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PETROLOGY, SEDIMENTATION AND PALEOGEOGRAPHY OF THE SMARTVILLE TERRANE (JURASSIC) - BEARING ON THE GENESIS OF THE SMARTVILLE OPHIOLITE

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ABSTRACT

Metavolcanic, metasedimentary and plutonic rocks rocks of Jurassic age in the Smartville terrane comprise the first ophiolite found in the Sierra Nevada of California. These rocks are exposed in the western foothills of the Northern Sierra between 39° N. and 39, 30° N. Evidence for an ophiolite includes trondjemites, diorites and gabbros overlain by sheeted diabase overlain by pillowed lavas. New data on the petrology, geochemistry and sedimentology of rocks in the Smartville terrane, however, indicates that the ophiolite did not form in a conventional ocean ridge or fully mature back arc basin setting. The geochemistry of tholeiites in the lower part of the terrane is like that of island arc tholeiites; volcanic rocks and clasts in volcanic derived sediments in the upper part of the terran are calkalkaline. The sediments in the upper part of the terrane were derived from volcanoes and deposition of sediments was in channels on the submarine slopes of the volcanoes near active vents. The data indicate that the ophiolitic rocks formed close to or within a group of calkalkaline volcanoes, an association that can be explained in one of three ways: (1) Ocean crust in a fully developed back arc basin was mostly subducted except for the arc and part of the ocean crust on its flank. (2) The ophiolitic rocks formed in an incipient back arc basin. (3) The ophiolitic rocks formed in tension fractures within an arc; the tension fractures could have formed in response to oblique subduction.

INTRODUCTION

The Smartville terrane forms part of the geologically complex Northern Sierra Nevada region (Fig. 1). The terrane includes Paleozoic to Jurassic metavolcanic and metasedimentary rocks intruded by plutons of mostly Mesozoic age. On the whole, the geology of the region is poorly known; there has been little recent mapping since the close of the 19th century (Turner, 1893, 1894, 1897, 1898; Turner and Ransome, 1897; Ransome 1899, Lindgren, 1894, 1900, Lindgren and Turner, 1894, 1895).

In the Northern Sierra, Clark (1960, 1964) recognized two major northwest trending fault zones (Fig. 1) containing ultramafic rocks. These faults divide the region into three belts (Fig. 1): (1) An eastern belt east of the Melones Fault Zone composed of three volcanic complexes resting on Paleozoic metasedimentary rocks. The volcanic complexes are superimposed on one another and separated by sedimentary intervals. Their ages are Devonian-Mississippian, Permo-Triassic, and Jurassic (see Fiske and Tobisch, this volume). (2) A central belt bounded by the Melones Fault Zone composed of highly deformed and metamorphosed rocks. Schweickert and Cowan (1975) consider this belt to be primarily melange although Hietanen (1974) proposed a stratigraphy which correlates with units in the eastern belt (Schweickert, this volume). Our own observations close to Highway 49 and around Grass Valley support the argument for melange comprising the central belt. (3) A western belt of Mesozoic intrusive and extrusive rocks and sedimentary rocks. This belt contains the Smartville terrane.

Lindgren and Turner (1894, 1895) were the first to map the Smartville terrane. They did not attempt any subdivision of the metavolcanics however, nor did they comment on the genetic relations between the metavolcanics and the metamorphosed hypabyssal and plutonic rocks exposed in the western margin of the foothills. Cady (1975) was the first to recognize the similarities between the pillow lava-sheeted dike-plutonic rock complex in the Smartville terrane and rocks in known ophiolites (Moores and Vine 1971). He proposed that the Smartville ophiolite represents a slice of oceanic crust and mantle. Similarly, Schweickert and Cowan (1975) following early models for the tectonic evolution of this region (Moores, 1970, 1972) suggested that the Smartville ophiolite developed in an interarc basin. Schweickert and Cowan further suggest that the ophiolite was emplaced by the collision of an island arc and a consuming plate margin at the edge of North America around 150 m.y. ago. Recent work on the stratigraphy, petrology and geochemistry in the Smartville terrane (Day, 1977, Menzies and Blanchard, 1977, Xenophontos, unpbl. data, Menzies, and others in press) has brought to light significant differences between the petrology and geochemistry of the Smartville ophiolite and the petrology and geochemistry of the ophiolites in conventional tectonic settings such as mid-ocean ridges and back-arc basins. Menzies and Blanchard (1977) reported trace element and rare earth compositions from the Smartville terrane that they believe are evidence of island arc rock types, and they referred to the Smartville ophiolite as an "arc-ophiolite".

The purpose of this paper is to describe new data on the igneous petrology, sedimentary petrology and sedimentation of the Jurassic rocks in the Smartville terrane and discuss the bearing of these new data on the issue of arc-ophiolite verses ocean floor ophiolite.

STRATIGRAPHY AND STRUCTURE

General Statement

The Smartville ophiolite, as defined by Schweickert and Cowan (1975) and Menzies and others (1975), is lenticular in shape, forming a gross anti-form with gentle limbs and a moderate plunge to the south. Within the ophiolite rapid changes in dip and in stratigraphic tops give the impression of tight folding. Nose closures, however, have not been observed. Lenticular, fault bounded, northwest trending blocks may represent original fold limbs; fracture and rotation may have occurred along axial planes as fold amplitude increased. The shear zone shown in Figure 2 was interpreted as the northern continuation of the "Bear Mountain Fault Zone" and believed to represent a major sutured boundary between an island arc complex to the west and the Smartville ophiolite (Cady 1975, Schweickert and Cowan, 1975, Moores and Menzies 1975, Menzies and others 1975). Recent mapping on either side of the shear zone (Buer, unp. data, Xenophontos, unp. data), however, has shown that units within the shear zone have lithologic equivalents in the terrane immediately east of the zone. We believe that only a minor to moderate amount of lateral movement has occurred along the shear zone and that it is not a sutured boundary.

Menzies and others (in press) distinguish four units within the Smartville terrane that are based on lithological and geochemical criteria. We adopt their divisions as the major stratigraphic units in the terrane. These lithologic units are (Fig. 2): (1) Upper Volcanic Unit: This unit is comprised mainly of volcanic derived sedimentary rocks with mafic and siliceous quartz bearing clasts interbedded with differentiated flows. Pillowed lava is scarce. (2) Lower Volcanic Unit: This unit contains pillowed, and brecciated extrusives with minor amounts of sedimentary rocks and cherts. (3) Dike Complex: In the northeastern part of the area the dike complex contains diabasic, andesitic and dacitic intrusives and grades upwards into the lower volcanic unit and downwards into the Plutonic Suite. To the southwest (Fig. 2) a similar and less extensive complex is tectonically enclosed within the upper volcanic unit. Pyroxenitic and quartz feldspar porphyry intrusives form a significant portion of this outcrop. (4) Plutonic Suite: Trondjemite, diorite, hornblende-pyroxene gabbro and pyroxene gabbro are characteristic of this suite.

