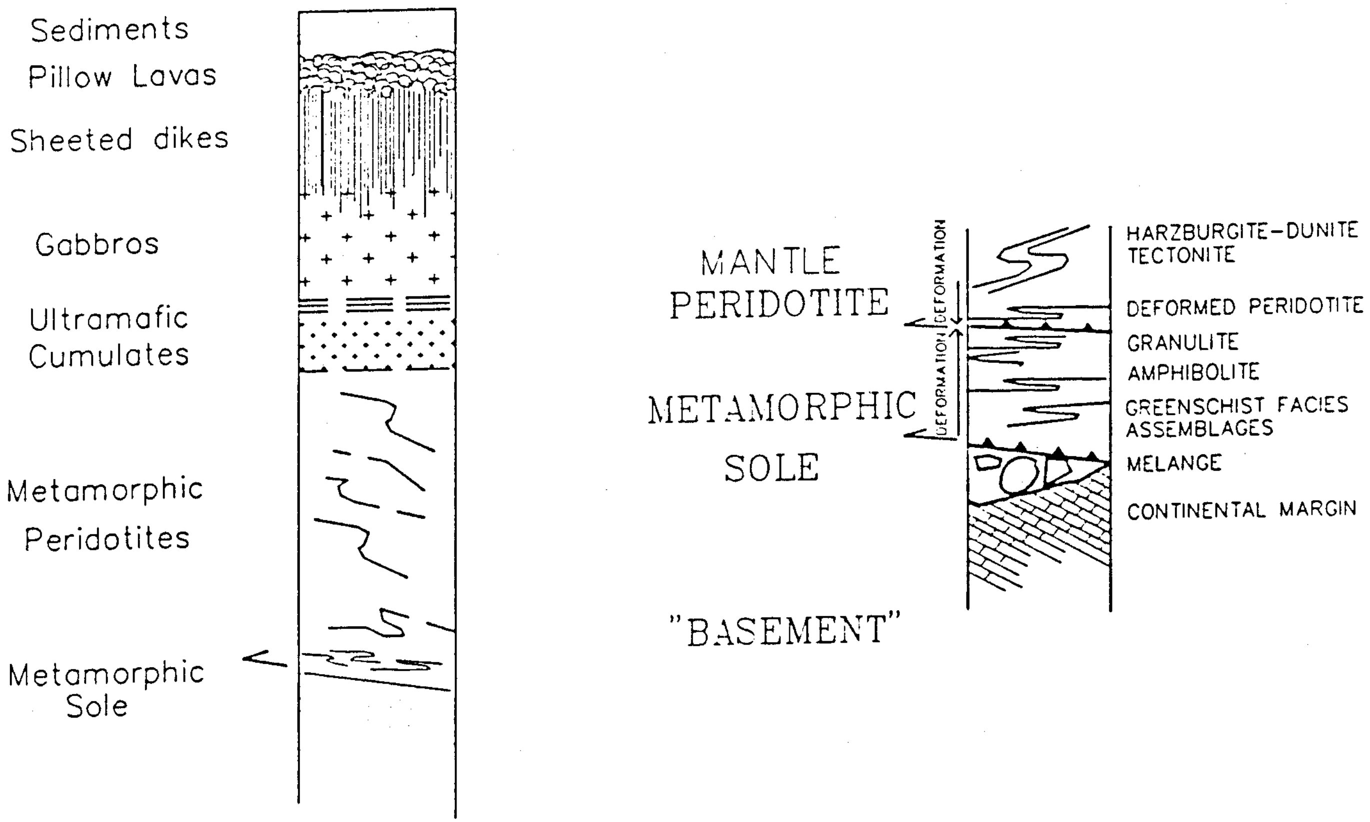


Fig. 1.2 Geology of ophiolites and their metamorphic soles (Spray, 1984)

3. Above the amphibolites, in the peridotite, is a 10-50 meter thick unit of highly strained peridotite. This unit contrasts with the high temperature (900 to 1200°C vs. 550-750°C), less-strained structures commonly observed further upsection in the peridotite (Nicolas, 1989). The structures of this less-strained peridotite have been interpreted as related to mantle flow (Nicolas, 1989), whereas the more highly-strained peridotite structures, which overprint the higher temperature structures, are thought to have formed during the detachment of the ophiolite. This interpretation is likely since the structures in the peridotite mylonites are concordant with the structures in the underlying metamorphic assemblages.

4. Typically, a melange sequence, which overlies continental margin rocks, is located beneath the metamorphic sole indicating obduction of the ophiolite onto a passive margin.

The high metamorphic grade and deformation suggest that high pressures and temperatures are associated with the development of these metamorphic soles. Malpas (1979), Jamieson (1981), and McCaig (1983) have all calculated temperatures of around 900°C to 1000°C for the granulite facies rocks and about 500°C to 750°C for the amphibolite facies rocks. High pressures have also been calculated for the metamorphic sole based on constraints for strain of the peridotite (7-11 kbars, Jamieson, 1980; McCaig, 1983).

Protoliths are not easily established but Jamieson (1980) for example considered them to be metabasalts, based on field description of the rocks. Searle and Malpas (1982) noted that upper units were generally mafic whereas the lower units contained many beds of metasediments, metacherts, and quartzites. Searle and Malpas (1982) characterized these mafic rocks further for the Oman ophiolite using trace element geochemistry. Their results are given in more detail in Chapter 4 but briefly appear to be transitional mid-ocean ridge to within plate basalts.

The assemblages of the metamorphic sole are sometimes extensively retrograded (Coleman, 1981, for Oman; Bill Kidd, pers. com. for Bay of Island). Since fluids are necessary for these retrograde reactions, any complete model will have to explain an influx in fluids during emplacement.

1.1.3 TECTONIC MODELS FOR FORMATION OF METAMORPHIC SOLES

Many authors since Williams and Smyth (1973) have contended that the metamorphism and structures must represent intraoceanic thrusting (e.g. Spray, 1984; Nicolas and Boudier, Lippard, 1982). Malpas (1979) mathematically modeled a thrusting event to examine how much shear heating, e.g. additional heat produced by friction in an effort to explain the high temperature assemblages found in metamorphic soles. By estimating the rate of motion along the thrust fault and the weight of the overlying slab, he calculated that shear heating would produce an additional maximum of 200°C, clearly not enough to produce the maximum metamorphic grade (900°C to 1000°C Malpas, 1979; Jamieson, 1981; and McCaig, 1983) that is required for formation of the metamorphic sole. Therefore, shear heating is apparently only a minor addition to the heat needed to produce the amphibolites. Malpas (1979) concluded that the detachment had to have occurred near the spreading ridge where enough residual heat is present to produce these high temperatures.

Jamieson (1980) proposed that the metamorphic sole formed by accretion of progressively shallower material to the base of the overriding ophiolite sheet during tectonic displacement in the mantle. Therefore, as initial detachment occurs in the upper mantle, a wedge of mafic crust is deformed, metamorphosed to amphibolite facies and attached to the base of the ophiolite. As thrusting continues, additional wedges are adhered to the base. The decrease in metamorphism is explained as the result of a loss of residual heat of the overthrusting ophiolite. This model explains fairly well the variations in geochemistry and rock type over the thickness of the metamorphic sole.

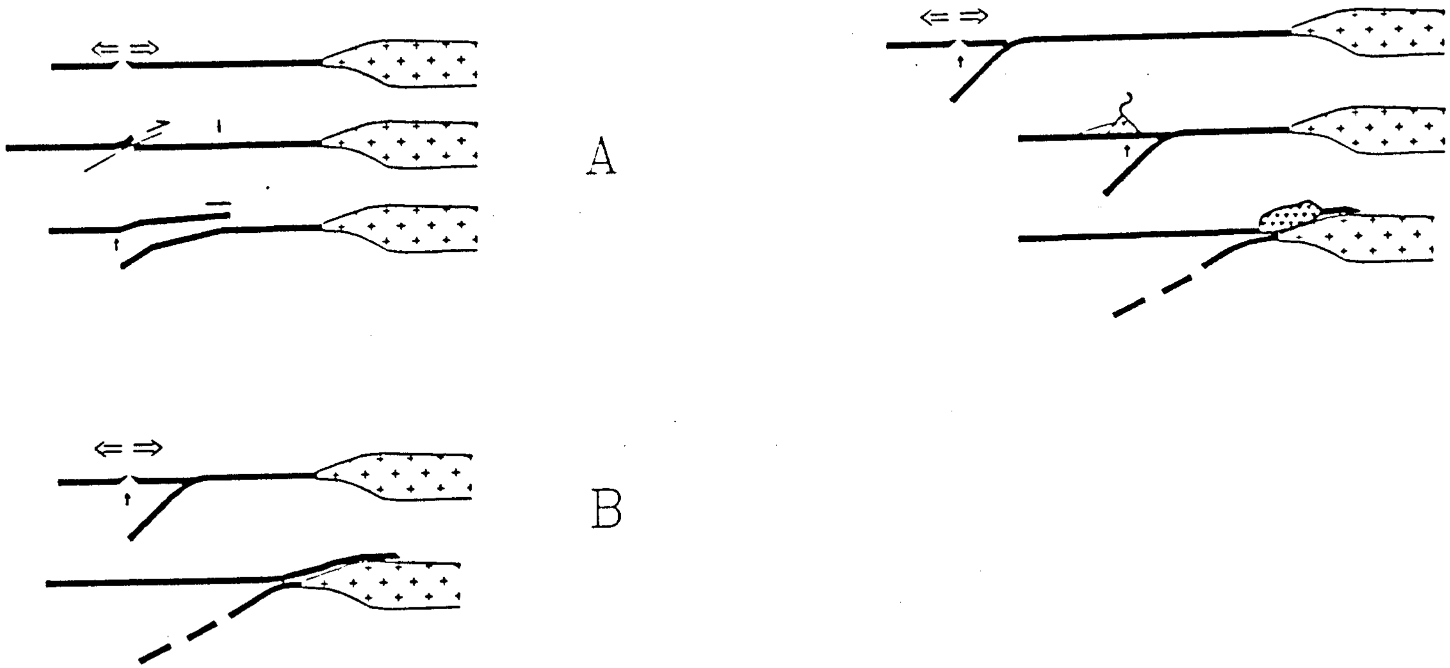


Fig. 1.3 Models for the obduction of ophiolites: 1.3a is intraoceanic thrusting by Nicolas and Le Pichon (1980); 1.3b was developed by Boudier, Nicolas, and Bouchez (1982) and MacCaig (1983); 1.3c developed by Dewey and Bird (1971).

Similar models were simultaneously being developed by Coleman (1981), Ghent and Stout (1981), and Searle and Malpas (1982) for the Semail ophiolite in Oman. Spray (1984) also summarized this model for the development of metamorphic soles. Nicolas and Le Pichon (1980) and Boudier, Nicolas, and Bouchez (1982) developed this scenario further.

Intraoceanic thrusting occurs in this model, due to changes of stress from tension to compression near the spreading axis. As thrusting occurs the sole develops through accretion to the base of the ophiolite (Fig. 1.3). They claim that for the amphibolites to have formed the decoupling would have to occur near the spreading axis to have enough residual heat to form the metamorphic assemblages and therefore, the ophiolite age and the sole age would be coincident or at least very close in age. Searle and Malpas (1982) date the Semail ophiolite nearly coincident. However, later dating by Montigny, et. al., (1988) reveals much older ages for some of the rocks in the metamorphic sole of the Oman ophiolite. Also, the age for the Bay of Islands ophiolite is about 504 Ma (U/Pb, Mattinson, 1976). Dunning and Krogh (1985), however, report a U/Pb date of 486 Ma. The metamorphic sole yields an $^{40}Ar/^{39}Ar$ age 20 to 50 Ma younger than the ophiolite (469 Ma, Dallmeyer and Williams, 1975 recalculated from the originally reported 460 Ma).

Another problem with this model is that it does not account for the high pressures calculated for the formation of the sole. Jamieson (1981) hypothesized that detachment occurs at a depth of twenty-five kilometers. Lippard et. al., (1983), McCaig (1983), and Jamieson (1981) all concluded that the ophiolitic nappes have to be thicker to create enough confining pressure and are later somehow structurally thinned. This structural thinning is quite unlikely because of the intact nature of the ophiolites.

Casey (1980), Boudier, Nicolas, and Bouchez (1982) and McCaig (1983) propose that the sole develops in the subduction zone where there is enough confining pressure to fit with those pressures calculated from the strained pyroxene. This model requires that an entire section of mantle rocks to somehow be removed followed by rapid uplift and attachment to the ophiolite rocks. This model is improbable because it is unlikely that greenschist facies rocks would develop and it is difficult to reconcile the removal of up to 12 kilometers of material.

1.2 REGIONAL FRAMEWORK

The Klamath Mountains geological province is composed of a number of east dipping thrust sheets separating terranes which generally become younger from east to west (Fig. 1.4 and Irwin, 1981, Burchfield and Davis, 1981, Harper, 1984). These terranes consist of ophiolitic sequences, magmatic arcs, and flysch. The eastern terrane, Eastern Klamath Terrane includes the oldest volcanic arc whose vulcanism ranged from early Paleozoic into the Jurassic period (Irwin, 1981) This arc is built on rocks of the Trinity ophiolite. During the Devonian time, rocks of the Central Metamorphic terrane were metamorphosed along the western edge of the Eastern Klamath terrane. During the Jurassic the North Fork, Hayfork, Rattlesnake Creek, and Western Klamath terranes were accreted to the North American continent.

The Josephine ophiolite is part of the Western Klamath Terrane and represents one of the most intact ophiolites of the Western North American Continent (Fig. 1.1 and 1.4; Harper, 1984). Ophiolites are typically composed of the following distinct assemblages from bottom to top: peridotite, tectonite, ultramafic cumulate, gabbro, and pillow lavas. All of these assemblages have been thoroughly described for the Josephine ophiolite by Harper (1984). The Galice formation, a pelagics and flysch sedimentary sequence, conformably overlies the Josephine ophiolite.

This study focuses on the basal thrust of the Josephine ophiolite in southwestern Oregon (Fig. 1.1 and 1.5). Beneath the Madstone thrust are other parts of the Western Klamath Terrane: the Dry Butte subterrane and the Rogue Valley subterrane (Fig., 1.6 and Blake, et al., 1985). The Dry Butte subterrane is composed of the Chetco Intrusive

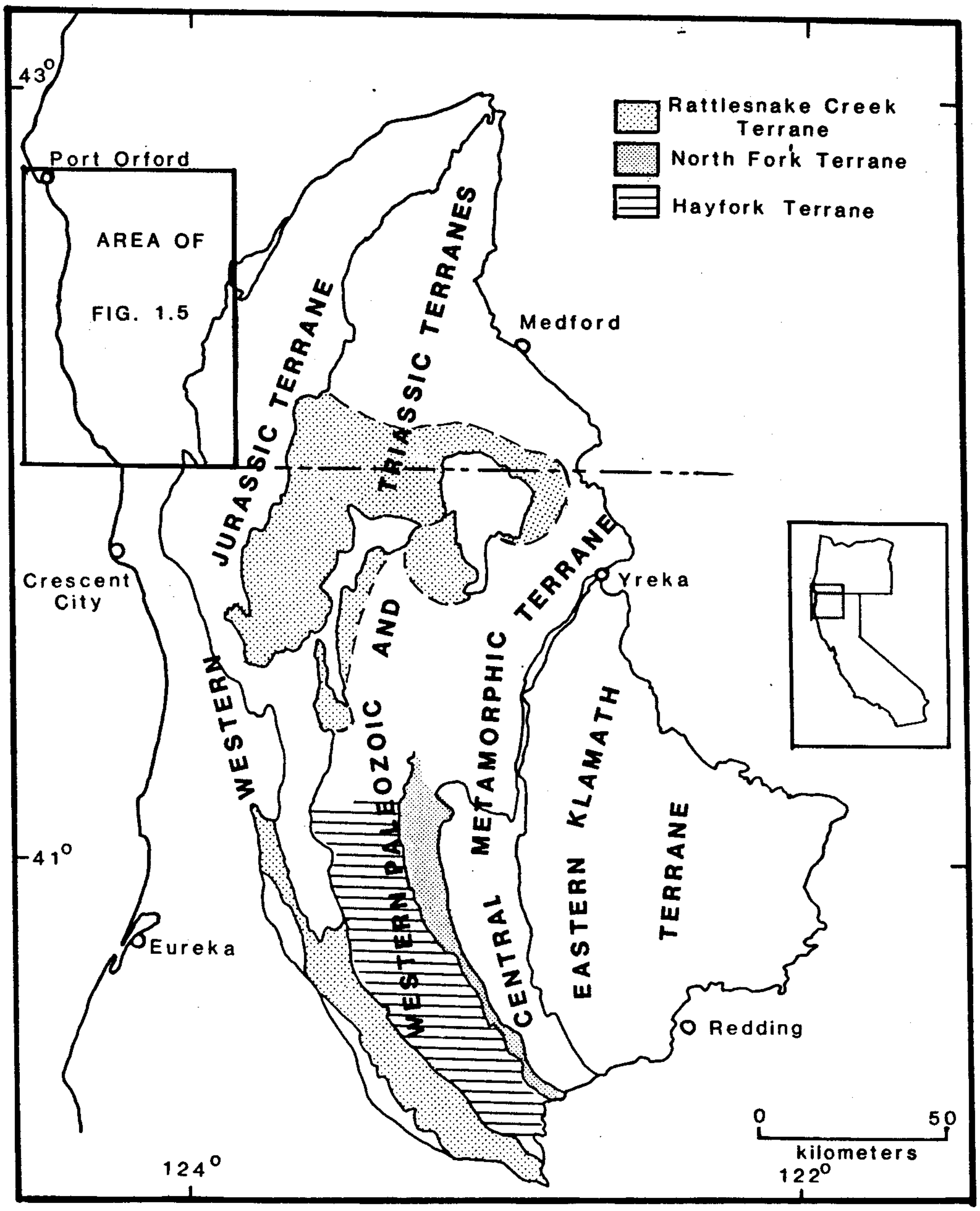


Fig. 1.4 Generalized map showing Klamath terranes in Northern California and Southwestern Oregon. (Modified from Irwin, 1985)

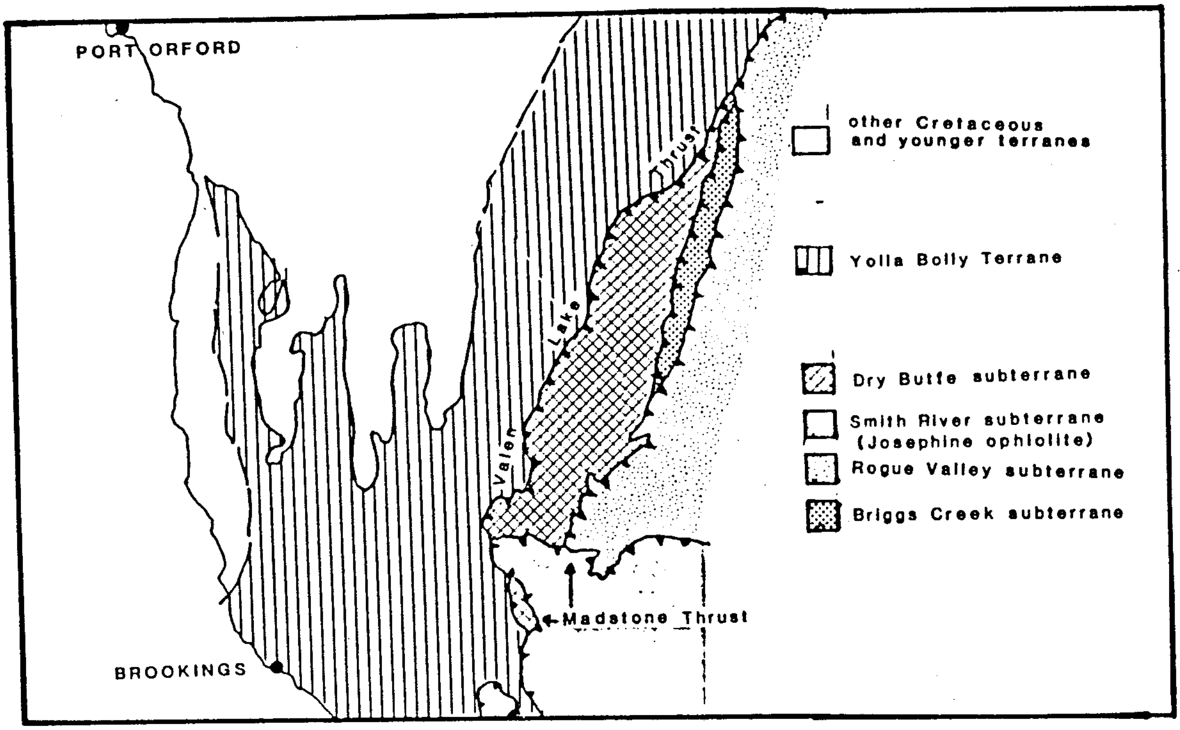


Fig. 1.5 Generalized map showing the tectonostratigraphic terranes in southwestern Oregon (Modified from Blake, et. al., 1985)

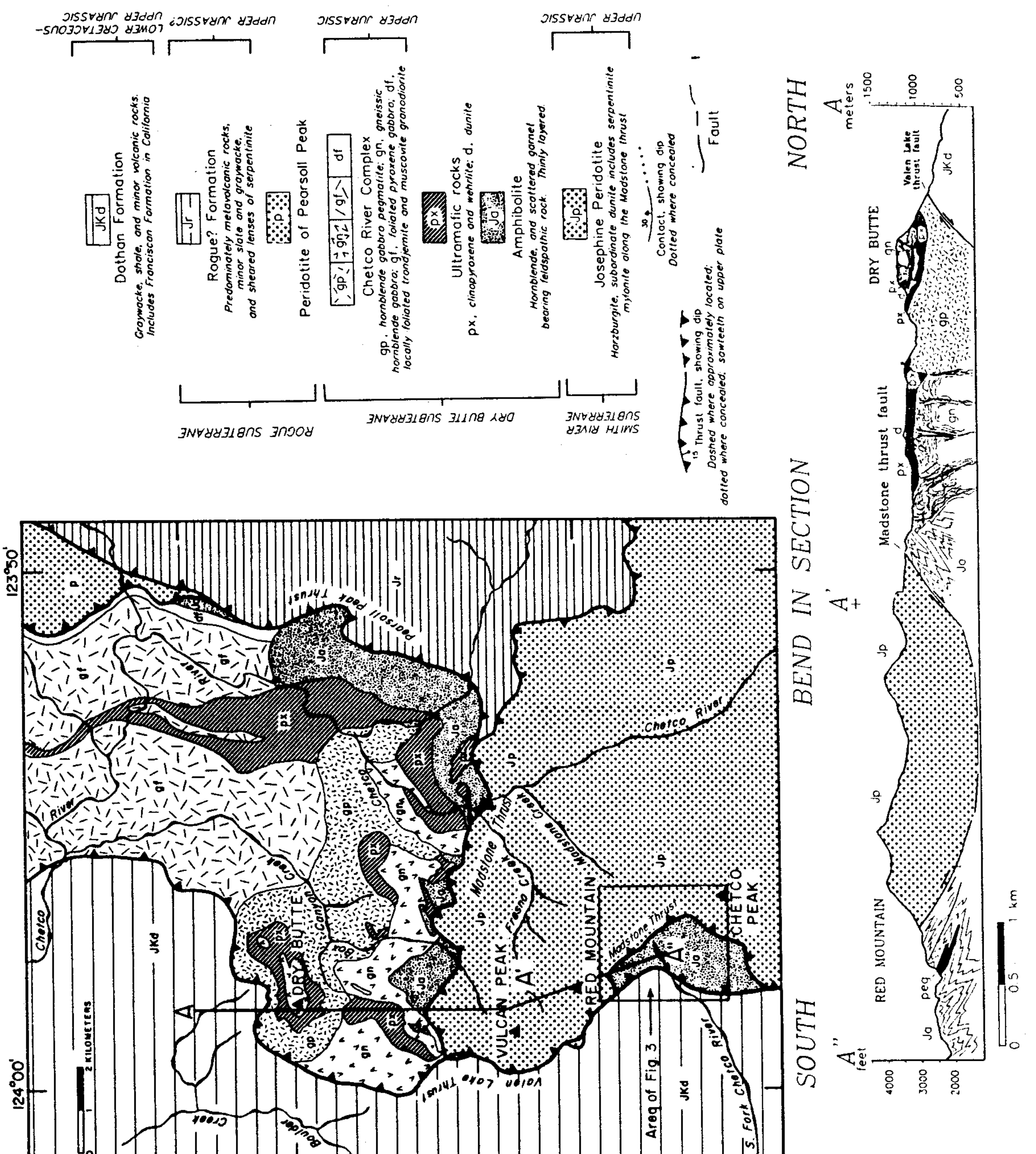


Fig. 1.6 Map and cross-section showing the relationship of the Madstone thrust and the Valen Lake thrust (modified after Loney and Himmelberg, 1977)

complex (Illinois River Gabbro). The Rogue Valley subterrane is composed of the Galice Formation which conformably overlies the Josephine ophiolite and the Chetco-Rogue complex (Harper, 1984). Finally, the Yolla Bolly subterrane roughly Cretaceous in age lies directly west and structurally beneath the Western Klamath Terrane (Blake et al., 1985).

1.3 TECTONIC MODEL FOR THE FORMATION OF THE JOSEPHINE OPHIOLITE

A tectonic model for formation of the Josephine ophiolite was developed by Harper and Wright (1984) and Wyld and Wright (1988). This model was updated with new geochronological work and is summarized by Harper and others (1989) and Harper and others (in review) and is the basis for the following review and Figure 1.7. Eastward subduction along the west coast resulted in the formation, beginning at about 177 Ma, of an Andean type magmatic arc (the Western Hayfork terrane) which was built on older, ophiolitic, rocks of the Klamath Mountains (the Triassic to early Jurassic Rattlesnake Creek terrane; Harper et al., in press). Magmatism continued until 162 Ma (Wyld and Wright, 1988). A major orogeny along the western North America involving thrusting and volcanism occurred during 170-165 Ma and was recently documented in the Klamath Mountains by Wright and Fagan (1988).

Rifting of this arc around 161 Ma opened a back arc basin which produced the Josephine ophiolite (Harper and Wright, 1984; Wyld and Wright, 1988). Initiation of this rifting probably split older Klamath basement (probably the Rattlesnake Creek Terrane) and a portion migrated oceanward, upon which the Late Jurassic arc (Dry Butte Subterrane) was built. Spreading in the back arc basin was probably subparallel to the continental margin, as a result of oblique subduction, based on sheeted dikes in the Josephine ophiolite (proposed by Harper and others, 1985; Wyld and Wright, 1988).

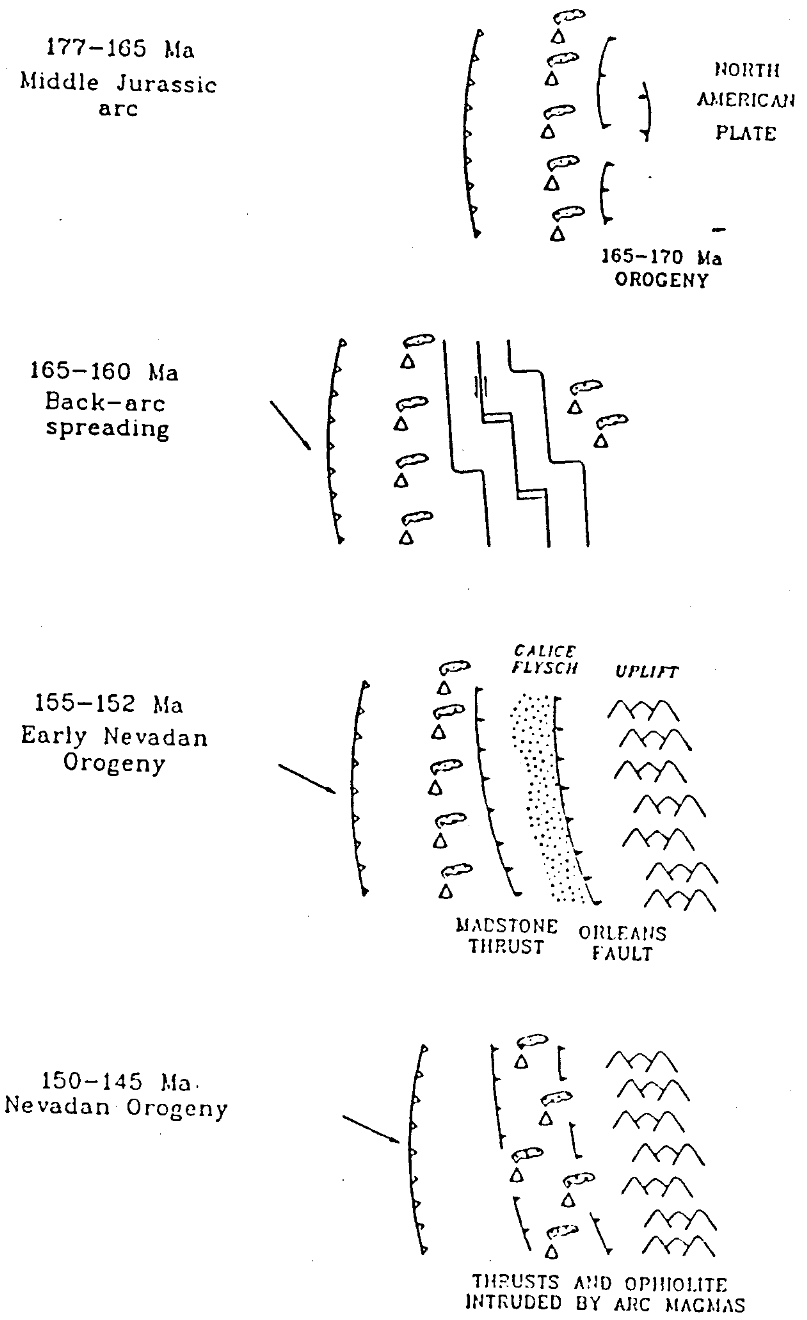


Fig. 1.7 Tectonic model for the Middle to Late Jurassic tectonic evolution of the Klamath Mountains (modified from Harper and Wright, 1984)

Wyld and Wright (1988) showed the effects of oblique subduction from the present day example of the Andaman sea which is opening asymmetrically and spreading is proximal to the arc margin.

During the Nevadan Orogeny (beginning ~150 Ma), this extensional system collapsed and the Josephine ophiolite was thrust under the continental margin. The active arc was also underthrust beneath the Josephine ophiolite. The Josephine ophiolite became situated over the zone of the active arc magmatism (Harper and Wright, 1984; Wyld and Wright, 1988; Harper et al., in press).

1.4 LOCATION AND DESCRIPTION OF THE FIELD AREA

This study focuses on the relationship of the thrusting of the Josephine ophiolite over the Chetco Intrusive complex. The Madstone Cabin fault, the basal thrust of the Josephine ophiolite, crops out in the Kalmiopsis Wilderness area in southwestern Oregon in two localities. (see Fig. 1.1 and 1.8). The Kalmiopsis Wilderness Area was preserved as a wilderness area by congress in 1964 and is roughly oval in shape being 27 miles long and 10 miles in width. Even though the area receives more than ~120-380 centimeters of rain in a year, little can grow on the poor soils of the peridotite. Exposures therefore are abundant and fairly easily accessible (Fig. 1.9)

This particular study encompasses an area about four miles long and a mile wide in the southern portion of the Kalmiopsis Wilderness Area along the southern exposure of the Madstone thrust (Fig. 1.1, 1.9, and 1.10). The southern area was chosen for this study for the following reasons: 1) Access to the southern area was good and afforded a suitable water supply. 2) the exposure is continuous in this area and 3) Cannat and Boudier (1985) collected their data in this area. Since the Kalmiopsis is a wilderness area, however, no motorized vehicles are allowed within its boundaries and access was obtained through a four mile trail. This field study was conducted near Chetco peak which can be located on the Chetco Peak 15 minute quadrangle.

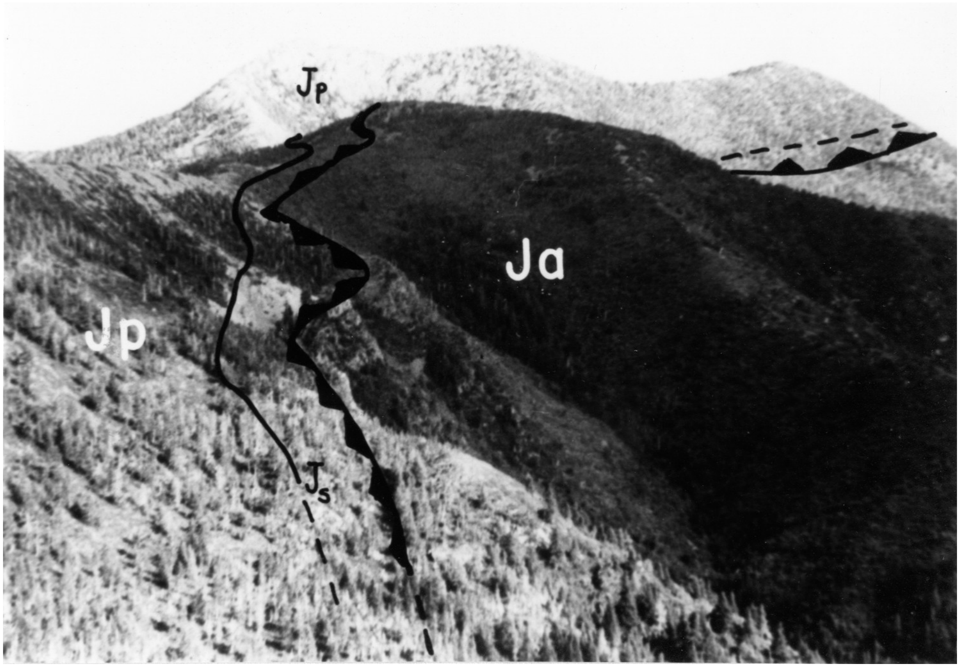


Fig. 1.8 Photograph of the study area. View is towards the northeast and shows the trace of the Madstone thrust. Ja=amphbiolite, Js=serpentinite mylontie, Jp=Josephine Peridotite.

