in "Tectonostratigraphic Terranes of the Circum-Pacific Region", D.G. Howell (ed) A.A.P.G. Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series No 1. 1985.

To Greg Davis,
Best wishes,
Nick

DAVID BLOOM

Structural and Metamorphic Aspects of Middle Jurassic Terrane Juxtaposition, Northeastern Klamath Mountains, California

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An approximately 18 km (11 mi) thick structural section of rocks assigned to the "western Paleozoic and Triassic belt" (TrPz belt) of Irwin (1966) is exposed in the northeastern Klamath Mountains of California. The division of these rocks into five terranes and identification of multiple episodes of deformation and metamorphism provide new information on the postdepositional history of the TrPz belt. Late Triassic deformation and blueschist facies metamorphism of the Fort Jones terrane is well established (Hotz et al, 1977; Borns, 1980). In this paper, evidence for a Middle Jurassic subgreenschist to amphibolite facies, low-pressure, progressive metamorphism affecting the North Fork, Salmon River, Hayfork, and Marble Mountains terranes is presented. A late Middle Jurassic igneous intrusion, the Vesa Bluffs pluton, cuts and contact metamorphoses all five TrPz belt terranes. Two major preintrusion deformations are recognized in the North Fork, Salmon River, Hayfork, and Marble Mountains terranes. The first was major faulting related to juxtaposition of the terranes along low-angle faults; the second (possibly continuous with the first) was a flattening deformation synchronous with the Middle Jurassic regional metamorphism. Postintrusion deformations were Late Jurassic open folding (the Nevadan orogeny) and regional doming and tilting of Neogene age. The Jurassic structural and metamorphic history of the terranes is consistent with assembly of the TrPz belt in a single, evolving Middle and Late Jurassic arc/subduction system. Gravity modeling indicates that low-angle Jurassic structures are essentially preserved intact in this part of the Klamaths.

INTRODUCTION

The Paleozoic and Mesozoic rocks of the Klamath Mountains province are exposed in the western United States between the Pacific Ocean and the Cascade volcanic arc (Fig. 1). Irwin (1966) divided the province into four major lithotectonic units called belts, bounded by east-dipping thrusts, and later subdivided the "western Paleozoic and Triassic belt" (TrPz belt) into smaller lithotectonic units he called terranes (Irwin, 1972). A recent summary of the geology of the Klamath Mountains is given by Irwin (1981).

This paper is concerned with the postdepositional history of the TrPz belt that occupies the central structural levels of the Klamath Mountains province (Fig. 2). In California, the TrPz belt has been divided into the Marble Mountains, Rattlesnake Creek, Hayfork, Salmon River, North Fork, and Fort Jones terranes by Blake et al, 1982. These terranes, like the larger lithotectonic units, are bounded by generally low-angle east-dipping faults and are interpreted by Davis (1968) and Irwin (1981) to constitute a series of stacked thrust plates (Fig. 2). To date, most of our knowledge regarding the geologic history of the TrPz belt has come from studies in the southern Klamath Mountains (e.g., Irwin, 1972; Davis et al, 1979; Wright, 1982; Ando et al, 1983). These and other studies have provided essential mapping and stratigraphic data but have tended not to emphasize aspects of structure and metamorphism. Ongoing and completed work in the northern California Klamaths (e.g., Hotz, 1967, 1977, 1979; Borns, 1980; Coleman et al, 1983; Kays and Ferns, 1980; Donato et al, 1982; Hill, 1984; Mortimer, 1984) is better able to address such aspects in part because of the higher grades of TrPz belt regional metamorphism to the north. This paper is the first published synthesis of structural and metamorphic data from a transect across the TrPz belt.

The issue of where the TrPz belt terranes originated (Davis et al, 1978; Wright, 1982) is addressed elsewhere (Mortimer, 1984); interpretations presented in this paper offer specific new constraints on the nature, timing, and location of TrPz belt deformation and metamorphism. Of more general interest, the data show how structural and metamorphic criteria can be used to constrain suturing and postsuturing events more precisely than intrusive and overlap relations. The timescale of Harland et al (1982) is used throughout this paper, and the old K–Ar ages of Lanphere et al (1968) have been recalculated using new decay constants to conform with this.

