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PETROLOGICAL SETTING AND INFERRED PLATE TECTONIC HISTORY OF THE SAWYERS BAR TERRANE, CENTRAL KLAMATH MOUNTAINS, NORTHERN CALIFORNIA

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ABSTRACT

The Lower Mesozoic Yellow Dog pillowed greenstones in the Sawyers Bar area are interlayered with, and apparently conformably overlie, associated distal turbiditic metasedimentary strata. These rocks crop out in the east-central portion of the western Triassic and Paleozoic (WTrPz) belt. The submarine volcanic rocks include two distinct types: (1) a stratigraphically lower, (Fe + Ti + P)-rich series of mildly alkaline, dark green lavas and breccias that represent within-plate oceanic basalts; and (2), an overlying, pale green extrusive + hypabyssal series of more massive arc tholeiites or calc-alkaline basalts. The volcanic and metasedimentary rocks were altered in a deep-sea environment during feeble but pervasive early Mesozoic seafloor recrystallization, then regionally metamorphosed in Early to Middle Jurrasic time to greenschist-facies assemblages accompanying deformation and accretion of the outboard Sawyers Bar terrane to the landward Stuart Fork subduction complex of Triassic metamorphic age. Thermal overprinting attended Middle Jurassic intrusion of felsic plutons in the area. Comparable assemblages and apparently similar geological relations characterize contiguous areas of the WTrPz lithotectonic belt to both the south and the northeast. The hypothesized Mesozoic plate tectonic evolution of the eastern part of the central WTrPz belt may be likened to a future westward convergence and collapse of the present-day Philippine Sea plate. Such a process would juxtapose the Marianas immature basaltic island-arc and continental-rise section constructed upon a within-plate oceanic basement (= Sawyers Bar terrane) against the Ryukyu – Sanbagawa subduction complex (= Stuart Fork terrane) along or near the Asiatic (= North American) margin. Sustained underflow associated with the conjectured closure of the marginal basin could account for the generation of calc-alkaline melts that invaded the amalgamated, post-collisional terrane assembly.

Keywords: plate tectonics, island arc, intraplate volcanism, Klamath Mountains, California.

SOMMAIRE

Les roches vertes du groupe de Yellow Dog (d'âge mésozoïque inférieur), affleurant dans la région de Sawyers Bar, dans les montagnes Klamath, partie nord de la Californie, sont interstratifiées avec, et recouvrent avec conformité, des strates métasédimentaires turbiditiques distales. Ces roches sont exposées dans la portion centre-est de la ceinture occidentale de roches triassiques et paléozoïques (WTrPz). Les roches volcaniques sous-marines forment deux groupes distincts: 1) une série stratigraphiquement inférieure de laves et de brèches vert foncé, riche en Fe, Ti et P, et à tendance légèrement alcaline, représenteraient des basaltes océaniques intra-plaques; 2) une série supérieure de roches vert pâle extrusives et sub-volcaniques, plus massives, de tholéiites associées à un arc ou de basaltes calco-alcalins. Les roches volcaniques et métasédimentaires ont d'abord subi une recristallisation répandue, mais de faible intensité, dans un milieu marin profond au cours d'un événement mésozoïque précoce, et ensuite un épisode de métamorphisme régional (facies schistes verts), d'âge jurassique précoce ou moyen, lors de la déformation et de l'accrétion du socle de Sawyers Bar, externe, au complexe de subduction de Stuart Fork, interne, d'âge métamorphique triassique. Un métamorphisme de contact a accompagné la mise en place de plutons felsiques d'âge jurassique moyen dans la région. Des assemblages et des relations géologiques comparables caractérisent des régions contiguës de la ceinture lithotectonique de WTrPz vers le sud et le nord-est. L'évolution mésozoïque des plaques tectoniques dans la partie orientale de la ceinture de WTrPz ressemblerait à la convergence vers l'ouest et le démembrement anticipés de la plaque actuelle de la mer des Philippines. Une telle évolution aura comme résultat la juxtaposition d'une section de détritus immatures à caractère basaltique et à affinité d'arc insulaire déposée sur un socle océanique intra-plaque (les Marianas, équivalent du bloc de Sawyers Bar) avec le complexe de subduction de Ryukyu – Sanbagawa (équivalent du bloc de Stuart Fork) le long ou près du la limite du craton asiatique (ici, nord-américain). Une subduction persistante associée à la fermeture du bassin marginal pourrait expliquer la génération de magmas calco-alcalins qui ont envahi l'ensemble de socles une fois réunis et contigus.

(Traduit par la Rédaction)

Mots-clés: tectonique des plaques, monts Klamath, arc insulaire, volcanisme intra-plaque, Californie.

Geological Sketch of the Klamath Province

The Klamath Mountains consist of an imbricate stack of fault-bounded, shallowly east-dipping composite terranes (Irwin 1960, 1972, Davis 1968, Burchfiel & Davis 1981). From east to west, these are: the eastern Klamath plate, the central metamorphic belt, the Stuart Fork complex, the western Triassic and Paleozoic (WTrPz) belt, and the western Jurassic belt. These terranes have been juxtaposed through inferred east-descending subduction during mid-Paleozoic to mid-Mesozoic time (Irwin 1981, Mankinen *et al.* 1989); most lithotectonic units contain prominent mafic + ultramafic masses, especially along the bases of terranes that overlie east-rooting but now subhorizontal sutures. In general, the ages of formation, and, from the central metamorphic belt westward, both times and grades of metamorphism decrease toward the Pacific Ocean (Ernst 1983).

The Klamath Mountains have been intruded by Middle + Late Jurassic and Early Cretaceous felsic plutons (Lanphere *et al.* 1968, Wright 1982, Irwin 1985, Wright & Fahan 1988) that locally mark the termination of terrane accretion. Stratified supracrustal units in general are right-side-up, and dip chiefly eastward. At least six areally and temporally distinct metamorphic episodes, spanning the Middle Ordovician - Late Jurassic time interval, took place in the Klamath province (Mortimer 1985, Cotkin & Armstrong 1987, Coleman *et al.* 1988). Regional geological and tectonic relations for northern California, and location of the Sawyers Bar map area in the central Klamaths, are shown in Figure 1.

The Stuart Fork terrane is a series of interleaved metapelitic and metamafic volcanic units that tectonically underlie the central metamorphic belt. Lawsonite- and glaucophane-bearing assemblages and rare eclogitic lenses characterize the northern part of the Stuart Fork (Hotz 1973, Borns 1980, 1984), whereas to the south, rocks of this unit contain epidote + crossite (Goodge 1989a). K/Ar and $^{40}Ar/^{39}Ar$ geochronological data indicate that the blueschists were produced during subduction (the Fort Jones event of Coleman *et al.* 1988) beneath the North American margin or an offshore arc; the 227 Ma apparent age, based on white mica (Hotz *et al.* 1977, Wagner & Saucedo 1987) may represent the time of return toward the surface and cooling through the argon-retention temperature. The Stuart Fork terrane subsequently was thrust over rocks of the WTrPz belt (Goodge 1989b) in early Middle Jurassic time (~170 Ma) at the latest; greenschist- to lower-amphibolite-facies metamorphism accompanied this tectonic juxtaposition (the Siskiyou event of Coleman *et al.* 1988). Rocks of the Stuart Fork and WTrPz belts have been overprinted by an approximately 158 Ma old or older thermal event (K–Ar data), the apparent age reflecting mineralogical annealing of micas and argon loss during, and following, invasion by Middle Jurassic calc-alkaline plutons (Lanphere *et al.* 1968, Irwin 1985).

Beneath the Stuart Fork, three north–south-trending lithostratigraphic segments of the structurally lower WTrPz belt were distinguished by Irwin (1972). From east to west, these are: (1) the ophiolitic North Fork terrane, (2) the Hayfork composite terrane, consisting of an older, eastern, terrigenous *mélange*, and a younger, western calc-alkaline arc (Wright 1982), and (3) the ophiolitic Rattlesnake Creek terrane. All three units are metamorphosed, to the subgreenschist facies in the south, increasing northward to amphibolite facies near the Oregon border (but lower grade on the east), and contain chert, dismembered fragments of oceanic crust, and variably disrupted volcanogenic sediments. All three WTrPz terranes contain (olistostromal?) limestone blocks enclosing Late Paleozoic and Triassic fossils. However, Triassic and Early Jurassic radiolaria occur in associated siliceous sediments of the North Fork, western Hayfork, and Rattlesnake Creek terranes (Irwin *et al.* 1978, Irwin 1981, Blome & Irwin 1983); the eastern Hayfork contains microfossils at least as young as Late Triassic.