Upper Volcanic Unit

The upper volcanic and lower volcanic units, here after called the upper and lower units, are in depositional contact in the Yuba River area (Fig. 2). Here the upper unit consists of coarse sediments (Fig. 3). Between the Yuba and the Bear Rivers pillowed and massive lava intercalations are abundant and enclose lenticular bodies of coarse sediments. The largest of these bodies consists of boulder to pebble size unsorted sediments with minor sandy intercalactions and has a maximum thickness of 1000 meters. Pillowed and massive lavas with abundant intercalated sediments are exposed along the Bear River between the shear zone and Highway 49. Coarse sediments, boulder to pebble size, predominate in the western part of this section, whereas pebble to sand sizes are more prevalent near Highway 49.

Along the Bear River for a distance of about 2.5 km upstream from the shear zone, the section (not measured) consists of coarse conglomerates with minor intercalations of sandstones (Fig. 2). Within this 2.5 km interval, strike orientations vary from northwest to east-west in places defining broad south plunging folds. Dips are steep close to the shear zone and along northwest trending faults. Along the Bear River from 2.5 to 3.5 km above the shear zone a fault bounded block (Fig. 2) contains 400 m of well bedded pebble to sand size turbidites with abundant tabular lithic fragments of sand and silt. Above this interval are 100 m of vesicular light colored siliceous (dacitic?) extrusives. The extrusives are overlain by 300 m of sandstones and conglomerates probably deposited by sediment gravity flow interbedded with a minor amount of thinly bedded sandstones and siltstones. Siliceous (dacitic?) fragments are abundant but are outnumbered by dark basaltic and andesitic clasts in this uppermost part of the section. Farther upstream, from the eastern edge of the fault block to the base of section A-E (Fig. 2) course grained turbidites predominate. Pillowed and massive plagioclase phyric extrusives form only a minor part of this interval. Thicknesses are difficult to measure since in most places the strike parallels the river and exposures outside the river are poor. The next 1400 m of section upstream consists of pillowed and massive lava flow breccias, massive intrusives and sedimentary rocks. This section has been measured and its details are shown in Figure 4.

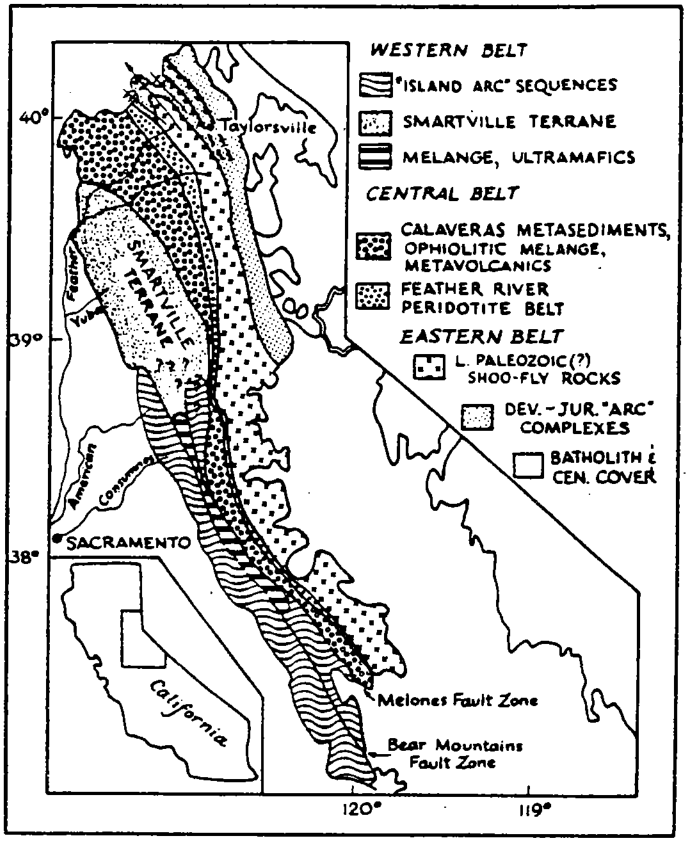

Figure 1. Regional geology of the Northern Sierra Nevada.

The relations between the lower and upper unit north of the Bear River have not been mapped. It is conceivable that the upper unit grades into the lower unit by a decrease in the amount of sediment and a concommitant increase in pillow lava. If this is true, then the two units as defined in the Yuba area have no time-stratigraphic significance but represent the products of different but coeval volcanism within a volcanic terrane.