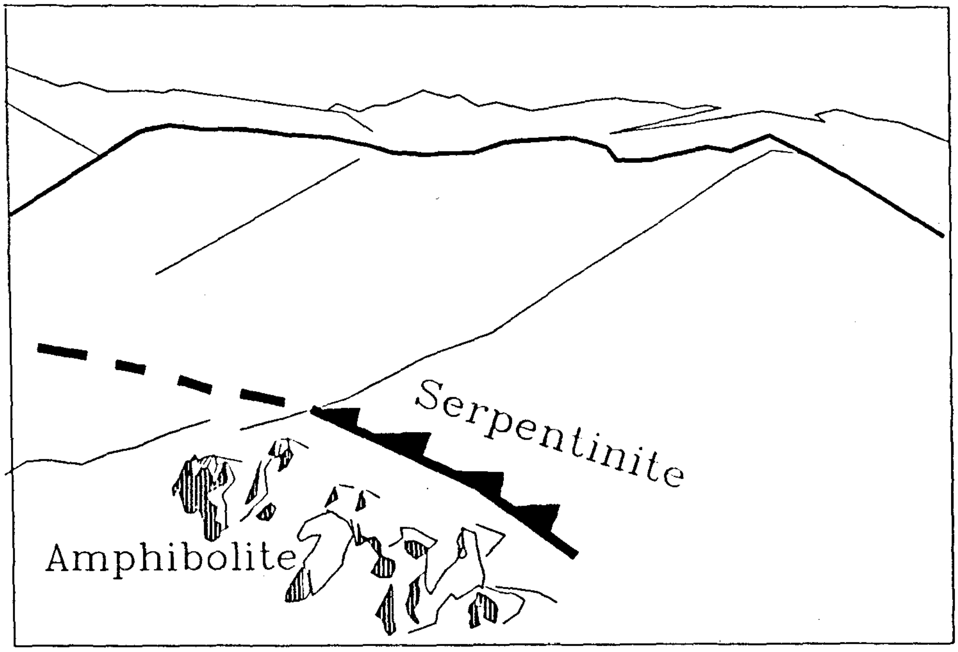


Fig. 1.9 Photograph of the field area showing the abundant and well exposed outcroppings. Amphibolite outcrops in foreground and Josephine peridotite composes the outcrops red-orange in color.

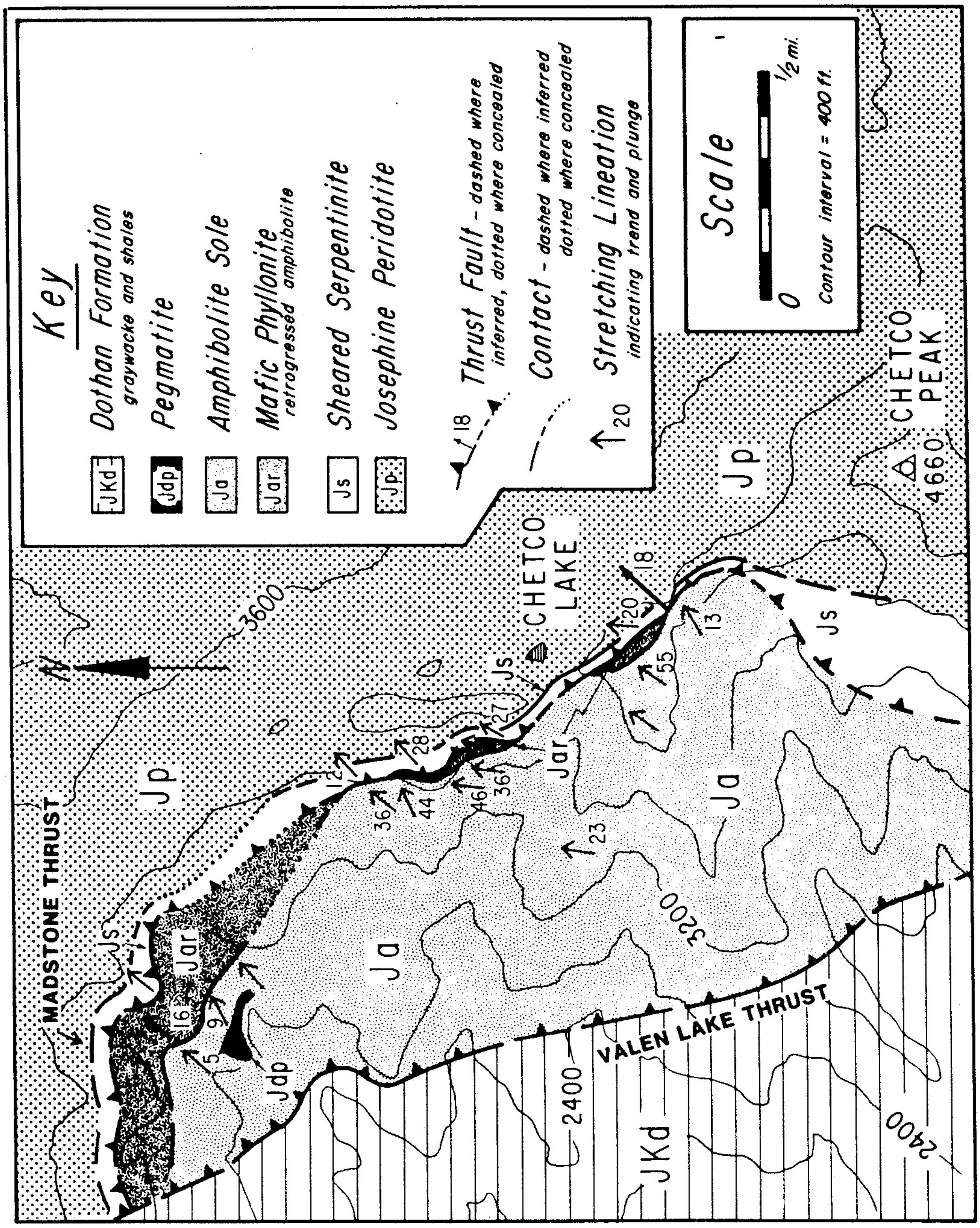


Fig. 1.10 Map of the study area near Chetco peak. The Josephine ophiolite is thrust over amphibolite along the Madstone thrust. The east dip of the thrust is the result of large-scale post-Nevadan folding.

Field work was conducted over two summers for a total of approximately seven weeks. The majority of the data collected was in the study area; however, additional data and rock collection was done along the northern outcrop of the Madstone thrust near Vulcan peak for comparison. Madstone Cabin Thrust trends generally East-West and is truncated by a North-South trending thrust named Valen Lake thrust by Ramp (1975)(Fig. 1.1, 1.9 and 1.10). The entire section is thrust over the younger Dothan Formation which is predominately composed of Cretaceous sedimentary rocks. The field area has been mapped previously by LePage (1976), Henry Dick (1977), and Len Ramp (1975); these provided excellent background to more detailed work along the Madstone Cabin Thrust.

1.5. PURPOSE OF THESIS PROJECT

The relationship of the underthrusting of the magmatic arc beneath the Josephine ophiolite has not been extensively studied (Dick, 1977; Garcia, 1982; Cannat and Boudier, 1985). The original objective of this study was to describe rocks below a fault in southwestern Oregon which lies south of the Madstone thrust and which generally has been mapped as a re-entrant of the Madstone Cabin thrust (Le Page, 1976; Ramp, 1985;, Dick, 1977, and Cannat and Boudier, 1985). The interpretation of these rocks has been debated. Armstrong and Dick (1976) and Loney and Himmelberg (1977) interpreted these rocks as part of the Chetco Intrusive Complex because of structural and geochemical data. Cannat and Boudier (1985) have argued that these amphibolites are related to the Josephine ophiolite and specifically with the thrusting of the ophiolite as a "metamorphic sole". During the course of this study it was evident that this thrust fault is a re-entrant of the Madstone thrust as suggested by previous workers (e.g. Ramp, 1975). The main questions addressed during this study were:

1) Are there structures which record the thrusting of the Josephine ophiolite?

2) If such structures are found, what is the nature of this relationship? a) what is the direction of thrusting? b) what is the protolith of these rocks? c) what is the age of thrusting?

3) How does this information compare to other ophiolite emplacement features?

4) Finally, how does this information constrain the model for emplacement of the Josephine ophiolite?

The following chapters will explore the structural, age, and chemical relationships of the rocks below the Madstone thrust. Chapter 4 discusses the differences between the characteristics described above and the amphibolite sole of the Josephine ophiolite and discusses the results with respect to the emplacement of the Josephine ophiolite.

CHAPTER 2: STRUCTURE

2.1 INTRODUCTION

Mapping of the field area was conducted over two summers (1987-1988) for a total of approximately seven weeks. The purpose as discussed in Chapter 1 was to map in detail the lithologic units and structures above and below the Madstone thrust fault in the central portion of the Kalmiopsis wilderness area (Fig. 1.1 and 2.1). This chapter describes the map pattern of the units in southwestern Oregon, the lithologic units, as well as discussing the mesoscopic and microscopic structures of these units, and the interpretation of these rocks.

2.2 MAP PATTERN

Figure 2.1 shows the majority of the Kalmiopsis Wilderness area and Figure 1.8, 2.2 and Plate 1 show the study area. The Madstone thrust displaces the Josephine peridotite over amphibolites and metagabbros. It trends roughly east-west for ten kilometers and is cut in the west by the Valen Lake thrust. The Valen Lake fault, which in northern California is called the South Fork fault, dips to the east and is post-Nevadan in age. The Josephine ophiolite, Chetco Intrusive Complex, and the amphibolites of this study are thrust over the Dothan Formation of the Yolla Bolly Terrane along the Valen Lake fault.

The map pattern of the Western Klamath Terrane in southwestern Oregon largely reflects the post-Nevadan folding and faulting. The Madstone thrust is folded by a large open southeast-plunging syncline producing two main areas of amphibolite in the Kalmiopsis Wilderness area (Figs. 1.1 and 2.1). In the northern outcrop, the Madstone thrust dips to the south-southwest, whereas in the south it dips about 18° to the northeast (Figs. 1.1, 1.8, 2.1, and 2.3). To the south, the Valen Lake thrust is also

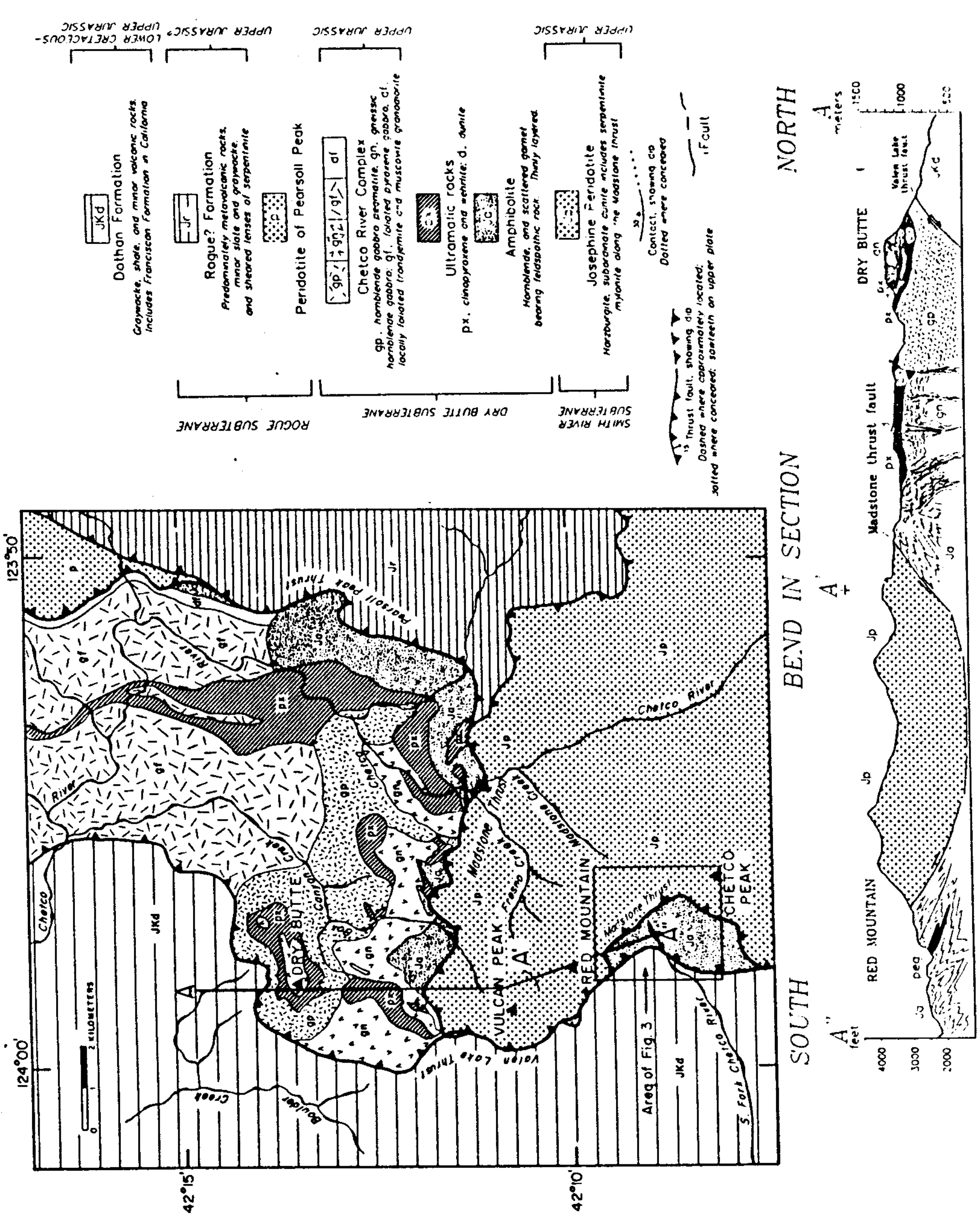


Fig. 2.1 Map and cross-section showing the relationship of the Madstone thrust and the Valen Lake thrust (modified after Loney and Himmelberg, 1977)

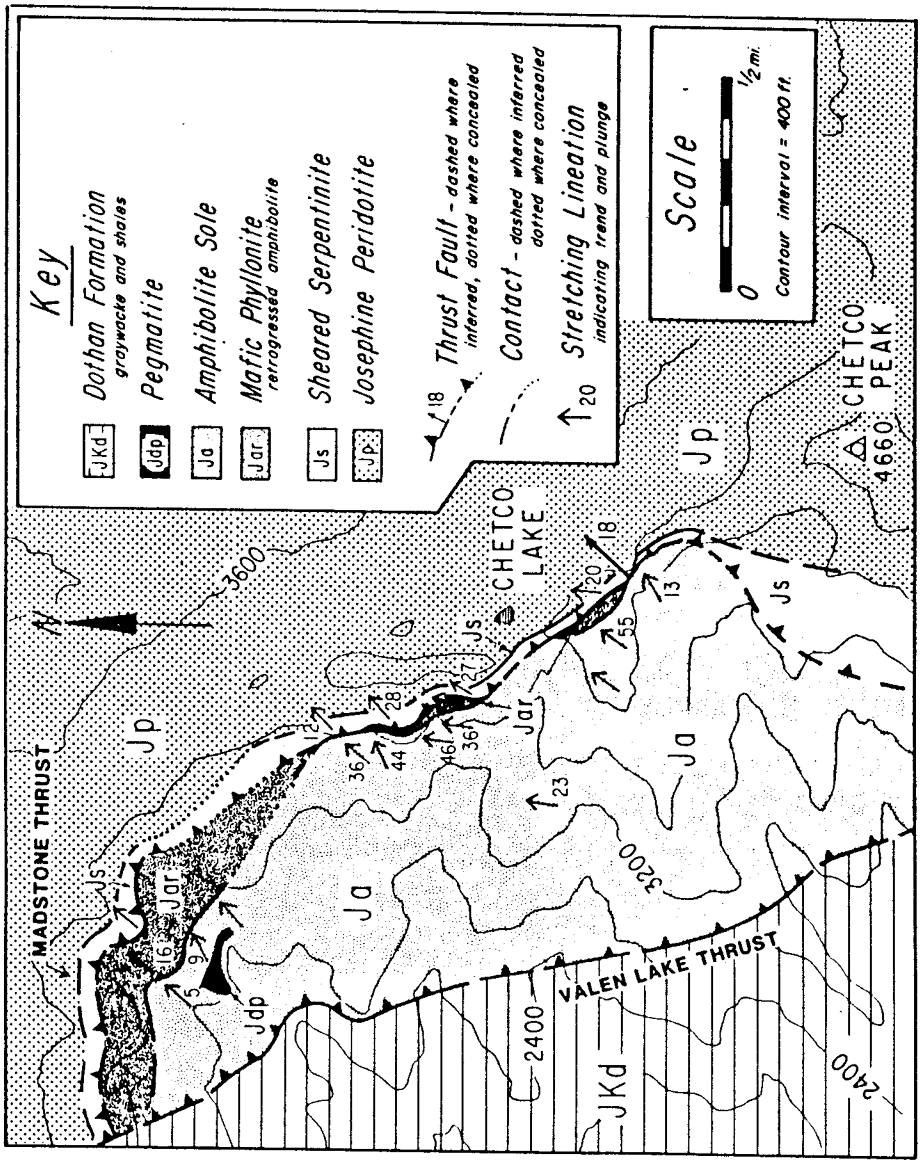


Fig. 2.2 Map of the study area near Chetco peak. The Josephine ophiolite is thrust over amphibolite along the Madstone thrust. The east dip of the thrust is the result of large-scale post-Nevadan folding. (The position of the Valen Lake thrust was confirmed from Ramp, 1975)

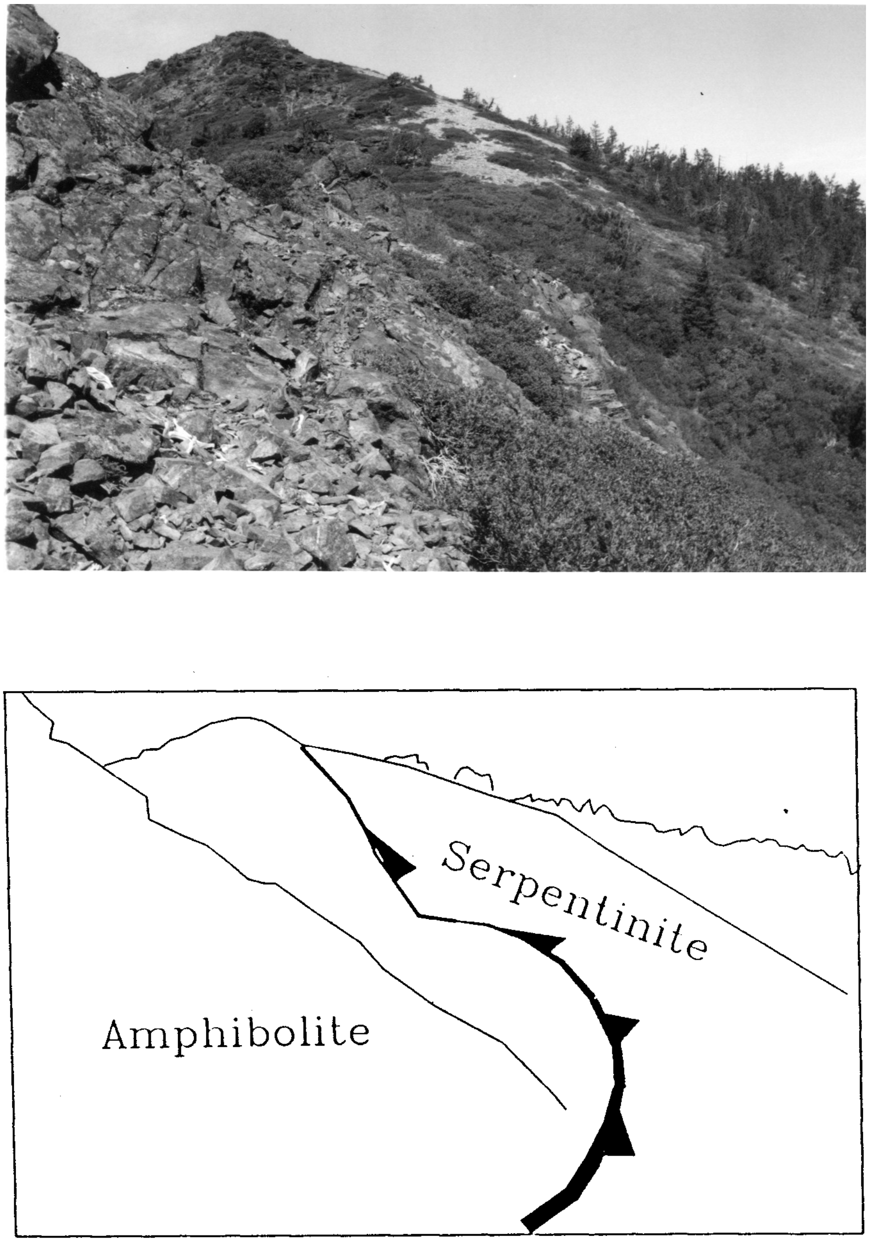


Fig. 2.3 **Field photograph of the amphbiolite sole and overlying serpentinites. The dip of the thrust sheet is about 18°.**

folded into a southeastern plunging anticline. In California, the Josephine ophiolite and the Orleans thrust fault, the roof thrust of the Josephine ophiolite, are also affected by southeastern plunging folds. The post-Nevadan age of these folds is evident from folding of the Valen Lake thrust, as well as from folding of Nevadan age foliations in the Josephine ophiolite and overlying Galice Formation.

2.3 ROCKS ASSOCIATED WITH THE MADSTONE THRUST

Below the Madstone thrust the distribution of rocks, as shown in Figs. 2.2 and 2.4, is as follows: 1) next to the thrust sheet are phyllonites. Upon examination in hand sample and thin section, these phyllonites are interpreted to be retrogressed amphibolites (see 3.3). 2) amphibolites extend over about two square kilometers of the field area beneath the thrust sheet and are approximately 300 meters thick. The amphibolites are cut by a pegmatite.

At their base, the amphibolites are intruded by the metagabbros of the Chetco Intrusive Complex. These rocks are syntectonically deformed along with the amphibolites (Dick, 1976; Loney and Himmelberg, 1977). Loney and Himmelberg (1977) discuss the difficulty of mapping this gradational and deformed contact between the amphibolite and the metagabbros which look very similar in outcrop.

The upper plate consists, from the Madstone thrust upward, of 1) local pockets of talc, actinolite, and tremolite which in places are up to a meter in thickness; 2) highly and weakly strained cohesive serpentinites derived from the Josephine peridotite; 3) peridotites of the Josephine ophiolite. Most of these peridotites are serpentinized to some degree, but magnetic studies in the Chetco Lake area indicate that these rocks are not magnetic and therefore are very fresh (Harding, 1987). Also, samples examined in the field were relatively unserpentinized.

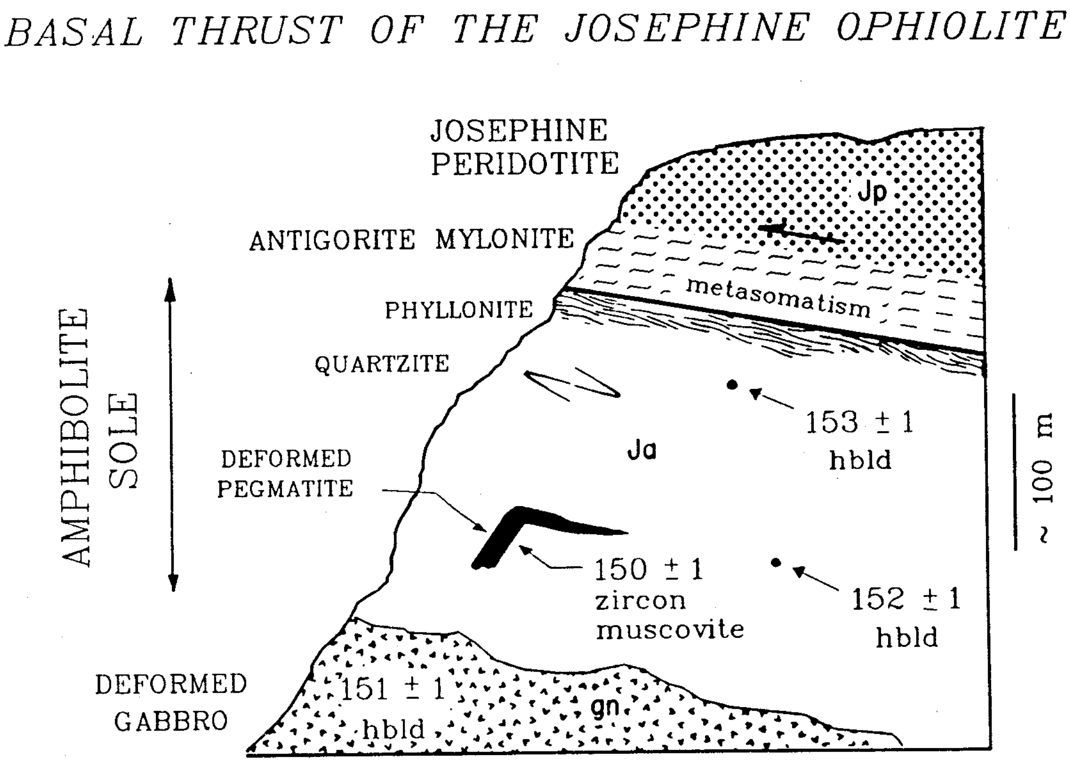


Fig. 2.4 Cartoon showing the structural sequence of the Madstone thrust near Chetco Lake.

2.3.2. AMPHIBOLITE

About 300 meters of amphibolite crops out below the Madstone thrust in the southern portion of the field area near Chetco Lake (Fig. 1.8 and 2.2). Amphibolite is also present below the northern exposure of the Madstone thrust. In these two areas, the amphibolite is similar in appearance and structure. The rocks are composed of dark and light gneissic layers, which defines a foliation (S_o). These layers, which range from a few millimeters to a centimeter thick, are composed mainly of strongly aligned hornblende, plagioclase, and locally quartz (see further discussion of mineral composition in 3.3.1). Other minerals, which are not readily observable in hand samples, may contribute to this foliation namely: Fe-Ti oxides, epidote, and sphene. Grain size varies from layer to layer from 0.1 to 5.0 millimeters and some samples display grain size reduction (Fig. 2.5). The abundance of hornblende, as estimated in the field, varies from ~50 % to 70 %. Plagioclase plus quartz varies from ~20 % to 50 %. The remaining percentage is composed of quartz veins.

In the eastern portion of the field area, the amphibolite is interlayered with micaceous and rhodonite (Mn-pyroxene) quartzites. These metaquartzites are mainly composed of quartz, biotite, and muscovite. The rhodonite quartzite is composed of rhodonite, quartz, and opaques.

Veins of quartz and epidote + albite, which cut the amphibolite, are common within 20-50 meters to the Madstone thrust and become less abundant further from the thrust. Most of the small veins which cut the amphibolite are sub-normal to the foliation and mineral replacement in and near these veins has occurred. In hand sample, these veins show a greenish color from the presence of epidote (Chapter 3 discusses the vein mineralogy in more detail). A deformed pegmatite clearly cuts the foliation of the amphibolites (Fig. 2.6). The pegmatite has the following assemblage: muscovite, biotite, k-spar, plagioclase and quartz.

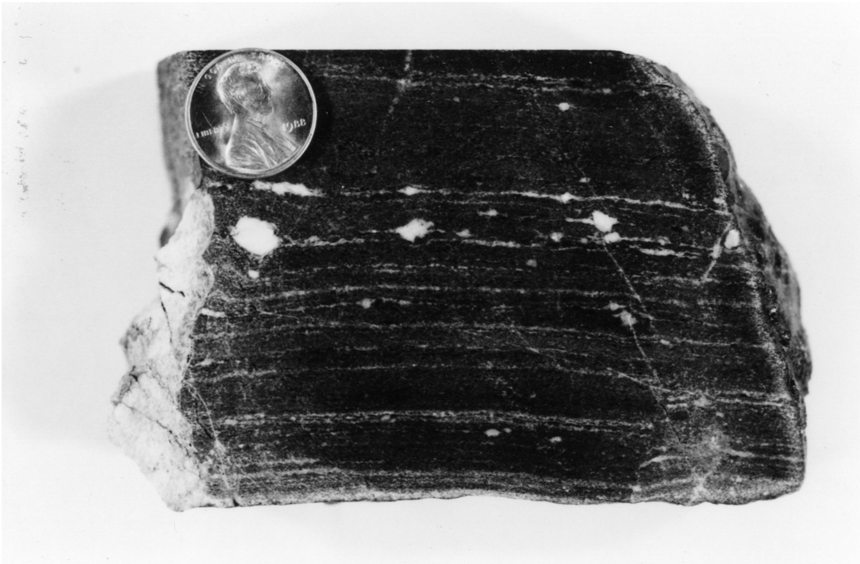


Fig. 2.5 Photograph of gneissic amphibolite that displays grain size reduction.

Fig. 2.6 Photograph of pegmatite dike northwest of Chetco Lake which cuts folded gniessic layering in the amphibolite. White line on the amphibolite is drawn parallel to lineation, and the view is toward the northeast.

2.3.3 PHYLLONITE

At the lithologic contact of the amphibolite with the Josephine peridotite, zero to fifty meters of hard, fine grained, green rock crops out. The hardness of the phyllonite is most likely due to total recrystallization. Upon close inspection, a foliation is defined by dark layers and aligned minerals. Examination of thin sections show that these dark layers are relict hornblende and that these phyllonites are retrogressed amphibolites (section 3.4). The phyllonite contains relict hornblende but is mainly composed of fine grained matrix of chlorite, actinolite and quartz, with porphyroclasts of hornblende, actinolite, and epidote. These rocks have a mineral foliation (S_o) defined by aligned actinolite and layers of relict hornblende.

2.3.4 SERPENTINITE OF THE HANGING WALL

Just above the Madstone thrust there are pods up to one meter thick of talc and actinolite or tremolite; these were observed in both the southern and northern exposures of the Madstone thrust. These rocks are generally massive; one exception, a talc schist, was found as float in the Chetco Lake area.

Above the talc amphibole rocks are 20-40 meters of serpentinized peridotite (Fig. 2.7). These serpentinites are difficult to distinguish in outcrop since they weather to the same reddish brown color of the overlying peridotites. They are, however, tougher than the peridotites and features due to strain are evident on the weathered surfaces of the rock as a foliation from aligned serpentine and strung out magnetites. In thin section, these rocks have complex textures with two generations of serpentinite (see section 3.4). The older serpentine has typical psuedomorphic textures (mesh and hourglass after olivine and bastite texture), which is typical of lizardite replacement (Wicks and Whittaker, 1977). These textures are overprinted by coarser grained serpentine which has a bladed habit characteristic of antigorite. Some of the samples collected are weakly foliated where the antigorite randomly overprints the pseudomorphic lizardite or lies within discrete shear zones, whereas others are composed mostly of aligned antigorite

Fig. 2.7 Field photograph of sheared serpentinite showing typical weathered surface. Hammer defines scale and foliation.

blades along with small patches of aligned chlorite and magnetite. These latter samples still contain small areas of relict finer grained lizardite as described above but are more overgrown by the antigorite. These more antigorite-rich rocks are similar to those defined by Norrell et al. (1989) within the Josephine peridotite as "serpentinite mylonites" although they appear to be less strained. Although the application of the term mylonite is debatable, Norrell, et. al., 1988 describes these rocks as being formed during high temperature ductile flow rather than by brittle faulting, since they are coherent in nature, are lineated, and contain asymmetric microstructures.

2.3.5 JOSEPHINE PERIDOTITE

Relatively "fresh" Josephine peridotite is exposed above the sheared serpentinites. The term fresh is in quotations here since the Josephine ophiolite is generally at least partially serpentinized. The peridotites in the Chetco Lake area in the field appeared to have very little serpentinization except locally along late fault zones. The peridotites display a foliation and lineation, which is defined by Cr-spinel and is typically attributed in other peridotites to represent high temperature (1200°C to 1300°C) mantle asthenospheric flow at the oceanic spreading center (Nicolas, et al., 1982 and Nicolas, 1989).

In most ophiolites which develop a metamorphic sole, there is a basal highly strained peridotite mylonite unit whose fabric is superimposed on the "asthenospheric" fabric (Nicolas and Violette 1982; Nicolas, 1989). No such unit was observed in the Chetco Lake area which led Cannat and Boudier (1985) to suggest this unit was faulted away. They interpreted that these serpentine mylonites were serpentinized after peridotite mylonite formed and the textures of the mylonite were preserved. In the next section, it is observed that the serpentinite mylonites are structurally equivalent to the highly strained peridotite unit, and reflect thrusting under lower temperature conditions than most other ophiolites.

2.4 STRUCTURES OF THE ROCKS ASSOCIATED WITH THE MADSTONE THRUST

2.4.1 AMPHIBOLITES

Folding events in the amphibolites are shown in Figure 2.8. The oldest structural feature of the amphibolites is the gneissic layering (So) which produced a foliation. F1a is characterized by tight folds where So has been bent around the fold axis (Fig. 2.9). F1b is characterized by the non-coaxial folding which refolds F1a folds around similarily oriented axial planes. This non-coaxial deformation is indicated by refolded hinges, thickening and pinching out of gneissic layers, and sheath folds and shown on Figure 2.8. The axes of these folds trend north-northeast and have gentle plunges; these axes are also parallel to a north-northeast stretching lineation which is defined by aligned hornblende (Fig. 2.10). The presence of sheath folds suggests that the F1a and F1b generations are related to the same folding event and that the axes were rotated into the slip direction during progressive simple shear (e.g., Bell and Hammond, 1984).

F2 is characterized by late open folds evident only in a few outcrops (Fig. 2.11); these have gently plunging north-northwest trending axes (Fig. 2.10). In the Chetco lake area, this late folding was not observed directly in outcrop but is responsible for the general northeast dip of the rocks in the southern outcrop of amphibolite, and may be responsible for the variation in the plunge of the lineations and the wide girdle defined by the poles to the foliation (So). These folds are apparently related to the large scale folding, evident on map scale, of the Madstone thrust and the younger Valen Lake thrust. Figure 2.12 is a sketch of how F1 and F2 are thought to be related.

The foliation and lineation were difficult to measure for the phyllonites and most often had to measured later in the laboratory; thus, only a limited number of data were collected. Despite this limitation, the foliations and lineations of F1 in the phyllonite plot on an equal-area projection similarily to those of the amphibolite (Fig. 2.10). Therefore, these rocks appear to be structurally concordant.