Meta-andesite of the western Hayfork possesses a minimum Middle Jurassic igneous age. Calc-alkaline stocks intrusive into the WTrPz and adjacent belts are as old as 159–174 Ma (U–Pb and K–Ar radiometric ages from Lanphere *et al.* 1968, Wright 1982, Snoke *et al.* 1982, Irwin 1985, Wright & Fahan 1988). Thus the WTrPz belt, which contains Lower Jurassic superjacent units, must have accreted to the Stuart Fork subduction complex and been regionally metamorphosed by early Middle Jurassic time at the latest. Because rocks of the WTrPz belt show no evidence of a precursor blueschist event, tectonic amalgamation with the Stuart Fork must have taken place after Triassic high-pressure metamorphism of the latter terrane. The Siskiyou tectonometamorphic event is therefore of approximately Early to Middle Jurassic age.

The present study focuses on the igneous petrogenesis and inferred plate tectonic development of a pile of metabasalts located in the vicinity of Sawyers Bar, California (Ernst 1987), along and west of the east-dipping thrust contact that juxtaposes the structurally higher Stuart Fork terrrane against underlying WTrPz belt lithologies.

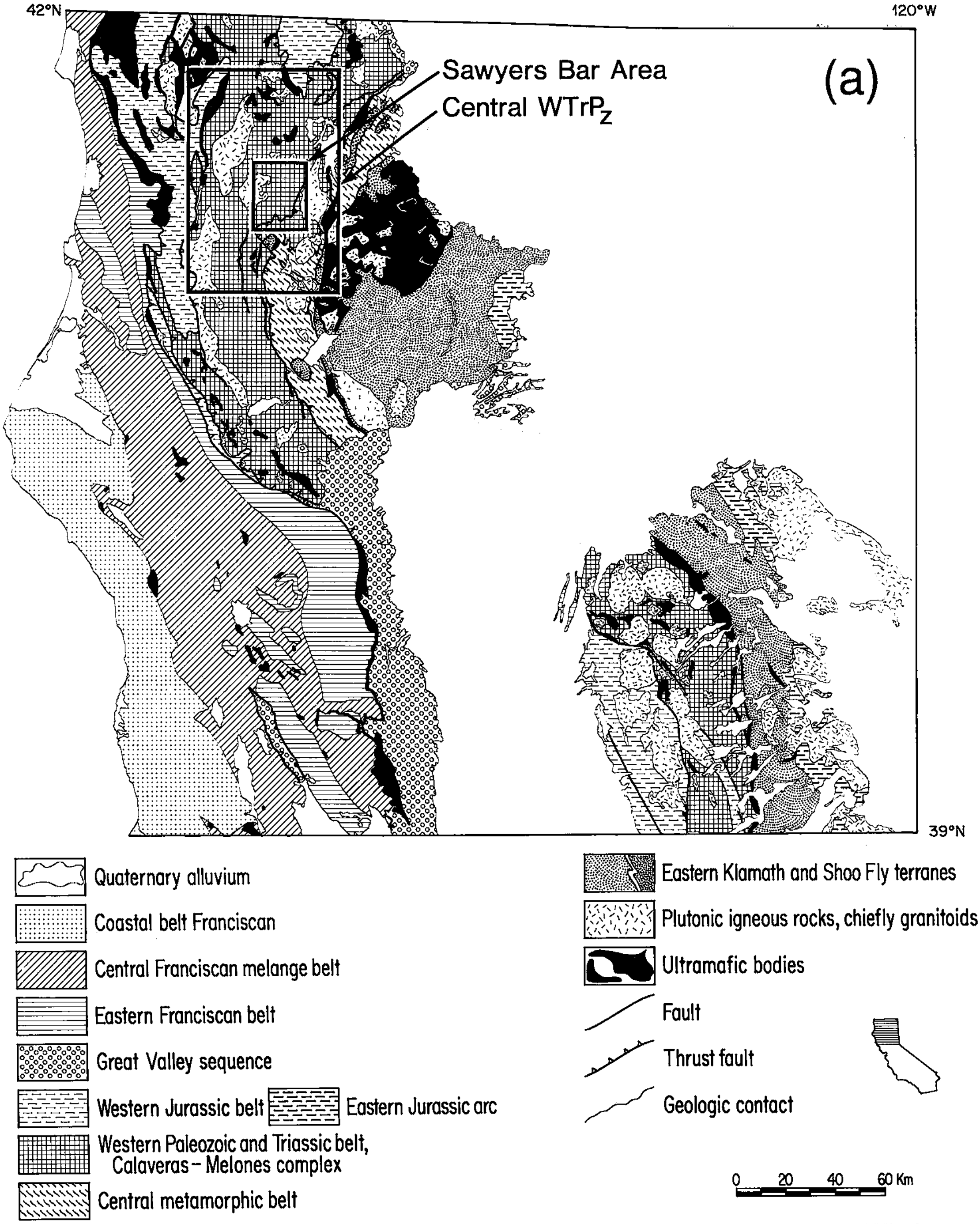
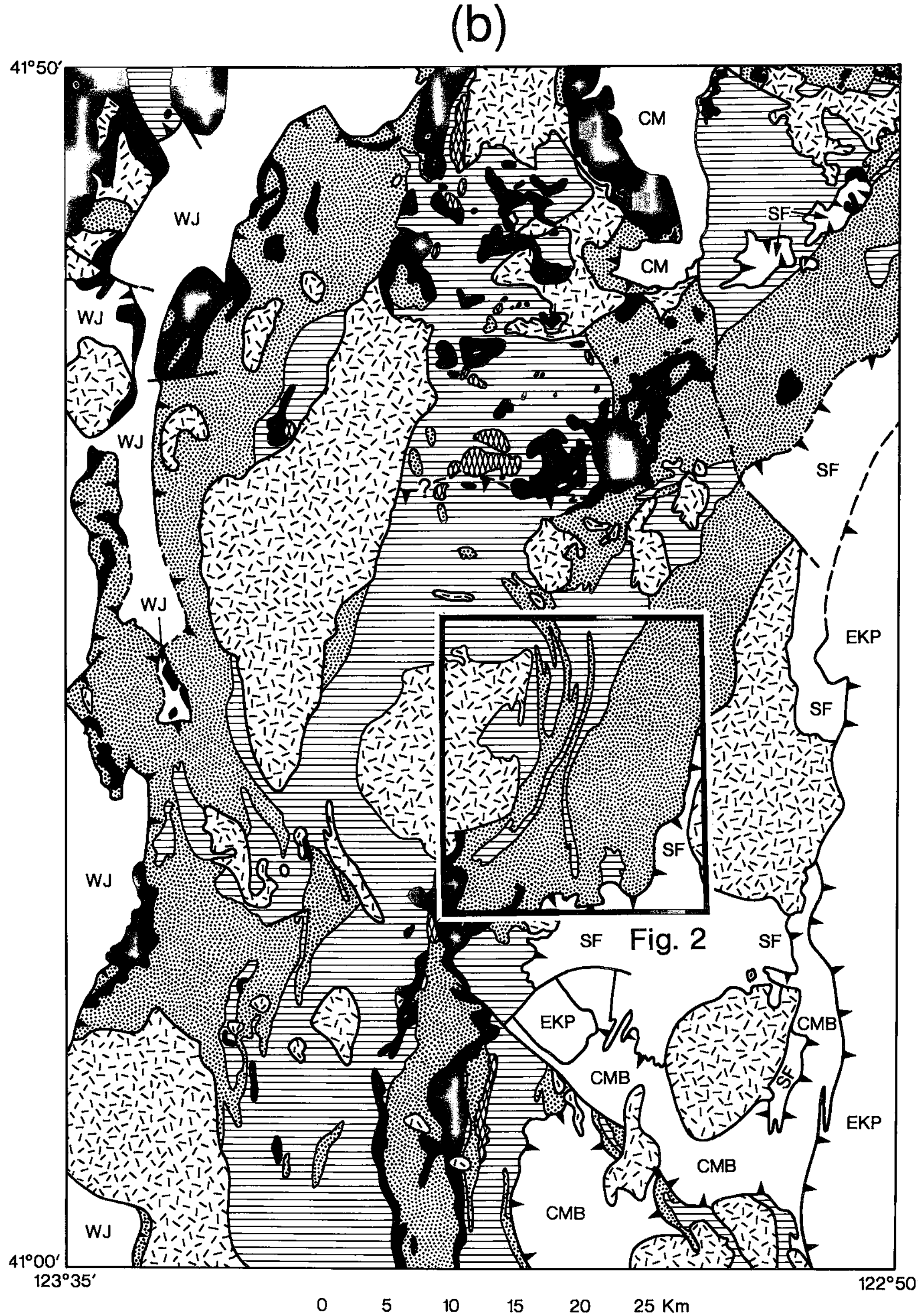


FIG. 1. (a) Index geological map of California north of latitute 39°N, after Jennings (1977) and Ernst (1983), showing location of Fig. 1b, the central part of the western Triassic and Paleozoic (WTrPz) belt, and of Fig. 2, the Sawyers Bar area. (b) Regional lithologic units of the WTrPz belt of the central Klamath Mountains, after Wagner & Saucedo (1987) and Ernst (1990). WTrPz units are: black: serpentinized peridotites, random dashes: Middle and Late Jurassic felsic intrusive complexes, stippled pattern: mafic metavolcanic rocks, horizontal lines: metasedimentary strata, cross-hatch pattern: marble beds and blocks. Abbreviations: EKP: eastern Klamath plate, CMB: central metamorphic belt, CM: Condrey Mountain terrane, SF: Stuart Fork terrane, WJ: western Jurassic belt. Barbs are shown on upper plates of thrust sheets, but some of these *décollements* have been reactivated during extensional movements (normal faulting) bringing the underthrust segments back toward the surface.