Sediments, including silicious pyroclastics,

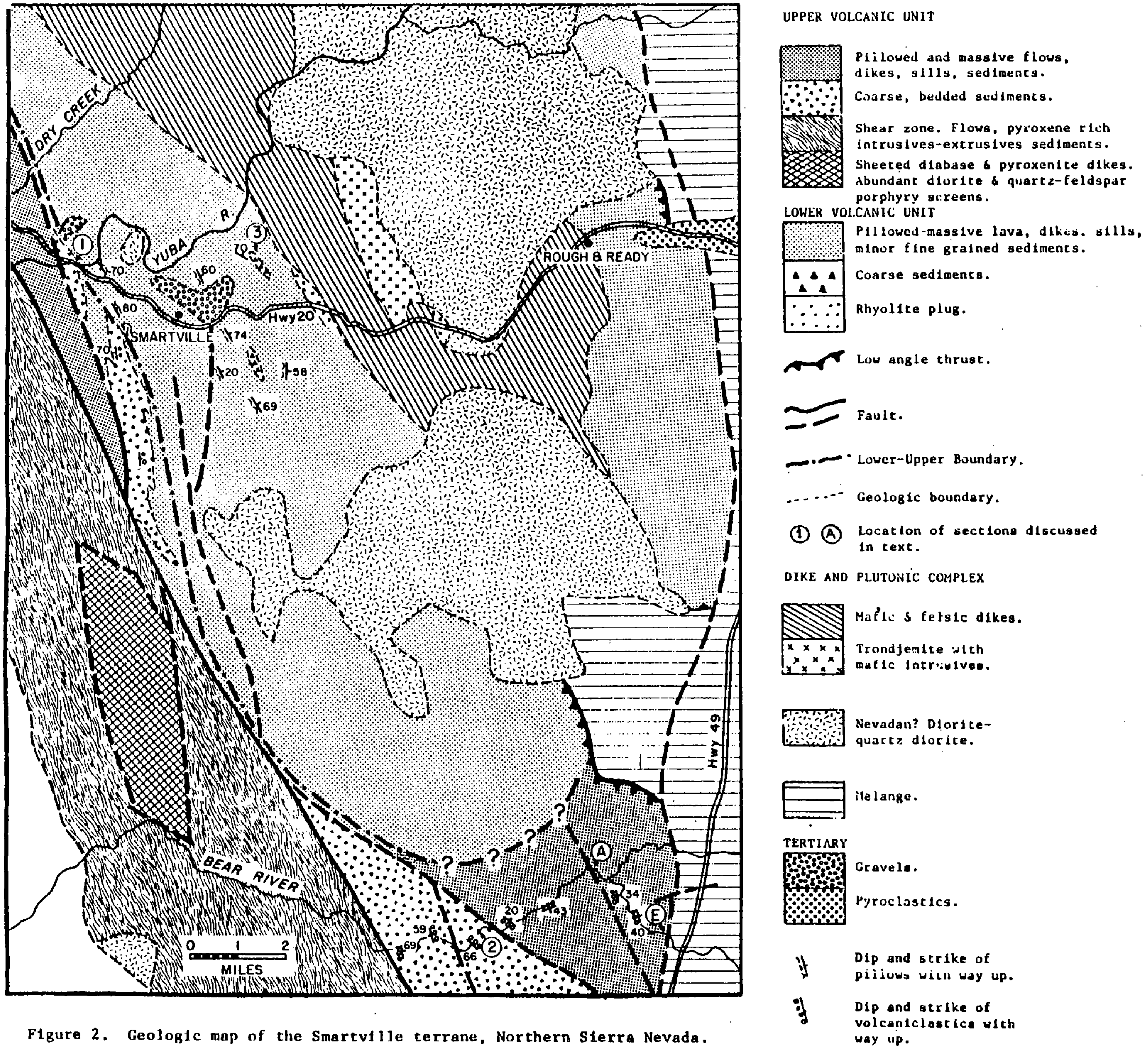

Figure 2. Geologic map of the Smartville terrane, Northern Sierra Nevada.

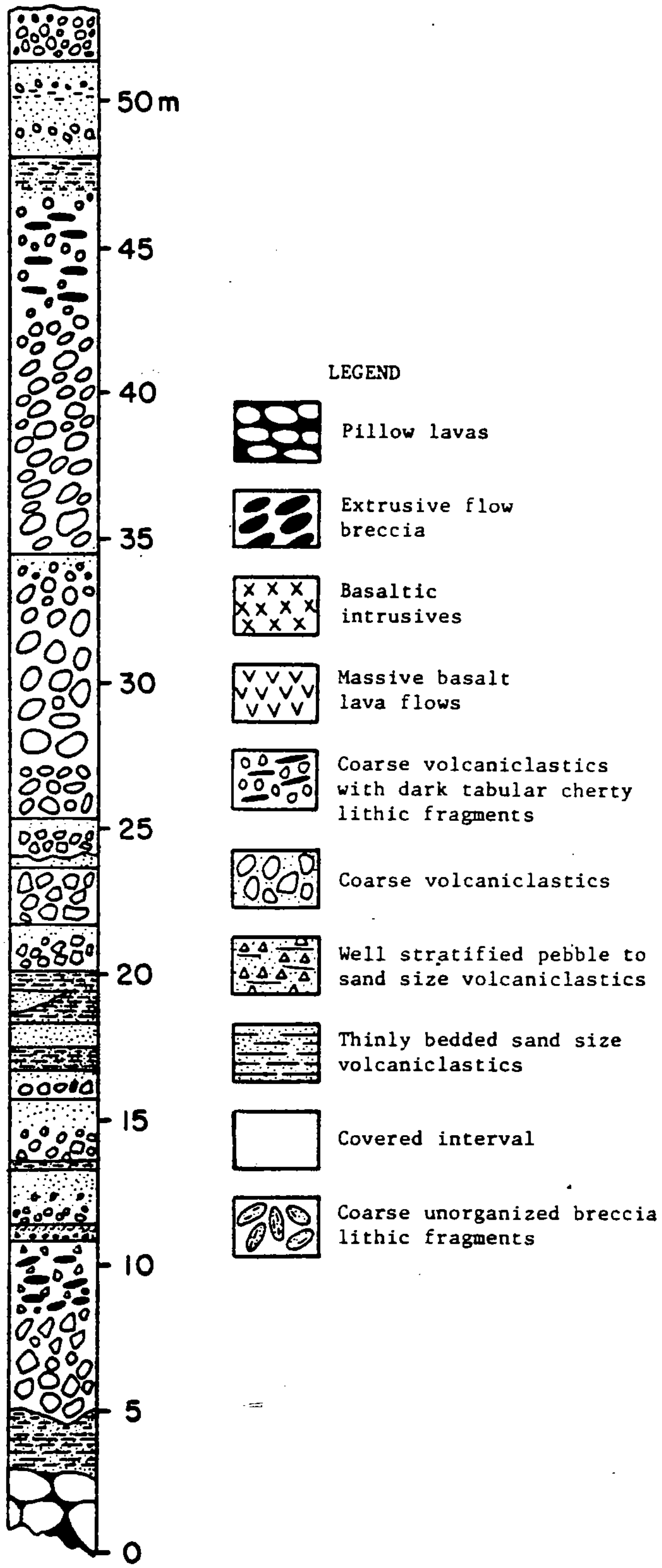

Figure 3. Measures stratigraphic section near the Yuba River at locality 1 on Fig. 2.

massive and minor pillowed extrusives, diabasic and silicious extrusives of the upper unit are found on both sides of the shear zone.

Lower Volcanic Unit

The lower unit includes mainly pillow lavas, massive flows, flow breccias and cross-cutting dikes and sills. Felsic dikes are volumetrically important locally in areas of sulphide mineralization. Lenticular bodies of coarse clastics have been mapped in the area between the Yuba and Bear Rivers (Fig. 2). Thin intercalations of chert and fine sand to silt-size sediments occur between flows but form a very minor component of the section. The thickness exposed section measured north of the Yuba (Menzies and others in press) is 1.5 to 2.0 km thick. In one locality coarse clastics rest against a wall (channel wall?) of pillow lavas (Fig. 5a. This, together with the lenticular outcrop of coarse sediment bodies elsewhere (Fig. 2) suggest rapid deposition in sinuous channels between lava flows.

Intrusives (Dike Complex and Plutonic Suite)

The dike complex and plutonic suite are best exposed in the north-eastern area (Fig. 2) and can be traced along strike into the Oroville area km north of Smartville. Dike orientations vary from N40°W to N15°W with dips averaging 60°NE. Contacts between the lower unit and the plutonic suite are gradational and marked by an increase of interdike screens of pillow lava upward and of trondjemite-diorite-gabbro downward. Between these transitions are areas of 100 percent dike injection (Day, 1977) with dikes showing both doubly chilled and one-way chilled margins similar to those described from other ophiolites (Moores and Vine 1971, Kidd, 1977).

A much smaller outcrop of sheeted dikes is found within the shear zone (Fig. 2) containing not only diabase with diorite screens, but also significant amounts of pyroxenite dikes and quartz-feldspar porphyry screens. Both pyroxenite and quartz-feldspar porphyry intrusives are present in the contiguous upper unit volcanics and sediments. This part of the dike complex is interpreted as a local dike swarm injected possibly through the lower unit into the upper unit.

