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TECTONIC INCLUSIONS IN SERPENTINITES

BY

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Abstract

Tectonic inclusions of diverse rock types are common in tectonized serpentinites that occupy suture zones in most of the major Phanerozoic fold belts. The host serpentinite bodies are usually tabular where they may form melange zones in imbricate nappe structures. Inclusion-bearing diapiric serpentinites generally are domical or discoid in shape and are commonly rootless. Protoliths for the host serpentinites may be harzburgite-dunites that represent depleted oceanic mantle of the ophiolite suite, or lherzolite-harzburgite-dunite of undepleted continental mantle. Water enters these mantle peridotites as they move into the water-rich environment of the upper crust during subduction, obduction, or transform fault movements. Where the temperatures are below 500°C during tectonic movement, these peridotite protoliths hydrate to serpentinite and, by incremental steps, change their rheology from brittle-massive to plastic-ductile. Thus in the tectonic environment of suture zones along continental margins, the peridotites of oceanic and continental mantle become progressively serpentinized until blocks of the more competent country rock become immersed in the plastic serpentinite. These blocks are then transported either vertically or horizontally depending on the tectonic movement of the host serpentinite. Furthermore, the blocks are affected by calcium hydroxide waters developed during serpentinization which are incompatible with minerals in the inclusions. Being supersaturated with respect to diopside and tremolite, these waters are responsible for the calcium metasomatism common along the boundaries of the tectonic inclusions. Development of mineral assemblages in these metasomatic zones of the tectonic inclusions reflect the P-T conditions and the time of their formation, and they are evidence of the crustal tectonic history of the enclosing serpentinites much as xenoliths are for igneous rocks.

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INTRODUCTION

TECTONIC INCLUSIONS IN SERPENTINITES

The study of tectonic inclusions in serpentinites has provided us with new insights on the formation of suture zones that mark the edge of former continental margins (Coleman, 1966; Dal Piaz, 1967; Vuagnat, 1967). These inclusions represent many rock types and provide clues as to the various types of country rock encountered by the tectonic transport of the serpentinites. The geologic history of the tectonic inclusions is closely related to the problem of ophiolite emplacement as most of the serpentinites containing tectonic inclusions were derived from peridotites associated with ophiolite nappes (Coleman, 1977). The purpose of this paper wil! be to describe various tectonic settings where inclusion-bearing serpentinites are found as well as the structural and chemical history of the tectonic inclusions themselves.

TECTONIC AND GEOLOGIC SETTING OF INCLUSION-BEARING SERPENTINITES

The occurrence of inclusion-bearing serpentinites can be tied directly to the world-wide distribution of ophiolite belts in orogenic zones as illustrated by Coleman and Irwin (1974). These large tracts of ophiolite often contain extensive areas of serpentinized peridotites that characteristically contain tectonic inclusions. Generalized ideas of processes leading to the emplacement of ophiolites are most easily tied to plate motions. Interaction between plates gives rise to orogeny, and many of the Phanerozoic orogenic belts can be related to zones of plate convergence (Dewey and Bird, 1971). In interactions within certain zones of convergence, such as the Alpine-Tethyan orogenic belt or the Circum-Pacific margins, allochthonous ophiolite masses are imbricated with nappes whose origin is quite different from that of the ophiolite. The emplacement of slabs of oceanic lithosphere onto continental margins and later tectonism is considered to be the tectonic setting where the subjacent peridotite becomes serpentinized and collects tectonic inclusions from the surrounding rock.

If we consider these processes in detail, it is possible to establish certain petrotectonic associations that can be related to the tectonic setting of these inclusions. Within the oceanic environment, it has been shown that the detachment of the oceanic crust is accompanied by the development of amphibolites at the base of the peridotite (Parrot and Whitechurch, 1978). Continued hydration of the peridotite to serpentinite provides a situation whereby amphibolites could be broken up and incorporated into the serpentinite. All of this takes place in an oceanic environment.

Furthermore, transform faults could produce a similar situation where amphibolites formed could then be included in serpentinized peridotite. Thus low-pressure and high-temperature amphibolites or other unmetamorphosed parts of the oceanic crust could be included into serpentinized portions of the mantle within the oceanic realm.

Continued plate convergence will bring these same parts of the oceanic crust towards a continental margin and, either by obduction or subduction, the peridotite could become further serpentinized and could collect inclusions from the continent which range in composition from sedimentary rocks, igneous rocks, to metamorphic rocks. Depending on the depth that inclusions were introduced, their P-T history prior to being included would also record retrograde and metasomatic alteration.