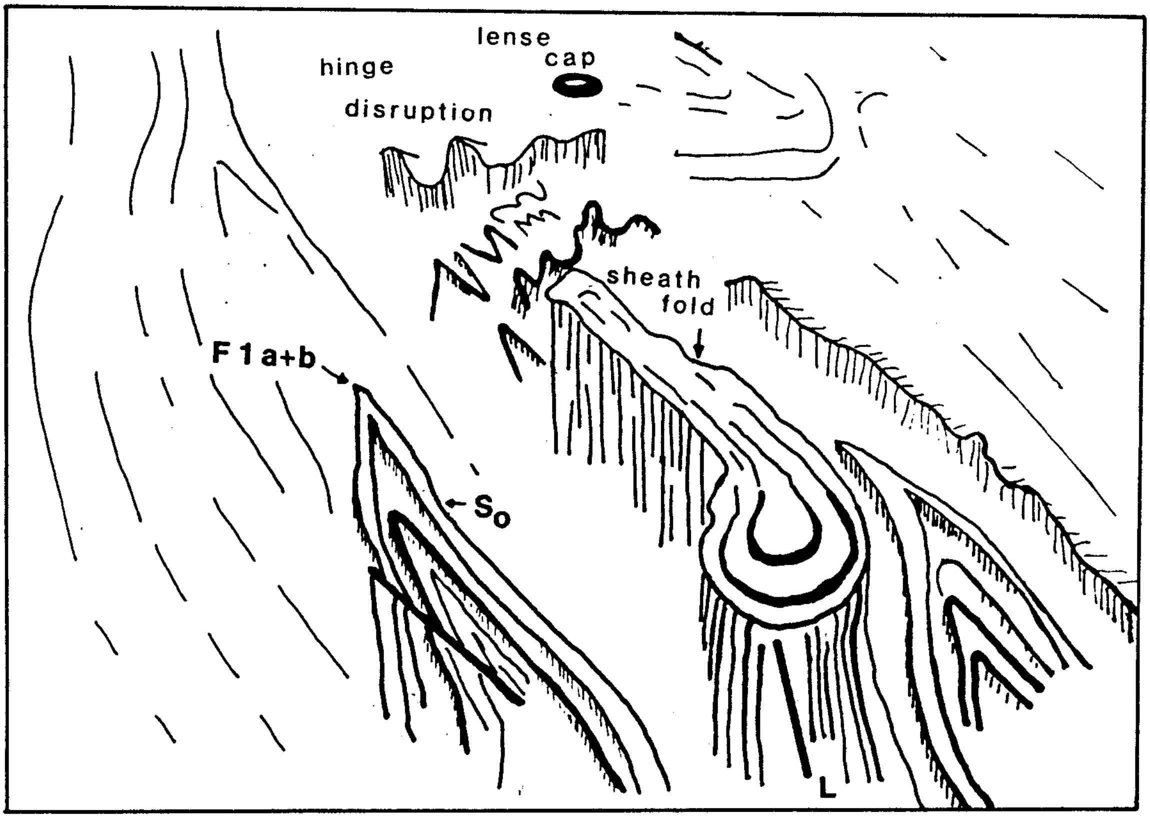


Fig. 2.8 Sketch of field photograph showing the relationship between So, Fla+b, So is folded around Fla+b. As deformation continues the sheath fold develops. Note the lense cap for scale and the hinge disruption around the sheath fold.

Fig. 2.9 Typical gneissic amphibolite in the Chetco Lake region showing folded foliation. The sample is cut normal to the fold hinges which are parallel to a stretching lineation.

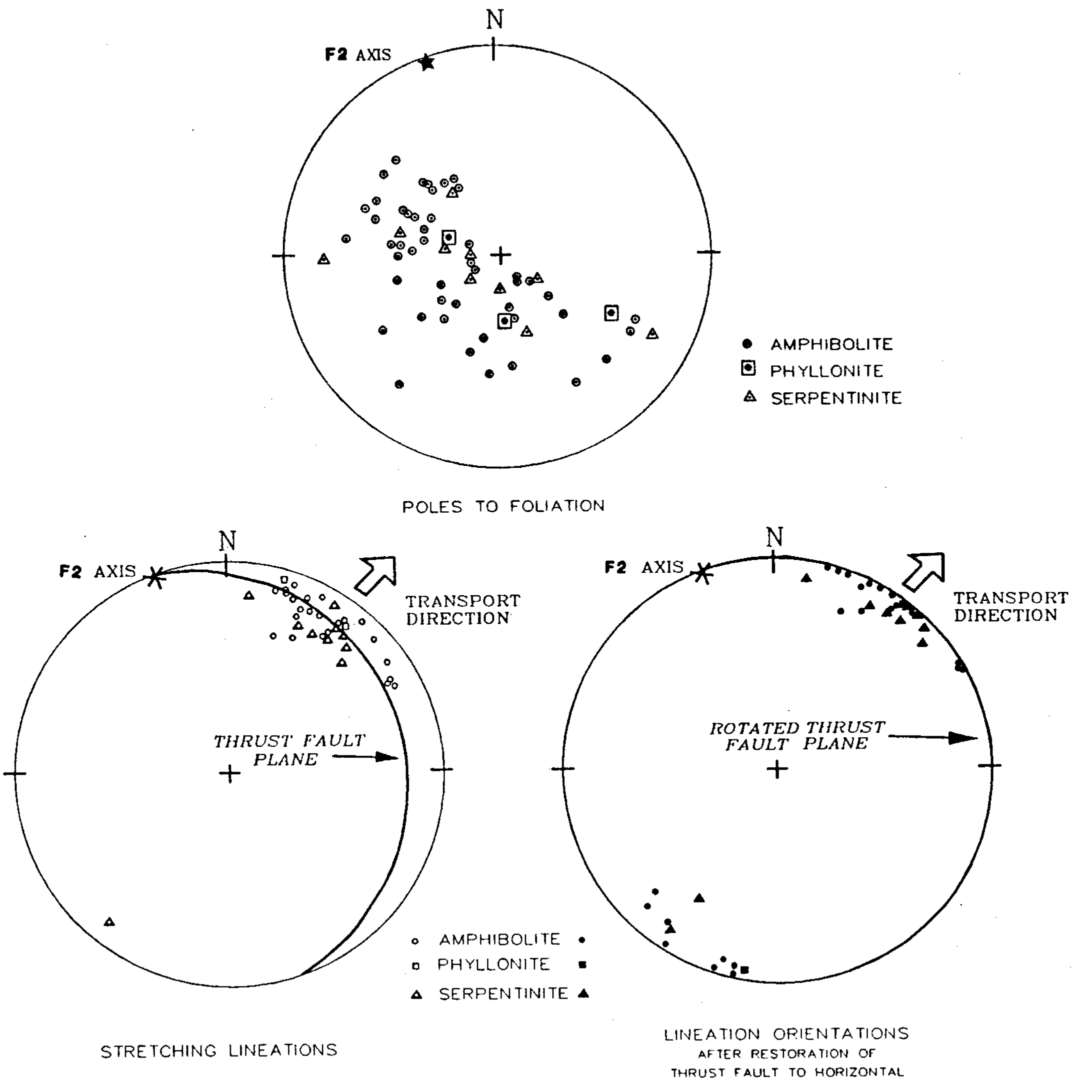


Fig. 2.10 Equal-area projection of the poles to foliations (unrestored) and lineations, and lineations after restoration of the thrust to horizontal by rotation around the F2 axis. F1a and F1b axes are parallel to lineations in the amphibolite. Trend and plunge of F2 based on two mesoscopic F2 axes and the axis defined by the orientation of the Madstone thrust in the two areas north and south of Vulcan Peak.

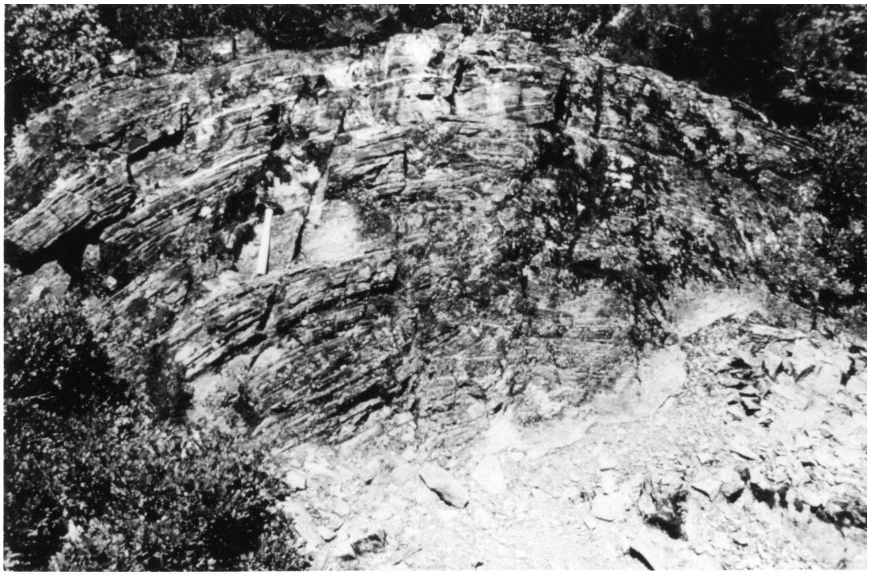


Fig. 2.11 Field photograph showing a typical example of an F2 fold near Vulcan Peak. Hammer shows scale.

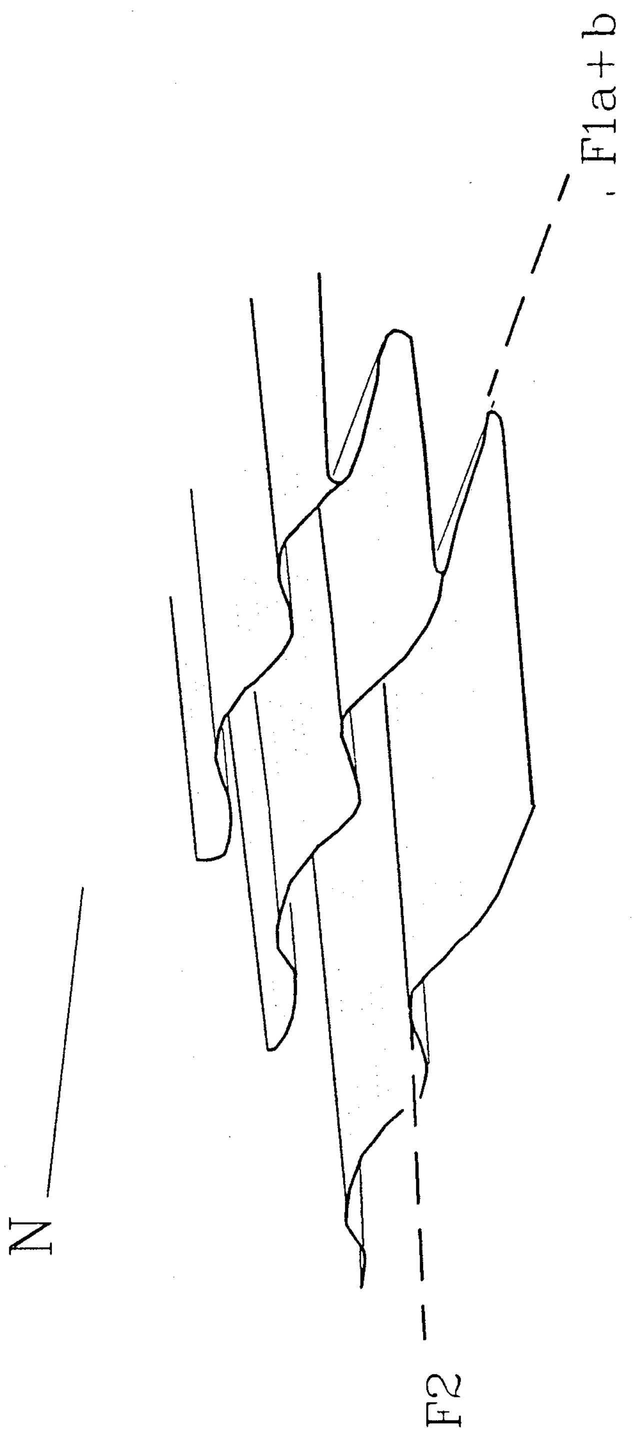


Fig. 2.12 Sketch showing the relationship between F1 and F2. F1 axes trend to the northeast, whereas F2 axes trend to the northwest.

2.4.2 SERPENTINITES

Although difficult, a limited amount of structures, such as foliation (Fig. 2.7) and more rarely lineation, were measured in the field (Fig. 2.7). The lineation is defined by elongated magnetites and aligned serpentine. Fig 2.10 shows the distribution of the poles to the foliation. They are similar in orientation to the poles of foliation in the amphibolite. What is most remarkable is the similarity between the lineation directions of the serpentinites and the amphibolites which both plunge gently to the north-northeast (Fig. 2.10).

2.4.3 CONCLUSION

Although only a limited amount of data were collected in the serpentinites and phyllonites, the similar orientation of the foliations and lineations indicate that the structures of the amphibolite, phyllonite, and serpentinite are concordant. This conclusion suggests that the structures observed formed during the same deformation event; along with age information presented in the next chapter, this conclusion suggests that the structures formed during the thrusting of the Josephine ophiolite, much like the structures in metamorphic soles beneath other ophiolites. The serpentinite mylonites in this case, however, occupy the same position of the highly strained peridotites in other soles.

2.5 MOVEMENT ALONG THE MADSTONE THRUST

Displacement on the Madstone thrust had to be $\geq$ 12 kilometers as indicated by the exposures of the Madstone thrust. This distance is the map distance perpendicular to strike between the two limbs of the Madstone thrust. Most likely the displacement is much larger than the 12 kilometers. The roof thrust above the Josephine ophiolite and the Galice formation has a minimum displacement of 40 kilometers (Harper, et. al., 1989).

The direction of thrusting can be determined by sense of shear criteria if these rocks represent mylonites and formed during thrusting. The rocks themselves display features typical of rocks that have been described as mylonites. The orientation of stretching lineations in the amphibolites and serpentine mylonites are concordant and interpreted to be parallel to the bulk transport direction.

If this interpretation is correct, then thin sections cut perpendicular to the foliation and parallel to the lineation will reveal microstructures which can give the sense of shear for these rocks. The sense of shear data are interpreted using criteria discussed by Berthe and others (1979), White and others (1980), Simpson and Schmid (1983), Lister and Snoke (1984), and Passchier and Simpson (1986) and Norrell (1989) and are as follows: composite fabrics (S-C), shear bands (C'), rotated porphyroclasts, and asymmetric pressure shadows. Also, crystallographic fabrics evident in thin section were used for hornblende (Hall, 1984), quartz (e.g., Lister and Hobbs, 1980) and plagioclase (Ji and Mainprice, 1989; Ji, et.al., 1988). Retrograde muscovite and sphene also appeared to have a preferred crystallographic orientation which is oblique to the main foliation and may give a sense of shear.

2.5.1 SENSE OF SHEAR INDICATORS FOR THE ROCKS ASSOCIATED WITH THE MADSTONE THRUST

Hornblende in the gneissic amphibolite has a strong preferred crystallographic and shape orientation parallel to the gneissic layering. The hornblende crystals have ragged edges and commonly show undulatory extinction. Quartz and plagioclase are intergrown and generally form relatively fine grained equant grains in the lighter layers. Plagioclase porphyroclasts, some of which show relict igneous zoning, along with the finer grain size of quartz and feldspar suggests that these rocks have undergone grain size reduction typical of mylonites.

In some of the amphibolites, some small hornblende grains appear to lie slightly oblique to the main foliation (Fig. 2.13 and 2.14). In some cases these grains may even appear to bend into the foliation direction. Although this obliquity is very subtle, these two foliations may define an SC foliation.

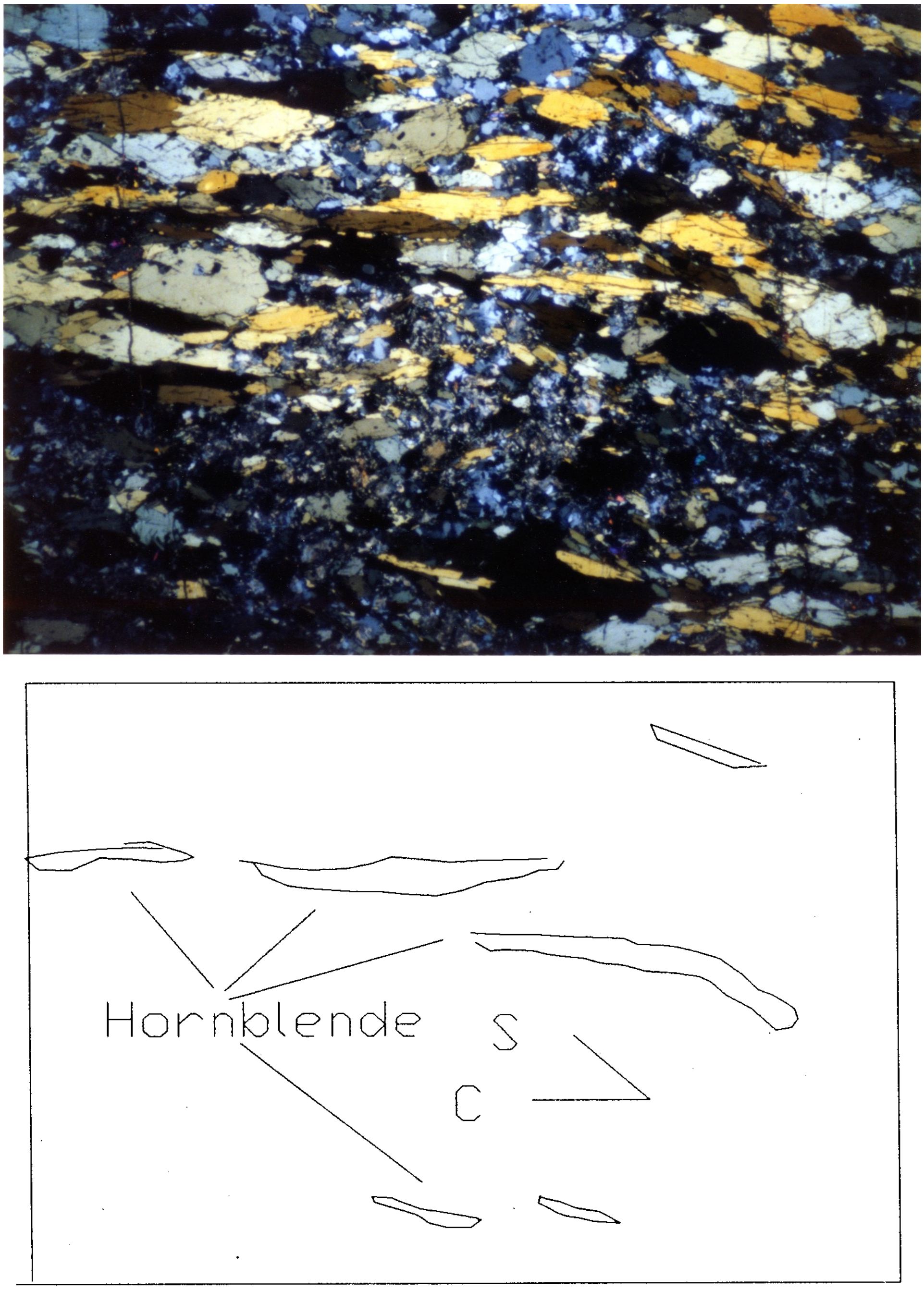


Fig. 2.13 Photomicrograph of gneissic amphibolite showing tow hornblende foliations indication upper block to the left. The long length of view is 5 millimeters across.

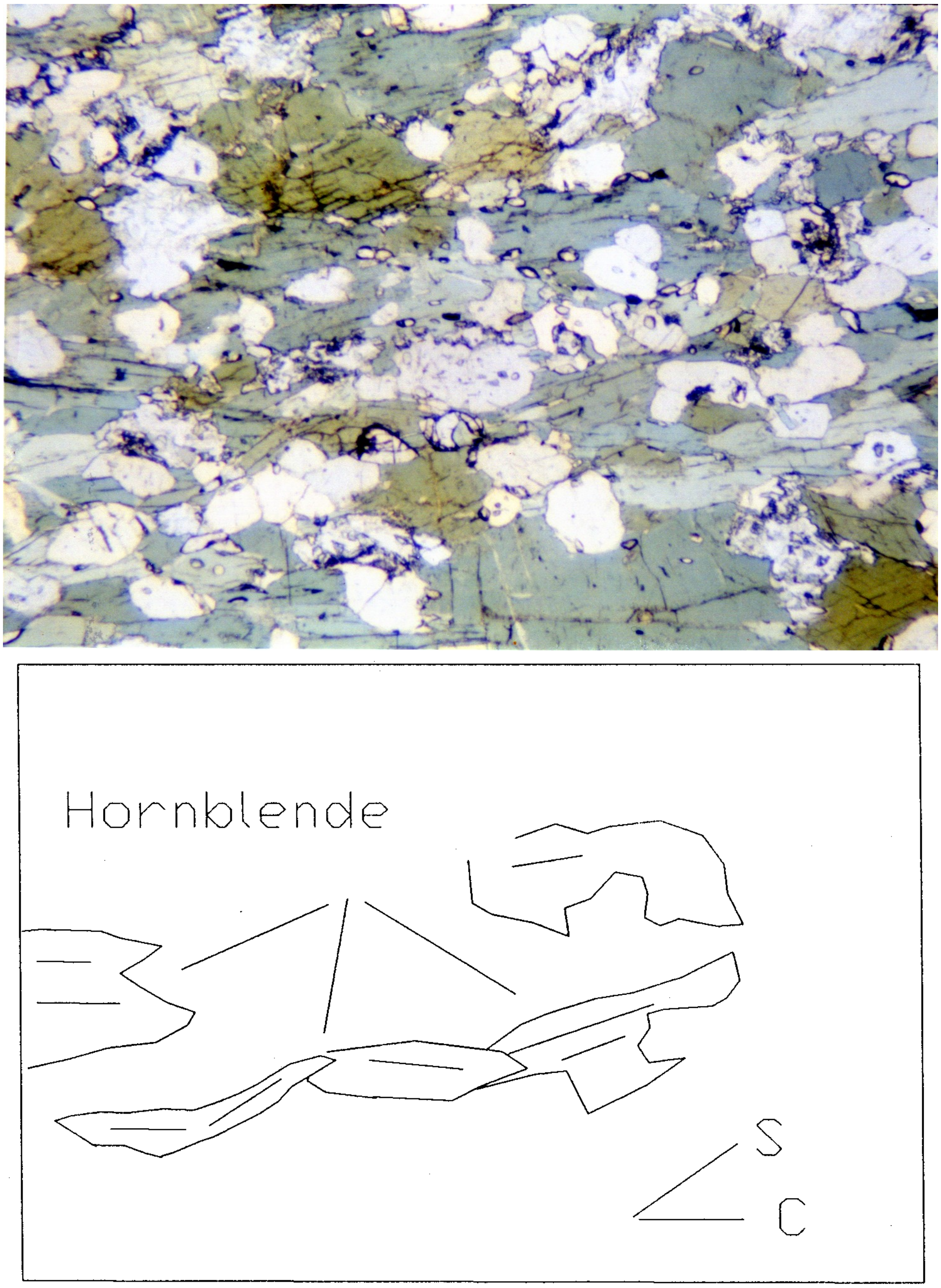


Fig. 2.14 Photograph of gneissic amphibolite showing two hornblende foliations indicating dextral shear. The long length field of view is 1.5 millimeters across.

The shear sense in the amphibolite was also determined using a technique developed by Hall (1984). In his work, he used ductile shear zones of known displacement determined from asymmetric augen to test his criteria: if c-axes of the hornblende are subparallel to foliation, an asymmetry is defined by the uniform inclination of a-axes. In Hall's case for dextral shear in the thin section, the a-axes were inclined in a clockwise sense with respect to the foliation (Fig. 2.15). This asymmetry can be identified in thin section using changes in pleochroism as the microscope stage is rotated. Thus, for a dextral sense-of-shear when the section is oriented so that the c-axes are parallel to the plane of polarization and then rotated equal distances in either direction, the pleochroism is lighter in the clockwise rotation than counterclockwise rotation. The slip system in hornblende is apparently the (100) plane in the [001] direction which would be subparallel to the c-foliation (Hall, 1984 and Brodie, et al., 1985).

Mechanical and/or growth twins in the plagioclase have a preferred orientation and are generally at an angle to the main foliation, similar to the a-axes of the hornblende. This crystallographic orientation may also be due to slip along the (010) plane which creates this asymmetric orientation (Ji and others, 1988).

One metaquartzite was examined for shear indicators. It contains quartz, biotite, minor garnet, and minor hornblende. This sample contains a biotite fabric which appears as two somewhat oblique foliations similar to an SC fabric. However, grainsize is too small to determine whether individual grains are bent into the foliation. It is possible, therefore that this feature represents coaxial flattening instead of shear. However, the quartz seems to have a preferred crystallographic orientation. Cannat and Boudier (1985) measured the c-axis orientations of quartz in stringers in the amphibolite and metaquartzite in the Chetco Lake area. They assumed intercrystalline slip along the basal plane and used the quartz wedge to determine the orientation. This observation was backed up by U-stage measurements of one sample. Unfortunately, they did not

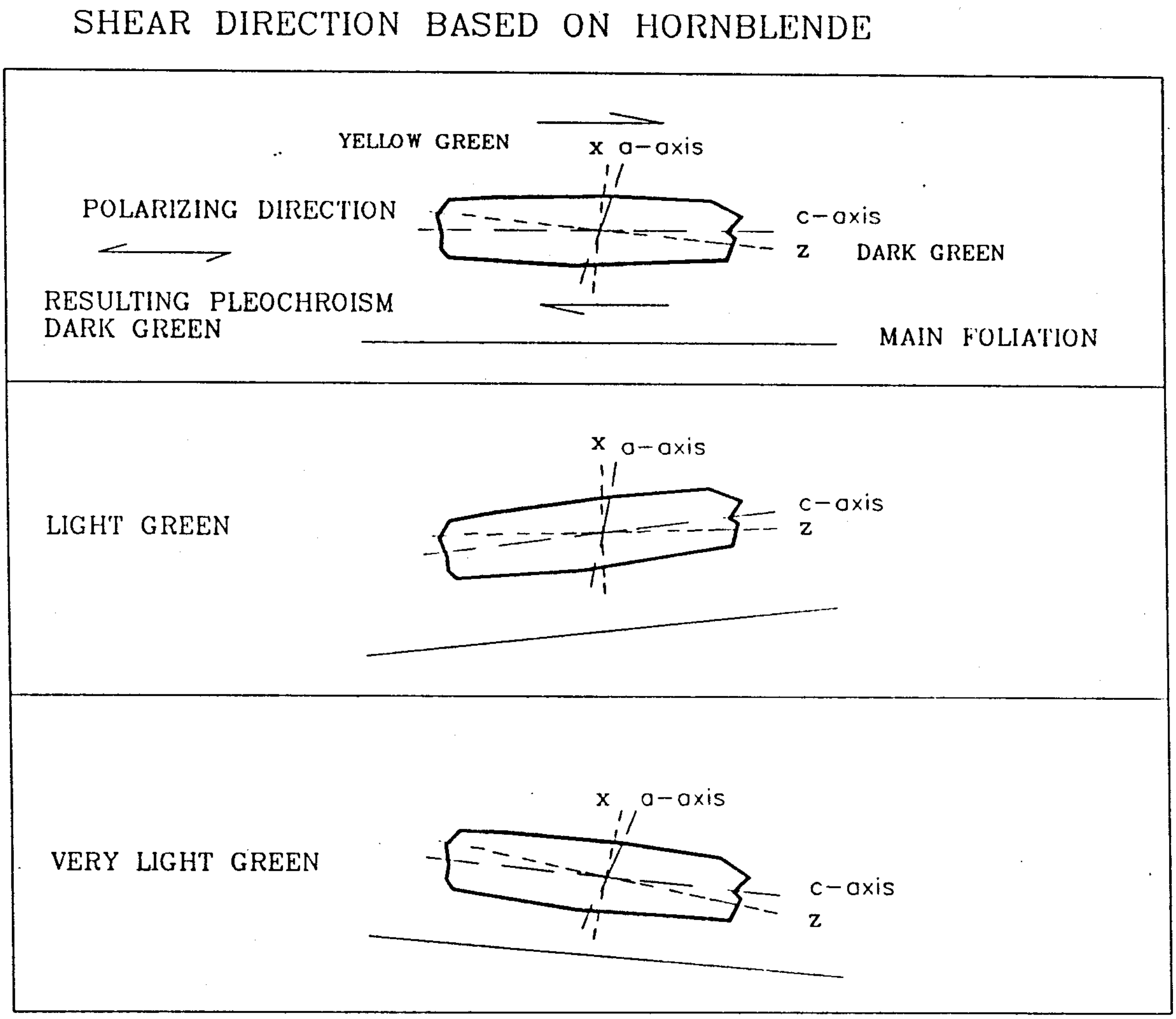


Fig. 2.15 Diagram showing the technique to determine sense of shear from pleochroism in hornblende.

reference their technique for determining sense of shear from this fabric. However, in a shear zone the basal plane of the quartz crystal will rotate into the shear direction, since the crystal slips along its basal plane at low temperatures. At higher temperatures both basal and prismatic slip can occur. However, Chapter 3 establishes a temperature range for the metamorphism which would indicate basal slip as the predominate slip system. Thus, in a thin section cut perpendicular to the foliation and parallel to the lineation, the c-axes will be parallel to the pole to the foliation. However, the c-axes orientations most often show an asymmetry which is measured by U-stage measurements and can be used to determine shear sense. This eventually should be done for the sample from Chetco Lake. The addition or subtraction using the quartz wedge gave the preliminary result of quartz preferred orientation presented in Table 2.1.

Sense of shear has also been determined for the later stages of deformation using 1) offset veins in the amphibolites 2) microstructures in mafic phyllonite, and 3) microstructures in a pegmatite dike which is deformed, but cuts gneissic layering in the gneissic amphibolite. In several amphibolites, there are en-echelon veins of greenschist facies assemblages (see 3.4) which give a sense of shear. The phyllonite, which has lineations concordant with the amphibolites, has perhaps the clearest shear indicators. Half of the phyllonite samples have abundant porphyroclasts of actinolite and hornblende that have asymmetric tails and shapes (Figs. 2.16, 2.17, and 2.18). In addition, epidote porphyroclasts have asymmetric shapes, and relict hornblende are broken and normal faulted (Fig. 2.18) Shear bands (C') are also abundant in the phyllonite samples (Fig. 2.16).

The pegmatite dikes are lineated and some have a well developed SC fabric defined by the preferred orientation of micas (Fig. 2.19) and by lenticular aggregates of recrystallized quartz. The orientation of these features in the Chetco Lake area indicates movement more towards the north than the amphibolites and phyllonites, suggesting that either locally a different direction of movement existed or during the pegmatite deformation a slightly different shear orientation regime existed.

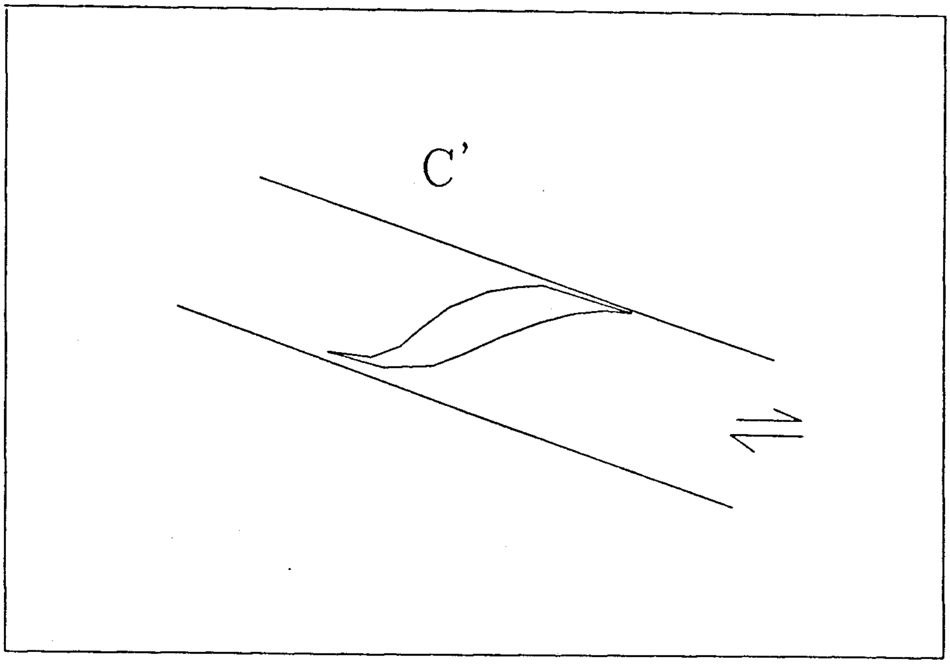


Fig. 2.16 Photomicrograph showing asymmetric porphyroclast of actinolite giving dextral sense of shear. A shear band is also identified giving the same sense of shear. The longest length of view is about 1 mm.