(b)
41°50′
41°00′
123°35′
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WJ
WJ
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CM
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SF
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SF
SF
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EKP
EKP
EKP
CMB
CMB
CMB
CMB
Fig. 2
0 5 10 15 20 25 Km

REGIONAL SETTING OF THE SAWYERS BAR AREA, CENTRAL WTrPz BELT

The three WTrPz terranes defined in the more feebly recrystallized southern Klamath Mountains by Irwin (1972) are not easily distinguished in the more intensely metamorphosed northern part of the range. A portion of the central WTrPz belt surrounding Sawyers Bar, California, is presented in Figure 2, based on geological mapping by the author. The amphibolite-grade Marble Mountain *mélange*, which is exposed north of the mapped area, apparently underlies and interfingers with metaclastic and metavolcanic units that pass southward into the Sawyers Bar area (Donato 1985, 1987, Ernst 1990). The North Fork ophiolitic terrane (Ando *et al.* 1983) adjoins the Sawyers Bar area directly to the south; a single, strongly discordant U–Pb age of 245–310 Ma for a zircon sample from feebly recrystallized ophiolitic

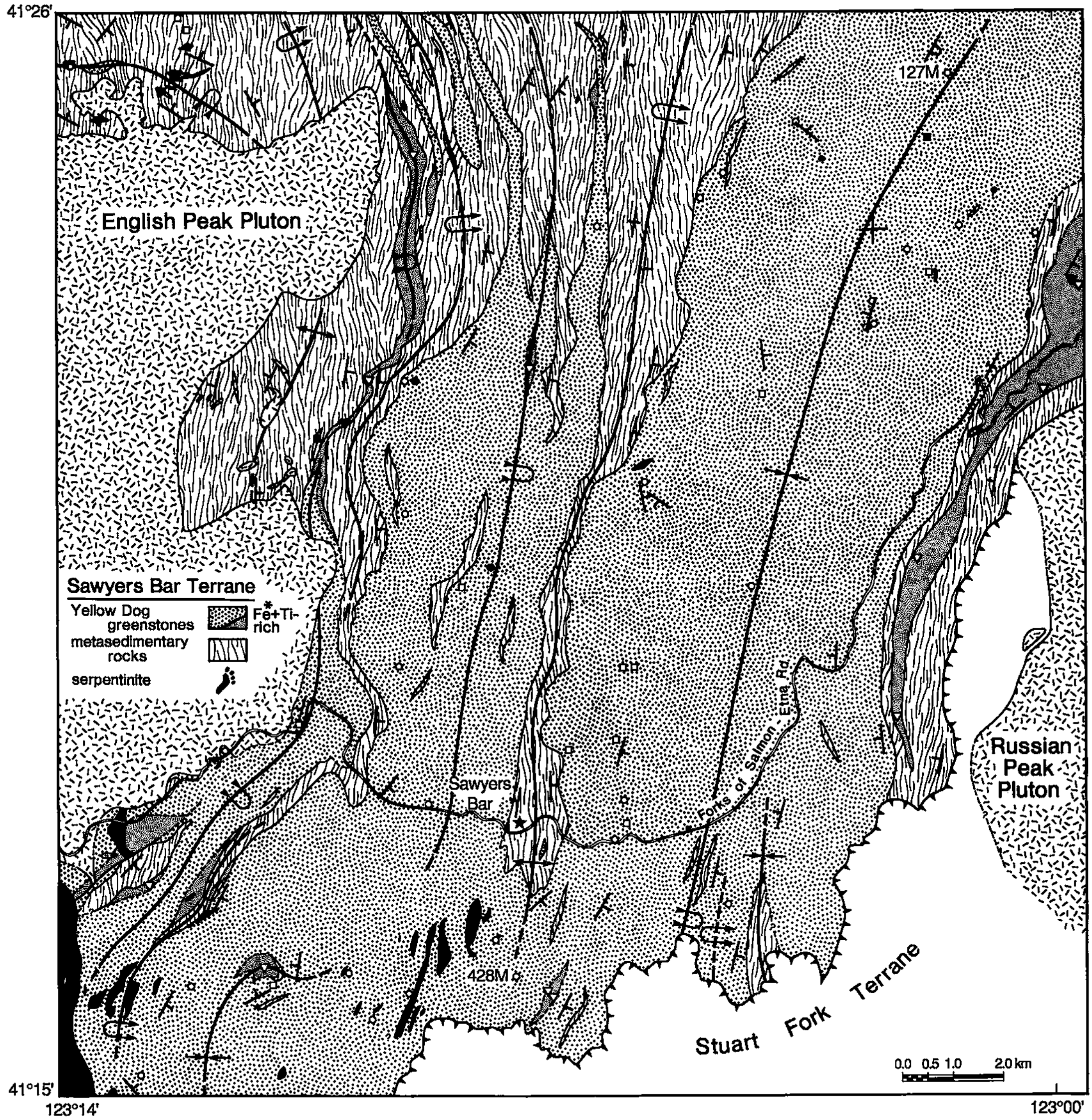


FIG. 2. Geology of the Sawyers Bar area. A preliminary version of a less extensive area was presented by Ernst (1987). Traces of axial planes are interpretive. Sample symbols for mafic metavolcanic rocks are as follows: upside-down triangles: darker, more schistose, amygdaloidal metabasalt flow breccias, circles: paler, more massive metabasalts, squares: diabasic dikes and sills, filled symbols: Mg-rich Yellow Dog meta-igneous rocks, open symbols: normal (basaltic) Yellow Dog meta-igneous rocks.

plagiogranite was reported by these authors. If correct, this would require some portion of the basaltic complex to be as old as Permo-Triassic age.

The metamorphosed mafic igneous suite, along with the associated coeval sedimentary strata in the mapped area, can be traced without interruption along strike both northeast and south of the Sawyers Bar area. As shown in Figure 2, pregranite units northwest of the thrust contact with the Stuart Fork terrane evidently belong to a single North Fork terrane, as originally defined by Irwin (1972). The structurally lower Marble Mountain complex to the north is tentatively correlated by the present author with disrupted rocks of the eastern Hayfork terrane, whereas Donato *et al.* (1982) regarded the Marble Mountain *mélange* as a northeastern equivalent of the Rattlesnake Creek terrane (for a similar interpretation, see Blake *et al.* 1982, and Silberling *et al.* 1987).

Stratigraphy, Structure, and Metamorphism of the Sawyers Bar Section

The major portion of the mapped region consists of massive to weakly foliated greenstones, and less voluminous, interlayered, chiefly metaclastic schists. A vague schistosity in the metavolcanic rocks and more distinct compositional layering in the metaclastic units coincide in attitude, strike NS to N30°E, and dip steeply, predominantly to the east. The greenstones are relatively massive, but excellent in-place pillows were recognized in the northeastern part of the area at locality 127M, and less obvious pillow structures were noted as float along the southern edge of the map west of locality 428M (Fig. 2). Based on top indicators (pillows) at 127M, the upright synformal fold in the eastern part of the Sawyers Bar area, and stratigraphic coherence displayed by the mapped lithologies, the region is interpreted to consist of a major greenstone-cored syncline on the east, and westward, overturned, west-verging metasediment-cored anticlines and greenstone-cored synclines. Regional relationships in the WTrPz belt (Fig. 1b) in general support this stratigraphic interpretation. Structural breaks between metasedimentary and metavolcanic lithologic units were not recognized locally, although a few small lenses of serpentinite, possibly emplaced along faults, are present in the northern part of the mapped area, and larger, extensively serpentinized ultramafic bodies occur near the southwest corner.