Finally, post emplacement tectonic and metamorphic processes superposed on the serpentinite and its inclusions would further modify their mineral assemblages according to whatever P or T was imposed, as well as continuing deformation of these phases (Coleman, 1977). During various possible stages in the development of inclusion-bearing serpentinites, the effects of metasomatic reaction within the serpentinite will have produced either mild or profound changes in the chemistry of the tectonic inclusion.

The protoliths for the serpentinites are usually depleted tectonized harzburgites and dunites that form the subjacent parts of most ophiolites. These rocks commonly consist of olivine and orthopyroxene with minor amounts of clinopyroxene and spinel. In the low-temperature serpentinization of these bodies, lizardite, chrysotile, brucite, and magnetite are the main minerals to form, and expansion during serpentinization is a common phenomena. At higher temperatures up to 500 °C, antigorite takes the place of lizardite and chrysotile (Trommsdorff and Evans, 1972). In some areas of the Alpine belt in Europe, inclusion-bearing serpentinites of the protolith have been found to be continental lherzolite (Nicolas and Jackson, 1972), but the serpentinization products are approximately the same as for the depleted oceanic harzburgites. Commonly, both the harzburgites and lherzolites will contain primary gabbro dikes or gabbro cumulates which undergo all of the metasomatic reactions and deformations observed in the tectonic inclusions (Boudier and Nicolas, 1972). These endogenous inclusions are not easy to distinguish from the exogenous types, particularly when they have been broken into blocks and moved away from their primary igneous setting.

SERPENTINIZATION AND METASOMATISM

Perhaps one of the most important aspects in the study of tectonic inclusions in serpentinite is to realize that metasomatic calcium hydroxide fluids are present during serpentinization. Evidence that calcium is released during serpentinization has been discussed in a number of papers (Barnes and others, 1967; Barnes and O'Neil, 1971), so this will not be further documented here. If we assume that the serpentinization process removes calcium from the protolith peridotite and that fluids developed from the process are calcium hydroxide-rich as well as being supersaturated with respect to diopside and tremolite, then we have the possibility of strong chemical reactions on any introduced tectonic inclusions or endogenous gabbros or diabase within the serpentinized peridotite. This general type of metasomatism produces a group of altered rocks that are generally referred to as rodingites (Coleman, 1966; Dal Piaz, 1967). All of the rodingite occurrences are within serpentinite but have developed from diverse rock-types. The reaction zones develop at the contact between tectonic inclusions and the serpentine, and may vary in width from several millimeters up to several meters. In some cases, the whole tectonic inclusion becomes completely metasomatized. Rodingitized tectonic inclusions are characteristically involved in tectonic movements producing synkinematic brecciation and mylonitization within the inclusions. The metasomatic changes found in rodingites trend towards a similar bulk composition in that most rodingites are undersaturated with respect to silica and are enriched in calcium and, to a lesser extent, magnesium (Coleman, 1966, 1967).

Hydrogarnet is the characteristic mineral of rodingites and is commonly associated with idocrase, diopside, prehnite, xonotlite, wollastonite, chlorite, sphene, and tremolite-actinolite (nephrite) where mafic igneous rocks have been metasomatized. In more silicic rocks modified by the metasomatism, xonotlite, albite, potassium feldspar, and fibrous actinolite are commonly present.

The wide-spread occurrence of rodingites within sheared serpentinites and serpentinite melanges indicates that calcium metasomatism is a normal product of serpentinization (Honnorez and Kirst, 1975; Vuagnat and Pustaszeri, 1964). By analogy, the pervasive presence of calcium hydroxide waters within serpentinized peridotites is very similar to the reaction that takes place in the formation of cement. Potentially, wherever these calcium hydroxide waters encounter rocks higher in silica than the peridotites, reactions will take place whereby calcsilicate minerals will replace and invade the host whether it be an exogenous inclusion or indogenous gabbro or diabase. There are many cases where inclusions in serpentinites do not show calcium metasomatism, and this can be explained by stating that following complete serpentinization, the calcium hydroxide waters are lost by reaction or by later tectonic movements.

Besides the very important geochemical regime of serpentinized peridotites, a few words need to be said about the change in physical properties that accompanies the serpentinization of a peridotite (Coleman, 1971). The density of most peridotites is $\sim$3.3, and their completely serpentinized equivalents are $\sim$2.55. If the serpentinite is sheared, then the density of a serpentine mass could be as low as 2.4. Therefore, the presence of low-density sheared serpentinite in geologic terrains with average densities of 2.65-2.70 could set the scene for diapiric movement of serpentines during tectonism. Furthermore, the strength of serpentine, when sheared, drops off dramatically as shown by Cowan and Mansfield (1970). The combination of low-density and reduced-work strengths, particularly in sheared serpentinites, illustrates that their rheology is such that emplacement of inclusions could easily be accomplished during tectonic movements.