Plutonic rocks are well exposed in close proximity with the major dike complex (Fig. 2). These range from trondjemite through diorite to gabbro. Rock types are gradational and are considered to represent the fractionation products of a single parent magma. Though in most exposures the plutonic rocks predate the dikes (they form screens with the dikes that are chilled against them) exposures on Deer Creek show trondjemite veins chilled against diabase and diabase chilled against trondjemite, a typical relation found in other ophiolites (Moores and Vine, 1971).

PETROGRAPHY

Volcanic Rocks

Upper Volcanic Unit

Volcanics within the upper unit include aphyric and highly porphyritic varieties. Euhedral plagioclase either as single crystals or as glomeroporphyritic clusters constitutes as much as 20 percent by volume in some flows. Clinopyroxene phenocrysts are less abundant in these plagioclase phyric types but are dominant, making up 20 to 30 percent in the pyroxene rich extrusives exposed on the right abutment of Camp Far West Reservoir. They are typically euhedral and range to 1 cm in size.

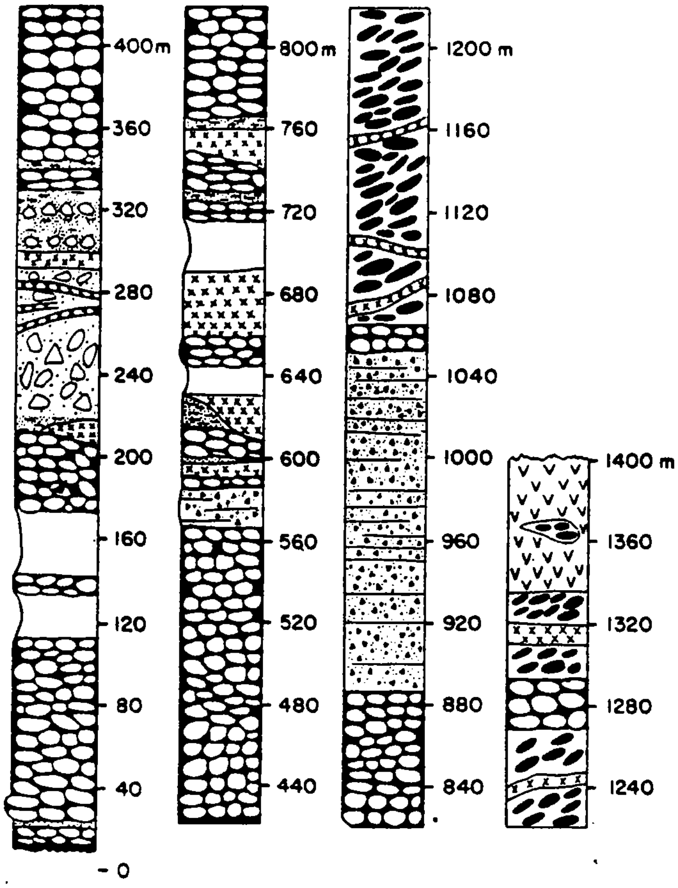

Figure 4. Measured stratigraphic section along the Bear River from A to E on Fig. 2. See Fig. 3 for explanation.

A greenschist facies assemblage of chlorite-albite-epidote-clinozoisite-sericite-quartz-actinolite-calcite, is typically present in all rocks examined. Igneous textures and original clinopyroxene are preserved in unsheared rocks but in sheared varieties original textures are destroyed and clinopyroxene phenocrysts are broken, pulled apart and replaced by fibrous actinolite.

Lower Volcanic Unit

Lavas in the lower unit are aphyric to porphyyritic with plagioclase and clinopyroxene the only phenocryst phases observed. Greenschist facies assemblages are prevalent though Menzies and others (in press) report minor amounts of lavas with prehnite-pumpellyite assemblages and zeolite vesicle fillings close to the top of the lower unit.

Original igneous textures are preserved remarkably well. Pillow rims show hyalopilitic to variolitic textures with the thin skeletal magnetite crystals, "swallow-tail" and "belt-buckle" plagioclase (Bryan, 1972) and feathery intergrowths of clinopyroxene and plagioclase indicative of rapid quenching. Inward from the rim, textures vary from intersertal to intergranular at the center where granular clinopyroxene and magnetite interstitial to plagioclase form the matrix. Vesicles are filled with chlorite, epidote, calcite and quartz or combinations of two or more of these minerals. Plagioclase, both as phenocrysts and matrix, is altered to albite, sericite, granular epidote-clinozoisite and minor anhedral quartz. Clinopyroxene is only slightly altered to chlorite and actinolite.

Intrusive Rocks (Dike complex and plutonic suite)

Intrusive rock types range from basaltic, andesitic, pyroxenite and gabbro to quartz-diorite, trondjemite, soda rhyolite, and quartz feldspar porphyry. Quartz feldspar porphyry is rare in the dike complex east of Smartville (Day 1977) but forms roughly 10 percent of the dike complex within the shear zones (Fig. 2). Pyroxenite dikes and sills are found only in this outcrop and in the contiguous extrusives and volcaniclastics. Igneous minerals and textures of diabasic intrusives close to younger (Nevadan?) major plutons have been replaced by a felted assemblage of fibrous actinolite anhedral albite, minor epidote and iron oxides. Elsewhere, original igneous textures are preserved though invariably a greenschist mineralogy is developed. The only mineral phase preserved is pyroxene. Diabasic intrusives are nonporphyritic to porphyritic. In the diabase clinopyroxene and plagioclase are the only phenocrystal phases observed, rarely exceeding 15 percent of the rock by volume. Plagioclase is invariably altered to albite, microgranular zoisite-clinozoisite, calcite, epidote and sericite. Microgranular sphene may rim ilmenomagnetite and chlorite is present in the groundmass.

Dacitic intrusives have been mapped at only one locality in the eastern dike complex (Day, 1977). They are more abundant close to the lower and upper unit contact. Commonly they are porphyritic, with euhedral plagioclase phenocrysts, subordinate clinopyroxene and anhedral polycrystalline quartz in a fine grained matrix of plagioclase, quartz and iron oxides. Alteration products include epidote, clinozoisite, chlorite and sphene.

Quartz feldspar porphyries typically have fluidal banding and carry euhedral plagioclase and subhedral quartz as phenocrysts. Quartz is invariably strained with some crystals breaking up to form polycrystalline aggregates. Sparse, small, subhedral clinopyroxene is the only mafic mineral present. Feldspar microlites set in microgranular quartz, chlorite, and dusty iron oxide make up the matrix.

Coarse grained pyroxene rich rocks represent crystal mushes emplaced as dikes or sills in the dyke complex and in extrusives exposed along the Bear River (Fig. 2). In thick sills, crystal settling gives rise to rocks ranging from 90 percent euhedral to subhedral clinopyroxene and 10 percent subhedral olivine to olivine free types containing 15 to 20 percent interstitial plagioclase. Where cooling was more rapid the liquid portion of the mush crystallized to small, subhedral plagioclase laths and clinopyroxene. Serpentine and granular masses of magnetite have partly or totally replaced olivine and a light brown amphibole has developed from clinopyroxene. Clinozoisite and chlorite are less abundant.