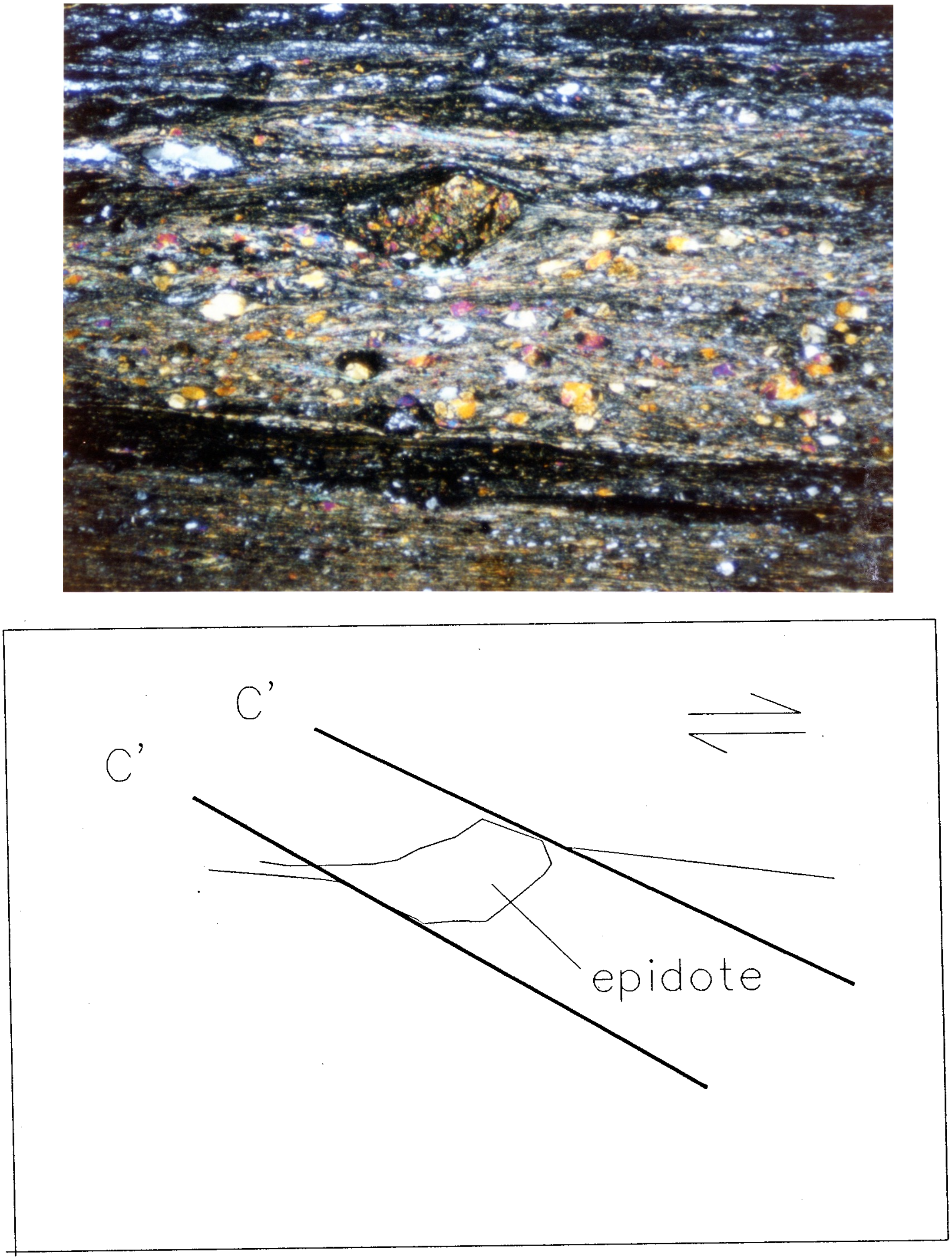


Fig. 2.17 Photomicrograph of asymmetric epidote porphyroclast the length of which is 0.5 mm across. Shear band gives dextral sense of shear.

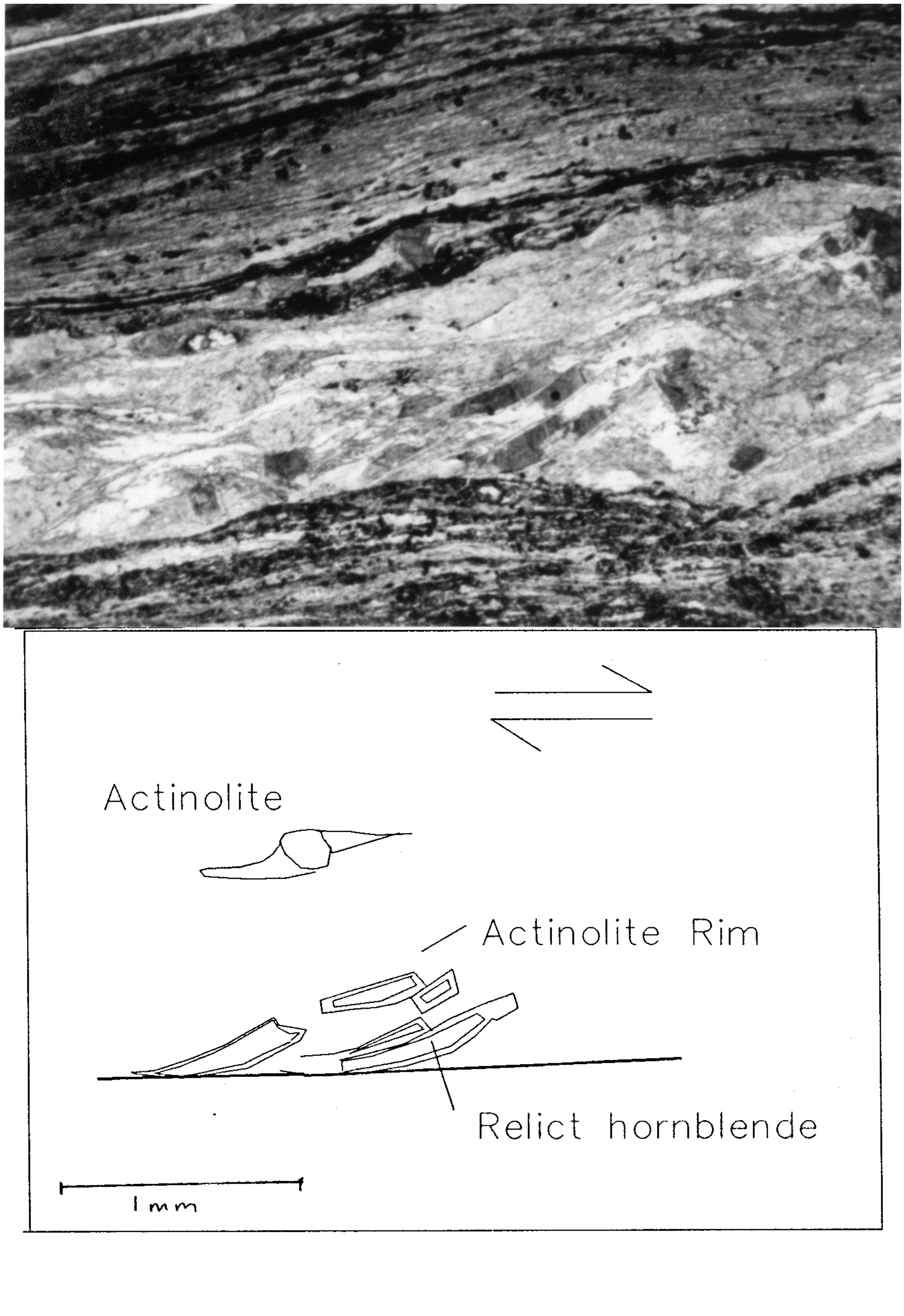


Fig. 2.18 **Photomicrograph of mafic phyllonite showing porphyroclasts of brown hornblende rimmed by blue-green hornblende and actinolite.**

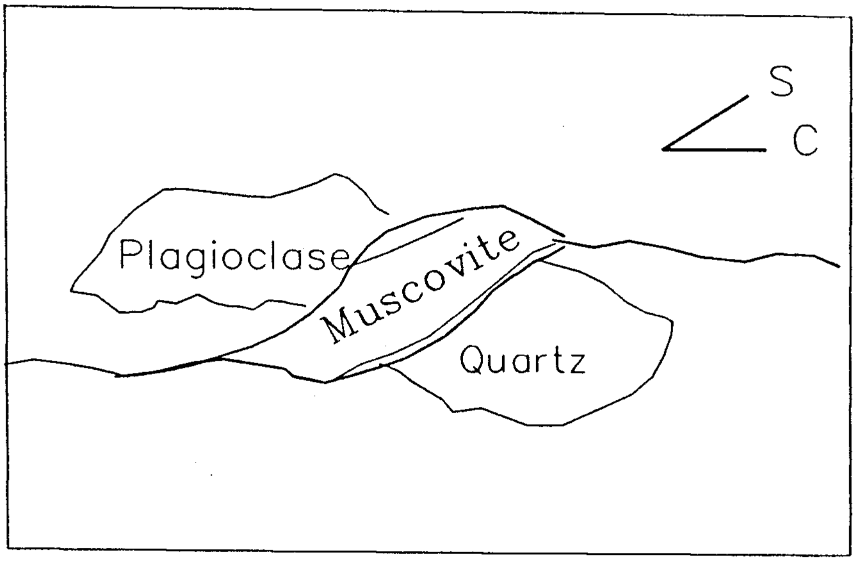


Fig. 2.19 Photomicrograph of pegmatite dike which has a well developed SC fabric defined by muscovite. Shown here is a close up view typical of asymmetric muscovite showing bending into the C surface. The long length field of veiw is 1.5 mm.

The foliated, antigorite-rich serpentinites of the hanging wall along the base of the Josephine Peridotite are structurally concordant with the amphibolite. Many of these rocks, however, are apparently not highly strained and do not have well developed shear sense indicators. The few samples which did display indicators had asymmetric magnetite porphyroclasts and shear bands (C') (Fig. 2.20).

2.5.2 SUMMARY OF THE RESULTS OF SHEAR CRITERIA

Table 2.1 is a summary of the results of the shear criteria. Twenty-five sections were cut perpendicular to foliation and parallel to the lineation. The amphibolite as well as the phyllonite consistently show upper block movement to the north-northeast. The criteria for the phyllonite was based on the majority of clasts that showed dextral sense of shear. A small percentage (less than 30 %) of the clasts showed the opposite sense of shear. Continued movement in the same direction is indicated by the shear indicators in the phyllonite, although the pegmatite appears to have sheared more northwardly. The north-northeastward direction of shear was also determined by Cannat and Boudier (1985) in their study of the quartz stringers and pressure shadows in the Chetco lake area. If these shear indicators give the sense of displacement this means that the Josephine Peridotite thrust to the north-northeast over the amphibolites.

Determination of actual thrusting direction along the Madstone thrust requires correction for the post-Nevadan folding. The dip of the thrust in the Chetco lake area is 18° to the northeast (Fig. 2.10). This dip was removed by rotation about the subhorizontal F2 fold axis as measured in outcrop (see Fig. 2.10). After this rotation, the lineation direction does not effectively change but the plunge becomes shallower. Thus, the thrusting direction on the Madstone thrust is essentially unchanged by later folding.

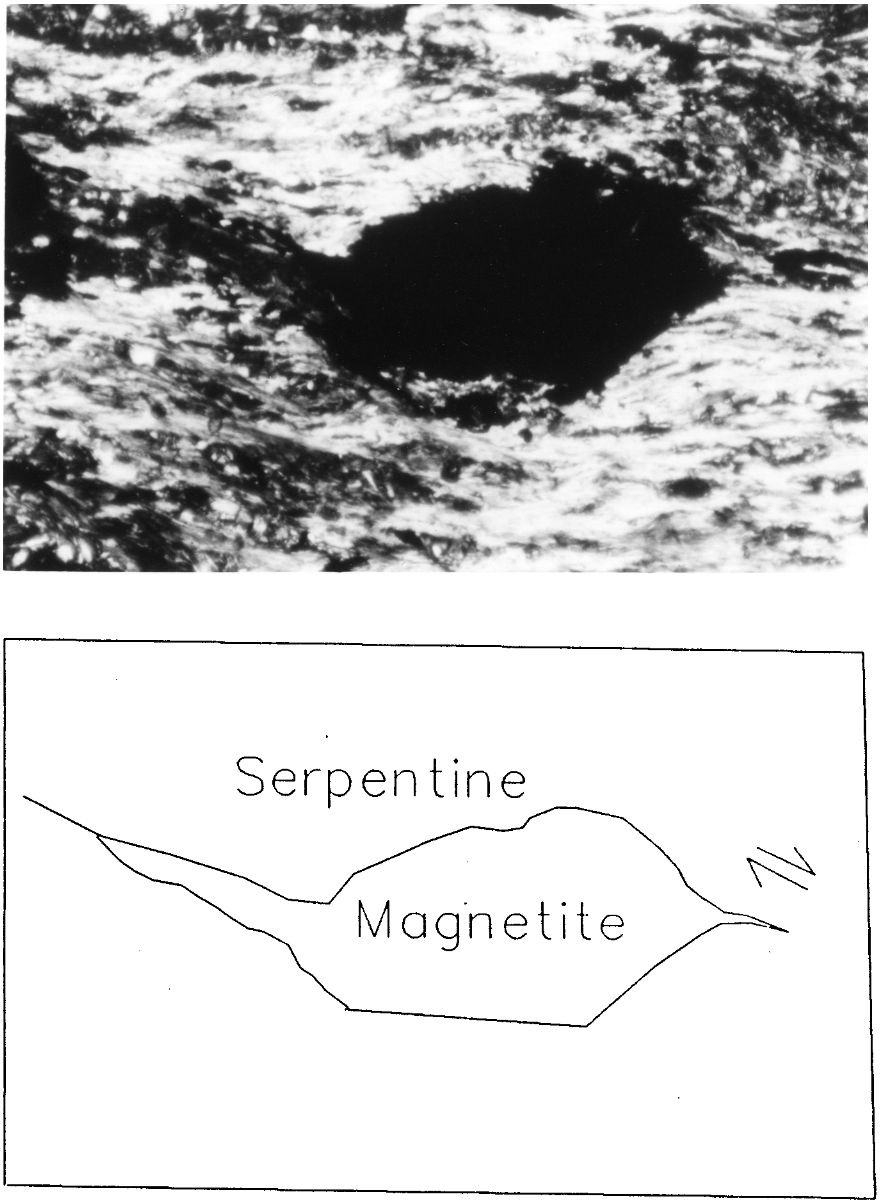


Fig. 2.20 Photomicrograph of serpentinite mylonite cut perpendicular to foliation and parallel to lineation. Dextral sense of shear suggested by the asymmetric tails on the magnetite porphyroclast. The matrix consists of antigorite with a grain size of ~0.2 mm. The long length field of view is 1.5 mm. In the field, these antigorite-rich rocks are coherent and commonly extremely tough.

TABLE 2.1 SHEAR SENSE FOR FAULT ROCKS ALONG THE MADSTONE THRUST

SERPENTINITE

Sample no.	Magnetite Porphyroclasts	Shear Band C'	Antigorite Preferred Orientation
K10		NE*	NE
K14	NE		NE
K16	NE?		NE
K19A1			NE?
SA109	NE	unclear	
MKG2B	unclear		NE?
MKG2D			NE?
MKG2F			unclear
MKG2G			unclear

AMPHIBOLITE

Sample no.	Shape Preferred Orientation	SC fabric	Crystallographic Preferred Orientation	Retrograde: Vein	Retrograde: Crystallographic Preferred Orientation
Sa12	NE?	NE?	h[†] NE	NE	s[§] NE
Sa13	SW?	NE	h NE?	NE	s NE
Sa 34		NE?	h NE	NE	m** NE
Sa 44		NE	h NE	unclear	
			q[††] SW?		
K12	NE	NE	h NE	NE	m NE
M2H		NE?			m NE?
MKG1F		NE	h NE		
K11-Quartzite		unclear	q NE		
Sa36-Pegmatite		NE			

MAFIC PHYLLONITE

Sample no.	Porphyroclasts	Shear Band C'	Retrograde Vein
SA100	NE		
SA 102	NE	NE	
K21	NE		SW?
Sa105		NE	
Sa150	unclear	NE	
K2	NE?		
K5	NE		

*Top to the NE or SW

†Hornblende

§Sphene

**Muscovite

††Quartz

2.6 DISCUSSION OF THRUSTING DIRECTION

This thrusting direction is very different compared to the known thrusting directions of the roof thrust (the Orleans fault) of the Josephine ophiolite although both thrust were active during the Nevadan orogeny (Harper et al; in press, Chapter 3 for age of Madstone thrusting). Regional mapping and mesoscopic structures in the Galice Formation indicate west- or northwest-directed thrusting on this thrust (Snoke, 1977; Harper, 1980; Norman, 1983; Gray, 1985; Jones, 1988; Harper and others, 1989, Harper, in prep; Griesau, in prep). Thus, the result of this study indicates a difference in thrusting of 70-90° between the roof (Orleans) and basal (Madstone) thrust. Also, this direction is subparallel to the inferred paleogeographic trends at this latitude during the Late Jurassic and parallel to the direction of spreading in the Josephine ophiolite. This difference may indicate the tectonic model for the emplacement of the Josephine ophiolite needs to be further modified (see Chapter 4).

Another structural correction may be required to restore the structures observed in the amphibolite and serpentinite to their Nevadan orientation. Paleomagnetic studies indicate a clockwise rotation in the Tertiary for the Klamath Mountains which produced the apparent oroclinal bending evident on Figure 1.1. The declination anomalies in the Klamath mountains appear to support oroclinal bending (Renne and Scott, 1988; Renne and others, 1988). If such a bending is inferred for the Chetco lake area the lineations could be corrected for this large rotation (Harper, et al., in press). The resulting lineation direction would be to the northwest but would only correct the difference of ~90° between the thrusting directions on the roof and basal thrust by ~20°. Thus, the thrusting directions would still be significantly different. However, paleomagnetic studies must be done in the Chetco lake area to determine whether this study area has undergone similar rotations, since parts of the Klamaths may have acted as separate blocks during this rotation.

2.7 CONCLUSIONS

The amphibolites below the Madstone thrust have concordant structures with serpentinite mylonites which are above the Madstone thrust. This compatibility and the geochronology (Chapter 3) suggests that the amphibolites represent a metamorphic sole of the Josephine ophiolite and that the serpentinites occupy the position of the highly-strained peridotite which is present in most ophiolites that contain metamorphic soles. The thrusting direction was determined by shear criteria and indicates that the Josephine ophiolite was thrust north-northeastward over the amphibolite sole. The phyllonite indicates that the thrusting continued throughout retrogressive metamorphism (discussed further in Chapter 3). This direction is distinct from known displacements on the roof thrust (Orleans). Probable Tertiary oroclinal bending in the Klamath Mountains may have resulted in a large clockwise rotation. The tectonic model for the emplacement of the Josephine ophiolite may require modification based on the results of this structural study and are discussed in conjunction with the data in this chapter and Chapter 3.

CHAPTER 3: GEOCHEMISTRY AND OTHER CONSTRAINTS

3.1 INTRODUCTION

The structure of the basal portion of the Josephine ophiolite gives part of the complex history for the emplacement of the Josephine ophiolite. Structural data alone, however, cannot complete a tectonic model. The following is preliminary data on geochemistry, Ar/Ar dates, geothermometry, and geobarometry, to constrain the possible tectonic model for the emplacement of the Josephine ophiolite (Chapter 4).

3.2 GEOCHEMISTRY

Ten samples of the amphibolites were collected in the study area as well as one additional sample which was collected near the northern exposure of the Madstone thrust (Fig. 1.6). The locations of these ten data points are shown in Fig 3.1. Major and trace element analyses by x-ray fluorescence were done at McGill University in Montreal (Ahmedali, analyst). The chemical results are given in Table 3.1.

After plotting the data on several diagrams, the author noted that the data fell into three distinct groups and these are referred to Groups 1, 2, and 3 in the rest of this text. KMS4, Sa 33, and Sa 34 make up Group 1. KMS4 lies along the northern exposure of the Madstone thrust and Sa 33 and Sa 34 both are approximately 300 meters from the thrust contact. Group 2 consists of Sa 12, Sa 13, Sa 8, and CLS. All of these are located east of Chetco Lake, except Sa 8 which is near Chetco Lake. The remaining four samples, Sa 4, Sa 9, Sa 44, and Sa 16 which make up Group 3 are all, except for Sa 4, in the near vicinity of Chetco Lake. Possible interpretations for the variance in geochemistry of Sa 4 and Sa 8 will be discussed after establishing the chemical relationships of the three groups.

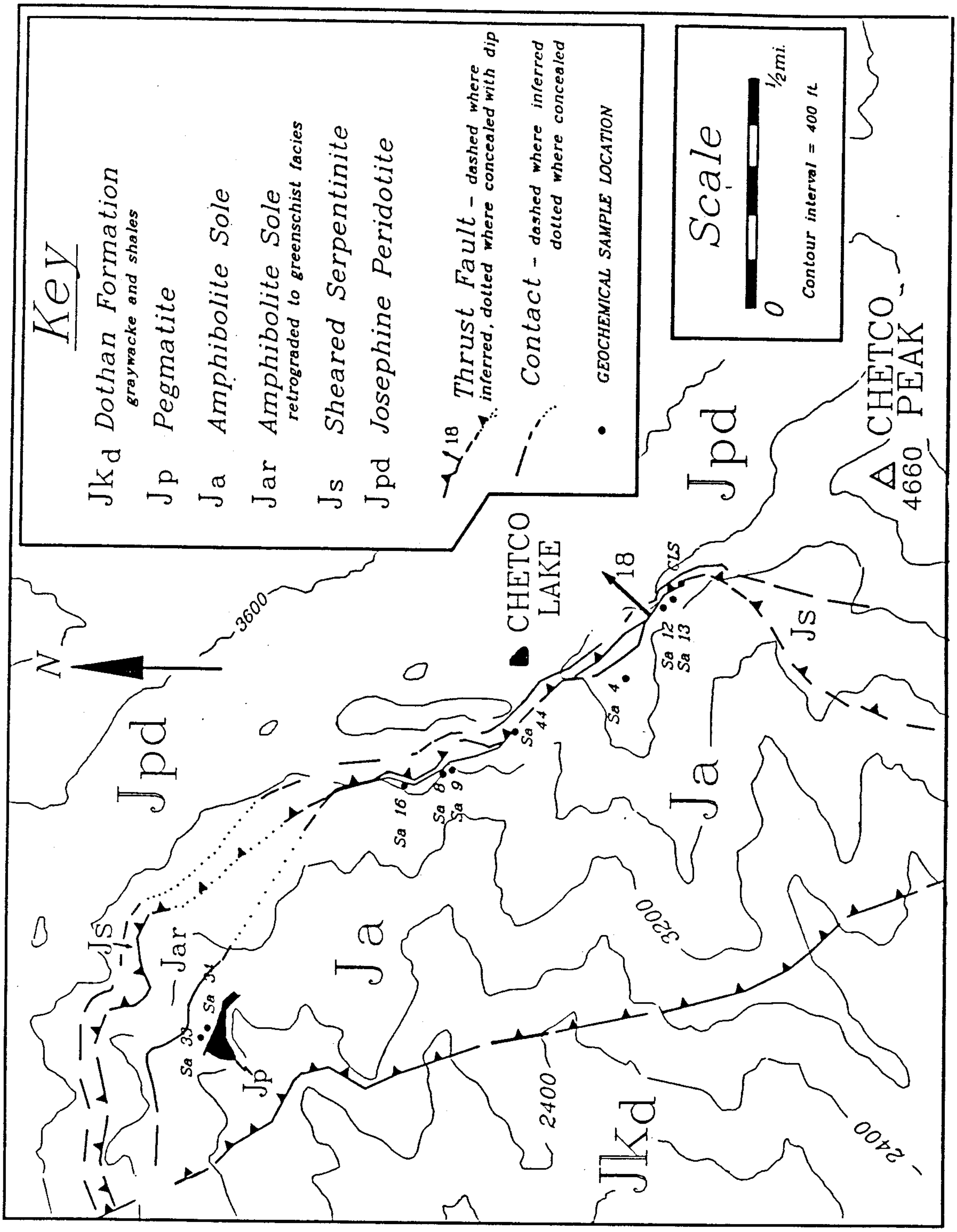


Fig. 3.1 Map of the study area showing the location of the samples collected for geochemistry.

Table 3.1a
Chemical Results of the samples near Chetco Lake

	CLS	SA4	SA8	SA9	SA34	SA12
SiO_2	45.68	46.24	48.65	47.10	56.91	45.51
TiO_2	1.59	2.94	1.46	3.21	0.54	1.16
Al_2O_3	16.42	17.09	14.65	16.91	15.37	13.52
Fe_2O_3	11.56	13.29	13.84	13.58	10.25	12.94
MnO	0.17	0.19	0.42	0.14	0.16	0.20
MgO	7.51	5.56	7.29	2.89	4.91	9.86
CaO	13.84	8.65	9.86	10.61	7.76	12.17
Na_2O	2.16	3.25	2.78	3.93	2.48	2.76
K_2O	0.30	1.25	0.74	1.15	1.09	0.35
P_2O_5	0.19	0.66	0.13	0.50	0.06	0.07
BaO	111.00	390.00	400.00	346.00	360.00	85.00
LOI	1.40	1.62	0.94	0.97	1.09	1.02
Total	100.91	100.84	100.85	101.07	100.70	99.62

Note: Detection limit for major elements: 10 ppm. All analyses done on fused beads prepared from ignited samples Total iron present has been recalculated as Fe_2O_3. In cases where most of the iron was originally in the ferrous state a higher total is the result.

Nb	14.00	44.00	12.00	29.00	9.00	6.00
Zr*	71.58	257.00	80.19	203.20	13.77	46.98
Y	25.00	34.00	37.00	31.00	12.00	26.00
Sr	189.00	380.00	189.00	444.00	226.00	71.00
Rb	14.00	31.00	22.00	27.00	38.00	5.00
Pb	<5.00	<5.00	<5.00	8.00	10.00	9.00
Th	<5.00	<5.00	<5.00	<5.00	5.00	<5.00
U	7.00	<5.00	<5.00	<5.00	7.00	<5.00
Cr	306.00	223.70	204.70	58.50	144.20	353.60
V	289.00	296.00	324.00	340.00	234.00	293.00
Ni	118.00	116.00	96.00	66.00	32.00	115.00

Note: All above analyses done on pressed powder pellets. Detection limit: 15 ppm for Cr; 10 ppm for V, Ni, Ba; 5 ppm for the rest.

* Zr measurements were recalculated using a correction curve for systematic labortory error (correction curve provided by J.W. Delano).

Table 3.1b
Chemical Results of the samples near Chetco Lake

	SA13	SA16	SA33	SA44	KMS4
SiO_2	45.79	46.75	52.32	45.58	57.51
TiO_2	1.35	3.08	0.53	2.77	0.62
Al_2O_3	15.07	16.79	14.47	16.82	15.06
Fe_2O_3	14.56	13.27	11.57	12.89	10.55
MnO	0.22	0.19	0.18	0.19	0.17
MgO	6.47	5.07	6.40	6.44	4.45
CaO	11.97	8.70	10.30	9.43	8.24
Na_2O	2.44	3.67	1.44	3.51	2.14
K_2O	0.92	1.22	1.15	0.64	0.64
P_2O_5	0.14	0.68	0.05	0.30	0.08
BaO	107.00	365.00	201.00	291.00	257.00
LOI	1.16	1.23	1.82	1.38	1.23
Total	100.18	100.77	100.32	100.02	100.75

Note: Detection limit for major elements: 10 ppm. All analyses done on fused beads prepared from ignited samples Total iron present has been recalculated as Fe_2O_3. In cases where most of the iron was originally in the ferrous state a higher total is the result.

Nb	7.00	37.00	5.00	22.00	8.00
Zr*	65.43	229.00	29.76	287.00	29.76
Y	30.00	35.00	14.00	49.00	13.00
Sr	136.00	403.00	177.00	546.00	295.00
Rb	13.00	25.00	39.00	12.00	24.00
Pb	10.00	10.00	<5.00	7.00	5.00
Th	<5.00	5.00	<5.00	7.00	<5.00
U	<5.00	<5.00	<5.00	5.00	5.00
Cr	191.10	202.60	195.20	106.80	91.00
V	317.00	302.00	243.00	279.00	257.00
Ni	119.00	93.00	43.00	75.00	22.00

Note: All above analyses done on pressed powder pellets. Detection limit: 15 ppm for Cr; 10 ppm for V, Ni, Ba; 5 ppm for the rest.

* Zr measurements were recalculated using a correction curve for systematic labortory error (correction curve provided by J.W. Delano).

Figure 3.2 is a plot of SiO_2 vs. Alkalis. Although this diagram is somewhat unrealistic to use for these samples since alkalis are commonly very mobile during metamorphism, it is still useful to distinguish the general character of the three groups. Groups 2 and 3 plot above the alkaline curve entirely in the basalt range and virtually in a straight line. This may show a fractionation trend of these basalts or alternatively the result of influx and removal of alkalis during metamorphism.

Group 1 lies within the andesitic basalt and andesite fields even though the rocks in all three groups look very similar in hand specimen. However, although fine grained, KMS4 does contain a few larger plagioclase porphyroclasts which suggests a gabbroic protolith. Given this observation and their higher silica content, it is possible that Group 1 is related to the Chetco Intrusive Complex. Dick (1976) and Loney and Himmelberg (1977) describe the contact between the metagabbros and amphibolites in this northern area as gradational and deformed. They also express the difficulty in distinguishing the deformed gabbros from the amphibolites in outcrop because the gabbros are also strongly deformed and commonly display considerable grain size reduction. The other two data points of Group 1 may also be related to the Chetco Intrusive Complex since they are similar chemically to KMS4 and they were collected furthest from the thrust contact. Figure 3.2 also contains the two end members of the Illinois River Gabbro which is part of the Chetco Intrusive Complex (Jorgenson, 1970). Interestingly, the three data points of Group 1 plot along the fraction between these two end members. Therefore, since these samples (a) are spatially close to the metagabbros of the Chetco Intrusive Complex, (b) display grain size reduction, and (c) plot along the fractionation trend of the Illinois River complex, it is likely that samples of Group 1 are derived from syntectonic intrusives of the Chetco Intrusive Complex which has been interpreted as the roots of the active arc during formation and emplacement of the Josephine ophiolite.

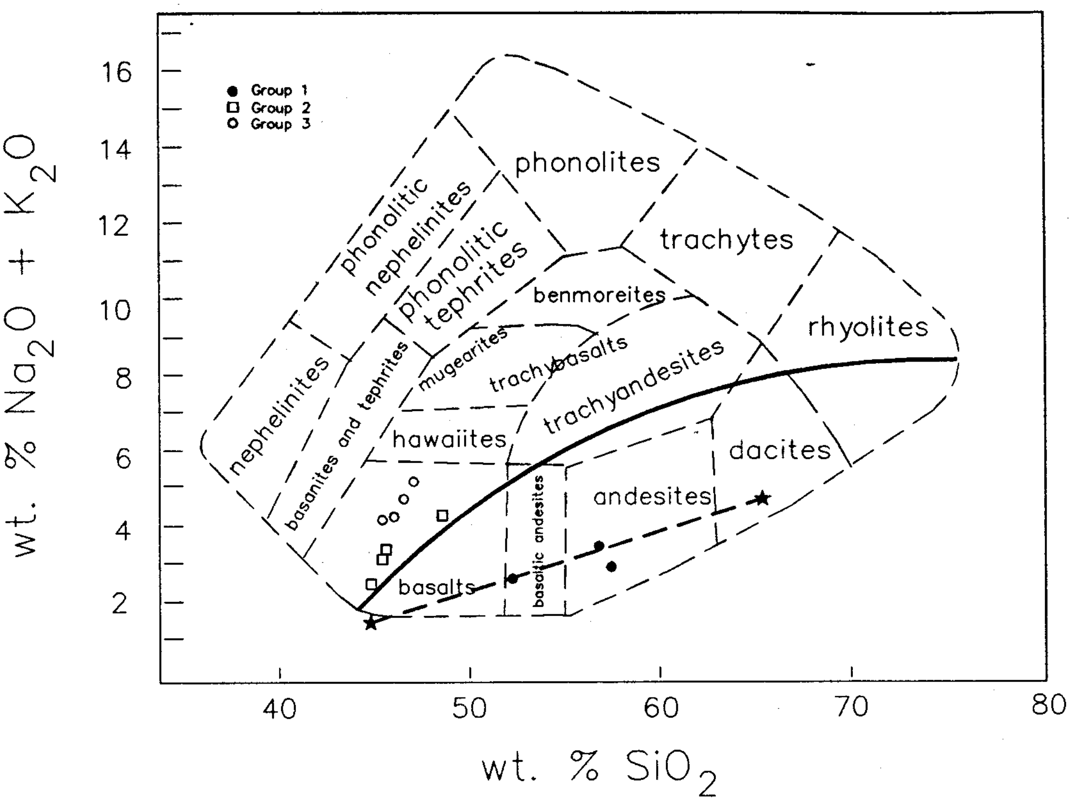


Fig. 3.2 Plot of samples on wt. % SiO_2 vs. Alkalis after Cox and others (1979). The heavy line separates alkalic and sub'alkalic magma series. The dashed line represents a fractionation trend of the Chetco Intrusive Complex.

An alternative hypothesis is that during metamorphism and deformation, these rocks experienced an input of silica from fluids. Abundant quartz veins were observed in the field and although care was taken during sample preparation to exclude these veins, it is possible their presence created a higher SiO_2 content for a whole rock analysis then for the original rock.

The Nb/Y vs. Zr/TiO_2 diagram developed by Winchester and Floyd (1977) is more appropriate to use in this case for general classification of rocks (Fig. 3.3), since Nb, Y, Zr, and Ti are known to be generally immobile during metamorphism. Unfortunately, analyses of standards suggest that Nb values from McGill Laboratory are erroneously high (G.D. Harper, pers. com.) which would result in a shift of the data into the more alkalic fields. In this diagram, Groups 1 and 2 plot in the sub-alkaline basalt field whereas Group 3 lies within the alkali-basalt region. This is generally consistent with the Na + K vs. SiO2 plot (Fig. 3.2) for groups 2 and 3 whereas group 1 plots in the basaltic rather than the andesite field. All three groups are probably less alkalic in character than either figure indicates.