The alteration of peridotites to serpentinite usually produces the low-temperature mineral assemblage: lizardite, chrysotile, magnetite, brucite. At high temperatures, antigorite may form in place of lizardite and chrysotile (Moody, 1976). However, high-temperature and high-pressure regional metamorphism of serpentinized peridotites involves a much more complicated series of mineral assemblages (Evans, 1977).

TECTONIC INCLUSIONS

The range in the type of tectonic inclusions is broad and diversified. Those serpentinites that are involved in surface or near-surface thrusting take on the characteristics of melanges with the serpentinite matrix representing perhaps only 10-20% of the mass. Diapiric serpentinites may contain a spectrum of metamorphosed to unmetamorphosed inclusions. Serpentinites occupying strike-slip faults such as those in California's San Andreas system are generally sparse in inclusions, but the serpentinite may form wedges and tend to surround their slices of country rock.

The size of inclusions within serpentinites may have some maximum value, but this is difficult to establish with good 3-D control. A statistical study of blueschist tectonic blocks in Oregon gives some limiting values. In that study, the maximum size appears to be about 1500 m in the longest dimension (Coleman and Lanphere, 1971). Initial wedging of serpentinite along active fault contacts could produce huge blocks (up to several km in length) but where geologic control is good, it appears that a limiting size for a tectonic inclusion completely immersed in serpentinite is around 500-1500 m in the major dimensions. The shape of smaller inclusions that have been metasomatized and tectonized is usually sphericaly to discoid. Larger blocks that exhibit deep-seated reaction boundaries usually also have a rounded to discoid shape. Tectonic inclusions that have the characteristics of having been included under near-surface conditions often have more irregular shapes without boudinage structures developing in the surrounding serpentine.

Structures characteristic of the tectonic inclusions should be divided into deep-seated vs. shallow inclusions. Deep-seated inclusions usually are metamorphic rocks that have fairly thick metasomatic borders that may consist of coarse-grained actinolite-talc-chlorite sometimes with rutile. Internally, primary lineations and foliations have been plastically deformed so that as you approach the outer surface of the inclusion, the foliations tend to follow its outer spherical surface (Coleman and Lanphere, 1971). Metamorphic reactions resulting from this deformation require considerable depths and temperatures.

Of course there are all gradations from the deep-seated deformation of the inclusions, but those features that seem to be clearly related to near-surface tectonic activity are brittle fracture, drusy filling of open fractures, slickensides of serpentine on outer surface, and general lack of metasomatic alteration. In melange terrains, it is difficult to establish if some tectonic blocks actually represent gravity slide or landslide material or are indeed inclusions emplaced by tectonic movement (Gansser, 1974). Of course, even the deep-seated tectonic inclusions have undergone near-surface brittle deformation, but the plastic deformation, wrap-around foliation, and contact metasomatic border provide the important clues of their deep-seated history. In some cases, complete destruction of the tectonic blocks into smaller angular fragments produces a situation where it is difficult to establish their origin.

The diversity of rock types contained in the serpentinite as tectonic inclusions can be partially explained by relating the rocks to their petro-tectonic origin in relationship to the probable tectonic history of the serpentinite. Amphibolites exhibiting low-pressure and moderate-temperature assemblages and perhaps showing some deep-seated metasomatic reactions are probably related to oceanic detachment metamorphism. This metamorphism forms during detachment of the peridotite in the oceanic realm, and emplacement of the amphibolite as inclusions in the serpentinite takes place after detachment and during development of serpentinite as part of its tectonic transport towards the continental margin. Transform faults in the oceanic realm could also produce amphibolite, and they could be emplaced into serpentinites either in the oceanic realm or doing later tectonic transport. Nearly all of these amphibolites would have a fairly strong fabric that would be distorted by second plastic deformation if the tectonic blocks were included in the serpentinite at depth. The presence of high P - low T eclogites and blueschists within tectonic inclusions having thick coarse-grained actinolite metasomatic boundaries with a wrap-around foliation indicates that the serpentinite either had been in a subduction mode or that its tectonic movement intersected a blueschist terrain at depth (Coleman and Lanphere, 1971). Sedimentary rocks from the continental margin, such as graywackes, limestones, and cherts showing calcium metasomatism borders and no regional-type metamorphism, represent moderate depth (less than 5 km) tectonic inclusions resulting from thrusting during serpentinite emplacement (Gansser, 1974). Presence of ophiolite igneous rocks, such as pillow lavas, diabase, and layered gabbros with calcium metasomatism but no regional metamorphism effects, probably represent inclusions emplaced into the serpentinite during its oceanic detachment or later emplacement onto the continental margin. Other situations exist where granite, gneisses, and granulites may become tectonic inclusions, and it is probable that, in most cases, rocks of these types could represent either deep-seated or shallow activity within the continent.