Metasedimentary rocks consist of undisrupted pelitic units, argillites, micrograywackes, calcareous quartzofeldspathic rocks, rare limey lenses, and minor cherty horizons. Compositional layering in the metasedimentary strata parallels the interfingered depositional contacts with the meta-extrusive units. In aggregate, this section displays stratal continuity, is of probable Permo-Triassic and Early Mesozoic age, and is interpreted as a volcanic arc–distal turbidite deposit.

Metavolcanic units appear to be interstratified with and predominantly overlie the fine-grained metaclastic rocks. Depositional interlayering and tight folding are evident from the intricately interdigitated patterns of outcrop of the metasedimentary and mafic meta-igneous units (Fig. 2). The greenstones consist chiefly of massive flows; however, cross-cutting and concordant tabular bodies, most of which display a coarser-grained, relict diabasic texture, confirm the presence of metamorphosed hypabyssal mafic intrusive bodies within the volcanic pile and predominantly subjacent metasedimentary section. Several consanguineous metadiabase dikes cut the tectonically overlying Stuart Fork terrane.

Schistose metavolcanic layers, chiefly situated adjacent to the English Peak and Russian Peak felsic plutons, are dark green, and have been mapped as a separate, more mafic greenstone flow unit. The eastern exposures contain distinctive amygdaloidal breccias; such lithologies are present in the western part of the mapped area but are less obvious because of intense contact metamorphism adjacent to the English Peak pluton. Most of these mafic flow breccias appear to be portions of a single, dark green metavolcanic sequence interstratified with the metasedimentary rocks; according to the structural interpretation, these dark-colored flows underlie the main pile of paler, more massive greenstones. Smaller, less continuous lenses of the darker, schistose metavolcanic breccia are distributed within the main belt of greenstones (Fig. 2). In the mapped area, hypabyssal rocks belong solely to the light green igneous series.

The entire mafic meta-igneous assemblage, including dikes and sills, here is referred to as the Yellow Dog greenstones, after the prominent peak northeast of Sawyers Bar. The intimate interlayering of mafic volcanic units with distal turbidites, and the interpretation that the extrusive section dominantly overlies the sedimentary rocks, argue for eruption in a continental-rise or island-arc setting. Metadiabase dikes and sills in the metasedimentary section also attest to roughly coeval formation. As shown by geochemical studies (Ernst 1987, Ernst *et al.* 1991), the basaltic rocks consist chiefly of somewhat more evolved, pale gray-green arc tholeiites or calc-alkaline basalts (or both), laid down over mildly alkaline, dark green, intraplate oceanic basalts. The occurrence of metadiabase dikes of the paler series that transect the Stuart Fork terrane demonstrates that Yellow Dog volcanism continued during amalgamation of this older, blueschist complex to the underthrusted North Fork arc.

At least three metamorphic events are recorded in metavolcanic and interstratified metasedimentary units of the Sawyers Bar area, as determined by petrographic investigation of more than 500 samples, and by electron microprobe + back-scattered electron image studies of coexisting minerals (Hacker *et al.* 1992). Compositional data (XRF, INAA and $^{18}O/^{16}O$ analyses) for selected rocks provide additional support for this conclusion. (1) Low temperatures (< 250°C) and very low pressures (< 2 kbar) accompanied feeble seafloor alteration. The time of recrystallization is poorly constrained as approximately Permo-Triassic to Early Jurassic. (2) Regional dynamothermal metamorphism attended accretion of the Sawyers Bar immature arc to the more easterly Stuart Fork terrane subsequent to Triassic blueschist metamorphism of the latter, probably by early Middle Jurassic time at the latest. Physical conditions attending accretionary deformation produced biotite-zone greenschist-facies assemblages (425 ± 75°C, 3–4 kbar) in the north, decreasing in grade southward to prehnite - actinolite subgreenschist facies (300 ± 100°C, 2–3 kbar) in the south. Farther to the northeast, the grade again gradually decreases. (3) Contact aureoles surrounding the English Peak and Russian Peak plutons transect the regional foliation, and were generated during subsequent intrusion of these felsic magma bodies in Middle Jurassic time. Conditions near the igneous contacts approached 600°C at 2.4 ± 0.5 kbar; the hornfelsic zones merge with regional metamorphic effects at distances 3–4 km from the plutons.

TABLE 1. **AVERAGE COMPOSITION OF YELLOW DOG METAVOLCANIC ROCKS, SAWYERS BAR AREA, CENTRAL KLAMATH MOUNTAINS**

rock type	dark green flow breccias	light green massive flows	light green dikes & sills	Mg-rich, all greenstone units
SiO_2 wt.%	47.88±2.47	50.78±1.92	53.26±2.98	49.18±2.52
Al_2O_3	12.86±1.85	12.85±1.68	14.04±1.78	10.95±0.99
MgO	9.95±3.09	10.72±2.96	9.19±3.20	14.44±1.91
CaO	8.44±2.62	10.21±2.23	8.15±1.39	10.02±1.99
Na_2O	2.06±1.00	2.34±0.77	2.43±0.70	1.47±0.53
K_2O	0.71±0.60	0.48±0.44	1.42±0.62	0.77±0.36
Fe_2O_3*	13.87±1.20	10.73±0.98	9.94±1.21	11.12±1.51
TiO_2	2.47±0.60	0.91±0.21	0.86±0.17	1.16±0.80
MnO	0.18±0.02	0.17±0.03	0.17±0.02	0.17±0.01
P_2O_5	0.34±0.17	0.11±0.05	0.22±0.08	0.20±0.11
Cr ppm	239±176	310±251	283±229	649±199
Ni	159±135	122±96	100±86	267±105
Rb	15±17	11±11	35±19	16±10
Sr	382±204	179±102	383±210	285±222
Zr	193±57	76±27	113±50	125±79
no. of samples	16	38	18	17

* total iron expressed as Fe_2O_2

compositions are averages from Ernst *et al.* (1991, Table 3)

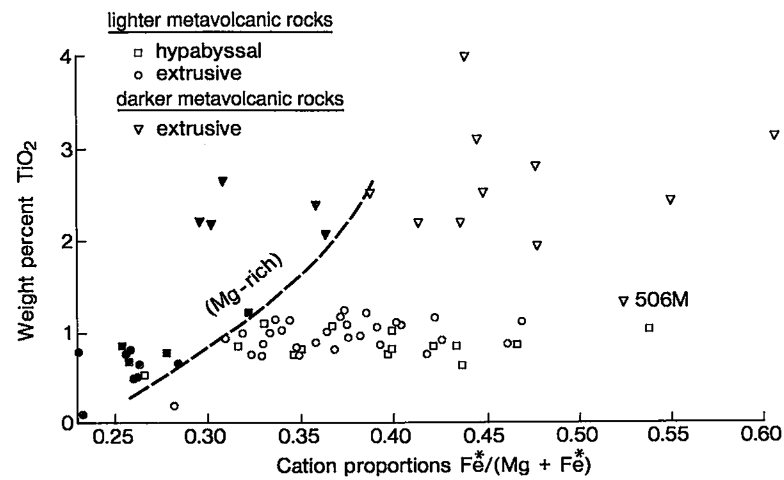


FIG. 3. TiO_2 in wt.% *versus* molar X_{Fe*} for Yellow Dog metavolcanic rocks from the Sawyers Bar area (Fe* = total iron). Sample symbols as in Fig. 2. Mg-rich meta-igneous rocks are richer in Ti than chemically more normal greenstones for a given degree of fractionation (X_{Fe*}). The dark green, schistose flow breccias appear to represent a metamorphosed series of flows chemically distinct from the more abundant, paler Yellow Dog metadiabases and metabasalts.