To further delineate the character of these groups, the data were plotted on the $MnO/P_2O_5/TiO_2$ discriminant diagram (Fig. 3.4) after Mullen (1982) which delineates calc-alkaline basalts (CAB) from island arc tholeiites (IAT), mid-ocean ridge basalts (MORB), and ocean island tholeiites and alkalic basalts (OIT and OIA, respectively). Group 1 plots along the IAT-CAB boundary. Since Jorgenson (1977) and Dick (1977) classify the protolith for the Illinois River metagabbro as calc-alkaline basalts, Figure 3.4 supports the conclusion above that Group 1 is related to the Chetco Intrusive Complex. Group 2 and 3 plot in the tholeiitic fields. Group 3 plots entirely within the oceanic island fields indicating a within-plate origin, whereas group 2 displays a spread from the MORB to IAT fields. It is important that Group 2 is geographically located next to a metaquartzite that has a manganese rich mineral assemblage (rhodenite; Ramp, 1975): metalliferous sediments rich in Mn that is often precipitated from low-temperature hot

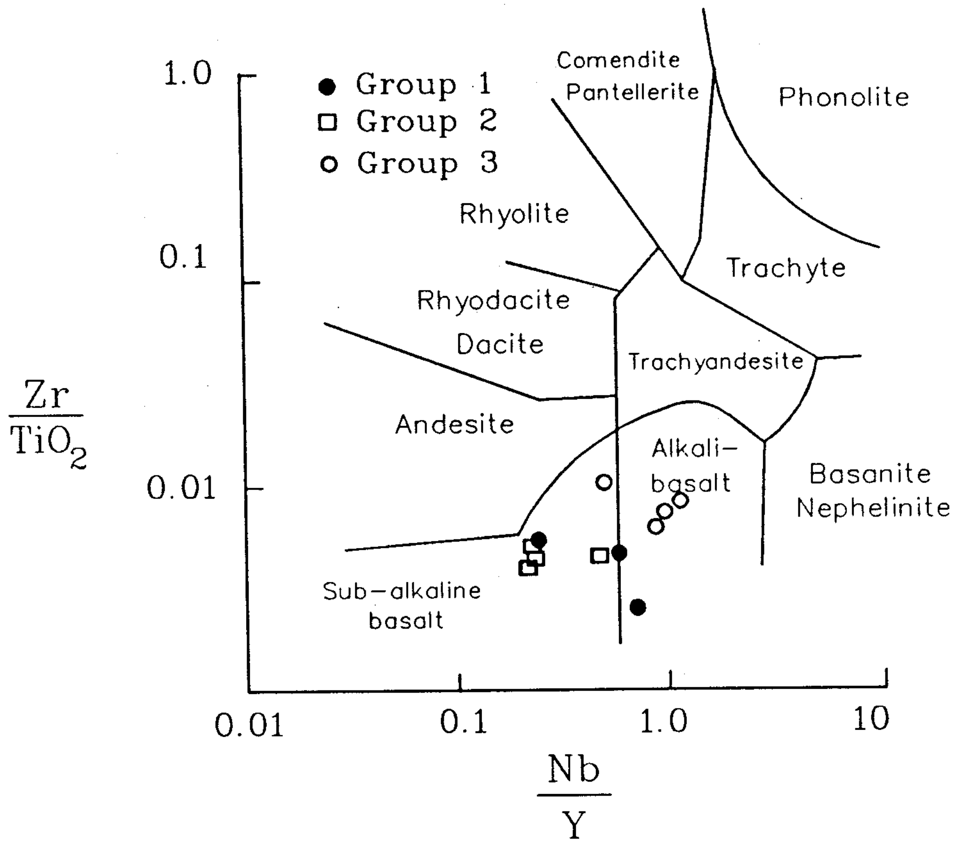


Fig. 3.3 Plot of Chetco lake samples on Nb/Y vs. Zr/TiO_2 developed by Winchester and Floyd (1977).

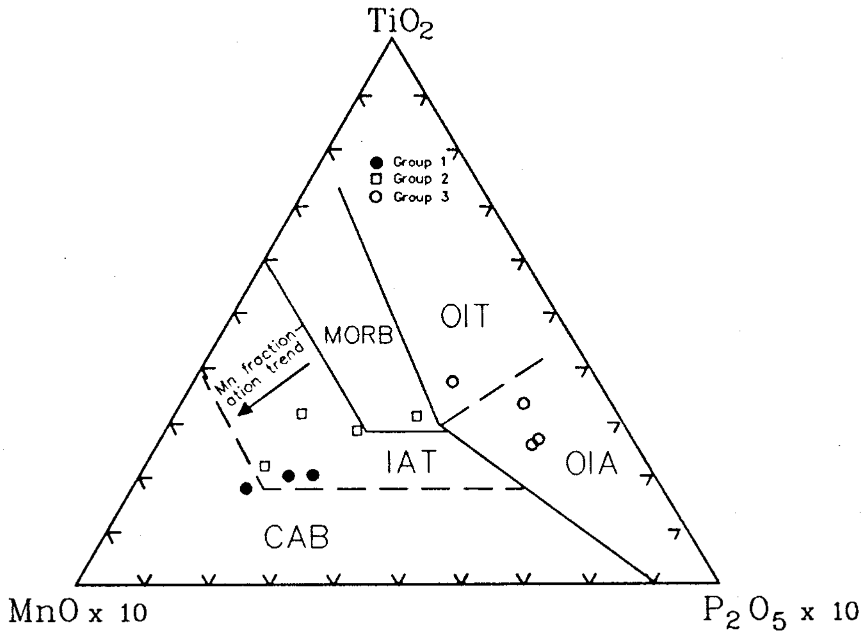


Fig. 3.4 Plot of Chetco lake samples on the $MnO/P_2O_5/TiO_2$ discriminant diagram.

springs such as those at mid-ocean ridges (Bonatti et al., 1976). Since manganese can be mobile during hydrothermal metamorphism, it is likely that Group 1 has had an enrichment of this element related to the nearby manganese-rich metaquartzites. This conclusion is supported by additional discrimination diagrams which indicate that Group 2 is entirely MORB in character.

Several discriminant diagrams using the relatively immobile trace elements (Cr, V, Ti, Y, Zr) are used below to further identify the magma types which produced the three groups. Figures 3.5, 3.6, 3.7 illustrate the three discriminating diagrams that can be used for Cr, V, Ti, Y, and Zr: TiO_2 vs. Zr (Pearce and Cann, 1973), Y vs. Cr (Pearce, 1984), and V vs. Ti (Shervais, 1982), respectively.

Figure 3.5 shows the amphibolite samples on a plot of weight percent TiO_2 vs. Zr developed by Pearce and Cann (1973). They showed that TiO_2 and Zr behave incompatibly (i.e. remain in the liquid phase) during partial melting and fractional crystallization processes and therefore can be used as an aid to show fractionation trends. Although the arc lava, mid-ocean ridge basalt (MORB), and within-plate basalts (WPB) fields overlap in this diagram, it is evident that the samples from the study area plot in three very distinct groups (Fig. 3.5). Group 1 plots in the arc lava field. As stated above, the $MnO/P_2O_5/TiO_2$ discriminant diagram are transitional IAT-CAB. In the present diagram, however, one can infer that Group 1 lies directly on a tholeiite fractionation trend with the other two groups. The negative slope which normally indicates a calc-alkalic fractionation trend is not evident because these three data points plot close to one another. Group 3 plots in the WPB field as it did on the $MnO/P_20_5/TiO_2$ discriminant diagram and Group 2 plots entirely within the MORB field.

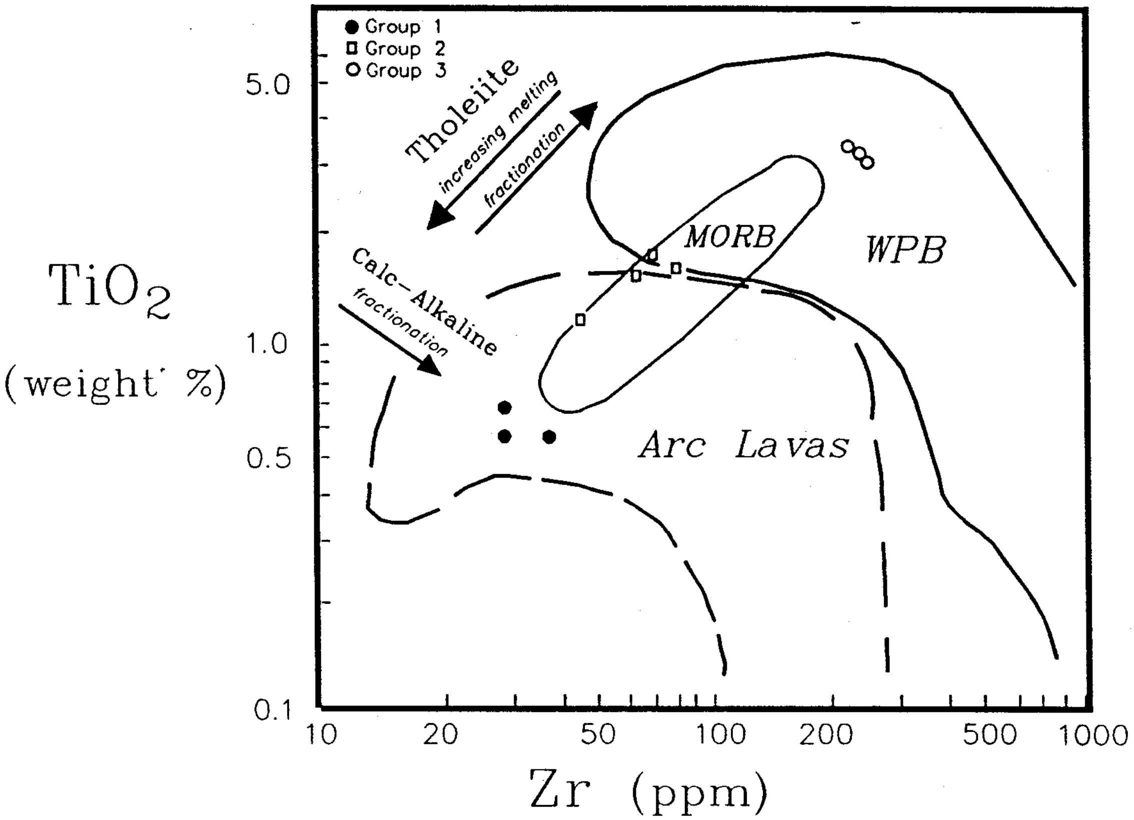


Fig. 3.5 Plot of Chetco Lake amples on the Ti/Zr diagram developed by Pearce and Cann (1973).

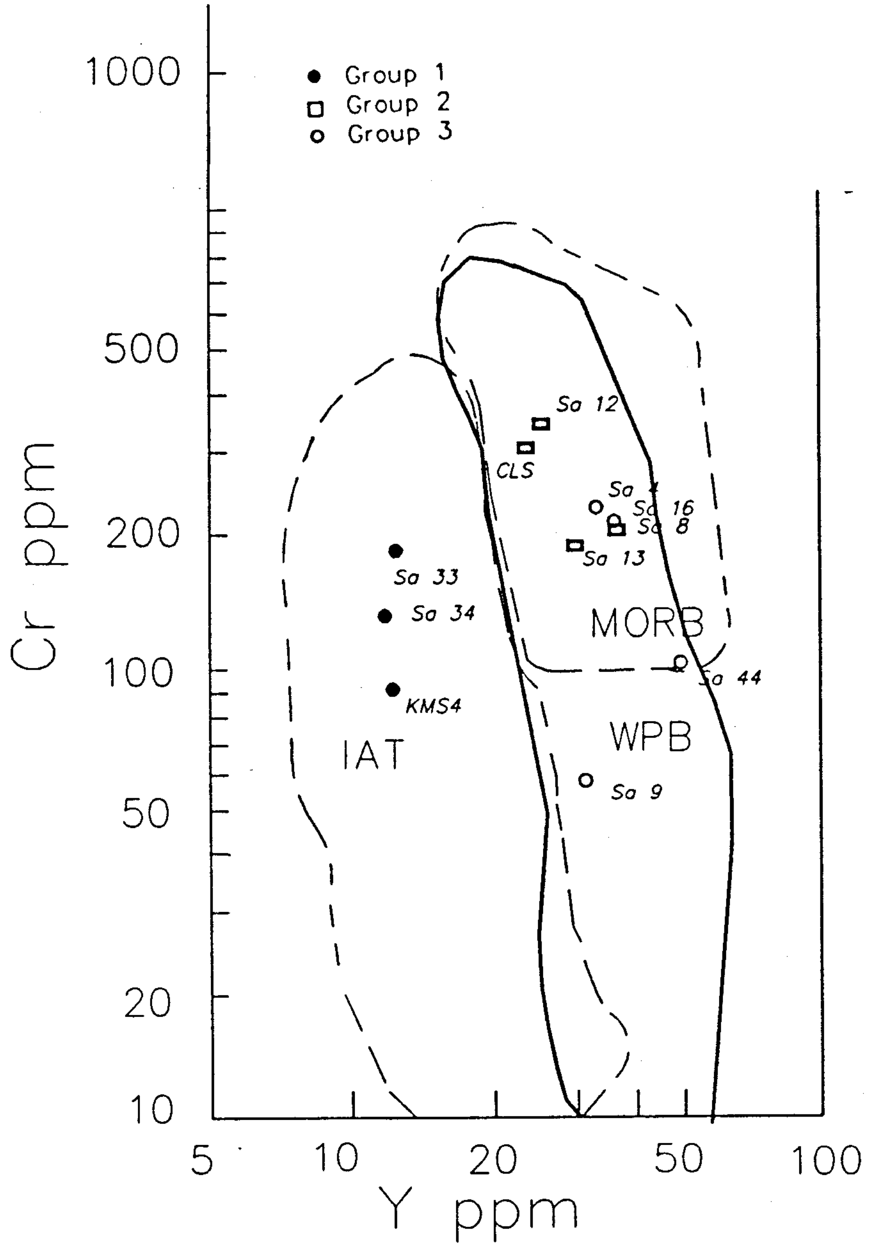


Fig. 3.6 Plot of Chetco lake samples on the Cr vs. Y diagram which was developed by Pearce and Cann (1973).

Similarly, on the Cr vs Y diagram (Pearce and Cann, 1973), the data fall into three groups (Fig. 3.6). Group 1 plots in the island arc tholeiite field, which is consistent with the Zr vs. TiO_2 diagram. Groups 2 and 3 have much higher Y values and thus fall in the MORB and WPB fields. However, this diagram is not very useful for discriminating between MORB and WPB affinities since these two fields overlap.

To delineate between these tholeiite rock types Shervais (1982) developed the V vs Ti diagram (Fig. 3.7). The tholeiite type is dependent directly on the ratio of these two elements. Ti/V ratios less than 10 are characteristic of island arc tholeiites, 20-50 ratios are characteristic of MORB affinity, and ratios greater than 50 are characteristic of within plate basalts. Again the amphibolite samples of Group 1 plot in the IAT field practically on top of one another and do not show the typical negatively-sloped trend expected of a calc-alkaline suite. In this diagram however, Group 2 plots clearly in the MORB field whereas group 3 is entirely within the WPB field.

3.2.1 SUMMARY

Even though only eleven samples were analyzed, the data define three very distinct groups and the following geological conclusions can be made:

a) Group 1 is calc alkaline or transitional IAT-CA and appears to represent syntectonic magmatism related to the Chetco Intrusive Complex. Geographically Group 1 is located the furthest from the Madstone thrust (one sample is along the northern exposure of the Madstone thrust) and is most likely metagabbros or diorites of the Chetco Intrusive Complex as shown on the MnO discriminant diagram (Fig. 3.3, Dick, 1977 and Jorgenson, 1977). These rocks are syntectonic intrusions which have been deformed along with the amphibolites of Groups 2 and 3 (see Chapter 2 and Loney and Himmelberg (1977)). The deformation has caused grain-size reduction and the metagabbros appear similar to the amphibolites in the field and hand sample.

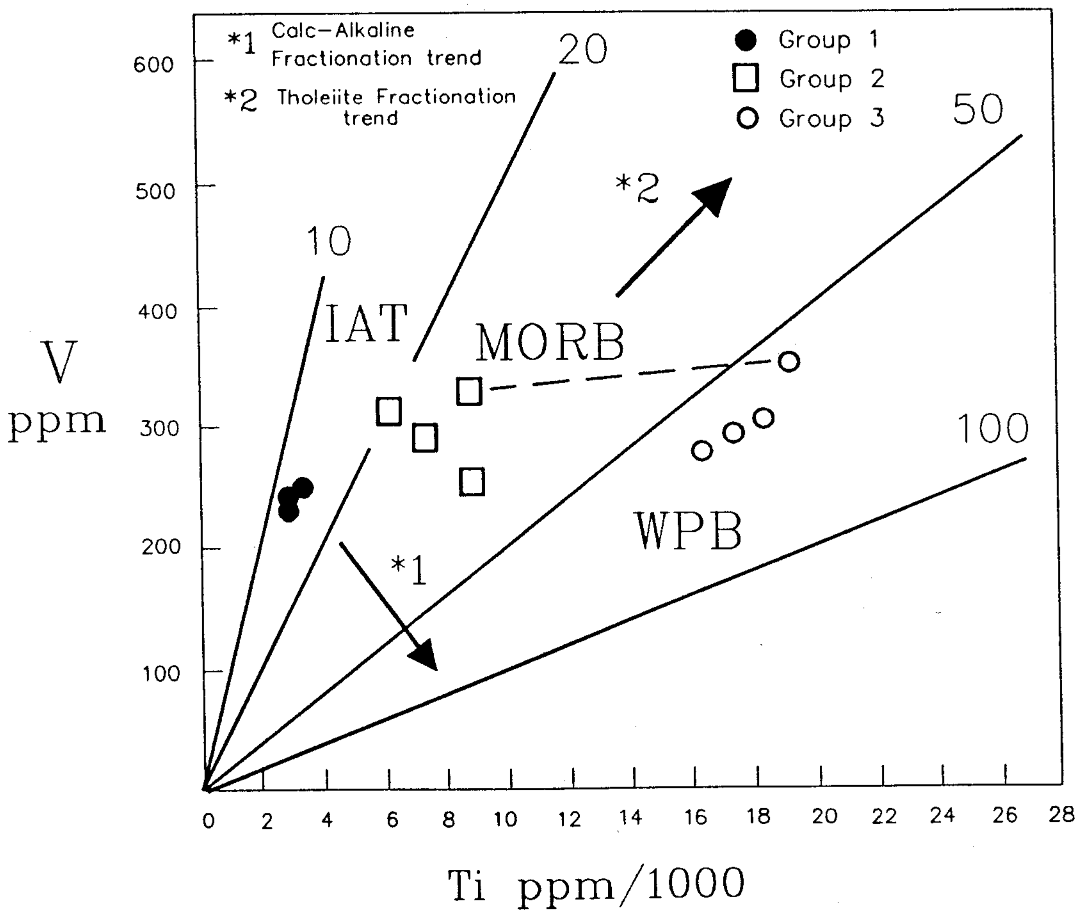


Fig. 3.7 Plot of Chetco lake samples on the Ti/V diagram developed by Shervais (1982).

b.) The amphibolites close to the thrust (Groups 2 and 3) include MORB and within plate basalts compositions. Most likely, these rocks formed as lava flows on the ocean floor since micaceous quartzites (impure chert) are interlayered with the amphibolites. Group 2 is geographically near the manganese deposit in quartzites and are of MORB affinity (Figs. 3.5, 3.6, 3.7). Modern MORB affinities form only at mid-ocean ridges or in back arc basin settings.

c) Group 3 plots on all diagrams in the within-plate basalt field. Perhaps these rocks formed on a seamount or as several off-axis dikes which intruded into the MORB basalts. This latter interpretation could explain why Sa 8 and Sa 9 (connected by a line on the Ti/V diagram), which are very close to one another geographically, do not plot in the same field.

3.2.2 COMPARISON OF THE AMPHIBOLITES WITH THE JOSEPHINE OPHIOLITE

Although the chemistry of Group 1 is clearly consistent with these data being related to the Chetco Intrusive Complex, such a protolith for the amphibolites below the Madstone thrust of Groups 2 and 3 is not as clear. Although these two groups display affinities (MORB and WPB) typical of ophiolites, when compared with the Josephine ophiolite they are much different. The Y vs. Cr diagram (Fig 3.6; Harper, 1989) shows that the Josephine ophiolite is comprised of a bimodal suite which is boninitic and primarily transitional IAT/MORB, whereas the amphibolite has higher Y contents and plot clearly in the MORB and WPB fields.

Since the Josephine ophiolite is apparently not the protolith for the amphibolite sole, it is likely that these rocks are older than the ophiolite. Groups 2 and 3 are similar to the chemistry of the Late Triassic-Early Jurassic Rattlesnake Creek Terrane (RCT) which structurally overlies the ophiolite, but appears to locally be present in the Western

Jurrasic Terrane (Wyld and Wright, 1986). The RCT is an ophiolitic assemblage which is older than the Josephine ophiolite and is interpreted (Gorman, 1985) to have formed in an oceanic fracture zone. The RCT lavas plot in the MORB and WPB fields (Gorman, 1985) in a similar distribution as the amphibolites. Likewise, the Ti/V ratios of the amphibolites are similar to the Ti/V ratios of 18 to 49 reported by Gorman (1985). Although the chemistry suggest that these amphibolites may be related to the RCT, an igneous age for the amphibolites could further constrain this hypothesis. Collection and analysis of a suite of rocks from the Chetco Lake area and dating them using Sm/Nd to try to calculate igneous ages could be useful in determining whether the amphibolites close to the thrust are indeed older and most likely Rattlesnake Creek terrane.

3.3 AR/AR DATING

Chapter 2 discussed structural information that showed the deformation of the amphibolites and the overlying serpentinite mylonites is concordant. The syntectonic deformation during the retrograde metamorphism and the pegmatite show that convergence and thrusting continued throughout the cooling history of these rocks. The Josephine ophiolite formed at 162 Ma (see Harper and others, 1989), whereas the geochronological data for the sole indicate this deformation and metamorphism are clearly Nevadan in age. "Nevadan" refers to the Nevadan orogeny documented throughout the western U.S. and Late Jurassic in age. Harper and Wright (1985) interpret the Nevadan orogeny as the time period of approximately 145-150 Ma when the back-arc basin, which produced the Josephine ophiolite, closed and the arc and remnant arc were imbricated. A complete discussion of the geochronological data for the metamorphic sole is presented elsewhere (Harper and others, 1989, and Harper and others, in review) and is summarized below.

Dick (1976), who worked on an extensive mapping project in the Kalmiopsis Wilderness area, dated samples near Chetco Lake area (J-87-6, an amphibolite sample and J-113-7, a pegmatite sample) and from the Chetco Intrusive Complex (seven samples) north of the Madstone thrust. From the amphibolites in the Chetco Lake area, the K/Ar ages on hornblende, which were recalculated from Dick (1976; Harper, et.al., in prep.) using new constants (Dalrymple, 1979), gave an age of 151 ± 3 Ma. The Chetco Intrusive Complex yielded K/Ar ages on hornblende between 153 ± 3 to 160 ± 3 Ma. If the assumptions inherent in K/Ar dating are correct, then the Chetco Intrusive Complex had cooled below the hornblende closure temperature of ~500°C by ~153 Ma. Dick (1976) also obtained a muscovite K/Ar age of 147 ± 3 Ma from pegmatite dikes intruding the amphibolite like the one in the Chetco lake region (Fig. 2.6).

Recent $^{40}Ar/^{39}Ar$ step heating dating of Dick's (1976) two samples, J-87-6 and J-89-1, from the Chetco Lake area and two additional samples, 7-16-10b and 7-6-15, have yielded similar results (Harper, 1989, Grady and others, 1989; Harper and others, 1989). The full explanation and interpretation of these new analyses are found in Harper and others (1989) and Harper and others (in review). The two samples from Dick were redated using Ar/Ar step heating method and yielded ages of 151 $\pm$ 1 Ma (Heizler, analyst). The spectra show few complexities and are most likely real rather than a composite age. Two samples collected from the amphibolite sole in the study area gave Ar/Ar ages of 151.9 $\pm$ 1.1 Ma and 152.8 $\pm$ 0.8 Ma (Heizler, analyst). Although the release sprectra are somewhat complex, Harper and others (in review) interpret 152 Ma date as a metamorphic age of cooling of the sole below 400 to 450^{o}C (the closure temperature of the hornblende; McDougall and Harrison, 1988). This means that the thrusting and emplacement of the Josephine ophiolite began prior to 152 Ma only about 10 Ma years after formation of the Josephine ophiolite (formation at 162 Ma).

The pegmatite dike, J113-7, which intrudes the amphibolite and is also deformed (Figs. 1.10 and 2.6) has a Pb/U zircon age of 151 $\pm$ 1 Ma. The $^{40}Ar/^{39}Ar$ date of muscovite indicates the pegmatite cooled slowly from 150-146 Ma below the closure temperature of muscovite (about 350-320^{o}C; McDugall and Harrison, 1988))

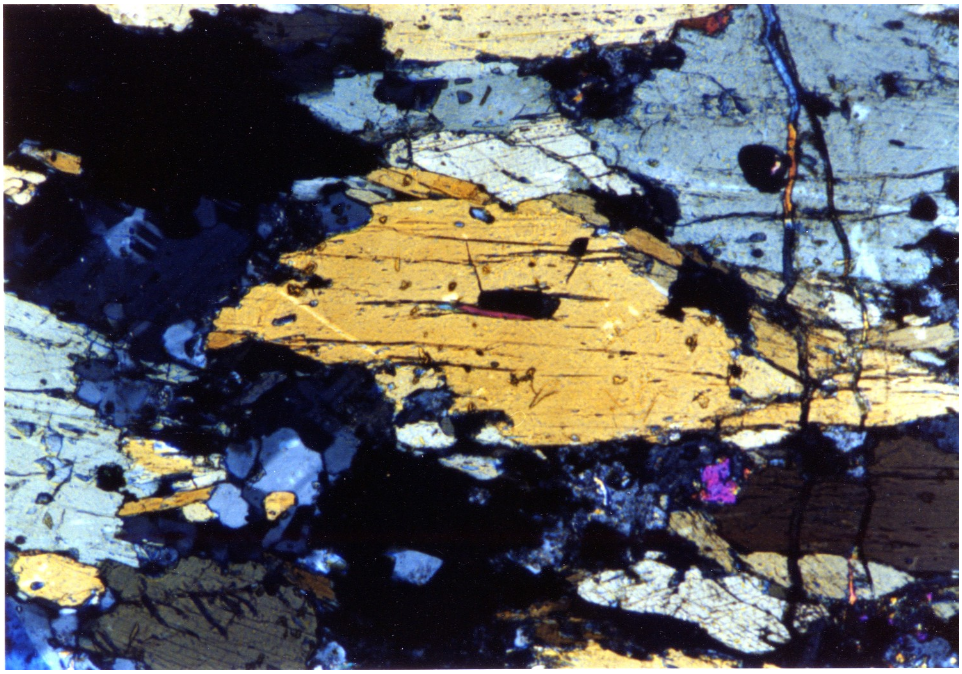
These ages indicate clearly that the emplacement of the ophiolite and the syntectonic intrusion of the Chetco intrusive complex began sometime before 150 Ma. Deformation proceeded at least through the cooling temperatures of muscovite at 350°C, which is also consistent with the deformation and greenschist facies observed in the phyllonites. The deformation probably proceeded as the sole cooled below 350°C, since amphibolite samples have pumpellyite veins which show and offset across the vein with pumpellyite fibers (Sa 44 and 34 for example). The presence of pumpellyite suggests temperatures of <300°C (Liou, et. al., 1985).

3.4 GEOTHERMOMETRY AND BAROMETRY

3.4.1 METAMORPHIC ASSEMBLAGES AND TEXTURES

Seven samples of the amphibolite below the Madstone thrust were examined in thin section. Ignoring alteration mineralogy and vein material, six of the samples had the following assemblage: hornblende + plagioclase(An30-40) + quartz + Fe-Ti oxides. Sa 34, MK1d, and M2H are all coarser in grain size. Sphene is present in two or three sections including two thin sections from the northern exposure of the Madstone thrust. The maximum absorbtion color of the hornblende is β = light green. Under plain light the hornblende shows maximum absorbtion in the same orientation, and thus, are strongly aligned. The hornblende is ragged and embayed by plagioclase especially in Sa 34. Two of the samples have quartz stringers but in the other samples quartz is a minor constituent. The amphibolites have been retrograded, which is evident by the replacement of hornblende and plagioclase by finer grain sized minerals. Plagioclase is often cloudy in appearance and has been altered to clinozoisite + muscovite + albite (?) and in at least one thin section, pumpellyite. Retrograde minerals also occur as veins which crisscross most of the thin sections. Replacement of hornblende by epidote or albite along these veins is common (Fig. 3.8). Other veins have fibrous actinolite along with albite between severed hornblende grains (see Fig 3.9). In K1R, Sa 12, and Sa 34, the latest veins are filled with prehnite + albite; these veins cut the epidote, and actinolite bearing veins (Fig. 3.10). Chlorite is also a common replacement of hornblende in several thin sections.

Sa 13 is much different from the other amphibolite sections. It has abundant epidote which is up to about one quarter the size of the hornblende and it appears to be



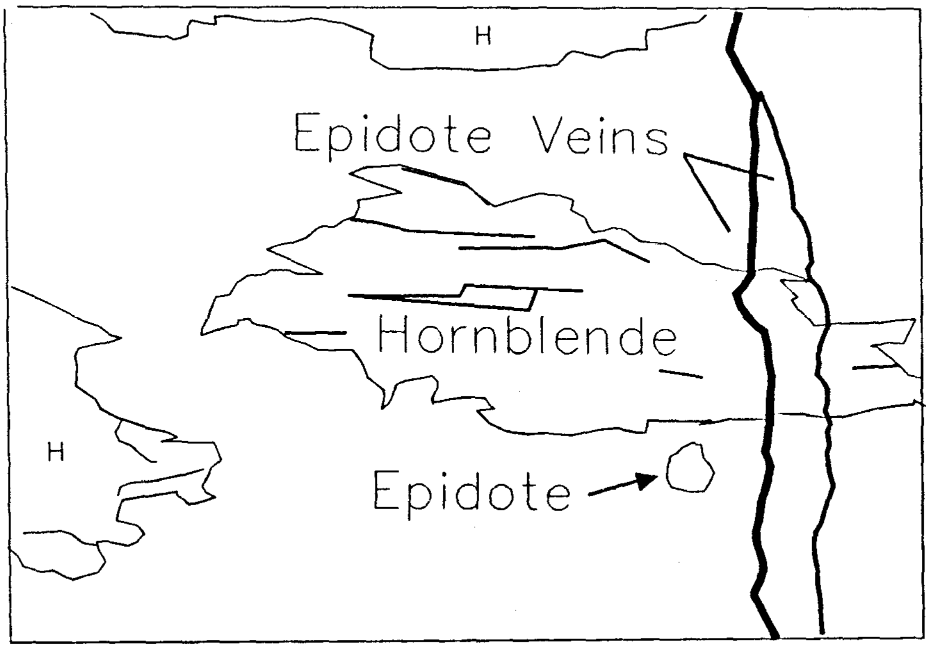


Fig. 3.8 Photomicrograph of gneissic amphibolite showing epidote replacement of hornblende in and around later veins. The long length of the field of view is about 0.5 millimeters.

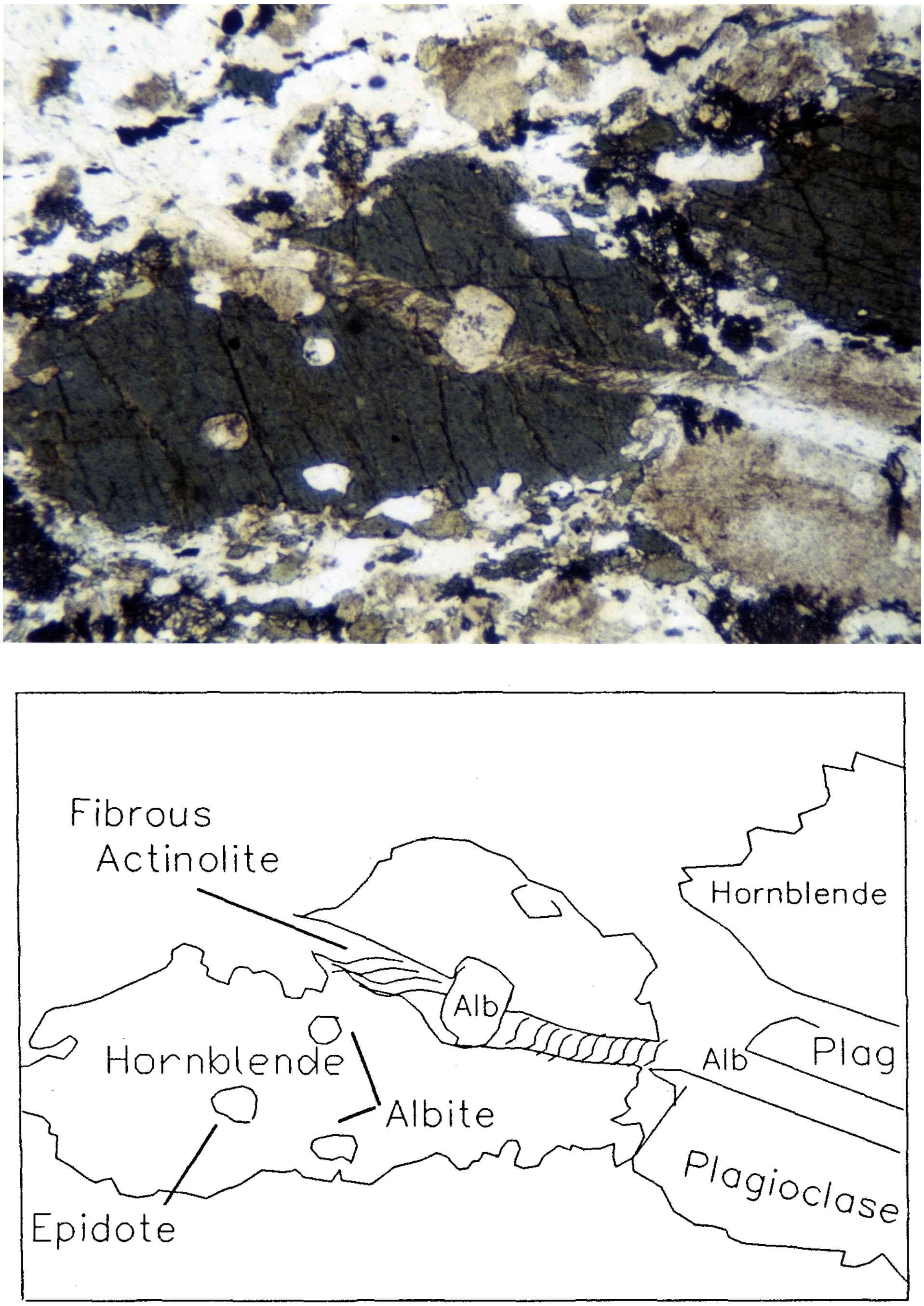


Fig. 3.9 Photomicrograph showing fibrous actinolite in the vein with albite. The long length field of view is about 1.5 millimeters.