The plutonic rocks vary from medium to coarse grained and have greenschist facies assemblages of albite-epidote-chlorite-actinolite and sphene. Relict clinopyroxene is found only in the gabbros.

Trondjemites contain euhedral to subhedral plagioclase forming the core of quartz-plagioclase granophyric intergrowths. Subhedral to anhedral amphibole is associated with chlorite, epidote and sphene. The modal content varies from 50 to 60 percent plagioclase, 15 to 30 percent quartz and 5 to 10 percent mafics.

Diorites and quartz diorites contain from 50 to 65 percent modaal plagioclase, 10 to 15 percent quartz; the remainder is intimately associated interstitial actinolite, chlorite, epidote and sphene that replaced original hornblende or clinopyroxene.

Gabbroic stocks within the lower unit are medium-grained iron rich rocks with 10 to 15 percent skeletal ilmenomagnetite. Textures are subophitic with subhedral plagioclase laths—altered to albite, epidote, clinozoisite, sericite—partly included by anhydral clinopyroxene. Clinopyroxene is only slightly altered to chlorite and actinolite. The gabbros exposed at Merle Collins Reservoir are coarse grained and have gradational contacts with the diorites (Day, 1977). They contain 45 percent subhedral plagioclase, 40 percent subhedral to anhedral amphibole and relict clinopyroxene, 12 percent iron oxides and sparse chlorite (Day, 1977).

Sedimentary Rocks

Petrologic study of the sedimentary rocks in the Smartville block is hampered somewhat by the greenschist grade of metamorphism. Plagioclase feldspar is partly to entirely albitized and/or replaced by epidote and carbonate. A small percent of the pyroxene contains secondary minerals such as albite and carbonate. Alteration of the lithic clasts appears to vary with composition and texture. The groundmass of some lithic clasts is thoroughly choloritized and was probably originally cryptocrystalline or glassy. Groundmass in coarser-grained clasts is largely replaced by a microcrystalline aggregate of chlorite, epidote and albite. Amygdules in vesicular clasts are filled with chlorite, albite, quartz and granular to euhedral epidote. Clasts with puniceous textures are completely chloritized. Most of the secondary chlorite is an iron rich type with anomolous birefregince. Sedimentary matrix is recrystallized to a fine-grained aggregate of chlorite, epidote and albite and can easily be confused with the groundmass of lithic clasts. Siltstones and mudstones contain scattered euhedral crystals of secondary albite and patches of secondary epidote, chlorite and carbonate.

The original textures of the sedimentary rocks are preserved well enough for a qualitative analysis of texture. Lithic clasts textures are still recognizable; commonly even cryptocrystalline and microporphyritic textures can be distinguished. Even the delicate textures of pumice are fairly well preserved. Reactions along contacts between lithic grains and between lithic grains and matrix, however, have destroyed some grain boundaries.

We have attempted to point count a few of these sediments to give a general idea of their composition. Identifying original boundaries between lithic grains and between lithic grains and matrix was arbitrary in some samples. To avoid this problem, all points landing on crystals larger than 30 microns were counted as minerals whether they are separate grains or phenocrysts and microphenocrysts in lithic clasts. All points landing on aphanitic groundmass in lithic clasts were counted as phanite and all points landing on groundmass that is entirely chlorite or on clasts that are entirely chlorite were counted as glass. Points were assigned to matrix only if the material was clearly matrix. This counting method (Dickinson, 1970) increases the size of the mineral component well above that obtained by the standard counting methods but it has the advantage of giving the mineralogy of all of the framework grains. The sediment compositions obtained by this counting method are useful because they can be compared directly with the mineralogy of the intrusive and extrusive rocks in the Smartville terrane.

Textures

The Smartville sediments indicate a high degree of textural immaturity. Pebble and sand grains are angular and many mineral grains have nearly perfect euhedral outlines. Others have angular, almost needle sharp edges typical of shattered crystals that have been transported only a short distance. Lithic clasts of sand and pebble size observed on plished slabs have highly angular and irregular shapes typical of rocks that have been crushed or shattered. Only cobble size clasts show some rounding. Most of the sediments are so poorly sorted that they have a continuum of sizes from the coarsest material to matrix. The angularity of the clasts and the presence of pumice and lithic clasts with predominately volcanic textures suggests that the Smartville sediments were produced by volcanic processes such as explosions and autobreccion of intrusives and extrusives. These processes of fragmentation could also account for the abundance of euhedral crystals and unstable minerals such as pyroxene in the Smartville sediments. It is not unlikely that fresh fragmental material accumulated continually around explosive vents and in front of advancing lava flows generating a vast amount of detritus that frequently moved downslope to sites of deposition.

Compositions

The sedimentary rocks in the Smartville terrane can be divided by composition into two broad categories. The first contains pyroxene, plagioclase and some vesicular glass but lacks true pumice; the second contains only plagioclase and is abundantly pumiceous.

Non-pumiceous pyroxene bearing sediments are present in both the upper and lower units of the Smartville complex, but the representative samples described here are from the measured sections of the upper unit along the Bear and Yuba rivers. The predominant minerals in these sediments are clinopyroxene and plagioclase (Table 1). Both occur as separate grains and as phenocrysts in lithic clasts. Within the fault block downstream from section A to E along the Bear River (Fig. 2) a trace amount of quartz is present as grains and as phenocrysts in lithic clasts. The quartz grains have euhedral to subhedral shapes and they are monocrystalline. The quartz crystals in the lithic clasts are anhedral polycrystalline phenocrysts typically occurring in aggregates with plagioclase. Clinopyroxene and amphibole phenocrysts also are present but not abundant in the quartz bearing lithic clasts. The groundmass of these clasts typically is trachytic. Lithic clasts with quartz have a light green color that contrasts sharply with the dark shades of green and purple typical of the majority of lithics in the sediments. The more abundant dark green lithic clasts have plagioclase

Sample	Plag.	Clinopyrox.	Lithic aphanite	Lithic glass	Pumice	Matrix	Unknown
9-8-77-1	45	15	17	0	0	22	1
9-8-77-2	33	20	37	0	0	10	0
9-9-77-2a	30	7	36	22	0	5	0
S76-236	5	11	26	0	0	6	7
S77-166c	44	5	37	0	0	7	7
S77-169	30	26	26	2	0	15	1
S77-166a	57	6	23	1	0	10	3 (tr. quartz)
S77-166	51	9	30	0	0	6	0

Table 1. Point counts on representative sedimentary samples from the Smartville terrane. Total of 200 points counted in each sample. Numbers are in percent.

and clinopyroxene or just plagioclase as phenocrysts and plagioclase in the groundmass in felted or trachytic textures. Intergranular textures with plagioclase or plagioclase-pyroxene also are common. Chlorite, presumably as a replacement of glass, occurs as groundmass in as much as 10 to 30 percent of the porphyritic clasts. Highly vesicular clasts of chlorite (after glass) are common to abundant in some beds but completely absent in others. Whether these glass clasts came from pillow rinds or scoriaceous tops of flows is not clear. The large size of bubbles and the moderately low density of bubbles, however, suggests that these clasts were not formed by highly gaseous magmatic eruptions (Heiken, 1972). Moreover, the shapes of the glassy clasts are blocky and subequant suggesting fragmentation by quenching rather than by expansion of vesicles (Heiken 1972). These glassy clasts may be true hyaloclastic ash and lapilli or they may be the product of low viscosity basaltic eruptions such as lava fountaning.