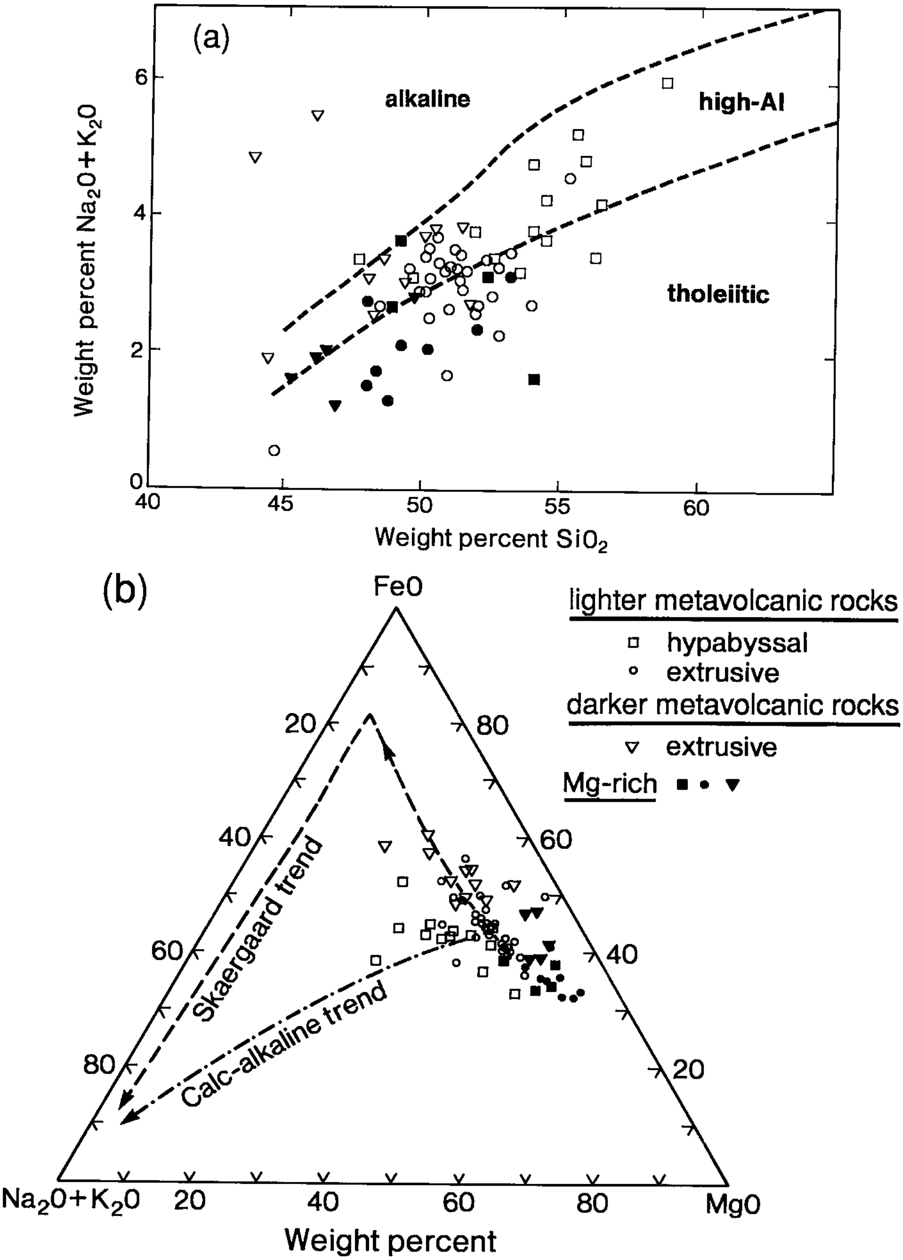


FIG. 4. Proportions in wt.% of major elements in Yellow Dog greenstones from the Sawyers Bar area: (a) conventional alkali *versus* silica variation diagram, with fields for fresh magma-types after Kuno (1966); (b) classical AFM diagram showing tholeiitic (Skaergaard) and andesitic island-arc (calc-alkaline) fractionation trends after Wager & Deer (1939) and Daly (1933), respectively. Sample symbols as in Fig. 2.

IGNEOUS GEOCHEMISTRY AND INFERRED PLATE TECTONIC SETTING OF THE YELLOW DOG GREENSTONES

Many of the relatively massive, pale green metavolcanic rocks, especially the coarser-grained meta-hypabyssal units, retain relict igneous phases

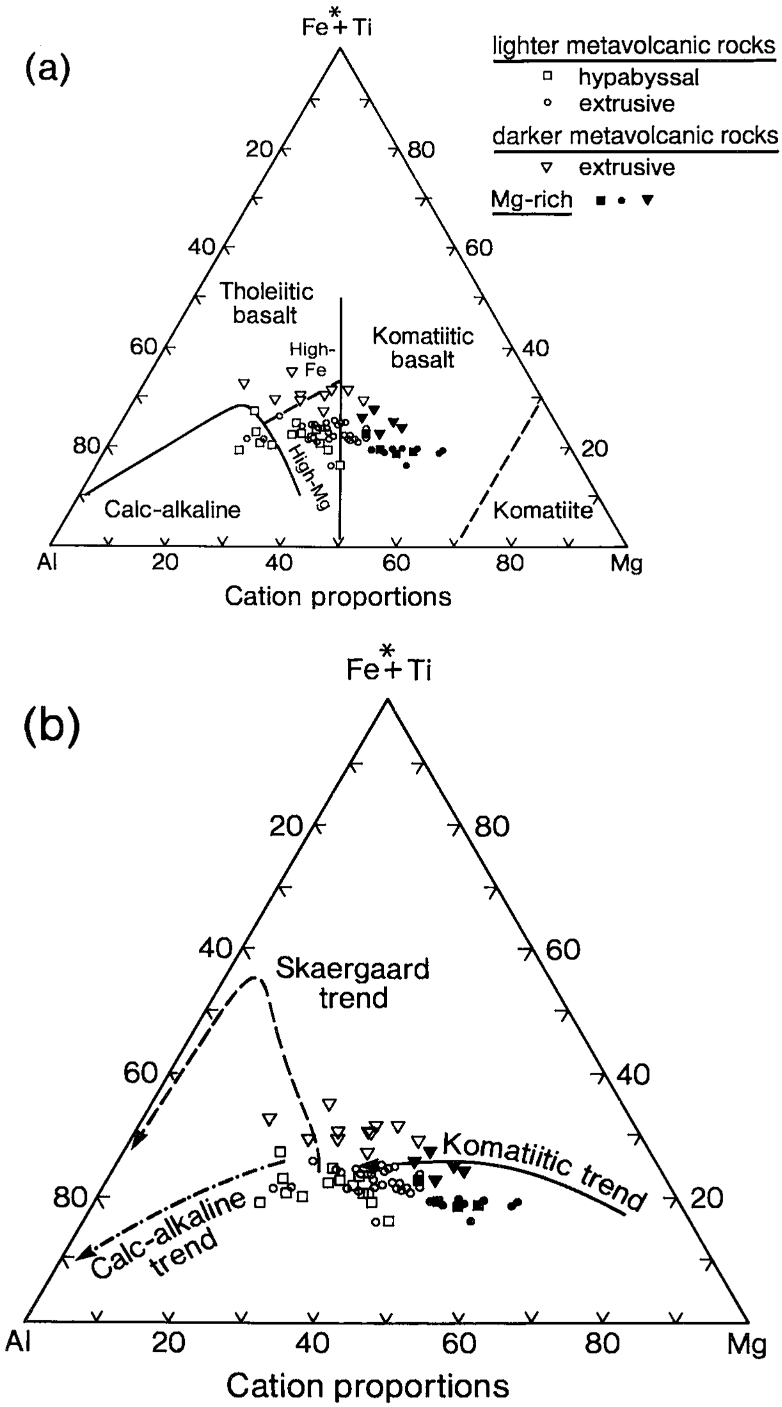
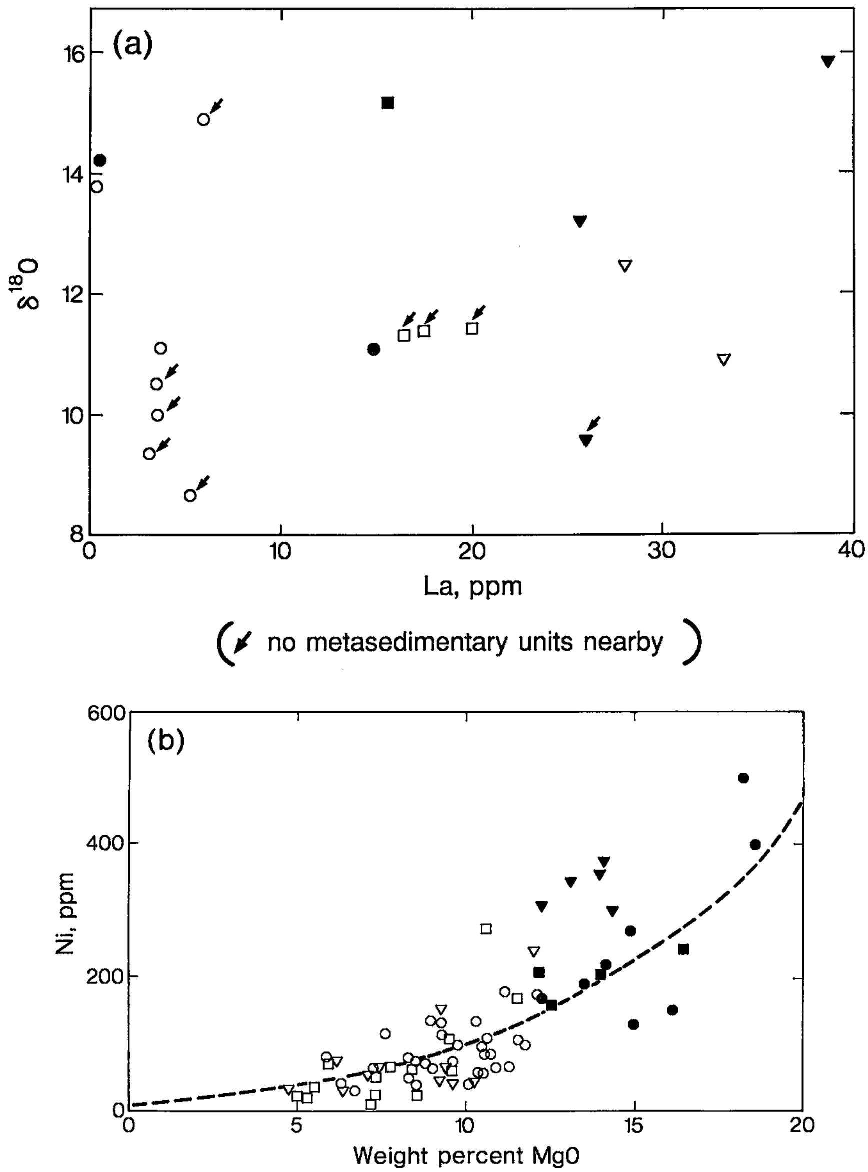