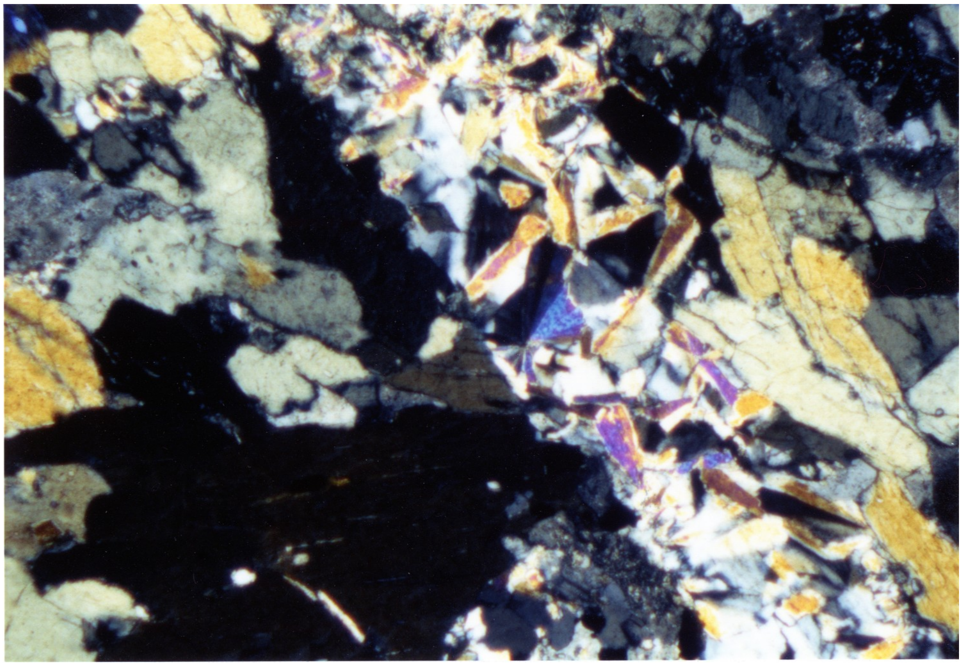


Fig. 3.10 Photomicrograph of prehnite vein cutting amphibolite. The long length field of view is about 1.5 millimeters.

in equillibrium with the hornblende (Fig. 3.11). The assemblage of this sample is hornblende + albite + sphene(euhedral) + epidote + chlorite. Later veins include actinolite + albite. The hornblende, epidote and sphene were most likely in equillibrium because these later veins cut those minerals but do not cut the albite (Fig. 3.12).

The six phyllonites are all similar in mineralogy but vary somewhat in grain size. Some are very fine grained without any porphyroclasts, whereas others, although they still have a fine grain size matrix, have abundant porphyroclasts. The matrix, although difficult to establish, appears to be mainly chlorite + actinolite + plagioclase + quartz(?)+ Fe-Ti oxides (magnetite?) + white mica. The porphyroclasts are typically epidote, actinolite, and relict hornblende . In two samples (Sa 102 and Sa 103) the hornblende is pleochroic brown suggesting a tshermakitic composition. It is rimmed by actinolite and has growth of new actinolitic hornblende. Epidote porphyroclasts in several samples are altered to chlorite plus actinolite. Two samples have veins in them which are folded. K21 has abundant quartz veins and has an albite vein which cuts the quartz. K5 veins are cloudy in appearance under the microscope and difficult to establish the mineralogy.

The pegmatite which intrudes the amphibolites in the study area has the following assemblage: k-spar + plagioclase + quartz + muscovite + minor biotite + minor garnet. The quartz appears mainly as abundant quartz stringers throughout the thin section. Along discrete veins the muscovite is altered to prehnite. In some cases, the plagioclase is cloudy in appearance and is altered to clinozoisite. A similar pegmatite from the northern exposure of the Madstone thrust which also cuts the amphibolite was examined (sample J-82-3 from Dick). It has a similar assemblage but contains more garnet.

From the seven samples examined of the roof rocks of the madstone thrust, namely the sheared serpentinites, all contained the following assemblage in various amounts: serpentine + magnetite $\pm$ carbonate (Fe-magnesite?). Two varieties of serpentine are present and texturally very different. The fine grained variety sometimes

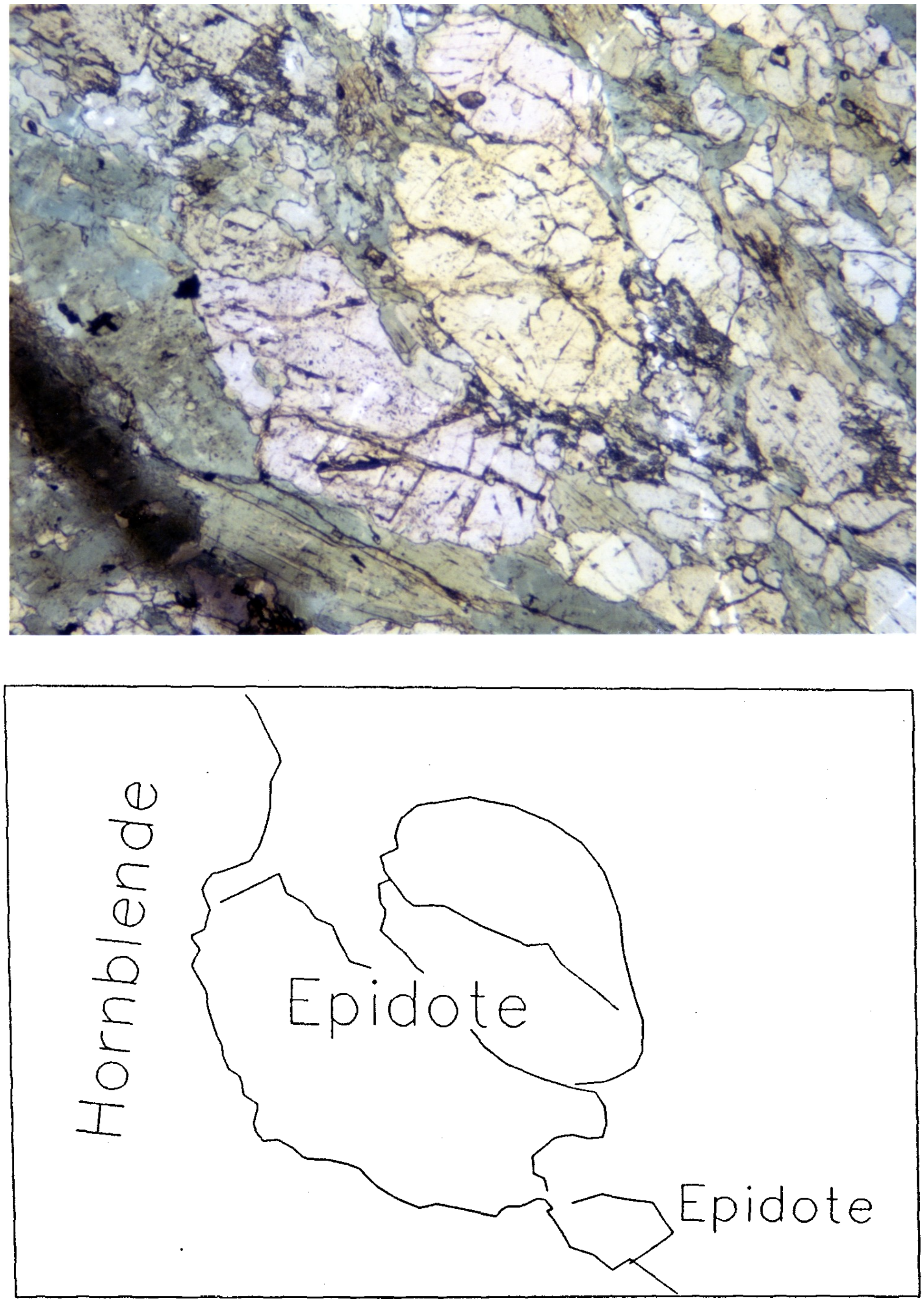
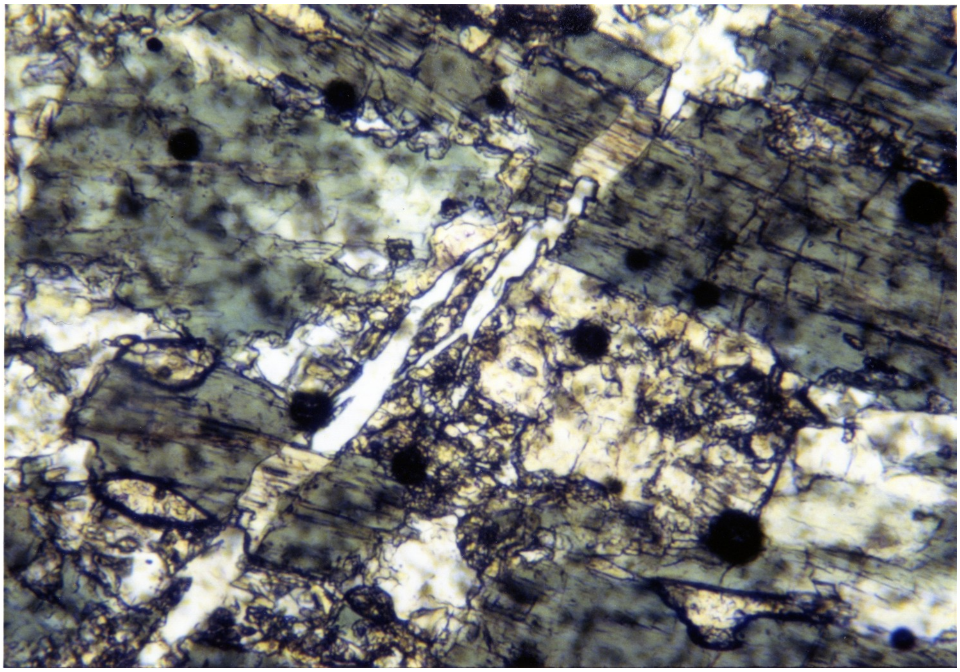


Fig. 3.11 Photomicrograph of Sa 13 which is epidote rich and may indicate epidote amphibolite facies metamorphism. The long length field of view is about 0.5 millimeters.



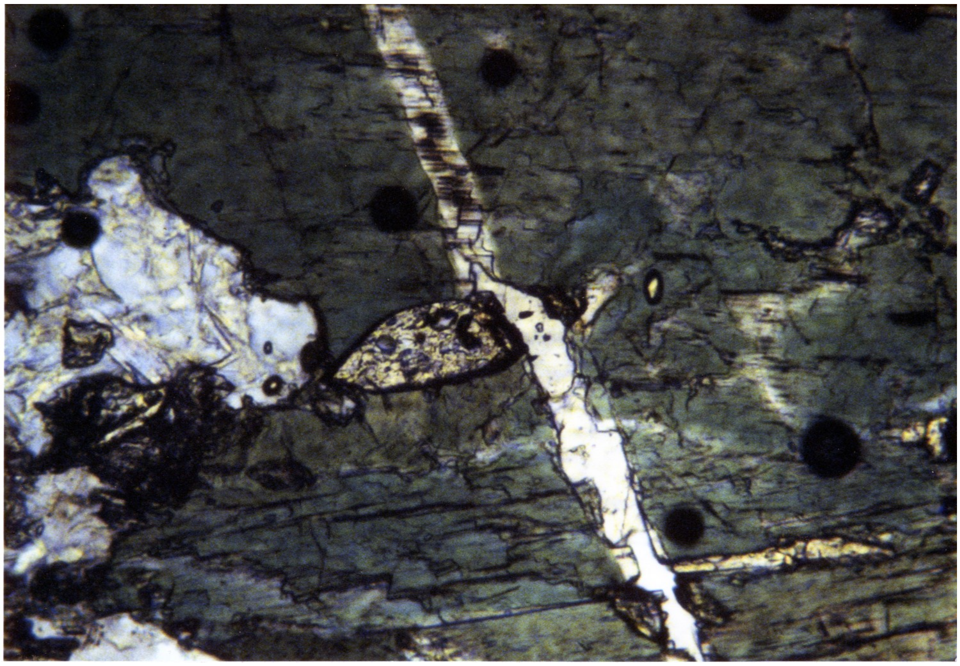


Fig. 3.12 Photomicrographs of veins showing mineral assemblage equilbrium (long length field of view is 0.5 millimeters):

a. albite vein cutting epidote and hornblende. Note that the hornblende is offset and has actinolite growt

b. Albite vein cutting sphene.

shows a bastite texture (serpentine after clinopyroxene) and in other cases an hour glass structure which is indicative of lizardite. The other serpentine is coarse grained and bladed which is typical of antigorite. The large porphyroclasts of magnetite are associated with patches of antigorite and finer magnetite is dispersed throughout the slide. Carbonate where present is usually around the magnetite porphyroclasts. Chlorite veins cut these serpentinites (Fig. 3.13).

3.4.1.2 Thermometry and Barometry

The prograde mineral assemblage of hornblende + An_{30-40} plagiclase is consistent with amphibolite facies metamorphism, for these basic rocks, which indicates temperatures roughly between 500°C and 600°C. The presence of epidote and relict albite may indicate that Sa 13 is in the epidote amphibolite facies which constrains the temperature for that sample to 400°C to 540°C and roughly indicates medium pressures (Apted and Liou, 1983; and Maruyama and others, 1983).

Probe analyses of hornblende in Sa 44 and Sa 13 were obtained by John Wakabayashi, U of Calif, Davis and are summarized in Harper et.al., (in press). It was hoped that results of these analyses would shed light on the pressures involved in the deformation and hopefully constrain the model for formation of these rocks. Estimating pressure from the NaM4 content of the calcic amphibole (Brown, 1977) resulted in pressures less than or equal to 4 kb for the two samples (see Table 2 in Harper et.al. (in press)). Hornblende in sample Sa 44 is rimmed by a younger amphibole. This amphibole is less aluminous with less Na content but overall the same NaM4 ratio. As described in Harper et.al. (1989) this suggests that the temperature was decreasing while this hornblende rim was forming at either constant or decreasing pressure (Raase, 1974, Brown, 1977)

Fluids must be present for basic rocks to retrogress. In the phyllonites and the amphibolite the abundance of veins which alter the assemblages indicate that there were plenty of fluids for retrograde metamorphism. In the amphbiolites the epidote + albite

Fig. 3.13 Field photograph showing typical chlorite veining in the peridotite.

veins indicate retrogressive metamorphism to epidote amphibolite facies at 400 to 540°C (Apted and Liou, 1983). The presence of actinolite and chlorite replacement along veins with albite is consistent with greenschist metamorphism and temperatures between 350°C and 550°C depending on the oxidation state of the samples. (Moody, et. al., 1983). The prehnite veins and the presence of pumpellyite indicate that temperatures had decreased below 380°C (Liou, et. al., 1985)

The phyllonites assemblage of white mica + actinolite + plag is consistent with greenschist metamorphism. The porphyroclasts indicate that these rocks were at one time amphibolite facies rocks (epidote+hornblende which is tshermakitic in composition). Hornblende in a phyllonite was also probed but it lacked the buffering assemblage required by Brown (1977) to determine pressure estimates. The relict tschermakitic amphibole is beautifully rimmed by a less aluminous actinolite hornblende (Fig. 2.18). Although not conclusive, the assemblage of tschermakitic amphibole + calcic plagioclase is indictative of higher temperatures. Unfortunately, not enough of the relict assemblage is preserved to determine the higher temperatures and pressures.

The phengite composition in the pegmatite was also analyzed for a pressure estimate. This estimate is plausible since the pegmatite contains the buffering assemblage of muscovite + biotite + K-felspar + quartz (Massonee and Schreyer, 1987). Although there are complications, an estimate of about 5 kbars was obtained for this sample (Harper et.al., 1989). Unfortunately this geobarometer is complicated and the effects of Fe and Fl may result in an erroneously low (in the case of high Fe) or high estimate (in the case of high Fl).

The sheared serpentinite above the Madstone thrust contains two kinds of serpentine. Different serpentines form under various temperature conditions. Generally, the presence of antigorite indicates higher temperatures whereas lizardite and crysotile represent lower temperatures (O'Hanley, 1989; O'Hanley, et.al., 1989). In most of the sheared serpentinite samples from above the Madstone thrust, coarsely bladed, schistose antigorite overprints the lower temperature lizardite. Although dependent upon pressure the stability field of antigorite is about 450 - 525°C (O'Hanley, 1989). These temperatures are consistent with those from the amphibolite.

In conclusion, the deformation of the metamorphic sole began at temperatures $\geq$500°C as indicated by the amphibolite facies metamorphism (probably greater than 650°C). The sole was about 400-450°C, the closure temperature of hornblende, at 150 Ma and still deforming. Shortening continued through greenschist facies retrogression evident by the deformed phyllonites and vein offsets in the amphibolite. Finally, strained pumpellyite and offset prehnite veins indicate some amount of deformation $\leq$380°C. Pressures, although uncertain to this point, were most likely $\leq$4 kilobars.

These observations are very similar to that described for the Trinity ophiolite (Peacock, 1987; Peacock, 1987; Peacock and Norris, 1989). Peacock and Norris (1989) describe a metamorphic sole for this Devonian age ophiolite with a temperature gradient of 650 $\pm$ 50°C to 500 + 50°C. Pressures are loosely constrained at 5 kilobars. They also describe veining of greenschist grade metamorphic minerals that are abundant near the thrust and become less abundant further from the thrust. Finally, assemblages above the peridotite such as serpentinite, tremolite and talc indicate that fluids infiltrated along the thrust such as is also seen with the Josephine ophiolite (Peacock, 1987; Peacock, 1989).

3.5 OXYGEN ISOTOPE DATA

Oxygen isotope measurements can aid in the determination of temperature and fluid type at the time of formation of the metamorphic sole and can help constrain a model. Fractionation factors for $\delta^{18}O$ in minerals with reference to water are related to T in the form for Δ (mineral - H_20) = m T^{-2} + b. These curves are empirically derived from experimentation and information from natural rocks and can be plotted on a diagram such as Figure 3.14. If $\delta^{18}O$ measurements of two mineral phases are determined which have well established fractionation equations, then the two fractionation equations

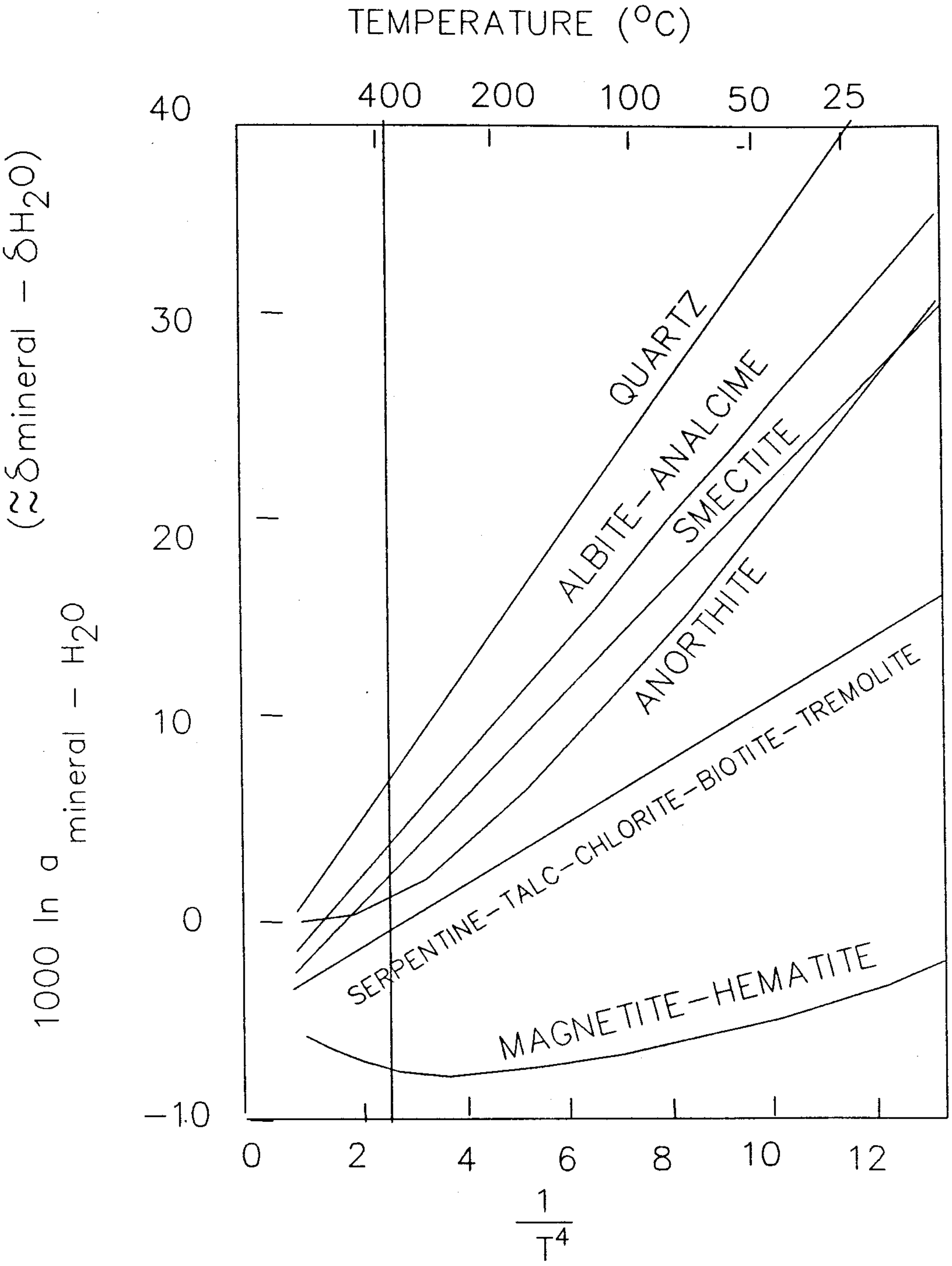


Fig. 3.14 An example of curves relating temperature and fractionation factors with reference to water.

Table 3.2

Oxygen Isotope Data for samples near Chetco Lake

SERPENTINITE

	$\delta^{18}O$ Serpentine	$\delta^{18}O$ Magnetite
Sa14	6.7	2.8

AMPHIBOLITES

	$\delta^{18}O$ Plagioclase	$\delta^{18}O$ Hornblende
Sa12	9.185	13.70
Sa44	8.59	12.60

Note: Stable isotopic compositions of serpentinites and amphibolites. Values were run relative to standard NDS-28 and are reported relative to standard mean ocean water (SMOW).

can be subtracted to obtain a geothermal equation. In other words, any difference between the two curves establishes a unique temperature.

Three samples from the study area were analyzed for $\delta^{18}O$ by J.R. Bowman at the University of Utah and the results are presented in Table 3.2. K14 is a serpentinite mylonite for which serpentine and magnetite $\delta^{18}O$ were determined whereas Sa 12 and Sa 44 are amphibolite for which hornblende and plagioclase were measured. The following fractionation equations for serpentine and magnetite will be used; serpentine equations were derived by Norrell (1989), who used the derivation by Wenner and Taylor (1971) but with the correct serpentine data from Clayton et. al. (1972):

$$\Delta_{(serpentine\text{-}water)} = 1.45 \times 10^6 T^{-2} - 4.31$$

(values from Bottinga and Javoy (1973) for magnetite).

$$\Delta_{(magnetite\text{-}water)} = -1.47 \times 10^6 T^{-2} - 3.70$$

Therefore, when these two equations are subtracted we find

$$\Delta_{(serpentine\text{-}magnetite)} = 2.92 \times 10^6 T^{-2} - 0.61$$

Substituting the serpentine and magnetite $\delta^{18}O$ values for sample K14:

$$(6.7-2.8) = 2.92 \times 10^6 T^{-2} - 0.61$$

$$4.51\ T^2 = 2.92 \times 106 / 4.51$$

$$T = 804^\circ\ K \text{ or } 531^\circ\ C$$

Using following equations derived by J.R. Bowman (pers. comm., 1990):

$$\Delta_{(serpentine - magnetite)} = 1.86 \times 106\ T^{-2} + 1.01$$

and

$$\Delta_{(serpentine - magnetite)} = 3.12 \times 10^6\ T^{-2} - 0.85$$

resulted in temperatures of 529°C and 537°C, respectively. Of course these geothermometer equations assume that the minerals were in equilibrium when they crystallized and require that the serpentine and magnetite mineral separates are pure.

To address the first assumption K14 was examined in thin section for textures. K14 is comprised of two serpentines. A fine grained serpentine has the hour glass texture characteristic of lizardite pseudomorphic texture after olivine (Wicks, et. al., 1977). The other serpentine, which clearly overprints the lizardite, is coarse grained and shows the typical bladed texture of antigorite (Wicks and Wittaker, 1977). This overprinting clearly indicates that the lizardite is older than the antigorite. The large magnetite porphyroblasts appear to have grown with the bladed antigorite, whereas the other magnetites throughout the slide are much smaller grain size. It is difficult to establish whether the mineral separate contains magnetite associated with the antigorite and/or lizardite. Since the antigorite associated magnetite was larger, however, it was assumed that the separate contains mainly those magnetites associated with the antigorite. Also, the smaller magnetites are more likely to form serpentine-magnetite composites and the separate was hand picked to remove composites grains.

Upon examination of the serpentine separate under the microscope, it is almost pure serpentine. Less than 10 % of the separate is lizardite, which is evident by texture, greenish color, and index of refraction. The magnetite separate, however, is more difficult to ascertain purity. The magnetite grains always have a small amount of serpentine contamination (in this case probably <10%) and relict Cr-spinel is difficult to separate from magnetite. Microprobe analysis is necessary to determine the amount of Cr-spinel in the sample and then a correction can be estimated assuming a $\delta^{18}O$ value for the relict Cr-spinel. K14 sample has not yet been analyzed for Cr-spinal impurities but the resulting temperatures are near the upper stability of antigorite which is consistent with the observed amphibolite facies-assemblage in the concordant amphibolite.

Substitution of these temperatures into the equations for serpentine - water and magnetite - water gives the composition of the water at the time of formation of the assemblages. $\delta^{18}O$ values for the water ranges between +8 to +9 indicating an enrichment in $\delta^{18}O$, e.g. $\delta^{18}O$ seawater = 0. Although deuterium was not analyzed these high numbers indicate that the fluids were highly evolved. According to Sheppard (1986) values of +8 to +9 indicate either metamorphic waters from metasediments (+8 to +26) or possibly hydrothermally altered metabasalts (+3 to +14). Dewatering of sediments during compaction possibly could produce these high numbers. However, one sample although indicative, can not be very conclusive. Since only one sample was examined for preliminary work, more oxygen isotope work and specifically deuterium is needed to better constrain the fluid type at the time of formation of the serpentinite.

Even though this result is preliminary, it is interesting that the $\delta^{18}O$ values and calculated water composition of K14 matches almost exactly with the data calculated by Norrell (1989) for serpentinite mylonites from shear zones in the Josephine Peridotite. Norrell (1989) interpreted these high $\delta^{18}O$ values for seawater-derived fluids which either had interacted extensively with the crustal sequence as hydrothermal waters or that the $\delta^{18}O$ value for the Josephine Peridotite originally had an unusually high $\delta^{18}O$ value. While these hypotheses are possible, it is unlikely that the waters evolved during deep hydrothermal circulation (whose calculated $\delta^{18}O$ values are +7 at most (Harper, et. al., 1988)) would produce the +8 to +9 values measured. Norrell (1989) interpreted the shear zones to be oceanic, whereas K14, is clearly associated with emplacement. Although more samples should be analyzed in the Chetco Lake study area, the results from K14 raises the possibility that Norrell's (1989) shear zones have an emplacement origin rather than oceanic faulting. However, Norrell discovered an opposite sense of shear than found in this study area. Hopefully, additional field study and careful collection of more data for isotope work will be able to reconcile these two possibilities.

For the two amphibolite samples, hornblende and plagioclase were analyzed for $\delta^{18}O$ (Table 3.2). The following fractionation curve for plagioclase from Bottinga and Javoy (1975) was used to determine the fluid composition.

$$\Delta_{(plagioclase-water)} = (3.13-1.04\beta) \times 10^6\ T^{-2} - 3.70$$

where β is the mole fraction of anorthite. By using the index of refraction of the mineral separate of plagioclase and examining Carlsbad twins, the plagioclase composition is estimated to be $\sim An_{35}$.

An amphibole curve was estimated by Bottinga and Javoy (1975) but may not be valid: Norrell (1989) used the amphibole equation for geothermometry but this resulted in unrealistically low temperatures, the amphibole curve is not well established and is very close to the plagioclase curve which creates large uncertainties. Instead of using the amphibole - water composition estimated by Bottinga and Javoy (1975), the author assumed a temperature of 500°C for the deformation and used the plagioclase equation to determine the composition of the fluid. This assumption is probably fairly accurate since petrographically the samples were found to belong to the amphibolite facies assemblage. The calculated $\delta^{18}O$ value for the fluid composition is +10 which is similar to the calculated values for K14.

3.6 CONCLUSIONS

Although the data above is preliminary, the results are significant. The following preliminary conclusions are drawn:

1. Chemically, the amphibolite sole is very different from the Josephine ophiolite. The structurally higher amphibolite samples have MORB and WPB affinities and are closer in affinity to the chemistry of the older ophiolitic rocks of the Rattlesnake Creek Terrane. Samples from greater than 300 meters beneath the Madstone

thrust are calc-alkaline and are apparently related to syntectonic intrusives of the underlying Chetco Intrusive Complex.

2. The metamorphic age of the amphibolite is 150 $\pm$ 1 Ma based on the Ar/Ar step heating method. The deformation proceeded through cooling of the sole as evident from the muscovite ages and offset pumpellyite veins, which indicate deformation proceeded below 300°C.

3. Temperatures during the onset of deformation appear to have been >550°C. Although the geobarometers are somewhat ambiguous, the amphibolite sole was most likely medium pressure at ~ $\leq$5 MPa. Retrogressive metamorphism in veins that are offset indicate that as the sole cooled from 500°C to <380°C, deformation continued. The deformed phyllonites are consistent with this greenschist facies deformation. The serpentinites formed at the upper stability of antigorite (525°C) which is consistent with the amphibolite and, as the system cooled, talc and chlorite veins became abundant. Since the amphibolite show very extensive retrogression near the thrust (e.g. phyllonites), it seems likely that the serpentinite acted as an impermeable barrier to the fluids channelizing them along the thrust. Only the local presence of talc and the chlorite veins is indicative of the retrograde metamorphism in the serpentinites.

4. $\delta^{18}O$ values yield temperatures of about 530°C, which is near the upper stability of antigorite (500°C), which is consistent with the amphibolite-facies metamorphism in the amphibolite below the Madstone thrust. Fluid compositions are heavy and may indicate metamorphic fluids of ultimately sedimentary origin.

CHAPTER 4: DISCUSSION AND CONCLUSIONS

4.1. COMPARISON OF JOSEPHINE SOLE WITH OTHER SOLES.

The amphibolite under the Madstone thrust most likely do represent a metamorphic sole of the Josephine ophiolite since the structures in the sheared serpentinites above the Madstone thrust are concordant with the structures of the amphibolite and the phyllonites below the Madstone thrust (see Chapter 2).

Typical characteristics of other metamorphic soles are conspicuously absent, however; and thus the mechanism of emplacement of the Josephine ophiolite is most certainly different than that of other ophiolites. A summary of the differences and similarities of the metamorphic sole of the Josephine ophiolite with "typical" characteristics of soles is presented below and in Figure 4.1.

4.1.1. INVERTED GRADE OF METAMORPHISM

As described in Chapter 1, the most distinctive characteristic of metamorphic soles is a sharp inverted grade of metamorphism over only a few hundred meters, varying from granulite, amphibolite, greenschist, to relatively undeformed metasediments. Although the amphibolite in the Chetco Lake area are 300 meters thick, they display no obvious decrease in metamorphic grade away from the contact with the Josephine Peridotite. Instead, the amphibolite is highly retrogressed to greenschist facies and highly deformed to phyllonite at the contact with the overlying peridotite. This deformation and retrograde metamorphism may have obliterated earlier higher temperature assemblages that may have existed prior to retrograde metamorphism. However, the presence of an earlier inverted grade of metamorphism may be recorded by relict tsermaktic hornblende, generally an indication of high temperatures, found as porphyroclasts in the phyllonite (Chapter 3). As pointed out in Chapter 3, collection of more phyllonite samples may confirm this higher temperature assemblage.

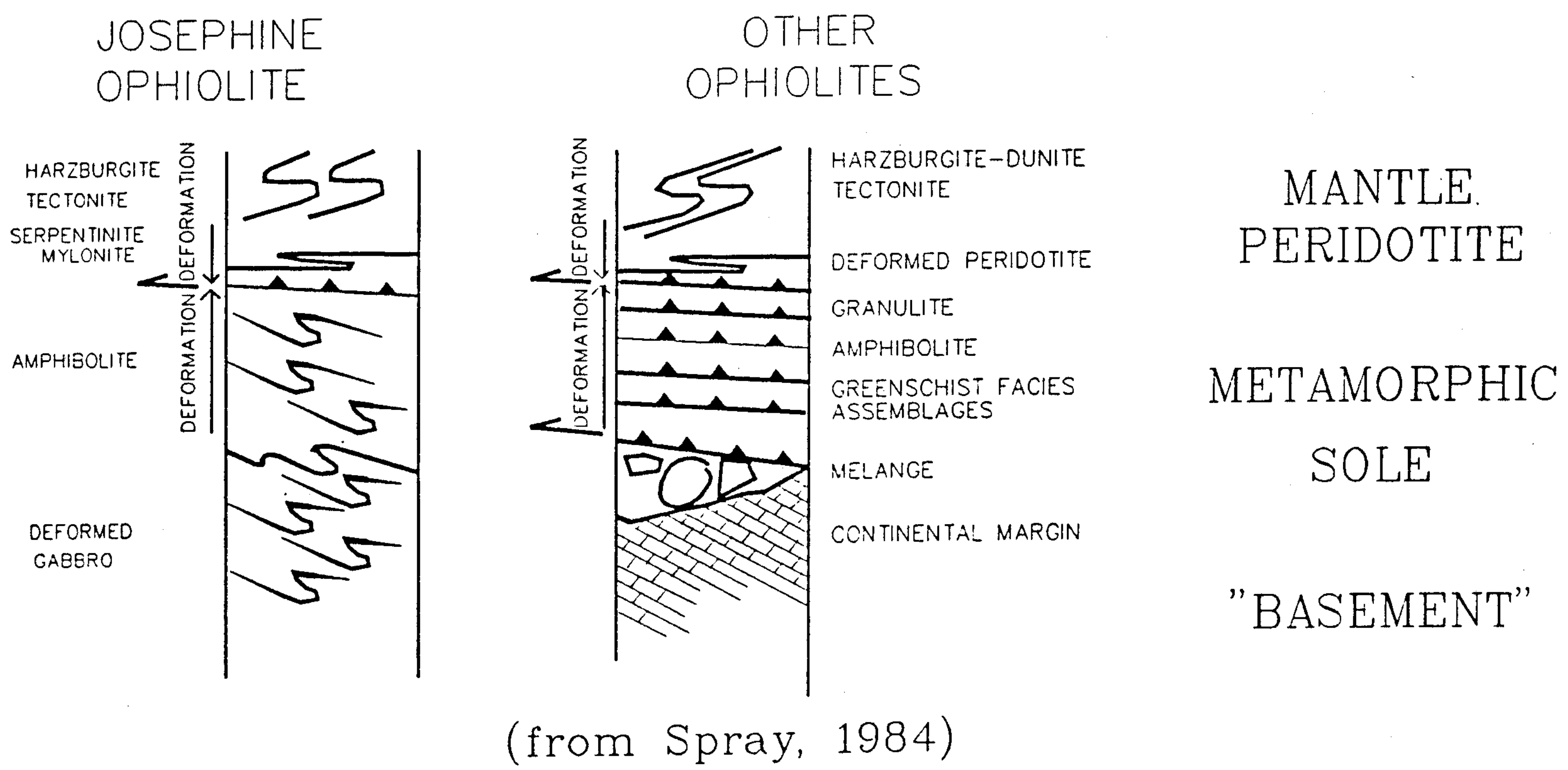


Fig. 4.1 **Sketch depicting the differences and similarities between the metamorphic sole of the Josephine ophiolite and other metamorphic soles.**

Prograde greenschist metamorphic facies occurs beneath the amphibolite in typical soles, but these are absent in the Josephine ophiolite. Cannat and Boudier (1985) interpreted this section to be faulted away by the Valen Lake thrust (the later Cretaceous thrust which truncates the Madstone thrust in the west). However, in the northern outcrop of the Madstone thrust the amphibolite are intruded by the Chetco Intrusive complex which is also metamorphosed to amphibolite facies. The metamorphic sole and the gabbros were cooled slowly and later during regional metamorphism retrograded to greenschist facies.