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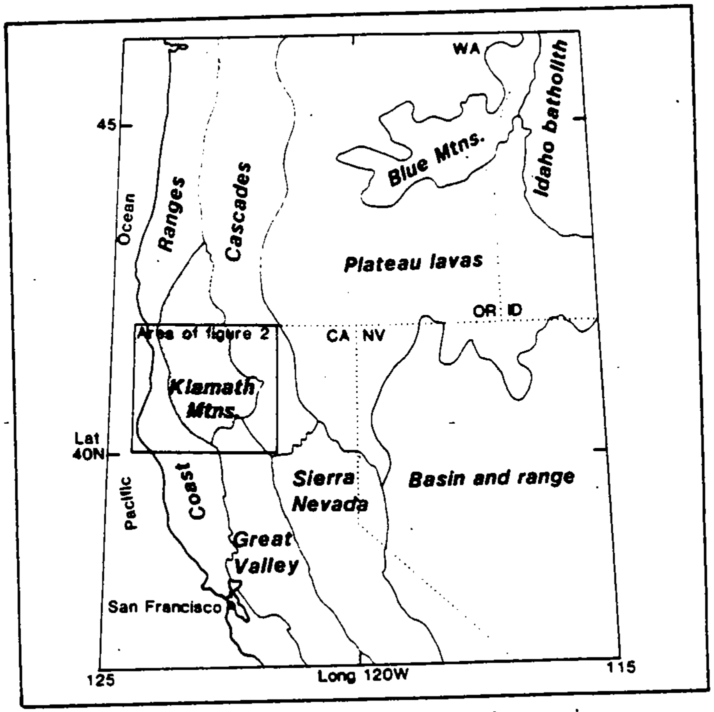

Figure 1—Location of the Klamath Mountains province.

GENERAL GEOLOGY

In the light of mapping in the northeastern Klamath Mountains from 1981-1983, a case can be made for division of the formerly undivided TrPz belt into five terranes that correlate with similarly juxtaposed terranes in the southern and central Klamath Mountains. The justification for this, along with relevant paleontologic, petrologic, and geochemical data, can be found in Mortimer (1984). Brief descriptions of the TrPz belt terranes as defined by Blake et al (1982) are given below.

The Fort Jones terrane was originally defined as the Stuart Fork Formation in the southern Klamath Mountains (Davis et al, 1965). In the northern Klamath Mountains, it consists of tectonically disrupted chert, argillite, marble, volcanic rocks, and gabbro (Hotz, 1967, 1977, 1979; Borns, 1980) that were metamorphosed to blueschist facies in Late Triassic time (Hotz et al, 1977; Borns, 1980). The North Fork terrane consists of tectonically imbricated Permian to Early Jurassic chert and argillite and Permian alkalic volcanic rocks and limestone (Irwin, 1972; Ando et al, 1983; Mortimer, 1984).

The Salmon River terrane is composed of tectonically disrupted ?Permo-Carboniferous tholeiitic volcanic rocks, diabase, gabbro, and harzburgite (Ando et al, 1983). The Salmon River terrane is considered by Irwin (1972) and Ando et al (1983) to be the basement portion of the North Fork terrane. The Hayfork terrane is a composite terrane (Wright, 1982) consisting of an eastern portion of Permian to Late Triassic or Early Jurassic chert, argillite, chert-argillite breccia, alkalic volcanic rocks, and late Paleozoic limestones (Irwin, 1981; Wright, 1982; Mortimer, 1984) and a western portion of Middle Jurassic volcanic and volcaniclastic rocks and their plutonic equivalents (Irwin, 1972; Fahan, 1982; Wright, 1982).