FIG. 5. Mg – (Fe* + Ti) – Al cation proportions for Yellow Dog metavolcanic units from the Sawyers Bar area. Sample symbols as in Fig. 2. Boundaries for magma types are from Jensen (1976). Analyzed rocks appear to represent a compositional continuum according to ratios of these constituents, but the stratigraphically lower, dark-colored unit is distinctly richer in Ti and Fe* than the overlying, paler greenstones. Both magmatic series contain samples that would be classified as komatiitic basalts according to these constituent ratios.



(Ernst *et al.* 1991). Included among these are oscillatorily zoned, prismatic hornblende, normally zoned calcic to intermediate plagioclase (An_{29-50}), augite, and magnesian chromite [$Mg_{0.6}Fe^{2+}_{0.4}(Cr_{1.3}Fe^{3+}_{0.2}Al_{0.5})O_4$]. Clinopyroxene ranges in composition from a $Wo_{43}En_{48}Fs_{09}$ core to a $Wo_{37}En_{34}Fs_{29}$ rim; TiO_2 contents approach 1.6 wt.%. Igneous hornblende consists of a magnesiohornblende – ferropargasite – hastingsite solid-solution; TiO_2 contents range up to 6.3 wt.%. Ernst *et al.* concluded that these relict phases are products of an arc-tholeiite or calc-alkaline magma.

The average oxygen isotope ratio of 24 mafic bulk rocks is $+11.0 \pm 1.8$; indicating that the Yellow Dog greenstones underwent variable metasomatic exchange with aqueous fluids during polymetamorphism. Chemical alteration during seafloor recrystallization also may have been responsible for the observed enrichment in CaO/Al_2O_3 and MgO noted in some of the metavolcanic rocks (Hacker *et al.* 1992). Nonetheless, certain immobile major and trace elements reflect protolithic characteristics of the eruptive rocks, and document igneous trends. Bulk-rock averages are presented in Table 1. Of 72 analyses, 16 represent the dark green, amygdaloidal

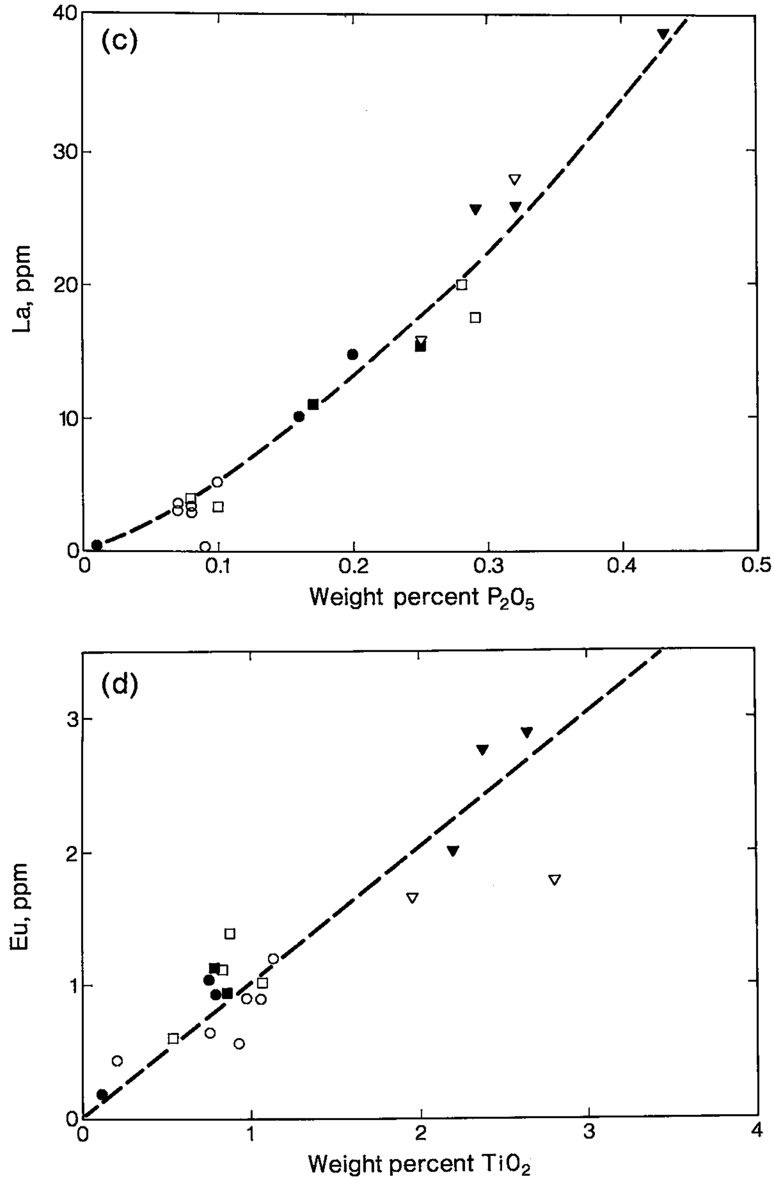


FIG. 6. Proportions of various major element and trace constituents for the Yellow Dog metavolcanic rocks from the Sawyers Bar area. Sample symbols as in Fig. 2. The lack of correlation between $\delta^{18}O$ and La exhibited in (a) indicates that metasomatism *per se* did not result in variance of *LREE* concentration with oxygen exchange; arrows denote analyzed greenstone samples at least 250 meters horizontally removed from the nearest metasedimentary unit. Covariances between major and trace elements, visually estimated and illustrated in (b)–(d), are typical of a process of igneous fractionation.

metabasalts, with the paler meta-igneous rocks chiefly flows (38) rather than dikes and sills (18). Among the total of 72 analyzed rocks, 17 are unusually Mg-rich, and are therefore distinguished in both the table and illustrations.

Chemical distinction between the stratigraphically lower, dark green metavolcanic rocks and the overlying, paler, more massive units is portrayed in Figure 3. Specimen 506M is correlated with the former group, but crops out within the lighter-colored, overlying greenstones, and is only modestly enriched in TiO_2 (1.3 wt.%). All other darker-colored metaflow breccias contain TiO_2 closely approaching or exceeding 2.0 wt.%, whereas all light green metabasalts contain less than 1.2 wt.% TiO_2.

An alkali *versus* silica diagram (Fig. 4a) exhibits the mildly alkaline nature of some of the darker green metalavas. Iron enrichment of these metabasaltic flow breccias is apparent from an AFM diagram (Fig. 4b); more evolved island-arc trends are evident for the meta-hypabyssal units. The less- and more-magnesian units appear to represent parts of a continuum rather than either separate suites of magma, or cumulate *versus* liquid compositions (see also Fig. 3). Of course, such elements may be mobilized during recrystallization, so that their concentrations are equivocal indicators of protolithic compositions.

Metasomatism may profoundly alter the chemical proportions of the more soluble constituents. The least mobile components provide a more reliable indication of original compositions, however. For metabasaltic rocks, proportions of the major elements Mg, (Fe + Ti), and Al allow the assignment of analyzed modern volcanic rocks to compositionally distinct fields for calc-alkaline, tholeiitic and komatiitic magma-types. With respect to these cations (Fig. 5), the light-colored, more massive Yellow Dog meta-extrusive units appear to be magnesian calc-alkaline basalts, whereas the dark green, more schistose, amygdaloidal metaflow breccias seemingly are high-Fe tholeiites and relatively magnesian iron-rich basalts. Although some are apparently highly magnesian, most of the meta-hypabyssal units exhibit chemical tendencies transitional toward calc-alkaline or island-arc tholeiites. The meta-igneous rocks of Sawyers Bar thus appear to represent two distinct magmatic suites, one rich in Fe + Ti, the other iron- and titanium-poor (see also Fig. 3). The relatively high proportions and broad areal dispersal of magnesian metabasalt samples (17 of 72 analyzed specimens) and the nearly continuous bulk-rock compositional spectrum support the contention that these supracrustal rocks are products of a widely operating and systematic process.