Pumice bearing sediments are abundant in the measured intervals from 0 to 20 m and 220 to 320 m along the Bear River (Fig. 4). They have not been found in other measured sections and appear to be much less common than the non-pumiceous sediment. As in the non-pumiceous sediments, plagioclase occurs as grains and as phenocrysts in lithic clasts, but pyroxene has not been found in any of the thin sections examined. Lithic clasts are minor to abundant and have textures similar to those in the non-pumiceous sediments. Quartz and quartz bearing clasts have not been found in the pumiceous deposits, but distinct light green clasts, presumably siliceous, with textures similar to the quartz bearing clasts are abundant in the interval in the Bear River section from 220 to 300 m (Fig. 4). The most easily recognized pumice is the long tube variety. This type is abundant in most samples and not uncommonly comprises 40 percent to 60 percent of the rock by volume. Some of the pumice is porphyritic with stubby to elongated plagioclase phenocrysts. The pumice bearing rocks are so thoroughly altered to secondary minerals, especially chlorite, that point counting was not attempted. Compositions appear to range from 20 percent to 80 percent glassy material and 20 percent to 80 percent plagioclase plus lithics. All of these pumice bearing sediments appear to have been deposited by sediment gravity flow, however, and the term pyroclastic is not appropriate. These rocks are probably reworked, volcaniclastic sediments (Fisher, 1966).

Within the shear zone sediments are present (Fig. 2) but they are too sheared and faulted for detailed description. Pyroxene bearing sediments occur in some localities and these are not unlike the pyroxene rich sediments described above. At one locality a narrow block apparently bounded by faults contains a sheared quartz rich rock that might have been a primary pyroclastic deposit. This rock differs from others in the shear zone in that it contains discontinuous sheets of chlorite interlayered with lenses of very finely crystalline quartz-muscovite-chlorite. Quartz crystals up to 5 mm in size are common and are suspended within the sheets and lenses of fine grained material. Although the quartz crystals are polycrystalline and partly drawn out along shear planes, a few of them have good crystal outlines. These quartz crystals probably were originally euhedral crystals. The sheets of chlorite may have been pumice that has been sheared and flattened by deformation.

GEOCHEMISTRY

Thirty eight rock samples from all four units of the Smartville ophiolite were analysed for major elements. The technique used and fourteen of these analyses are reported in Menzies and others (in press). In addition to their data, evidence is drawn from twenty-four other analyses (Xenophontos, unpd. data) of extrusives and intrusives in the Upper and Lower Volcanic Units in the discussion that follows. When plotted on conventional AFM and Ni vs Mg/Mg+Fe diagrams, both a tholeiitic and a calcalkaline trend are evident (Day 1977, Xenophontos, unpd. data). Tholeiitic trends predominate in the lower unit, calcalkaline trends predominate in the upper unit and both trends are equally important in the dike complex. The use of major element chemistry of altered and metamorphosed basalts as the sole criteria for defining magma parentage (Miyashiro 1973) has been vigorously disputed by many (Gass et. al. 1975, Moores 1975, Hynes 1975). Experimental (Hajash, 1975) and field studies (Smith, 1975, Gass and Smewing, 1973, Garcia, 1977) have demonstrated the mobility of most major and trace elements. Consequently the value of FeO/MgO and AFM diagrams as petrogenic indicators appear to be limited. Certain trace elements, Ti, Zr, Y, and R.E.E., however, are considered to be relatively immobile in low grade metamorphism (Pearce, 1975, Cann, 1970, Kay, et. al., 1970, Frey, et. al., 1974, Menzies and others (in press), and, therefore, they can be used to define the tectonic setting of metavolcanic rocks. Menzies and Blanchard (1977) and Menzies and others (in press) conclude, principally from the REE abundances in rocks from the Smartville terrane that the lower unit is similar chemically to island arc tholeiites and that the upper unit is calkalkaline.

SEDIMENTATION

The sedimentology of the Smartville terrane suggests deposition in a slope-submarine fan setting. Deposition from sediment gravity flow is clearly indicated by the abundance of graded bedding, scouring at the base of graded beds, and beds with Bouma sequences. Deposition within channels appears to have been especially common. One interesting deposit was channeled along the side of or on top of a pillow lava (Fig. 5a); most channel fills, however, accumulated within channels cut into well bedded siltstones and sandstones. One well exposed channel in sediment is at least 20 m deep along one wall (Fig. 5b). Here, the channel fill is a disorganized conglomerate comprised of a great variety of volcanic clasts, some up to 1 meter across, and also many angular clasts of sediment as much as 2 meters across (Fig. 6). The sedimentary clasts are identical to the sedimentary material in the channel wall; they must have been ripped from the wall as sediment moved through the channel, and they probably were transported only a short distance. Other coarse deposits are not obviously in channels but the deposits contain numerous outsized sedimentary clasts that probably were ripped from channel walls. Many of these sedimentary clasts are highly contorted and show strong internal soft sediment deformation. These soft clasts could not have been transported far beyond the channel walls from which they were eroded.

The coarse-grained sediments that are channel fills or that contain abundant sediment clasts torn from channel walls are organized and disorganized conglomerates and pebbly sandstones of facies A$_1$ through A$_4$ of Walker and Mutti (1973). Structures in the organized subfacies are mainly crude parallel stratification (Fig. 7) and crude normal grading, often developed only at the tops of the beds. Commonly, these coarse layers occur in a thining upward cycle typical of channel fills (for example, Fig. 3, 5m to 20 m). Sandstones typically are interbedded with the conglomerates and are common in the sediments comprising the channel walls. Some of these sandstones are massive, ungraded and without dish structures (facies B$_2$) and others are graded but mostly with only Bouma Ta, e intervals (facies C). Deposits of facies C with Bouma Ta, b, e, and Ta, b, c, e, intervals are present but not common. Slump structures (facies F) also are common in many of the sandstone beds. The least common deposits are mudstones and silty mudstones, some with radiolaria. These fine grained deposits probably are pelagic to hemipelagic sediments belonging to facies G. The bulk of the sediments, at least in the areas examined, belong to facies A$_1$ to A$_4$. Sediments in facies B$_2$, C and F are less common and only locally abundant, particularly in the upper parts of thining upward cycles. The irregular, lenticular beds of facies E that characterize overbank or levee deposits appear to be rare or absent. The proportions of facies types suggests deposition either on a slope with canyons or in an inner fan with deeply eroded channels (Walker and Mutti, 1973, Ricci-Lucchi, 1975).