Thus the careful study of tectonic inclusions within serpentinites can provide information on its tectonic evolution, particularly if radiometric ages can be established on minerals within the inclusions. Establishing the paragenetic sequences within each tectonic block can produce detailed information on depth, style of deformation, and P-T conditions that have been superimposed on each block.

DIAPIRIC SERPENTINITE AND INCLUSIONS NEW IDRIA, CALIFORNIA

The New Idria area is located in the southern extension of the Diablo Range of the California Coast Ranges (Eckel and Myers, 1946) (Fig. 1). The New Idria Serpentinite diapiric dome is 19 × 6 kms and lies between the San Andreas fault on the west and the Great Valley of California on the east. The sedimentary rocks that surround the dome are folded into a series of anticlines and synclines that trend N70°W oblique to the NW trend of the San Andreas fault. The elongate oval body of serpentinite is flanked by the Franciscan formation of Cretaceous age and the Great Valley Sequence of Late Cretaceous age. These flanking sediments and the serpentinite mass together comprise an asymmetric anticlinal dome that is the northern extension of the Coalinga anticline. The contact of the serpentinite with the sediments is marked by high-angle faults and shear zones that indicate upward movement of the serpentinite mass (Coleman, 1961).

The serpentinite body consists mainly of highly sheared and crushed incoherent fragments of soft, crumbly sheets and clumps of asbestiform material. This material has little strength and forms a terrain of low rounded hills composed of flaky and fibrous serpentine minerals. Nearly all of the original ultramafic protolith that gave rise to this serpentinite mass has been altered to serpentine minerals. Where original olivine and orthopyroxene have survived, their compositions and textures indicate that they represent tectonite harzburgites and dunites characteristically found associated with the Coast Range ophiolites. Chrysotile is the major serpentine mineral of the friable and flaky serpentinite accompanied by lizardite, brucite, and magnetite as less important mineral phases (Mumpton and Thompson, 1975).

Estimates of the 3-dimensional shape of the New Idria serpentinite body have been aided, in part, by a gravity survey and a single magnetic line (Byerly, 1966). A pronounced negative gravity anomaly (–58 mgals) over the serpentinite body indicates that it may extend to a depth of 5 km. The elongate axis of the New Idria serpentinite dome coincides with the northward extension of the Coalinga anticline, and it is inferred from this that the serpentinite forms a diapiric mass that has moved into the crest of the Coalinga anticline and breached to the surface sometime in the Miocene.