The Marble Mountains terrane consists of structurally disrupted peridotite, basic igneous rocks, siliceous sedimentary rocks, and marble that are metamorphosed to amphibolite facies (Rawson and Petersen, 1982; Donato et al, 1982; Hill, 1984). Rawson and Petersen (1982) suggest that the Marble Mountains terrane is correlative with the less metamorphosed Rattlesnake Creek terrane of the southern and central Klamath Mountains (Irwin, 1972; Wright, 1981) whose protolith ages are Late Triassic and Early Jurassic. The terranes structurally above (Central Metamorphic terrane) and below (Condrey Mountain terrane) the TrPz belt are not considered in this paper.

This structural and metamorphic synthesis draws directly on the data and interpretations of Hotz (1967, 1979) for the Marble Mountains terrane and Borns (1980) for the Fort Jones terrane. The author has collected samples from but not mapped these terranes. Interpretation of TrPz belt deformation is more straightforward when considered in a metamorphic framework. For this reason, metamorphism is dealt with separately and before deformation in the following sections.

METAMORPHISM

Prior to the subdivision of the TrPz belt in the northeastern Klamath Mountains, Hotz (1967, 1979) and Kays and Ferns (1980) proposed an east-to-west increase in metamorphic grade from greenschist to amphibolite facies in rocks that are now recognized as the Salmon River, Hayfork, and Marble Mountains terranes (Fig. 3). Hotz (1979) realized that the Triassic blueschist facies rocks of the Fort Jones terrane had undergone a different deformational and metamorphic history from the other (structurally underlying) Jurassic metamorphic TrPz belt rocks. This current study confirms and expands on Hotz's interpretation of two separate metamorphic events that are discussed separately below. The Triassic event has been investigated in detail by Borns (1980), thus in this paper more attention is devoted to the Jurassic metamorphism.

High-Pressure Late Triassic Event

The diagnostic blueschist facies minerals lawsonite and jadeite were first recognized in rocks of the Fort Jones terrane (Stuart Fork Formation) by Hotz (1973) although glaucophane schists were previously noted by Masson (1949). The age of metamorphism was established by Hotz et al (1977) who reported Late Triassic (214 to 222 m.y.) K-Ar and Ar-Ar (white mica) ages from three lawsonite-bearing schists near Yreka.

The blueschists are not isolated blocks in melange, but blueschist-facies metamorphism is coherent and regional in nature (Borns, 1980). Borns (1980) estimated P-T conditions during metamorphism to be 300 to 400°C and 9 to 11 kbar. The structurally underlying TrPz belt terranes do not contain blueschist-facies minerals and have not experienced this high-pressure Late Triassic metamorphism. The fault zone separating the Fort Jones terrane from the North Fork terrane is therefore a major structural and metamorphic break.