This retrograde, greenschist facies metamorphism and deformation is recorded, however, by the phyllonites directly underneath the Madstone thrust and en-echelon offset veins in the amphibolite. These features indicate that deformation probably proceeded through slow cooling of the amphibolite sole below greenschist facies metamorphism.

4.1.2. INVERTED DEGREE OF DEFORMATION

Deformation of most metamorphic soles also decreases away from the contact (Spray, 1984). This relationship is evident by gneissose foliation close to the contact which grade downwards to phyllitic and relatively undeformed rocks at the base of the sole. In the Josephine the deformation during peak amphibolite facies is somewhat obscured by the presence of phyllonite, which was deformed during retrograde greenschist facies metamorphism. In the amphibolite there is no clear indication that the deformation becomes less further from the contact. However, the underlying gabbro of the Chetco Intrusive complex has been mapped and described as gradational and probably displays a gradient further from the Madstone thrust (Wells et.al., 1949; Ramp, 1975; Loney and Himmelberg, 1977). Additional study of this contact could be beneficial in establishing a decrease in strain further from the Madstone thrust.

4.1.3. STRAINED PERIDOTITE UNIT

Above the amphibolite in most soles is a unit of highly strained peridotite at the base of the ophiolite whose structures are concordant with the underlying amphibolite. In the Josephine ophiolite, this peridotite unit is missing. Cannat and Boudier (1985) interpreted the highly strained peridotite unit to have been faulted away, although they interpreted the serpentine mylonite as "serpentinite peridotite mylonite". This interpretation suggests that the serpentinization was post thrusting of the Josephine ophiolite. This study has shown that instead of a peridotite mylonite, there is a 20-40 meter thick unit of serpentinite mylonite, apparently formed at ~500°C, whose structures are concordant with the amphibolite. These temperatures and structures, along with an exposed sharp contact between the serpentinites and amphibolite with undeformed talc-actinolite/tremolite reaction zone, supports the conclusion that these serpentinite mylonites formed during thrusting of the Josephine ophiolite.

4.1.3.1 FLUIDS AND RETROGRESSIVE METAMORPHISM

Retrograde metamorphism is common in metamorphic soles (Idleman, in prep.; Coleman, 1981). In the Josephine ophiolite it is apparent that the serpentinite acted as a barrier to metamorphic fluids since the peridotite is very fresh above the serpentinite mylonite, whereas the amphibolite is strongly retrogressed to phyllonite with only veins of chlorite. The fluids were therefore probably channeled along the thrust contact, allowing hydration to form phyllonite and the talc-chlorite rich rocks at the contact between the amphibolite and serpentinite mylonite. Further away from the contact, veins occur showing alteration of the amphibolite assemblages to greenschist facies metamorphism. The veining becomes less abundant farther from the contact. Peacock (1987) describes similar metasomatic assemblages in the Trinity ophiolite.

4.1.4. MELANGE SEQUENCE AND CONTINENTAL MARGIN

The underlying melange sequence and continental margin present beneath most metamorphic soles is absent in the Josephine ophiolite. Instead, the sole grades downwards into the syntectonic gabbros of the Chetco Intrusive Complex. Therefore, the Josephine was thrust over the then active arc complex (Dick, 1976). This difference is an artifact of the tectonic mode of emplacement of the Josephine ophiolite under the continental margin instead of obducted onto a passive margin.

4.1.5. GEOCHEMISTRY OF OPHIOLITES AND THEIR SOLES

The Josephine ophiolite is chemically very distinct from its amphibolite sole (Chapter 3). The sole typically has magmatic affinities to mid-ocean ridge basalt or within-plate tholeiitic compositions, whereas the Josephine ophiolite is transitional between island arc and mid-ocean ridge composition. Therefore, it is likely that the amphbiolite sole is actually older and probably represents the roof rocks of the Chetco Intrusive suite. This discrepancy in magmatic affinities is also observed in the Oman ophiolite. The Oman ophiolite has affinites to arc tholeiites whereas the amphibolite sole show MORB affinities (Alabaster, et. al., 1982; Pearce 1984; and Searle and Malpas, 1982).

4.1.6. AGE RELATIONSHIPS OF OPHIOLITES AND THEIR SOLES

The Josephine ophiolite is dated at 162 $\pm$ 2 Ma and the metamorphic sole cooled slowly from ~450°C to 350°C from 152-146 Ma. Spray (1984) described ophiolitic soles as practically coincident in age with the upper ophiolitic assemblages. Isotopic data in Oman has been debated and uncertainties are very large (K-Ar and $^{40}Ar/^{39}Ar$ Montigny, et.al. 1988).

The Bay of Island ophiolite also has a 20-50 Ma difference in age between the ophiolite and sole. These timing constraints are very important in modeling the emplacement of the ophiolite.

4.2 REVIEW OF OBDUCTION MODELS FOR THE JOSEPHINE OPHIOLITE.

Ophiolites are found world wide but mainly within collisional tectonic belts. These belts are often divided into three different groups: 1. ophiolite obduction onto a passive margin (arc-continent collision) which are generally relatively low pressure, 2. melanges in trenches which record high pressures, and 3. continental-continental plate collision. The following discussion will discuss present models for the emplacement of ophiolites related to arc-continent collision, since they are often associated with the development of metamorphic soles (Spray, 1984). Figure 4.2 is a summary of the tectonic models for the emplacement of ophiolites.

4.2.1 OBDUCTION MODELS FOR EMPLACEMENT OF OPHIOLITES

Ophiolites, which are thought to have been obducted, are according to Nicolas (1989) the most intact ophiolites. These ophiolites have been thrusted onto a passive margin and often record conditions of emplacement in their associated metamorphic soles. The soles typically record high temperatures and medium to high pressures. Several models have been developed for the obduction of ophiolites, which will be described briefly below and are summarized in Figure 4.2 (Coleman, 1981; Nicolas, 1989; Spray, 1984; Nicolas and LePichon, 1985; Wyld and Wright, 1988; Dewey and Bird, 1971, Dewey, 1976; Andrews-Speed and Brookfield, 1983; Robertson, 1988, and Edelman, 1988).

Figure 4.2.A shows the model after Coleman (1981), Spray (1984), LePichon (1985), and Nicolas (1989) of intraoceanic thrusting with eventual emplacement onto the continent. This model was proposed for the Oman ophiolite. Detachment occurs at a mid-ocean ridge as the regime changes from extension to compression creating a subduction zone that dips away from the continent. As thrusting continues the metamorphic sole develops and the oceanic crust is emplaced onto the passive margin. This model explains the high temperatures of the ophiolitic sole since thrusting began at

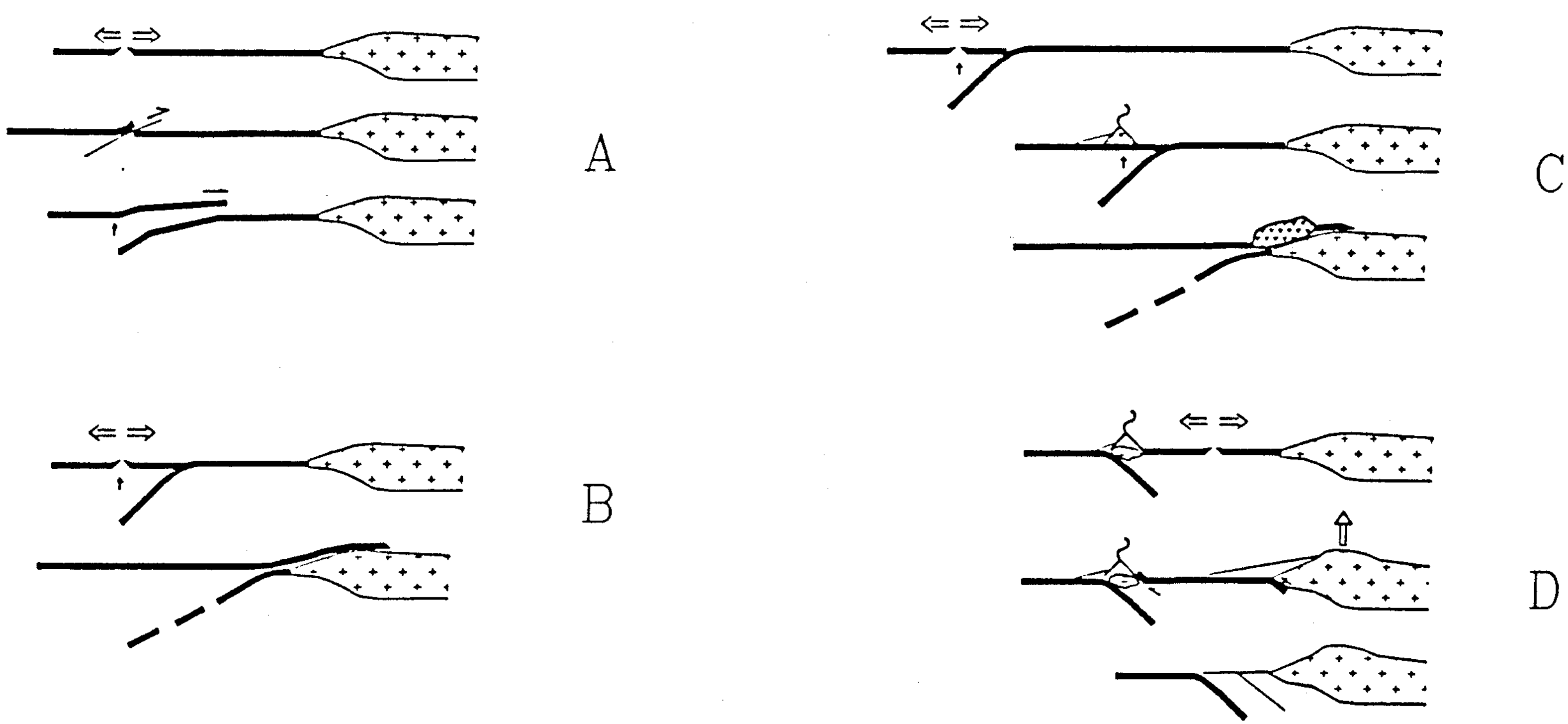


Fig. 4.2 Sketch depicting the possible models for the emplacement of ophiolites (see text for description and sources).

the ridge where the oceanic lithosphere is still very hot. It explains the mid-ocean ridge basalt affinity of the sole rocks. This model also accounts for the similar ages of the sole and ophiolite by detachment at the ridge. However, this model does not explain the high pressures associated with the metamorphic sole (up to 7 kbars) nor the island arc affinities of the Oman ophiolite, since this model predicts mid-ocean ridge basalt (MORB) affinities. Nicolas (1989) explains that the ophiolitic MORB affinites could have been contaminated by the development of magmatism from the subduction zone as intraoceanic thrusting continued. This seems unlikely, especially since the metamorphic sole and the igneous age of the ophiolite appear to by nearly the same. Also, although there is a change in volcanics in the Oman ophiolite to more island-arc affinities, the earliest volcanics are still not MORB affinities (Alabaster, et. al., 1982).

A much easier model to envision for the emplacement of the Oman ophiolite is one developed by Andrews-Speed (1983), Robertson (1988), and Edelman (1988) and represented in Figure 4.2.b In this model a subduction zone which dips away from the continent forms. The upper plate is under extension, probably due to steep subduction, and arc volcanism occurs by spreading. If subduction is short lived, the oceanic crust behind the subduction zone would then be emplaced onto the continent. This model explains the island arc magmatic affinities of the Oman ophiolite and the absence of arc volcanoes and volcaniclastic sediments. The model also explains the high temperatures found in the sole: the spreading creates young "hot" lithosphere: the sole probably detached from the downgoing oceanic slab as it was overridden by the ophiolite which explains the high pressures and the MORB affinities (the old oceanic crust would have MORB composition).

Additional evidence that this model may be possible comes from the East Scotia sea where spreading occurred prior to the development of the arc volcanoes; this is evident on Fig 4.3 where the magnetic anomalies are as old as anomaly 4 on the west side of the back-arc spreading center but the arc is located where anomaly 4 should be located on the east side (Hill and Barker, 1980). This scenario is represented in Figure 4.2.c.1: first subduction occurs with the slab dipping away from the distant continent. Behind the subduction zone, the upper plate is in extension and spreading occurs rather than development of discrete arc volcanoes. As mentioned above collision at this stage would produce the Oman ophiolite and sole. If the system continues, the spreading center moves away from the trench, and an arc is built on this lithosphere (like the present East Scotia sea). If subduction continues and the downgoing plate is faster than the back-arc spreading, collision with a continent is possible (e.g. Bay of Islands, Dewey and Bird, 1971).

4.3 TECTONIC MODEL FOR THE EMPLACEMENT OF THE JOSEPHINE OPHIOLITE

The Josephine ophiolite is quite distinct from all of the previous models since it was not emplaced onto a passive margin, but yet is well preserved and contains a metamorphic sole. Figure 4.2.d is a summary of the model for the emplacement of the Josephine ophiolite, which was described in Chapter 1 (after Wyld and Wright, 1988). Instead of obduction of the ophiolite, the Josephine was thrust >40 km (probably >100 km) <u>beneath</u> the continental margin during the Nevadan orogeny, was regionally metamorphosed and syntectonic magmatism intruded the Josephine ophiolite and its metamorphic sole. This underthrusting accounts for the ubiquitous greenschist retrograde metamorphism in the metamorphic sole.

The collapse of the back-arc basin and subsequent thrusting of the Josephine ophiolite beneath the continental margin and its coeval arc occurred during the Nevadan Orogeny at about 150 Ma which is also the metamorphic age of the "sole". This change

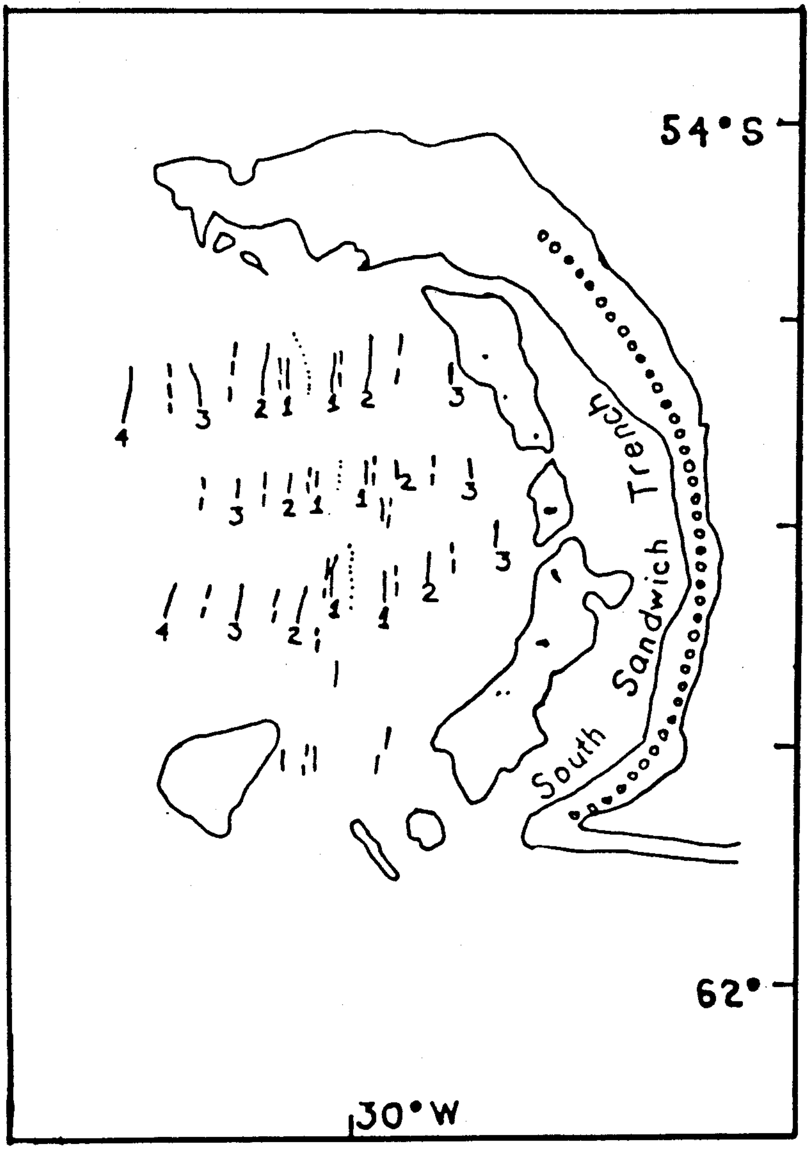


Fig. 4.3 Chart of the eastern portion of the Scotia Sea showing the magnetitic anomalies (Barker, 1972). Note that the arc sits of what would be anomaly 4.

of the system from extension to compression appears to correspond to a major change in plate motions (May et.al., 1989), which is evident from precise determination of the North America polar wander path. This change in plate motion may have created sinistral oblique convergence from about 150-135 Ma (May et.al., 1989).

A sole is well preserved in the Josephine ophiolite despite the thrusting of the ophiolite beneath the continental margin and has lower overall temperatures than many obducted metamorphic soles. The conclusions from this thesis support the Wyld and Wright (1988) model because the cooling ages fit the Nevadan Orogeny, the temperatures are reasonable for overthrusting of the Josephine ophiolite, and <5 kbars is acceptable for the model.

What is not resolved at this time is how the north-northeast thrusting direction fits into this model. According to the model, this direction is parallel to the continental margin where there is westward or northwestward convergence. The roof thrust (Orleans fault) has thrusting directions that are predominantly northwest, but rotate clockwise from the southwest to the northwest (Harper, in prep. and Griesau, in prep.). Plutons which intrude this fault indicate thrusting concurrent with the Madstone thrust (Harper, et.al., in press).

The northwest direction on the roof thrust is reasonable for the collapse of the back-arc basin and thrusting of the Josephine ophiolite beneath the continental margin, but the north-northeastward thrusting direction, from amphibolite facies through retrograde greenschist facies metamorphism is, however, apparently parallel to the inferred paleo-geographic trend of the arc and parallel to the length of the Nevadan Orogeny. One possibility is the recent observation that lineations in transpressional regimes form sometimes at a high angle to thrusting direction and parallel to the orogenic belt (Ellis and Watkinson, 1987) due to oblique thrusting.

An alternative hypothesis is related to intra-arc wrench faults. Figure 4.4 shows how this would occur for the Josephine ophiolite. An oblique subduction direction results in decoupling of the back-arc basin into several plates. This develops an intra-arc wrench fault which separates the area between the trench and this fault into a microplate. This plate acts independently from the Josephine ophiolite, which moves as one plate, and the North American continent. This hypothesis is supported by Saleeby (1983) who suggests that strike slip motion is important on the western edge of the North American continent.

Recent studies of strike-slip faults suggest that these faults may actual flatten at depth (e.g. Sylvester, A.G., 1988). If this is the case, the deep seated intra-arc wrench fault shown in Figure 4.4 may also flatten with depth. If this is possible, then this flattened wrench fault would look very much like a thrust fault with movement of the upper block towards that northeast.

4.4 CONCLUSIONS

The main conclusions of this thesis are as follows:

1. The structures of the amphibolite and serpentinite are concordant and thus related to thrusting of the Josephine ophiolite along the basal thrust (Madstone). The deformation continued during retrograde metamorphism. The sense of shear criteria indicate north-northeast thrusting of the Josephine ophiolite.

2. Geochemistry indicates that the amphibolite of the metamorphic sole is not related to the Josephine ophiolite. Instead, these rocks may be older and related to the Rattlesnake Creek Terrane.

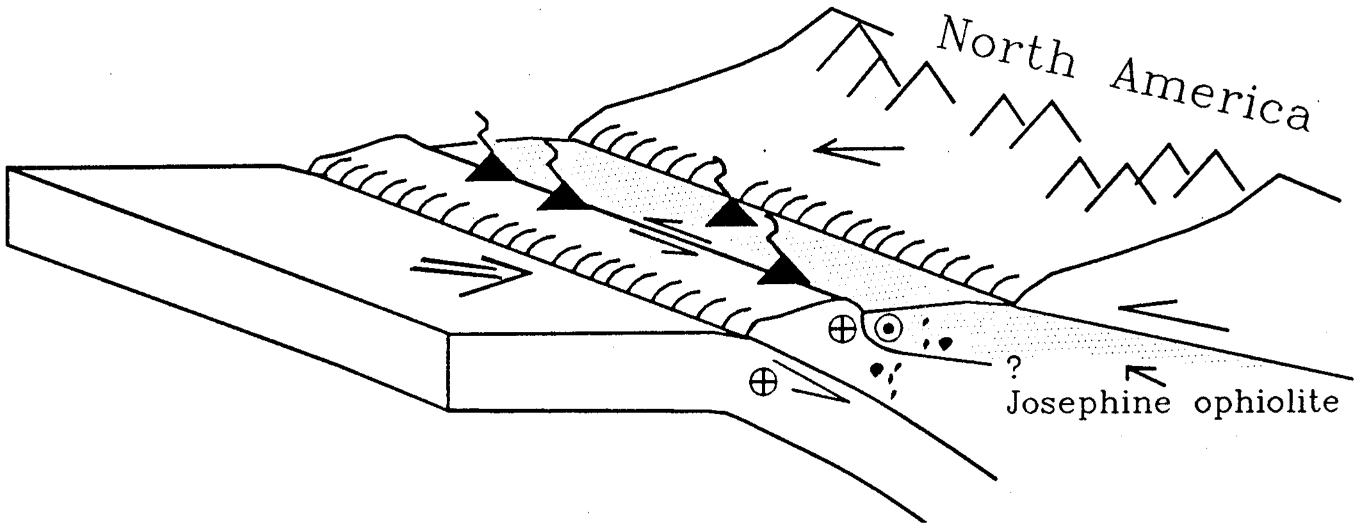


Fig. 4.4 Possible plate tectonic model for the emplacement of the Josephine ophiolite. Circles with a plus indicate motion out of the plane of the paper, whereas those with a dot indicate motion into the plane of the paper. See text for further discussion.

3. $^{40}Ar/^{39}Ar$ dating of the amphibolite sole suggests that the metamorphism and deformation of the metamorphic sole occurred during the Nevadan orogeny. This supports the conclusion that these structures represent the emplacement of the Josephine ophiolite. Dating of the pegmatite indicates deformation proceeded during slow cooling from 150 to 146 Ma.

4. Preliminary temperature and pressure estimates suggest that the peak metamorphism was amphibolite facies between 500°C and 600°C and pressures were >2 Kbars but $\leq$5 Kbars during deformation.

5. Preliminary data $\delta^{18}O$ measurements indicate heavy fluids were present when these rocks were cooling.

6. The data support the model for the emplacement of the Josephine ophiolite; but the thrusting direction is very different from what is observed in the roof thrust of the Josephine ophiolite.

7. One possible explanation for this difference could be that this thrust is actually a flattened intra-arc wrench fault at depth. If this is the case, strike slip motion might also be very important in the emplacement of ophiolites and the development of metamorphic soles.

4.5 FUTURE WORK

Many of the conclusions in this thesis could be better supported with the following work:

1. The population of samples for the serpentinite and phyllonite were rather small for this study. Additional microstructural work would enhance the conclusions presented here. Also, measurements of the veins could constrain the stress field during fluid infiltration and perhaps delineate between the hypotheses presented above (i.e. do the lineations form at an angle to plate motion or does this represent a flattened intra-arc wrench fault).

2. Sm/Nd dating of the amphibolite could be done to determine whether the amphibolite are older roof rocks of the Chetco Intrusive complex.

3. $\delta^{18}O$ work could be enhanced by separation of lizardite and antigorite to yield better constraints on the temperatures at which these rocks were deformed. Secondly, these measurements could enhance the interpretation of the source of the fluids which were present during formation of the serpentinite. This information could also better constrain the model for emplacement of the Josephine ophiolite.

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APPENDIX I:

PAPER IN PRESS IN GSA SPECIAL VOLUME ON KLAMATH TERRANES

A STRUCTURAL STUDY OF A METAMORPHIC SOLE BENEATH THE JOSEPHINE OPHIOLITE, WESTERN KLAMATH TERRANE, CALIFORNIA-OREGON

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ABSTRACT

The 162 Ma Josephine ophiolite was emplaced over an active mafic batholith (Chetco River complex) along the Madstone thrust in southwestern Oregon during the Nevadan orogeny, beginning at ~155 Ma. Strongly deformed amphibolite and minor quartzite occur between the ophiolite and the batholith and is interpreted to be a metamorphic sole formed during thrusting. Retrograde metamorphism is ubiquitous, and amphibolite has been locally been converted to greenschist-facies mafic phyllonite adjacent to the Madstone thrust. Pegmatite dikes locally cut the amphibolite but are also penetratively deformed, indicating syntectonic intrusion. A geochonologic study (Harper and others, 1989) indicates cooling from ~450°C at 153 Ma, intrusion of the pegmatite at 150 Ma, and cooling to ~350°C at 146 Ma. Geobarometry using amphibole composition and phengite content of muscovite indicates relatively low P/T metamorphism. The lower contact of the amphibolite sole with the Chetco River complex, as described by previous workers, is intrusive and syntectonic with deformation of the amphibolite sole.

In the hanging wall of the Madstone thrust, 20-40 m of high-T serpentinite mylonite occurs along the base of the Josephine peridotite. The serpentinite apparently formed during ophiolite emplacement because it is structurally concordant with the underlying amphibolite and phyllonite. In addition, the serpentinite locally shows metasomatism which probably resulted from interaction with fluids derived from the amphibolite sole.

The amphibolite shows two generations of folds having fold hinges parallel to a north-northeast stretching lineation. These structures, along with grain-size reduction and asymmetric fabrics, indicate that the amphibolites are mylonites formed by progressive simple shear. The lineations and sense-of-

shear criteria for the amphibolite and serpentinite mylonite indicate thrusting of the Josephine ophiolite toward the north-northeast, over the Chetco River complex. Continued north-northeast thrusting during greenschist retrograde metamorphism is indicated by lineations and microstructures in phyllonites and a pegmatite dikes. A minimum displacement of 12 km is inferred from the outcrop pattern of the Madstone thrust.

The metamorphic sole and regional geologic setting of the Josephine ophiolite is distinct from other ophiolites. There is no inverted gradient, maximum temperatures were lower, syntectonic magmas were intruded into both the metamorphic sole and the ophiolite, and the ophiolite was thrust over an active magmatic arc rather than a continental margin. In addition, the ophiolite and overlying Galice Formation were thrust beneath the North American continent by >40 km along the roof thrust (Orleans fault) and regionally metamorphosed to low grade.

Geochronologic and structural studies indicate that the basal Madstone thrust and the roof thrust were both active at 150$\pm$1 Ma, but the thrusting direction along the roof thrust appears to have been west or northwest. The cause and tectonic significance of nearly orthogonal thrusting directions between the basal and roof thrusts of the ophiolite is enigmatic. One possibility is that thrusting occurred during sininstral oblique subduction, and the Josephine thrust sheet was effectively decoupled along the roof thrust due to high pore-fluid pressures in the Galice Formation.

INTRODUCTION

Regional thrust faults are one of the fundamental structural aspects of the Klamath Mountains (Burchfiel and Davis, 1981; Snoke, 1977). Determination of the direction of thrusting is important for fully understanding the tectonic evolution of the Klamath Mountains and for relating orogeny to plate motions (e.g., Engebretson and others, 1985; May and Butler, 1986). Thrust faults are a major feature in the Western Klamath Terrane, including the basal (Madstone) and roof (Orleans) thrusts of the Josephine ophiolite and overlying Galice Formation (Fig. 1). These thrusts were both active during the Late Jurassic Nevadan orogeny (Harper and others, 1989).

A tectonic model for the formation and emplacement of the Josephine ophiolite is shown in Figure 2 and provides the framework for the study of the basal thrust. It is modified from Harper and Wright (1984) with the addition of new geochronologic data (Wyld and Wright, 1986; Wright and Fahan, 1988; Harper and others, 1989). A Middle Jurassic magmatic arc was built on older rocks of the Klamath Mountains beginning at ~177 Ma in response to eastward subduction beneath western North America. Following a major intra-arc orogeny at 165-170 Ma, rifting and formation of a back-arc basin resulted in generation of the Josephine ophiolite; the inferred east-west orientation of spreading centers in the Josephine ophiolite suggests that the back-arc basin may have been dominated by arc-parallel transforms formed in response to oblique subduction (Saleeby, 1983; Harper and others, 1985). The back-arc basin was short-lived, and the Josephine ophiolite was buried by flysch and thrust beneath the Klamath Mountains. The active arc to the west was also buried by flysch and thrust beneath the Josephine ophiolite. With continued shortening, the ophiolite became situated over the zone of arc magmatism, resulting in syntectonic intrusion of the ophiolite, Galice Formation, and thrust faults.

This paper focuses on the basal thrust of the Josephine ophiolite (Madstone thrust, Figs. 1, 3, 4), including an amphibolite sole. The main objectives of this paper are 1) to document that metamorphism and deformation of the amphibolite sole occurred during ophiolite emplacement, 2) to determine the direction of thrusting, and 3) estimate pressure and temperature conditions during thrusting.

REGIONAL FRAMEWORK

The Klamath Mountains province consists of thrust slices of Paleozoic and Mesozoic marine volcanic arc and sedimentary strata, along with ophiolitic rocks (Irwin, 1966, 1981; Burchfiel and Davis, 1981). The major tectonic units are generally younger towards the west and are separated by regional east-dipping thrust faults (Davis and others, 1978; Wright and Fahan, 1988).

The Western Klamath Terrane (western Jurassic belt of Irwin, 1966) is a generally east dipping belt of ophiolitic rocks, island-arc intrusive and volcanic rocks, and Upper Jurassic flysch (Galice Formation) which is bounded at the top and base by regional thrust faults (Irwin, 1966, 1981). Blake and others (1985) subdivided the Western Klamath Terrane into three subterranes (Fig. 1): the Smith River subterrane (Josephine ophiolite and overlying flysch), the Dry Butte subterrane (primarily intrusive rocks), and the Rogue River subterrane (mostly volcaniclastics and flysch).

The structurally highest thrust sheet in the Western Klamath Terrane is the Smith River subterrane which includes the Josephine ophiolite and overlying Galice Formation (Harper, 1984). The ophiolite has been dated in the area of Figure 1 at 162±1 Ma by Pb/U dating of zircon (Saleeby, 1987) and latest Callovian by radiolaria in mudstone interbedded with lavas (E. Pessagno, written communication, 1989). A southern remnant of the Josephine ophiolite has yielded a Pb/U zircon age of 164±1 Ma (Wright and Wyld, 1986). The Galice Formation conformably overlies the ophiolite and consists of ~50 m of radiolarian argillite and chert, ranging from early to middle Oxfordian age, which grade upward into flysch of middle Oxfordian to Kimmeridgian age (Pessagno and Mizutani, 1988).

The Rogue River subterrane (Fig. 1) consists of marine volcanic-arc strata (Rogue Formation) overlain by turbidites (flysch) of the Galice Formation. The Rogue Formation has yielded Pb/U zircon ages of 157 Ma (Saleeby, 1984). The Galice Formation conformably overlies the Rogue Formation (Wood, 1987) and is the same age and petrographically similar to flysch of the "Galice" that overlies the Josephine ophiolite (Harper, 1983; Pessagno and Blome, 1988; Pessagno and Mizutani, 1988). The Rogue and Galice Formations were folded and regionally metamorphosed during the Nevadan orogeny (Wells and Walker, 1953; Garcia, 1979; Riley, 1987; Park-Jones, 1987). The Briggs Creek amphibolite forms an elongate belt structurally beneath the Rouge Formation and was defined by Blake and others (1985) as a separate subterrane. The Briggs Creek amphibolite, along with a large ultramafic body to the west, are tentatively included in the Rogue River subterrane, consistent with the interpretation that they may represent ophiolitic basement upon which the Rogue arc was built (Garcia, 1982).

The Dry Butte subterrane (Fig. 1) consists of a Late Jurassic batholithic complex, known as the Chetco River complex or Illinois River gabbro (Hotz, 1971), and probably represents the plutonic roots of the Rogue volcanic arc (Dick, 1976, 1977; Garcia, 1982). The intrusive rocks range from gabbro through quartz diorite. The Chetco River complex is generally isotropic in the central part, whereas it becomes foliated and lineated near its margins, with the foliation dipping towards the east-southeast (Wells and others, 1949).

Gneissic amphibolite north of Vulcan Peak occurs adjacent to the Madstone thrust along the southern margin of the Dry Butte subterrane. These rocks, along with amphibolite near Chetco Lake to the south, form the metamorphic sole of the Josephine ophiolite, and also form the roof of the Chetco River complex (Fig. 3, cross section). This contact is intrusive, but the intrusive rocks are also deformed along with the amphibolite (Loney and Himmelberg, 1976; Dick, 1976), indicating syntectonic intrusion. Deformed ultramafic rocks appear to be associated with the amphibolite and locally form the roof of the batholith (Fig. 3).