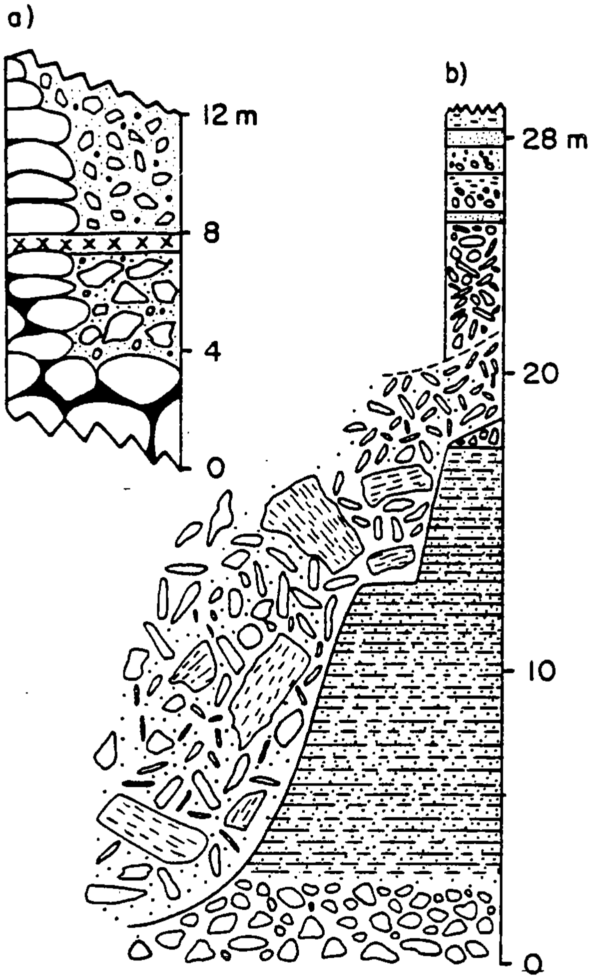

Figure 5a. Channel fill in or against a pillow lava near Fig. 2. From a field sketch. See Fig. 3 for explanation.

Figure 5b. Channel edge and channel fill in the Bear River section, A to E on Fig. 2. See Fig. 3 for explanation.

The Smartville terrane probably formed near or within active volcanic islands (see section on Conclusions-Paleography, this paper). Marine sedimentation models for island volcanoes have not been developed and there is no modern analogue with which to compare the Smartville sediments. Bathymetric maps of modern island volcanoes, however, show deeply eroded channels and canyons trending radially away from vents and island crests. During eruptions large quantities of debris must move through these channels and canyons, and the sediment probably accumulates in fans or fan-like wedges near the base of the volcanoes. It is not unreasonable to suggest that the Smartville sediments accumulated in a similar depositional setting.

The extrusion of pillow lavas, which was contemputaneous with sedimentation, modified some of the sedimentary deposits. Sediments immediately below the pillow lavas are scoured and squeezed up into spaces between pillows. Soft sediment deformation is common along the contact between the base of the flow and the sediment. In the interval 0 to 20 m

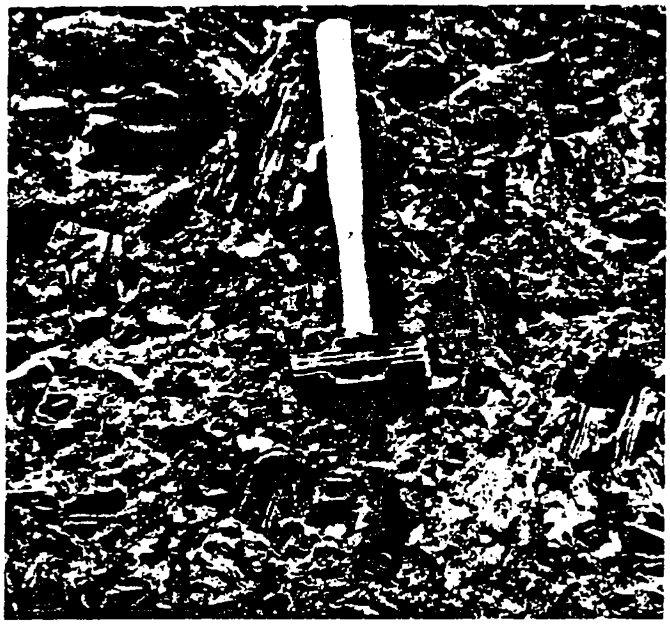

Figure 6. Photo of the sedimentary clasts in the channel fill sketched in Fig. 5b.

in the section along the Bear River, sediments at the top of a pillow lava are banked against pillow lobes at the flow surface and extend down into the flow between pillows for at least a meter. The sediments that extend farthest into the flow contain significantly larger amounts of secondary epidote and albite than the sediments at the surface of the flow, probably because the interior of the flow was still hot when the sediment filtered into it. Sediments in contact with dikes and sills along the Bear River show a soft sediment style of deformation along some of the intrusive contacts indicating that the intrusive activity also occurred while the sediments were still watery and soft.

Sediments are rare in the lower unit except locally and they have not been studied in detail.

CONCLUSIONS - PALEOGEOGRAPHY

Physiographic Setting

The Smartville terrane is postuated to have been formed close to or possibly within a group of active volcanoes (Fig. 8). The abundance of coarse volcanic derived pumiceous sediment and coarse angular volcanic clasts with shapes produced by grinding and shattering requires nearby volcanic activity. Also, most of the sedimentary rocks in the terrane were deposited in numerous channels cut into relatively steep slopes and the most probable location of these slopes was on the flanks of active volcanoes. Moreover, the compositions of lithic clasts in the sediments are similar to the basaltic, andesitic and dacitic (?) compositions of shallow intrusives that are common in the Smartville terrane. Pyroxene-plagioclase lithic clasts are abundant and so are intrusives with pyroxene and plagioclase phenocrysts (Fig. 2). The light colored siliceous clasts, some with quartz, are similar in texture and composition to the scattered rhyolitic (?) plugs and dacitic intrusives that occur in and east of the shear zone. These mafic to siliceous intrusives most likely are remnants of the vent complexes from which the Smartville sediments were derived.

Figure 7. Photo of organized conglomerate, facies A_2, from 44 m above the base of the Yuba River section, Fig. 3.

At least some of the active vents must have been near or above sea level judging from the presence of pumice in the sediments. The large expansion of gas needed to form pumice requires that vents are either subaerial or in shallow water. Furthermore, the lack of rounding on most clasts suggests little if any sediment transport in rivers and beach-nearshore environments. These environments should be rare or absent on volcanoes whose vents are below or only slightly above sea level.