In terms of bulk-rock *REE* data, 28 Yellow Dog greenstones (Ernst *et al.* 1991) resemble those of modern intraplate oceanic basalt (*LREE*-enriched) and island-arc tholeiite (flat) patterns.

Additional compositional features of the Yellow Dog metavolcanic rocks, as well as systematic trends of chemical differentiation in terms of minor and trace elements, are portrayed in Figure 6. The absence of a correlation between La and $\delta^{18}O$, and between La concentration and proximity to *LREE*-rich metasedimentary strata, suggest that enrichment of the greenstones in ^{18}O, alkalis, and silica during metamorphism accompanying aqueous fluid flow did not systematically involve the *REE* (Fig. 6a). The correlation of Ni with MgO and the substantial increment in nickel with elevated MgO contents indicate that early-formed crystals concentrated Ni with respect to Mg (Fig. 6b), a characteristic phenomenon of magmatic fractionation. La and Eu contents vary systematically with P_2O_5 and TiO_2, respectively (Figs. 6c,d), also signalling igneous differentiation. Accordingly, *REE* patterns probably are related to the precursor igneous rock-types. Marked bimodality in the chemographic trends is not obvious, although compositions of the darker meta-extrusive units form a distinct, high-Ti field. Strong positive correlations likewise exist between the pairs Fe_2O_3–TiO_2, P_2O_5–TiO_2, and Zr–P_2O_5, between the pairs *LREE* – Sr, – Zn, – Zr, – TiO_2, and – P_2O_5, and between the pair Cr – MgO (similar to Fig. 6b); these correlations suggest the preferential early incorporation of Cr in a liquidus phase, presumably spinel, relative to Mg. Such regular behavior in general is characteristic of igneous differentiation and varying degrees of partial fusion.

Systematic bulk-rock variations of P, Hf and Ce concentrations with respect to Zr are presented in Figure 7. The elevated concentrations of Zr in the dark green amygdaloidal flow breccias are characteristic of alkaline intraplate lavas, whereas low Zr abundances in the pale-colored, overlying, more massive flows and hypabyssal rocks are typical of immature-arc lavas. Typical concentrations of P, Hf, Ce and Zr in basaltic rocks world-wide are shaded.

The systematic compositional relationships described above for mafic metavolcanic rocks of the Sawyers Bar area lead to the following conclusions: (1) Fractionated, dark green (Fe + P + Ti)-rich, and nonevolved, pale gray-green (Fe + P + Ti)-poor members of two distinct, somewhat intergradational suites are present. (2) The overlying, low-Ti basalts and diabases exhibit features of an immature arc-basalt, whereas the stratigraphically lower, high-Ti amygdaloidal flow breccias are mildly alkaline and exclusively intraplate, oceanic basalt in character. Somewhat similar alkaline basalts and magnesian andesites rich in Ti (and Nb + Ta) are rare in arc environments, but have been described by Saunders *et al.* (1987) and by Reagan & Gill (1989). However, such lavas do not appear to be as evolved as those studied here. (3) Seafloor alteration may account in part for the enrichment in CaO/Al_2O_3, and in the Mg-rich compositions of some of the Yellow Dog greenstones, as suggested

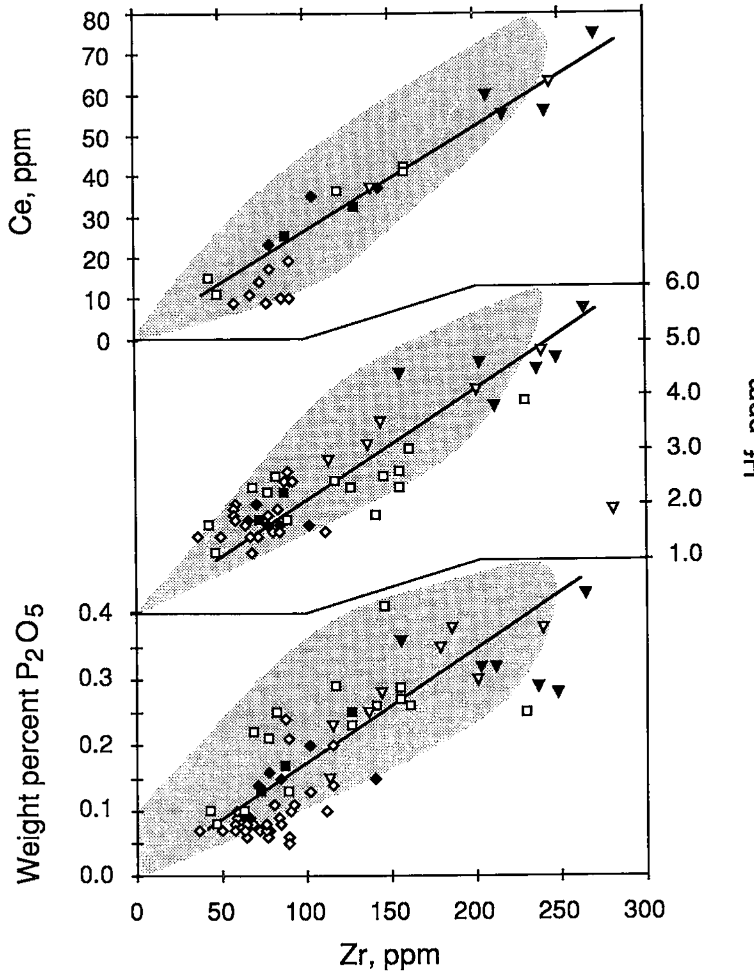
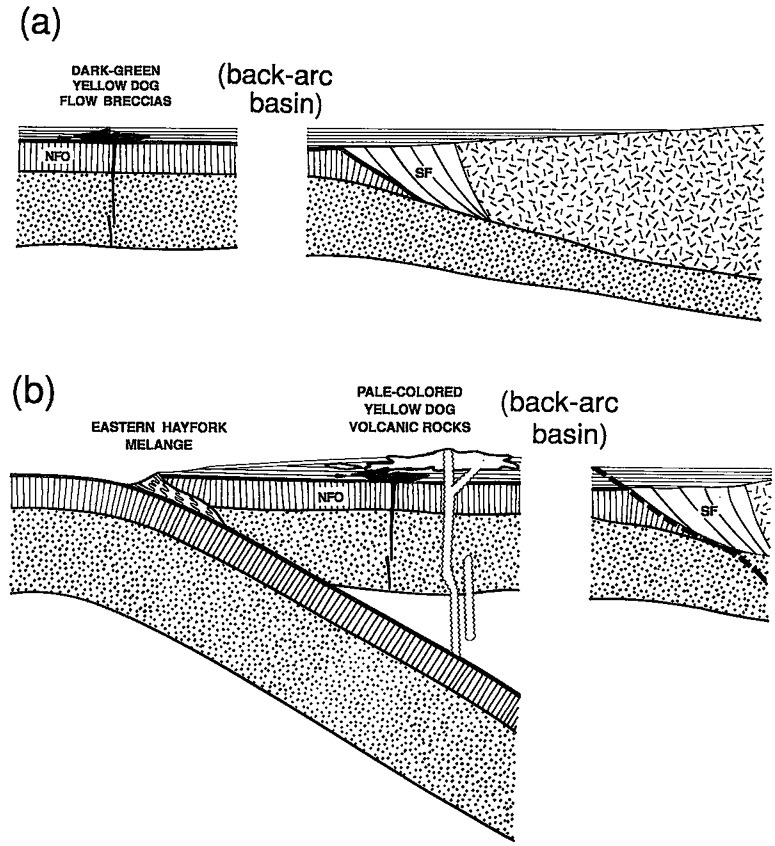


FIG. 7. Bulk-rock variations of Yellow Dog greenstones for minor and trace elements as a function of Zr contents, a measure of magmatic differentiation. Sample symbols as in Fig. 2, except that circles in Fig. 2 are shown as diamonds in this illustration. Typical concentrations of P, Hf, Ce and Zr in world-wide mafic volcanic rocks are shown by the stippled pattern (Hacker *et al.* 1992). The observed chemical trends for the Sawyers Bar metabasaltic rocks are compatible with crystal-melt fractionation.

by Ernst *et al.* (1991) and Hacker *et al.* 1992. Nevertheless, systematic igneous trends indicate that primary crystal-melt fractionation also was partially responsible for the range of observed bulk-rock compositions.