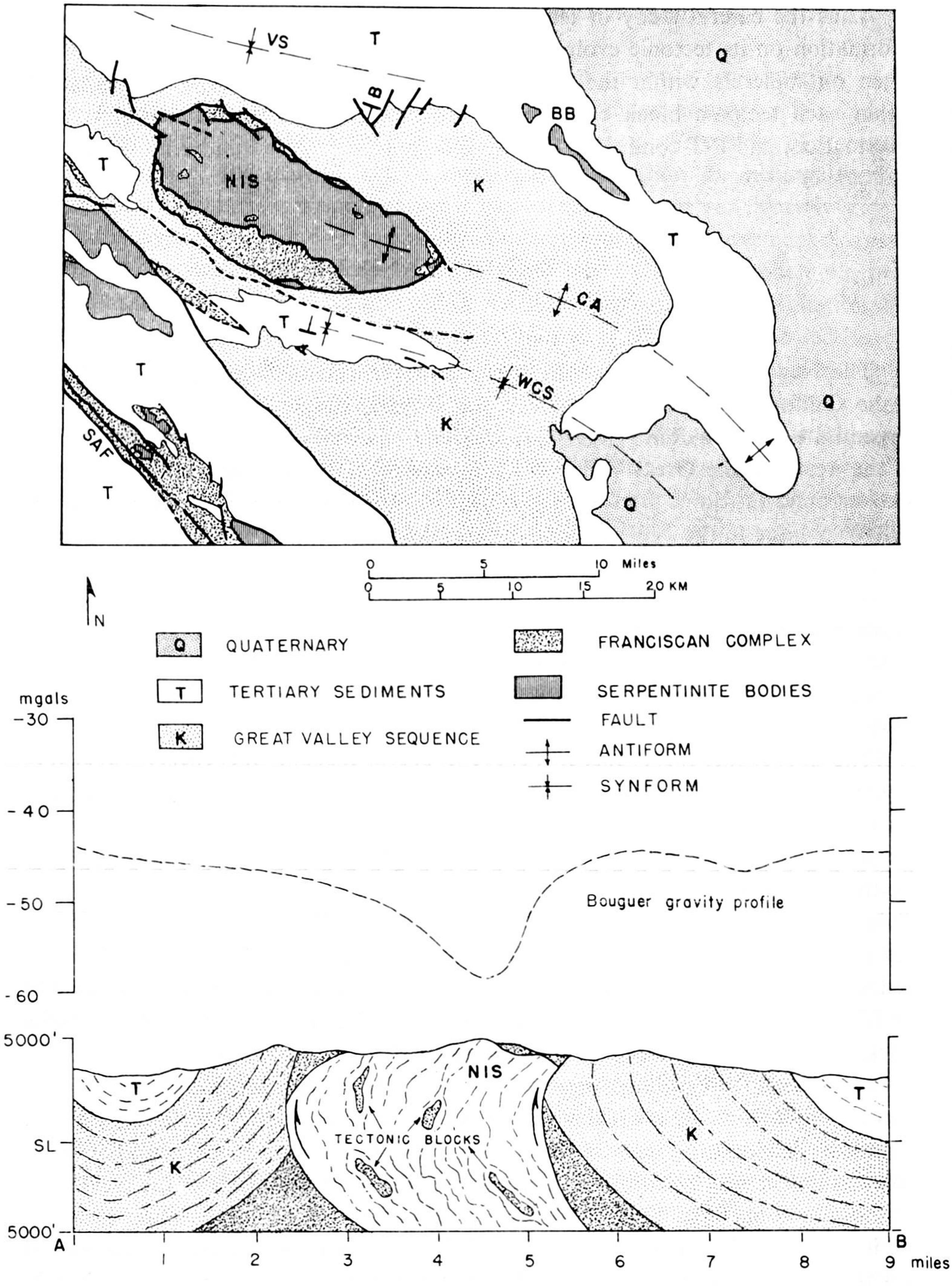

FIG. 1.

Geologic sketch of the New Idria serpentinite (NIS) mass showing outcrop patterns of the Big Blue Formation (BB). The main structures illustrated are the Vallecitos synform (VS), Coalinga antiform (CA), White Creek synform (WCS) trending obliquely to the San Andreas fault (SAF). Cross section illustrates the diapiric nature of the New Idria serpentinite mass as well as the strong negative Bouguer gravity anomaly.

Within the New Idria serpentinite are numerous tectonic inclusions up to 1500 meters in length and down to less than 1 meter. The distribution of these inclusions is entirely random as well as their internal structural attitudes; however, the larger elongate bodies are roughly parallel to the axis of the Coalinga anticline. Contacts between the serpentinites and inclusions are invariably sheared and faulted. In some instances, calcium metasomatism can be found along the contacts within the inclusions, but multiple movements of the serpentinite mass have obscured the original structural relationships at the contact. The movement of the tectonic inclusions within the New Idria serpentinite is difficult to interpret. The tabular and elongate shape of the larger inclusions, combined with the vertical dip of the bedding or schistosity, indicate vertical movement within the serpentinite. Semi-parallel orientation of these inclusions with the bounding faults demonstrates that such an alignment may have developed during the upward squeezing of the semiplastic serpentinite. These relations suggest that the inclusions were incorporated into the dome after serpentinization as part of a sequence of tectonic movements that moved the serpentinite higher into the surrounding sedimentary rocks (Coleman, 1961).

The tectonic inclusions within the serpentinite represent diverse rock types, but nearly all of these inclusions have undergone high-pressure, low-temperature blueschist facies metamorphism. The protolith for nearly all of these inclusions can be traced to the Franciscan formation. In general, the Franciscan-type metamorphosed tectonic inclusions are derived from mafic volcanic rocks, graywackes, cherts, and mafic pyroclastics. Glaucophane, lawsonite, pumpellyite, albite, chlorite, and stilphomelane are the characteristic blueschist minerals present. These blueschist generally have textures and schistosities characteristic of the Type II and Type III blueschists of Coleman and Lee (1963). No coarse-grained Type IV gneissic blueschists or eclogites (Coleman and Lanphere, 1971) have yet been found as tectonic inclusions within the New Idria serpentinite. Unique to certain inclusions is the occurrence of pure jadeite veins and jadeite masses within some of the albite-crossite schist inclusions (Coleman, 1961). In addition to these exogenous tectonic inclusions, there are the endogenous tectonic blocks of antigoritic serpentinites that represent deeper level serpentinization under higher temperature and pressure conditions (Evans, 1977). Smaller pods of rodingite are present but are generally scarce when compared to other areas of rodingite (Coleman, 1967).