Tectonic Setting

The most widely accepted tectonic settings for the generation of ophiolites are: (a) Mid-Ocean Ridges (Moores, 1969, Gass and Smewing, 1973, Greenbaum, 1972, Moores and Vine, 1971, Cann, 1974) and (b) Marginal or inter-arc basins (Karig, 1971, Dewey and Bird, 1971). Detailed studies of the better exposed Tethyan ophiolites (Moores, 1969, Mesorian, and others, 1973, Gass and Smewing, 1973, Smewing, 1975, Parrot, 1977) have established a consistent stratigraphy of pelagic sediments at the top, followed downwards by pillow lavas, sheeted dikes, cumulate gabbros-peridotites and tectonite peridotites. Seismic reflection profiles (Christensen and Salisbury, 1975), dredging from the ocean ridges (Cann, 1969, Aumento and others, 1971, Miyashiro and others, 1971), and studies from Deep Sea Drilling Project, further supported the ophiolite-oceanic lithosphere analogy. Data from marginal basins are meager and those that are available come almost exclusively from the Lau Basin (Hawkins, 1975, Hawkins, 1976). Oceanic basalts and basalts from the Lau basin have similar geochemistry. Characterized by low K and higher values of Ni and Cr than island arc tholeiites (Hawkins, 1976, Kay and others, 1970, Ewart and Bryan, 1971). Classification of ophiolites on the basis of geochemical criteria alone has given at best ambiguous results (Miyashiro, 1975a, Moores, 1975, Gass and others, 1975). Detailed geologic, lithologic and geochemical studies are considered more fruitful in ophiolite studies.
In the Smartville terrane we have: (1) An incomplete ophiolite sequence (cumulate and tectonite sections

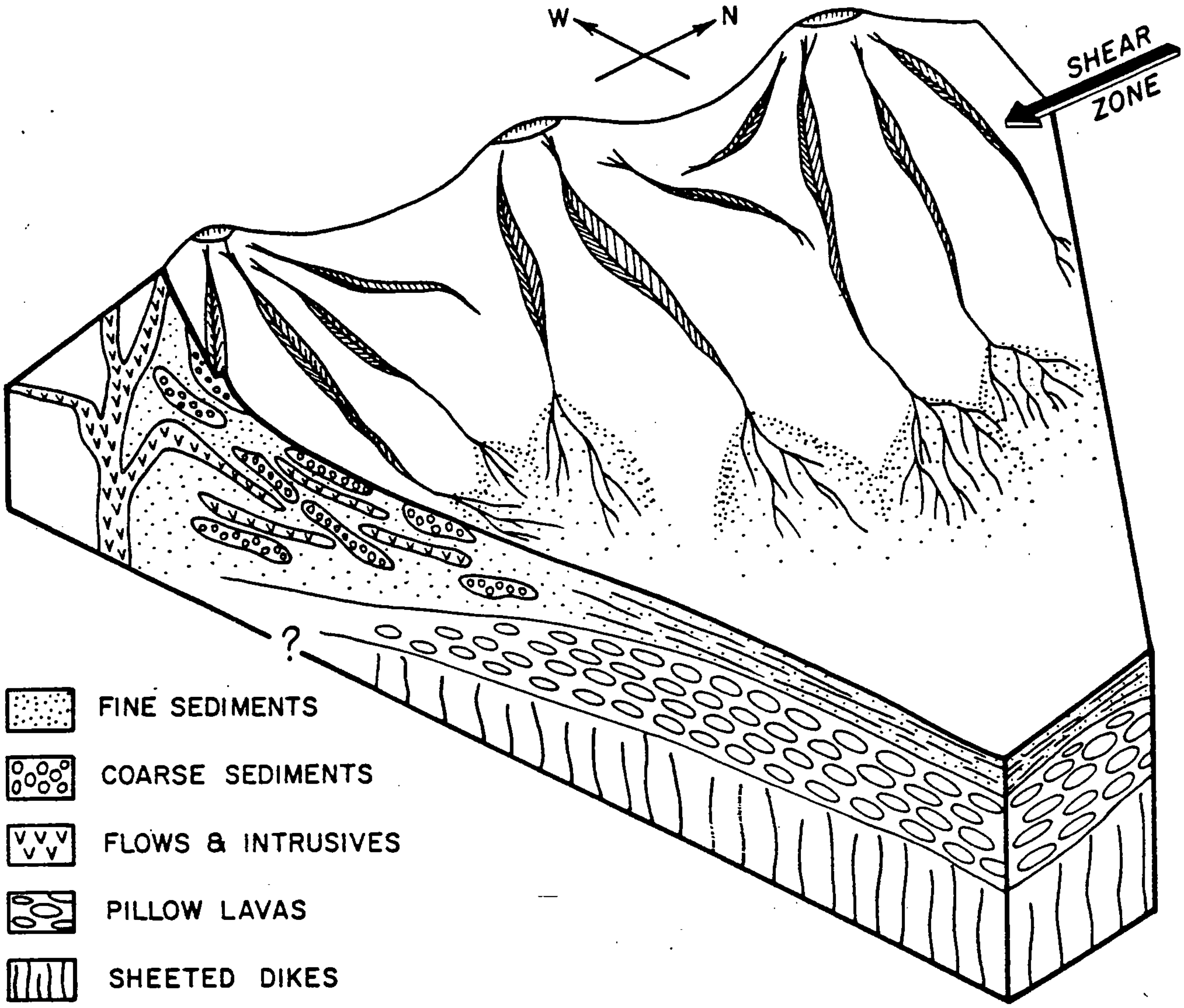

Figure 8. Sketch of inferred paleogeography in the Smartville terrane. Arrow marks the rough location of the shear zone (Fig. 2).

missing), (2) A pillow lava sequence with island-arc tholeiitic affinities (lower unit) overlain by and possibly interfingering with (3) calcalkaline extrusives (upper unit) and abundant volcaniclastics.

The geochemical evidence excludes formation of the Smartville ophiolite at a mid-ocean ridge or in a fully developed marginal basin such as the Lau basin. The regional geology, the nature of the volcanics and the associated sediments together with the available geochemical data suggest that the Smartville ophiolite formed in one of three possible settings: (1) A very young inter-arc basin in which the chemistry of the volcanics is dominated by arc volcanism. A modern analog is to be found in the small marginal basins of the Scotia Arc (Bell and others, 1977, Tarney and others, 1976): (2) The edge of a marginal basin such as the Lau basin with basalts having affinities to arc-tholeiites and intercalated calc-alkaline sediments derived from the adjacent arc. Younger more centrally situated basalts with ocean-tholeiite affinities are subducted. Such an edge is a remnant of and should resemble the ophiolite in (1) above. (3) An intra-arc extensional setting within and at the base of an arc. Extension could be caused by oblique subduction as seems to be the case in the Bonin Arc (Kaizuka, 1975, Nakamura and others, 1976).

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