INFERRED PLATE TECTONIC HISTORY OF THE EASTERN WTrPz

Although few analytical data exist, geochemical analogues of the Yellow Dog greenstones have been reported from the North Fork ophiolite directly to the south (Ando *et al.* 1983), and from the Marble Mountain terrane to the northeast (Donato 1987, 1989). Immature, arc-tholeiitic volcanic units, associated terrigenous sedimentary rocks and less voluminous mildly alkaline, within-plate Ti-rich oceanic basalts therefore typify the east-central portion of the WTrPz belt. Highly magnesian greenstones also seem to characterize this region. A tectonic model based on geochemical discrimination of the metabasaltic units, and compatible with the inferred structural-stratigraphic relationships documented in the Sawyers Bar area, is illustrated



in Figure 8. The geological history may be conjectured as follows.

(a) The dark green metavolcanic rocks formed first, during Early Mesozoic (and perhaps Permian) deposition of the terrigenous section on the continental rise in an oceanic within-plate setting. For the contemporaneous deposition of intraplate basalts and fine-grained clastic strata, a deposition site within ~ 1000 km of the North American or island-arc margin seems likely. Presumably, a mid-plate fracture zone extended through the lithosphere, and tapped a deep-seated, slightly alkaline melt within the upper asthenosphere. The separation of seaward, intraplate mafic lavas and landward, Stuart Fork subduction complex by an intervening back-arc basin would be plausible but not essential.

(b) The slightly later extrusion and intrusion of paler, more massive eruptive rocks took place as an outboard oceanic-crust-capped lithospheric plate apparently descended beneath the slab, carrying the mildly alkaline flows and interstratified distal turbidites, at the site of the evolving Sawyers Bar immature island arc. Either the westward initiation of an east-dipping subduction zone occurred (at the site of the eastern Hayfork *mélange*?) trapping the within-plate, (Fe + Ti + P)-rich basalts and clastic strata in a forearc setting, or polarity reversal of a westward downgoing lithospheric slab took place during early Mesozoic time. The first possibility seems simpler, because it helps to account for inboard location of the Triassic Fort Jones high-P metamorphic belt of Coleman *et al.* (1988), but few constraints on these speculations are available. Postulated eastward underflow of the paleo-Pacific lithosphere resulted in accumulation of the overlying, lighter green arc-tholeiites which, as pillowed and massive basalts and diabases, constitute the major part of the section.

(c) Early to Middle Jurassic collapse of a hypothesized inboard marginal basin bordering the immature arc on the east, or intraplate imbrication, resulted in collisional encounter of the evolving, more westerly Sawyers Bar (+ eastern Hayfork) terrane with the previously accreted Triassic Stuart Fork blueschist terrane. The scenario involving destruction of a conjectured back-arc basin separating the Sawyers Bar and Stuart Fork terranes is favored, because it allows for the accumulation of

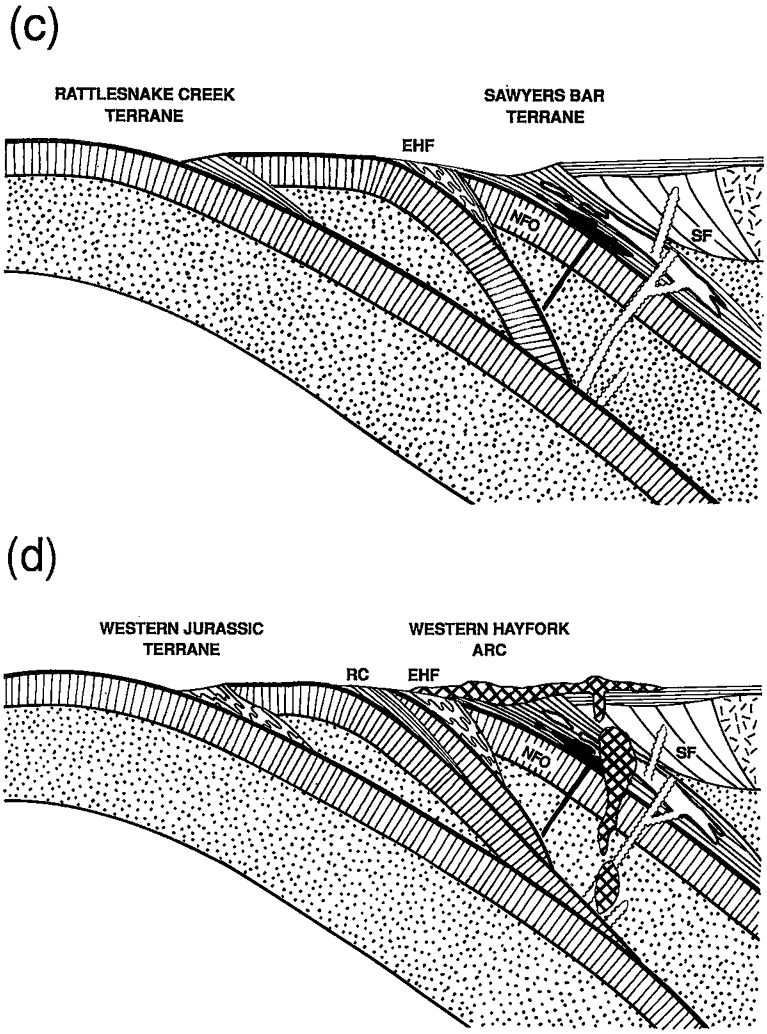


FIG. 8. Plate-tectonic scenario for lithologic and structural relationships in the east-central WTrPz belt of the Klamath Mountains. Stipples: mantle lithosphere, vertical lined pattern: oceanic crust, random dashes: North American continental margin or nearby island arc, NFO: North Fork ophiolite, SF: Stuart Fork terrane, EHF: eastern Hayfork *mélange*, RC: Rattlesnake Creek terrane. Schematic individual stages, inferred from limited paleontological and radiometric data, are as follows: (a) Triassic (immediately post-Fort Jones high-P metamorphic event), (b) Early Jurassic, (c) Early to Middle Jurassic (Siskiyou low-P metamorphic event), with Sawyers Bar terrane associated with oceanic basement (North Fork ophiolite) and structurally lower eastern Hayfork terrane (not shown separately), and (d) Middle Jurassic (western Hayfork arc construction and associated contact metamorphism). The hypothetical back-arc basin diagrammatically indicated in (a) and (b) probably would have been several hundred kilometers wide. It is presumed to have been consumed by eastward underflow utilizing faults near the Triassic Stuart Fork subduction – accretion zone; the location of the closure zone prior to onset of underflow is shown as a dashed line in stage (b). Continued deformation, uplift, and erosion since stage (d) have now stripped off the cover series of Middle Jurassic western Hayfork volcanic units and older sedimentary strata, exhuming the Stuart Fork complex on the east and the Sawyers Bar terrane on the west, as well as the felsic plutons that were emplaced in this suture zone.

an immature, outboard basaltic arc overlapping and outlasting the time interval in which the inboard subduction-related complex was subjected to high-pressure metamorphism, with the more westerly volcanic arc subsequently being sutured beneath the more easterly blueschist complex. The occurrence of Yellow Dog metadiabase dikes transecting the Stuart Fork complex indicates that mafic arc volcanism attended (and probably was terminated by) accretion of the Sawyers Bar terrane to the North American continental margin or offshore island arc. Regional dynamothermal metamorphism (the Siskiyou event of Coleman *et al.* 1988) accompanied the suturing of the terrane.

(d) This accretionary process was succeeded by continued outboard, east-directed subduction and initiation of the western Hayfork calc-alkaline arc, and the emplacement of felsic magmas in Middle Jurassic time. Finally, uplift and erosion exposed the bedrock now cropping out in the Sawyers Bar area. Judging by the fact that regional metamorphic grade reaches an upper-greenschist-facies culmination in and north of the northern part of the mapped area, and declines both to the south and the northeast, the Sawyers Bar (and Marble Mountains) segment of the terrane would appear to have been uplifted to a greater extent than the along-strike portions.

The tectonic setting may be likened to a small-scale mirror image of the modern-day Philippine Sea plate: northwestward underflow of this plate beneath the Asiatic margin (the North American margin analogue) would juxtapose the outboard, within-plate Marianas oceanic crust-rise section and overlying immature, island arc (the Sawyers Bar terrane analogue) against the pre-existing Ryukyu – Sanbagawa subduction complex (the Stuart Fork terrane analogue). Continued underflow of the outboard system would have produced post-collisional felsic melts, which would have risen into the inboard assembly of amalgamated terranes. Accretionary growth of the continental margin would undoubtedly have involved a strike-slip component among the several lithotectonic packages, as well as an important component of convergence.

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