The structural setting of the New Idria serpentinite suggests that it must represent serpentinized peridotites that may have been part of the ophiolite sequence that made up the basement of the Franciscan Formation. Mesozoic plate convergence produced conditions for the formation of blueschist assemblages and later hydration of the peridotite. Subsequent folding and tectonic movements with the Coast Range initiated diapiric uprise of the New Idria serpentinite. Incorporation, at depth, of the high P-low T assemblages as tectonic inclusions were modified by Ca-metasomatism that allowed massive jadeite to form. Continued diapiric uprise of the now highly sheared and pulverized serpentinite provided the mechanism by which this assemblage was brought to surface. Casey and Dickinson (1976) in describing the Big Blue formation of Miocene age suggest that sedimentary serpentinous strata were derived from protrusion of the New Idria serpentinite during rapid Miocene motion along the San Andreas fault.

SERPENTINITE MELANGE AND INCLUSIONS SOUTHWEST OREGON

Serpentinite melanges containing numerous tectonic inclusions are present in southwestern Oregon within the Dothan and Otter Point Formations of Jurassic and Cretaceous age (Coleman, 1972). The mapped outlines of the serpentinite masses shows them to be mainly tabular units with low dips except where they are cut by vertical faults (Fig. 2). The close association of the serpentinites with thrusting is demonstrated by the parallelism between the serpentinite sheets and thrust planes. Irregular and patchy distribution of smaller serpentinite sheets resulted from dissection by erosion of much larger coextensive serpentinite sheets that occupied a zone of major thrust dislocation. Aeromagnetic anomalies related to the exposed serpentinites demonstrate that they are generally thin tabular sheets. Anomalies resulting from concealed masses of serpentinite indicate that the amount of serpentinite in the upper crust is more extensive than implied by the surface map.

The lithology of the serpentinites is chaotic and consists of massive to completely sheared and incompetent flaky serpentinite. The protolith for the serpentinites is mainly dunite and harzburgite with minor orthopyroxenites.

Clinochrysotile and lizardite are the main serpentine minerals with lesser amounts of magnetite and brucite. Typical exposures reveal tectonically rounded blocks of massive serpentinized peridotite set in a matrix of sheared and flaky serpentinite. Intimately associated with these serpentinites are irregular masses of diabase, gabbro, and plagiogranite which are interpreted as parts of a dismembered ophiolite. In addition, there are numerous exotic, tectonic inclusions ranging in diameter 500 meters down to several meters within the serpentinite malange (Coleman and Lanphere, 1971). Where contacts between the serpentinite and the surrounding country rock are exposed, serpentinite invariably shows strong shearing and small incorporated tectonic inclusions of country rock. There is no evidence of igneous contacts along these sheared serpentinites.

Tectonic inclusions within the serpentinite melange consist of schists derived from sediments with mineral assemblages indicating transition between blueschist and greenschist, metamorphosed mafic volcanic rocks, gneissic Type IV glaucophane schists ($\sim$150 m.y.), amphibolites, and rodingites derived mainly from mafic igneous rocks. A careful study of blueschist tectonic blocks in a 150 sq. mile area east of