The Josephine ophiolite of the Smith River subterrane is thrust over the Dry Butte subterrane along the Madstone thrust (Figs. 1, 3, 4). The nature of fault contacts between the other subterranes is uncertain, but mapping by Dick (1976) and Harding (1987), along with areomagnetic interpretation by Harding (1987) suggest that the Josephine ophiolite (Smith River subterrane) is thrust over the Rogue River subterrane, probably along an eastward and northeastward extension of the Madstone thrust. The boundary between the Rogue River and Dry Butte subterranes is tentatively taken to be a north-northeast striking thrust fault which forms the eastern boundary of the Dry Butte subterrane (Ramp, 1984); we will informally refer to this fault as the Pearsoll Peak thrust (Fig. 1). Mapping of the Pearsoll Peak thrust by Ramp (1984) show similarities to the Madstone thrust: foliated intrusive rocks and locally amphibolite are present along the thrust (Ramp, 1984). In addition, a locally foliated intermediate-granitic intrusive sheet extends along the thrust and locally intrudes the peridotite in the hanging wall (Hotz, 1981; Ramp, 1984); a 151$\pm$4 Ma K/Ar age on muscovite from this unit is similar to K/Ar and $^{40}Ar/^{39}Ar$ muscovite ages of deformed pegmatite dikes that intrude the gneissic amphibolite below the Madstone thrust (Dick, 1976; Harper and others, 1989).

The roof thrust of the Smith River Subterrane is the Orleans fault (Fig. 1). The outcrop pattern of the Orleans fault, including a large northeast trending reentrant (Fig. 1), indicate that the Western Klamath Terrane has been thrust

>40 km beneath older terranes of the Klamath Mountains. Gravity data suggests that the fault extends much further eastward, implying >110 km of horizontal displacement, assuming west-directed thrusting (Jachens and others, 1986). The timing of movement on the Orleans fault is constrained by 150-139 Ma plutons that cut the thrust (Fig. 1) and contact metamorphose the upper and lower plates (Snoke, 1977; Wright and Fahan, 1988; Harper and others, 1989).

Regional metamorphic grade in the Rogue River and Smith River subterranes ranges from prehnite-pumpellyite to lower greenschist facies (Irwin, 1966; Garcia, 1978; Harper, 1984; Harper and others, 1988). As disscussed in this study, Nevadan age amphibolite-grade metamorphism occurred in the metamorphic sole of the Josephine ophiolite, but was was continuous with greenschist-facies retrograde metamorphism. The additional heat required for the amphibolite grade metamorphism was probably provided by syntectonic intrusion of the underlying Chetco River complex. The regional metamorphism and deformation along thrusts shows that the present exposure of the Western Klamath Terrane was at mid-crustal depths during the Nevadan orogeny (~150 Ma). Uplift and exposure occurred by ~125 Ma as indicated by a Lower Cretaceous angular unconformity south of Cave Junction, Oregon (Fig. 1).

The western boundary of the Western Klamath Terrane is an east-dipping thrust (Fig. 1) called the Valen Lake thrust in Oregon and the South Fork fault in California. The Valen Lake thrust is post-Nevadan in age and truncates the Madstone thrust (Fig. 1). Within the area of Figure 1, the footwall of the thrust consists of latest Jurassic to Early Cretaceous graywacke and shale (broken formation) and melange assigned to the Yolly Bolly terrane of the Franciscan complex (Aalto and Harper, 1982; Blake et al., 1985; Aalto, 1989).

The map pattern of the Western Klamath Terrane in the area of Figure 1 largely reflects post-Nevadan folding and faulting. The Josephine ophiolite, the Orleans thrust, the Madstone thrust, and the Valen Lake thrust are folded by large open southeast-plunging anticlines and synclines (Fig. 1). The post-Nevadan age of these folds is evident from folding of the Valen Lake thrust, as well as from folding of Nevadan age foliations in the Josephine ophiolite and overlying Galice Formation.

THE MADSTONE THRUST AND THE METAMORPHIC SOLE

The Madstone thrust in southwestern Oregon forms the basal contact of the Josephine peridotite. Along the northern edge of the peridotite, the trace of the Madstone thrust is appoximately east-west (Figs. 1, 3). Along the western 10 km of the thrust, the Josephine peridotite is thrust over its amphibolite sole and intrusive rocks of the Chetco River complex, whereas further east the peridotite is thrust over the Rogue River subterrane. The present outcrop pattern of the Madstone thrust is due to post-Nevadan folding: the east-west trending segment is in the hinge of a southeast plunging syncline (Fig. 1, 3, cross section; Dick, 1976), and a north-south segment, exposed further south near Chetco Peak, is situated on the west-dipping limb of the syncline (Figs. 4, 5).

The basal Josephine peridotite adjacent to the contact with underlying amphibolite has been converted into serpentinite having a fabric structurally concordant with the amphibolite. The actual contact is well exposed on a ridge northeast of Vulcan Peak and in a canyon west of Chetco Lake (Fig. 6). At both localities, the contact is sharp with no evidence of later faulting. As much as one meter of coarse-grained talc-actinolite schist occurs along the contact and probably represents a metasomatic reaction zone between the serpentinite and amphibolite.

Hanging Wall of the Madstone Thrust

The upper plate of the thrust in the Chetco Peak area consists of nearly fresh harzburgite of the Josephine ophiolite, underlain by a 20-40 m sole of serpentinite along the Madstone thrust (Figs. 4, 6). The serpentinites are coherent, often tough, and vary from weakly to strongly foliated and lineated. Carbonate is present in many of the serpentinites, and may comprise 15% or more of the rocks. Talc-rich serpentinite and chlorite veins occur locally near the thrust.

In thin section, two generations of serpentine are evident. An older serpentine is apparent from pseudomorphic textures after olivine (mesh and hourglass textures) and orthopyroxene (bastite) which are typical of lizardite (Wicks and Whittaker, 1977); these textures are variably overprinted by coarser grained serpentine having a bladed habit characteristic of antigorite. In weakly foliated samples, antigorite occurs as randomly oriented blades overprinting pseudomorphic lizardite and within discrete shear zones. Strongly foliated samples consist mostly of aligned antigorite blades, patches of aligned chlorite, and streaks of magnetite; lozenges of relict finer grained lizardite partially overgrown by antigorite are common. The coherent nature, lineation, and microstructures of the antigorite-rich rocks suggest that the later serpentinization formed during relatively high temperature ductile flow rather than by brittle faulting and are can be termed "serpentinite mylonite" as defined by Norrell and others (1989).

Where the contact between the serpentinite and underlying gneissic amphibolite is exposed, as much as 1 m of coarse-grained, non-lineated tremolite + talc schist. Talc-rich zones and chlorite seams also occur within the overlying serpentinite mylonite. In thin section, the chlorite is in textural equilibrium with antigorite and has a preferred orientation parallel to the antigorite, indicating metasomatism occurred during the second higher temperature serpentinization which appears to have occurred during emplacement of the ophiolite.

Footwall of the Madstone Thrust

Gneissic amphibolite. The amphibolite beneath the Madstone thrust is gneissic and has a stretching lineation defined by aligned hornblende and aggregates of recrystallized plagioclase and quartz. The thickness of the amphibolite is ~200 m in the Chetco Lake area but is highly variable further north near Vulcan Peak (Fig. 3). Ultramafic rocks exposed on and south of Dry Butte are strongly deformed and are probably related to the gneissic amphibolite (Fig. 3; Loney and Himmelberg, 1977; Cannat and Boudier, 1985). Amphibolite exposed north of Vulcan Peak (Fig. 3) have large plagioclase porphyroclasts (Fig. 7), suggesting a gabbro protolith. Some of the amphibolite is apparently metabasalt because it is associated with thinly layered micaceous quartzite (metachert) near Chetco Lake. A manganese deposit (rhodenite) occurs in the quartzite (Ramp, 1975); these sediments are probably hydrothermal, analogous to Fe-Mn sediments which commonly overlie ophiolites and which are known to form from hot springs on mid-ocean ridges (e.g., Crerar and others, 1982). The protoliths of the gneissic amphibolite unit are thus typical of an ophiolitic assemblage, but their igneous age is only contrained to be pre-Nevadan.

The gneissic layering and quartzite is folded by two generations of tight to isoclinal, nearly similar folds (Figs. 8, 9), and sheath-like fold profiles have been observed. Fold hinges of both generations of folds are parallel to the hornblende lineation (Fig. 10). The geometry of these folds suggests that both generations formed during a single continuous deformation; the folds are thus termed F_{1a} and F_{1b}. Late open folds (F_2) are evident in some outcrops and have subhorizontal north-northwest trending axes; these folds appear to be related to large-scale folding of the Madstone thrust and the younder Valen Lake thrust (Figs. 1, 10). In the Chetco Lake area, this late folding accounts for the northeast dip of the thrust (Figs. 3, 4), as well as minor scatter in the plunge of lineations and broadening of the girdle defined by poles to foliation (Fig. 10).

In the Chetco Lake area, the gneissic amphibolite consist of hornblende + plagioclase + sphene or Fe-Ti oxide ± epidote ± quartz ± biotite. Retrograde metamorphism to greenschist or prehnite-pumpellyite facies is evident from veinlets of epidote, quartz, and rarely pumpellyite. In addition, much of the primary plagioclase is cloudy due to alteration to epidote, muscovite, and albite(?), and hornblende is commonly partially altered to actinolite ± chlorite.

Mafic phyllonite locally occurs along the Madstone thrust (Fig. 4; Ramp, 1975; Dick, 1976). These rocks are highly retrogressed amphibolites as indicated by the presence of relict hornblende as porphyroclasts (Fig. 11, Table 1). The foliated matrix consists of actinolite, chlorite, and locally muscovite, along with equant epidote and quartz.

Pegmatite dikes locally intrude the gneissic amphibolite and cut folds in the gneissic amphibolite (Figs. 4, 9). Of three samples examined in thin section, all contain abundant primary muscovite, two have garnet, and the third sample has minor biotite. Secondary minerals observed in one sample include prehnite, epidote, and chlorite. Microstructures indicate the dikes are strongly deformed (Fig. 12): foliations are defined by aligned mica and aggregates of quartz, relict quartz grains have undulous extinction and subgrains, some quartz is very fine-grained and is apparently recrystallized, micas are kinked and bent, and some plagioclase is bent and has deformation twins.

The gneissic amphibolite, quartzite, phyllonite, and pegmatite have mesoscopic and microscopic features that are characteristic of mylonites such as stretching lineations, grain-size reduction, composite foliations, and rotated porphyroclasts (Figs. 7, 11, 12). Furthermore, coaxial and sheath folds, such as those observed in the gneissic amphibolite, are common in other high strain zones, and the parallelism of fold hinges with the stretching lineation suggests rotation of fold hinges into the displacement direction during progressive simple shear (e.g., Bell and Hammond, 1984).

Chetco River complex. The Chetco River complex (Figs. 1, 3) has been mapped and described by Wells and others (1949), Ramp (1975), Dick (1976), and Loney and Himmelberg (1977), and the following summary is taken from this previous work. In the vicinity of the Madstone thrust, the Chetco River complex consists predominantly of hornblende metagabbro (Fig. 3), partially retrogressed to fine-grained greenschist-facies assemblages. Late stage undeformed gabbro pegmatite occurs north of the Madstone thrust (Fig. 3).

The contact between the the Chetco River complex and the gneissic amphibolite is intrusive (Fig. 3); it is gradational and difficult to map because the gneissic amphibolite and the intrusive rocks are foliated, lineated, and have amphibolite facies mineral assemblages (Wells and others, 1949; Ramp, 1975; Dick, 1976; Loney and Himmelberg, 1977). Thus intrusion of the metagabbro, as well as the granitic pegmatite dikes in the gneissic amphibolite, was apparently syntectonic, a conclusion that is supported by geochronologic data discussed below.

Displacement Direction on the Madstone Thrust

Shear Sense Indicators. The sense of shear in the mylonitic rocks associated with the Madstone thrust can be interpreted using criteria discussed by Berthe and others (1979), White and others (1980), Simpson and Schmid (1983), Lister and Snoke (1984), and Passchier and Simpson (1986). These criteria include composite planar fabrics (S-C), shear bands (C'), rotated porphyroclasts, and asymmetric pressure shadows. In addition, crystallographic fabrics evident in thin section were used for hornblende (Hall, 1984) and quartz (e.g., Lister and Hobbs, 1980).

The orientation of stretching lineations in the mylonite associated with the Madstone thrust are interpreted to be parallel to the bulk transport direction. They plunge gently toward the northeast in the Chetco Lake area for both the gneissic amphibolite and serpentinite mylonite (Figs. 4, 10). The phyllonite and pegmatite dikes also have northeast trending lineations (Figs. 4, 9).

Hornblende in gneissic amphibolite has a strong preferred crystallographic and shape orientation parallel to the gneissic layering. The hornblende crystals have ragged edges and commonly show undulatory extinction. Quartz and plagioclase are intergrown and generally form relatively fine grained equant grains in the lighter gneissic layers. The much finer grain size of quartz and feldspar, along with the local presence of plagioclase porphyroclasts (Fig. 7), some of which have relict igneous zoning, suggests that these rocks have undergone significant grain size reduction typical of mylonites. In some gneissic amphibolites, the sense of shear can be inferred from S-C fabrics. A foliation oblique to the gneissic layering, interpreted as an S foliation, is defined by the shape and crystallographic preferred orientation of hornblende, sphene, plagioclase, and/or epidote. The shear sense in amphibolite was also determined using a technique developed by Hall (1984) using ductile shear zones of known displacement: if c-axes of the hornblende are subparallel to foliation, an asymmetry is defined by the uniform inclination of a-axes; for dextral shear in thin section, the a-axes are inclined in a clockwise sense with respect to the foliation. This asymmetry can be identified in thin section using changes in pleochroism as the microscope stage is rotated. The shear sense in a quartzite (Table 1) was determined using a strong asymmetric crystallographic preferred orientation; for intercrystalline slip on the basal plane of quartz, the trace of the c-axes should be inclined in a counter-clockwise sense from the normal to the foliation.

The foliated, antigorite-rich serpentinites along the base of the Josephine Peridotite are structurally concordant with the amphibolite (Fig. 10). Many of these rocks, however, are apparently not highly strained and do not have well developed shear sense indicators. Sense of shear indicators are evident in a few antigorite-rich mylonites and include asymmetric porphyroclasts and shear bands (Fig. 13).

Sense of shear has also been determined for the later stages of deformation using 1) microstructures in mafic phyllonite, and 2) microstructures in a pegmatite dike which is deformed, but cuts gneissic layering in the gneissic amphibolite. The sense of shear is the mafic phyllonite is indicated by porphyroclasts having asymmetric tails (Fig. 11) and by shear bands. The pegmatite dikes are lineated and some have a well developed S-C fabric defined by the preferred orientation of micas (Fig. 12) and by lenticular aggregates of recrystallized quartz. In addition, the sense of shear in some gneissic amphibolites during retrograde metamorphism is interpreted from 1) very fine-grained muscovite which defines a planar fabric oblique to the gneissic layering, and 2) extension veins (some with fibers) which are at a high angle but oblique to the gneissic layering. Both of these criteria assume that the plane of shear is essentially the same during both amphibolite and later retrograde metamorphism; this assumption seems justified based on the similar orientation of foliations and lineations in the amphibolite, pegmatite, and mafic phyllonite (Fig. 4, 10).

Results. The results of the shear sense determinations are given in Table 1. The lineations and sense of shear for amphibolite, quartzite, pegmatite, and serpentinite consistently indicate north-northeast thrusting of the Josephine ophiolite over the gneissic amphibolite and Chetco River complex. Continued thrusting in the same direction is indicated by lineations and the sense of shear for phyllonite, late veins and minerals in amphibolite, and the pegmatite. The same sense of shear was determined by Cannat and Boudier (1985) for quartzites in the Chetco Lake area, who used asymmetric crystallographic fabrics and pressure shadows. A minimum displacement of 12 km is indicated by the current exposures of the Madstone thrust.

Determination of the actual displacement direction during the Nevadan orogeny requires that the structural data be corrected for post-Nevadan rotations. The east dip of the Madstone thrust near Chetco Lake is the result of late folding and was removed by rotation about the subhorizontal F_2 fold axis. Rotating the thrust to horizontal results in the average lineation still trending northeast, but the plunge becomes subhorizontal (Fig. 10). Thus, the direction of thrusting is essentially unchanged.

A less certain structural correction involves possible Tertiary clockwise rotations as suggested by paleomagnetic studies. Declination anomalies in the Klamath mountains are generally compatible with Tertairy oroclinal bending of the Klamath Mountains and initial structural trend similar to pre-Tertiary rocks in the Sierra Nevada foothills to the south (~N40W; Renne and Scott, 1988; Renne and others, 1988). If the regional change in structural grain from northwest to northeast in the Klamath Mountains (Fig. 1) is assumed to be the result of oroclinal bending, then the structural grain in the Western Klamath Terrane at the latitude of the Madstone thrust (~N20E) would suggest ~60° of clockwise rotation. Declination anomalies determined northeast of the study area are compatible with large rotations: 78±26° for the 139 Ma Grants Pass pluton (Fig. 1) and 99±10° for probable Nevadan-age magnetization near Galice, Oregon (Schultz and Levi, 1983; Bogen, 1986). Removal of a 60-100° clockwise rotation would change the north-northeast transport direction for the Madstone thrust to northwest. Additional paleomagnetic and structural data are needed, however, to determine the size of domains that have undergone rotations (e.g., Renne and Scott, 1988). The amount of rotation could best be evaluated with a paleomagnetic study on rocks in close proximity to the Madstone thrust.

Relative Ages and Geochronology

Based on the geometry and structure of the gneissic amphibolite, several workers have interpreted these rocks as a metamorphic sole formed during emplacement of the Josephine ophiolite (Armstrong and Dick, 1974; Dick, 1976; Cannat and Boudier, 1985). Cannat and Boudier (1985) assumed that the amphibolite was a metamorphic sole and suggested that a thick basal section of peridotite mylonite in the upper plate had been faulted away. They noted the presence of a few meters of "serpentinized peridotite mylonite", which the present study has shown is actually serpentinite mylonite.

In contrast, Loney and Himmelberg (1977) considered the Madstone thrust to be younger than the earliest deformation in the amphibolite. These workers, along with Cannat and Boudier (1985) and the present study, recognized two generations of folds which have axes parallel to a stretching lineation. Loney and Himmelberg (1977) observed gabbro dikelets that cut "F_1" (F_{1a}) folds but which are folded by "F_2" (F_{1b}) folds. In the context of the present study, this observation is consistent with dike intrusion during a single progressive deformation which produced both sets of folds.

Additional relative age control from the present study which indicates that the amphibolite was deformed during thrusting and magmatism include the following: (1) pegmatite dikes (Figs. 4, 9, 12) cut folded amphibolite but are also deformed; (2) gneissic amphibolite and overlying serpentinite mylonite are structurally concordant (Figs. 4, 10); and (3) the serpentinite has undergone metasomatism along the thrust, apparently from fluids derived from the footwall.

A Nevadan age for thrusting, intrusion, and amphibolite-grade metamorphism is indicated by gechronologic studies. Dick (1976) obtained ~150 Ma K/Ar ages on hornblende from both the amphibolite and Chetco River complex, as well as on muscovite from pegmatite dikes intruding the amphibolite. $^{40}Ar/^{39}Ar$ dating has yielded similar results (Fig. 6; Grady and others, 1989; Harper and others, 1989), but allows evaluation of some of the assumptions inherent in K/Ar dating. Two amphibolites gave $^{40}Ar/^{39}Ar$ hornblende cooling ages (~400-500°C) of 152±1 and 153±1 Ma, and a metagabbro north of Vulcan Peak yielded a 151±1 Ma hornblende cooling age. A pegmatite dike intruding the amphibolite (Figs. 6, 9) has a Pb/U zircon age of 150±1 Ma and $^{40}Ar/^{39}Ar$ dating of muscovite indicates slow cooling near its closure temperature (~350°C) from 150-146 Ma.

Thus, the relative and absolute ages, along with field relationships, clearly demonstrate that ductile deformation and syntectonic magmatism along the

Madstone thrust is Nevadan in age. Furthermore, the cooling history evident from hornblende and muscovite ages is consistent with the observed retrograde metamorphism associated with continued displacement along the Madstone thrust.

Pressure, Temperature, and Fluids

Two gneissic amphibolites collected from the Chetco Lake area contain pargasitic hornblende + plagioclase (largely altered) + epidote + minor chlorite + quartz + sphene + Fe-Ti oxide. For these samples, no quantitative estimate of metamorphic temperature is possible, but the mineral assemblage suggests a temperature range of 400-540°C (Apted and Liou, 1983; Maruyama and others, 1983). Pressure can be estimated using the NaM4 content of calcic amphibole (Brown, 1977). For this estimate, the amphibole formalae obtained from microprobe analysis were recalculated by normalizing the number of cations (excluding Ca, Na and K) to 13, then adding ferric iron to balance a charge of 46; other normalization schemes do not change the calculated NaM4 content enough to significantly alter the pressure estimate. The resulting pressure estimate is $\leq$ 4 kb for two samples (Table 1; SA13, SA44). Sample SA44 is rimmed by a less aluminous calcic amphibole having approximately the same NaM4 but less total Na than the amphibole core, suggesting decreasing temperature at constant or decreasing pressure (Raase, 1974; Brown, 1977).

A mafic phyllonite from beneath the Madstone thrust contains pophyroclasts of relict brown tschermakitic amphibole + calcic plagioclase (altered). Although no quantitative pressure or temperature estimates can be made from these relict minerals, the assemblage of tschermakitic amphibole +

plagioclase, as well as the high TiO_2 content of the calcic amphibole (Table 2; SA 102), is suggestive of higher temperatures than the other amphibolite samples. The brown hornblende is rimmed by a less aluminous hornblende, which is in turn rimmed by actinolite (Fig. 11; Table 2). The only other brown hornblende observed in samples from the Chetco Lake area was from a second phyllonite near the Madstone thrust. The zoning trend in amphiboles from the phyllonite (SA 102) is consistent with retrograde metamorphism from amphibolite-facies to greenschist-facies conditions (Raase, 1974).

Pressure can be estimated from the phengite content of muscovite in a deformed pegmatite dike (Figs. 9, 12), because it has the assemblage muscovite + biotite + K-feldspar + quartz (Massonne and Schreyer, 1987). Because the assemblage in the pegamatite is an igneous assemblage, the derived pressure corresponds to the time of the dike intrusion: the low-T alteration assemblage, field relations, and age of the dike indicate that it was intruded during greenschist-facies retrograde metamorphism. Temperature is needed to apply the geobarometer and can be estimated from the upper temperature stability of this assemblage which melts at ~700°C in the presence of water at pressures >3 kb (Massonne and Schreyer, 1987). For an equilibration temperature of 700°C and assuming $a_{H2O} = 1$, the measured Si content per formula for muscovite (J113-7; Table 2) gives a pressure of ~5 kb. Muscovites in this sample have a uniform composition and no zoning was detected. The quantitative effects of iron in muscovite on the geobarometer are not known, but addition of Fe^{2+}, and especially Fe^{3+} result in a lower Si content and thus a pressure estimate that is too low. The effect of $a_{H2O}<1$ is relatively small and also causes a shift toward higher pressures at a given Si content. The uncertainty in temperature has a relatively small affect on the estimated pressure. The phengite barometer is sensitive to fluorine content, however, which is likely to be high in a pegmatite muscovite: pressure will be overestimated by approximately 1.5 kb for each increase in F/(F+OH) ratio of 0.1 (Massonne and Schreyer, 1987). Thus, it is likely that the higher pressure given by the phengite geobarometer (5 kb) compared with the amphibole geothermometer ($\leq$4 kb) is the result of fluorine in the anlalyzed muscovite.

A further constraint on pressure is given by regional and contact metamorphism in other rocks of the Western Klamath Terrane. Mineral assemblages formed during regional prehnite-pumpellyite facies metamorphism in northwestern California suggest conditions of ~300°C and 2-4 kb (Harper and others, 1988). The presence of andalusite in contact aureoles around Nevadan plutons which intrude the Galice Formation (Harper, 1980; Wyld and Wright, 1986; Harper and others, 1989) also indicates low pressure (<4 kb). These data, along with the geobarometry of the metamorphic sole indicate relatively low P/T metamorphism during emplacement of the Josephine ophiolite.

Serpentinite mylonite above the Madstone thrust contains bladed, typically schistose antigorite (Fig. 13). In general terms antigorite is the high-temperature serpentine mineral, whereas lizardite and chrysotile are the low-temperature minerals (Wenner and Taylor, 1974; Evans, 1977). For the Josephine samples (serpentinized harzburgite), the stability of antigorite at ~4 kb can be estimated using the following reactions in the Al-poor system: lizardize = antigorite + brucite (~225°C), antigorite + brucite = forsterite (~450°C), and antigorite = fosterite + talc + H_2O (~530°C; O'Handley and others, 1989). The abundant carbonate associated with the antigorite suggests that CO_2 was present in the fluid phase and would reduce the maximum stability temperature of antigorite (~30°C for a fluid with 20% CO_2; Trommsdorff and Evans, 1977). Thus, the antigorite is estimated to have formed at temperatures between 250-550°C. The relict pseudomorphic low-T (<250°C) lizardite evident in some samples could be either oceanic or early Nevadan in age and indicates that the hanging wall of the Madstone thrust was heated during thrusting to form antigorite mylonites.

The presence of essentially fresh peridotite within 40 m of the thrust suggests that the basal serpentinite mylonite formed an impermeable barrier to metamorphic fluids during thrusting. Such a barrier may have resulted in channeling of fluids along the Madstone thrust, resulting in extensive hydration of amphibolite to the mafic phyllonite localized beneath the thrust (Fig. 4). The high strains evident from the fabrics of the phyllonite suggest that shearing was localized in these rocks during retrograde metamorphism, probably due to strain softening resulting from abundant fluids allowing formation of relatively weak phyllosilicates (e.g., White and Knipe, 1978).

Infiltration of fluids from below the thrust into the antigorite serpentinites is indicated by local metasomatism evident from talc, chlorite, and carbonate. Talc + actinolite schist, as much as 1 m thick, which occurs along the contact with underlying amphibolite or phyllonite apparently represents a metasomatic reaction zone. These metasomatic features are similar to those in antigorite serpentinites formed during iniltration of fluids along the basal thrust of the Trinity ultramafic sheet in the eastern Klamath Mountains (Peacock, 1987).

Retrograde metamorphism is evident from amphibolite-facies assemblages overprinted by typical greenschist-facies assemblages. The presence of a pumpellyite vein in an amphibolite sample and prehnite in the synetectonic pegmatite in the Chetco Lake region suggest that retrograde metamorphism extended down to the prehnite-pumpellyite facies. The regional metamorphic grade higher in the Josephine thrust sheet at this latitude is prehnite-pumpellyite facies (Harper and others, 1988). Thus it is likely that the excess heat needed for amphibolite grade metamorphism beneath the Madstone thrust was supplied by the underlying syntectonic intrusive rocks of the Chetco River complex.

DISCUSSION AND CONCLUSIONS

This study has documented the presence of a metamorphic sole beneath the Josephine ophiolite. Emplacement of the ophiolite, however, was much different than other ophiolites, such as the Semail and Bay of Islands, which also have metamorphic soles (Spray, 1984; Moores, 1982):

(1) The Josephine ophiolite is thrust over a magmatic arc complex (Figs. 1, 3) rather than over a continental shelf. The ophiolite and overlying Galice Formation were thrust <u>beneath</u> the continental margin and metamorphosed to low grade during the Nevadan (Harper and others, 1989).

(2) An inverted metamorphic gradient is absent.

(3) A basal zone of very highly strained peridotite is absent in the Josephine ophiolite. Instead, a 20-40 m zone containing antigorite mylonite occurs above the basal thrust. The presence of antigorite mylonite rather than perdotite mylonite, as well as the absence of granulite facies metamorphism, suggests lower maximum temperatures (<~600°C) during thrusting, compared to those in metamorphic soles of other ophiolites (≥~800°C; Nicolas and Le Pichon, 1980; Spray, 1984).

These differences are a reflection of tectonic setting of ophiolite emplacement. The Josephine ophiolite represents back-arc basin lithosphere thrust over an active arc (Fig. 2). In contrast, emplacement of other ophiolites appears to have involved collision in which the continental margin was carried beneath the ophiolite (Moores, 1982).

The gneissic amphibolite and quartzite, retrogressed amphibolite, pegmatite dikes, and antigorite serpentinite are all structurally concordant and show evidence of deformation by progressive simple shear. The concordant structures, along with metasomatism of the serpentinite, indicate that these rocks were deformed during north-northeast emplacement of the Josephine ophiolite over a gabbroic batholith (Chetco River complex). Metamorphism was retrograde in nature, ranging from amphibolite through prehnite-pumpellyite facies, and occurred under low P/T conditions. Geochronologic studies (Dick, 1976; Harper and others, 1989) demonstrate that thrusting and magmatism is Nevadan in age (Fig. 6) and indicate cooling from ~450°C at 153 Ma to ~350°C at 146 Ma (Harper and others, 1989). The minimum offset along the Madstone thrust is 12 km., which gives a minimum displacement of ~1.2 mm/y.

In contrast to the north-northeast directed thrusting on the basal (Madstone) thrust throughout the retrograde metamorphism, west- or northwest-directed thrusting on the roof thrust (Orleans fault) has been inferred from regional mapping and mesoscopic structures in the Galice Formation in the area of Figure 1 (Snoke, 1977; Harper, 1980; Norman, 1983; Gray, 1985; Jones, 1987; Harper and others, 1989). The offset along the fault is very large: >40 km based on its map pattern (Fig. 1) and probably ≥110 km based on gravity studies (Jachens and others, 1986).

The north-northeast emplacement of the ophiolite thus appears to have been at a high angle to synchronous thrusting along the roof thrust and is essentially parallel to the inferred paleogeographic trends at this latitude during the Late Jurassic. It is also subparallel to the spreading direction in the Josephine ophiolite, based on the ~east-west strike of sheeted dikes. The differences in thrusting direction may result at least partly from differing amounts of Tertiary clockwise rotation, especially since the size of rotating domains is not known. Different thrusting directions during the Nevadan orogeny might result from decoupling of the Josephine thrust sheet from the Klamath Mountains as a result of high pore-fluid pressures in the Galice Formation; such high pressures are likely since the Galice flysch is syntectonic and was thrust beneath the Klamath Mountains shortly after deposition (Fig. 2; Harper and others, 1989).

If paleogeographic trends in the Late Jurassic were roughly parallel to the arcuate shape of the Klamath Mountains, then the thrusting directions may reflect sininstral oblique subduction during the Nevadan orogeny. An dramatic change in North American plate motion at ~150 Ma is suggested by the North American polar wander path and should have resulted in sininstral oblique convergence from ~150-135 Ma (May and others, 1989). Future structural studies of thrust faults and paleomagnetic data are needed in the western Klamath Mountains to provide quantitative constraints on the kinematics of thrusting and its relationship to plate motions during the Nevadan orogeny.

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FIGURE 1 Generalized geologic map of the western Klamath terrane modified from Harper (1989)(see Fig. 1.1).

FIGURE 2 Tectonic model for the Middle to Late Jurassic tectonic evolution of the Klamath Mountains (modified from Harper and Wright, 1984)(see Fig. 1.7).

FIGURE 3 Geologic map in the region where basal (Madstone) thrust of the Josephine ophiolite is exposed (modified from Loney and Himmelberg, 1977; see Fig. 1.6).

FIGURE 4 Map of the study area near Chetco peak. The Josephine ophiolite is thrust over amphibolite along the Madstone thrust. The east dip of the thrust is the result of large-scale post-Nevadan folding (see Fig. 1.10).

FIGURE 5 Photograph of area shown on Figure 4. View is towards the southwest and shows the trace of the Madstone thrust. Ja=amphibolite, Js=serpentinite mylonite, Jp=Josephine Peridotite (see Fig. 1.9).

FIGURE 6 Geologic and age relationships of the rocks along the Madstone thrust. U/Pb zircon age of pegmatite and $^{40}Ar/^{39}Ar$ ages of hornblende and muscovite are from Harper and others (1989) (see Fig. 2.5).

FIGURE 7 Amphibolite (metagabbro) from the metamorphic sole north of Vulcan Peak showing strong foliation, apparent grain-size reduction, and asymmetric plagioclase porphyroclasts. The asymmetric porphyroclasts of plagioclase and offset vein offset indicates a dextral sense of shear(see Fig. 2.6).

FIGURE 8 Typical gneissic amphibolite in Chetco Peak region showing folded foliation. The sample is cut normal to the fold hinges which are parallel to a stretching ineation (see Fig. 2.9).

FIGURE 9 Photograph of pegmatite dike northwest of Chetco Lake which cuts folded gneissic layering in amphibolite. White line on amphibolite is drawn parallel to lineation, and view is toward the northeast. The pegmatite is lineated and has an S-C fabric (Fig. 12), although it is not apparent in the photograph (see Fig. 2.7).

FIGURE 10 Equal-area projection of poles to foliations and lineations, and lineations after restoration of thrust to horizontal by rotation around F2 axis. $F1_a$ and $F1_b$ axes are parallel to lineations in amphibolite. Trend and plunge of F2 is based on two mesoscopic F2 axes and the axis defined by the orientation of the Madstone thrust in the two areas north and south of Vulcan Peak (see Fig. 2.10).

FIGURE 11 Microphotograph of mafic phyllonite showing porphyroclasts of brown hornblende rimmed by blue-green hornblende and actinolite (Table 2, sample SA 44). Assymetric fabric indicates dextral sense of shear (top to the northeast). The matrix consists of very fine-grained actinolite, chlorite, albite, and quartz. The hornblende porphyroclasts show that the phyllonite is a retrogressed amphibolite. Field of view is 3 mm (see Fig. 2.18)

FIGURE 12 Microphotograph of pegmatite dike (Fig. 9) which has a well developed S-C fabric defined by muscovite. Shown here is a close up view of a typical asymmetric muscovite showing bending into C surfaces. Field of view is 1.5 mm (see Fig. 2.19).

FIGURE 13 Thin-section of serpentinite mylonite cut perpendicular to foliation and parallel to lineation. Dextral sense of shear (top to the northeast) suggested by the asymmetric tails on magnetite porphyroclast. The matrix consists of antigorite with a grain size of ~0.2 mm. Field of view is 1.5 mm. In the field, these antigorite-rich rocks are coherent and commonly extremely tough (see Fig. 2.20).