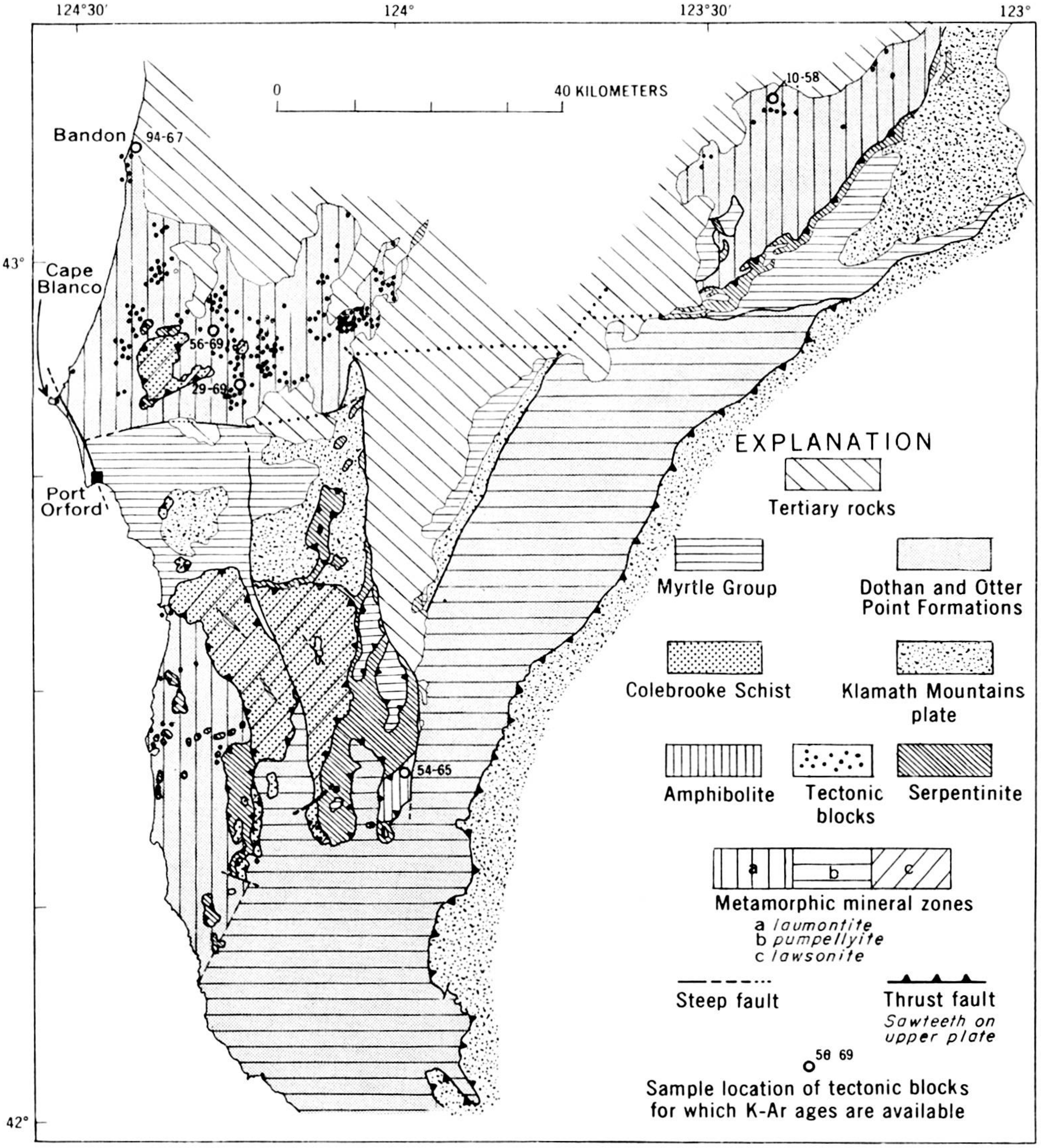

FIG. 2.

Geologic map of southwestern Oregon showing distribution of serpentinites and tectonic blocks of the area.

Cape Blanco, Oregon revealed no systematic relation between size and geographic location (Coleman and Lanphere, 1971) (Fig. 3). The shape of individual blocks can best be described as ellipsoidal with the outer surfaces grooved and striated as a result of tectonic movement. Tectonic blocks greater than 500 meters usually have a tabular shape and appear to be more like klippe than rounded inclusions completely immersed in serpentinite. Apparently then, tectonic blocks have a maximum size of approximately 500 meters. Internal structures of the gneissic high-grade blueschist tectonic blocks are complex showing intricate plastic folding of synkinematic metamorphic minerals. Often at least two periods of folding may be observed within these gneissic inclusions. Characteristically, a coarse-grained actinolite-chlorite-talc rind up to 18 inches may be found on the outer perimeter of the gneissic high-grade

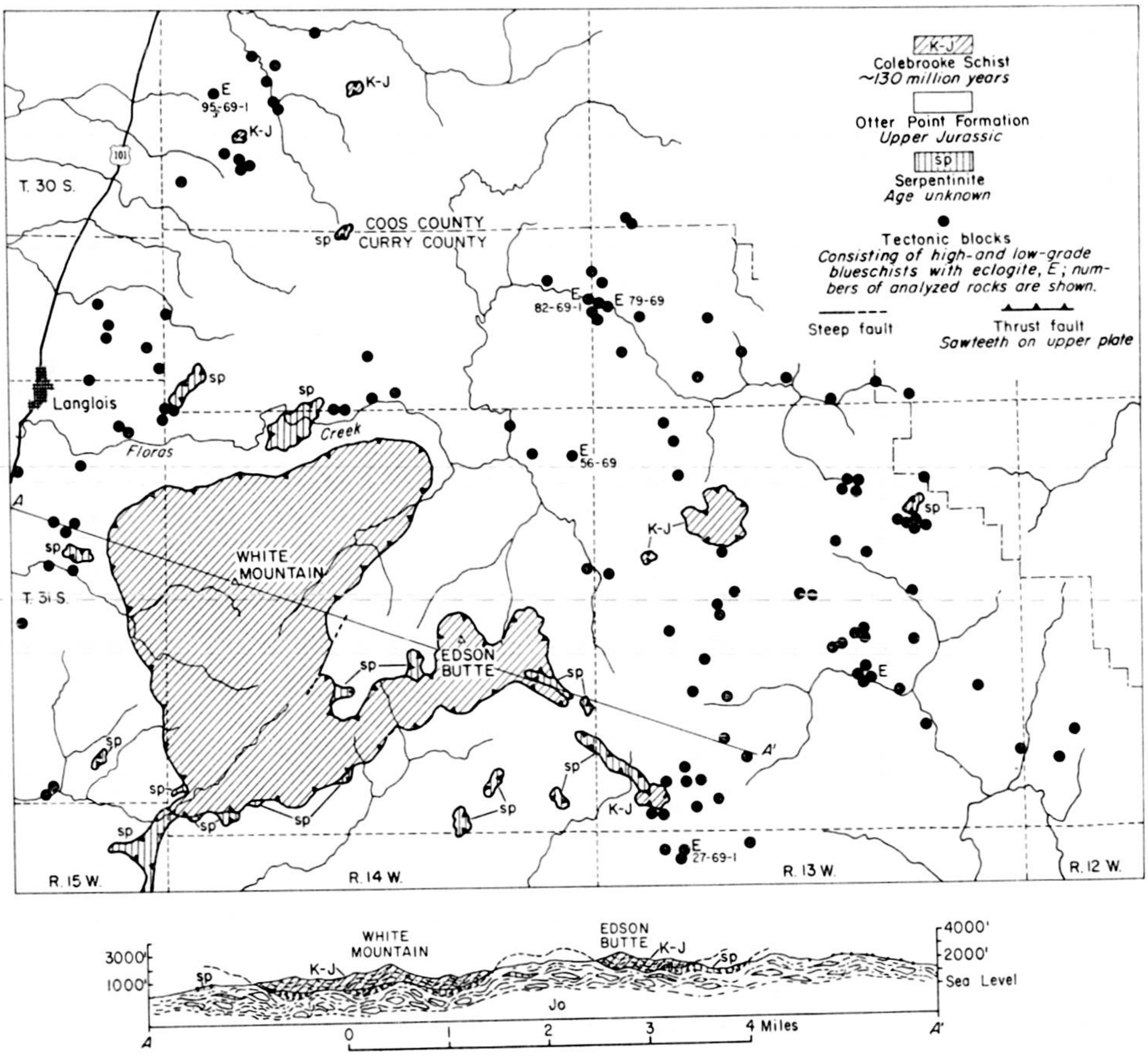

FIG. 3.

Geologic map of the Langlois, Oregon area illustrating the distribution of tectonic blocks in relationship to the White Mt. klippe and underlying serpentinite.

blueschists. The minimum age of these high-grade blueschists is 150 m.y., thus making them much older than the surrounding sedimentary rocks. Tectonic inclusions amphibolites formed in a different P-T realm are often found together with the blueschist blocks in the serpentinite melange.

In southwestern Oregon, the Colebrook schist forms several large allochthonous nappes that have been transported over the Otter Point and Dothan Formations (Coleman, 1972). This thrusting was facilitated by the serpentinite melange which underlies the Colebrook Schist and into which the tectonic inclusions were incorporated. The occurrence of tectonic inclusions of amphibolites and blueschists with mineral K/Ar ages older than the sedimentary and volcanic parts of melange zones in which the blocks are found suggests that the tectonic transport of these blocks may be related to continental margin subduction or obduction. The source of the metamorphic tectonic blocks may be from within an eastward dipping fossil subduction zone containing a cryptic pre-Tithonian metamorphic terrain.

CONCLUSIONS

The hydration of peridotites associated with ophiolites during the tectonic situation of plate collision along convergent continental margins produces plastic serpentinites that easily incorporate tectonic inclusions. During the alteration of these peridotites, a special calcium hydroxide fluid is produced within the serpentinite that has the capacity to metasomatize inclusions or contacts leaving behind a distinct calc-silicate assemblage that may reflect the P-T conditions during its formation. The presence of various exotic tectonic inclusions within serpentinite melanges and diapirs provides additional evidence by which the tectonic history can be further understood. The occurrence of high-pressure low-temperature blueschists in some serpentinite melanges and diapirs indicates that they may represent vertical transport of many kilometers.

Careful studies of diapiric and melange serpentinites in California and Oregon have provided new insights on the tectonic evolution of this region. Because these serpentinized peridotites represent oceanic mantle, the history of their serpentinization and tectonic transport can be much better understood by detailed mineralogical, petrological, and structural studies of their enclosed inclusions.

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