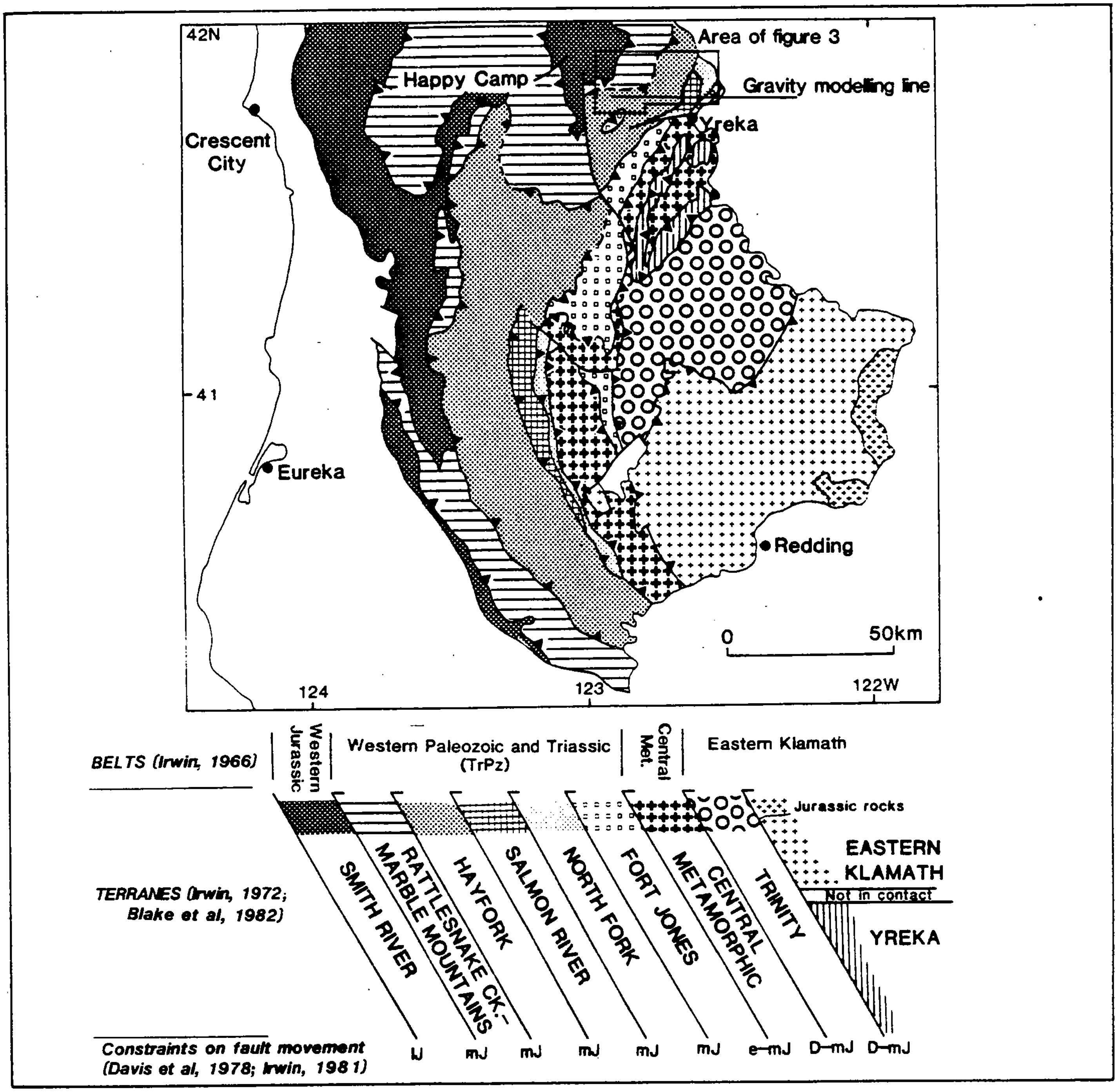

Figure 2—Major lithotectonic subdivisions of the California Klamath Mountains. Terrane boundaries in the northeast part of the province are slightly modified from Blake et al (1982). Plutons are omitted for clarity.

Low-Pressure Middle Jurassic Event

The North Fork, Salmon River, Hayfork, and Marble Mountains terranes consist of five lithologies: tholeiitic metabasites, alkalic metabasites, siliceous metasediments, calcareous metasediments, and metaperidotites. Metacarbonates in the area of Figure 3 are almost always pure calcite marbles and do not show any mineralogical variation with metamorphic grade. Metaperidotite assemblages were not used as indicators of metamorphic grade in this study because of the difficulty in distinguishing relict from metamorphic olivine and prograde from retrograde antigorite. Alkalic metabasites, which can be distinguished from the tholeiites on the basis of major element chemistry (Mortimer, 1984), are generally calcite bearing and contain the assemblage albite + chlorite + calcite + sphene ± epidote. This assemblage is stable over a wide range of P-T conditions and is indicative of high P(CO_2) during metamorphism (Miyashiro, 1973). Locally high P(CO_2) during metamorphism of these rocks is readily accounted for by abundant interbedded limestone and marble.

In contrast, tholeiitic metabasites (and a few alkalic

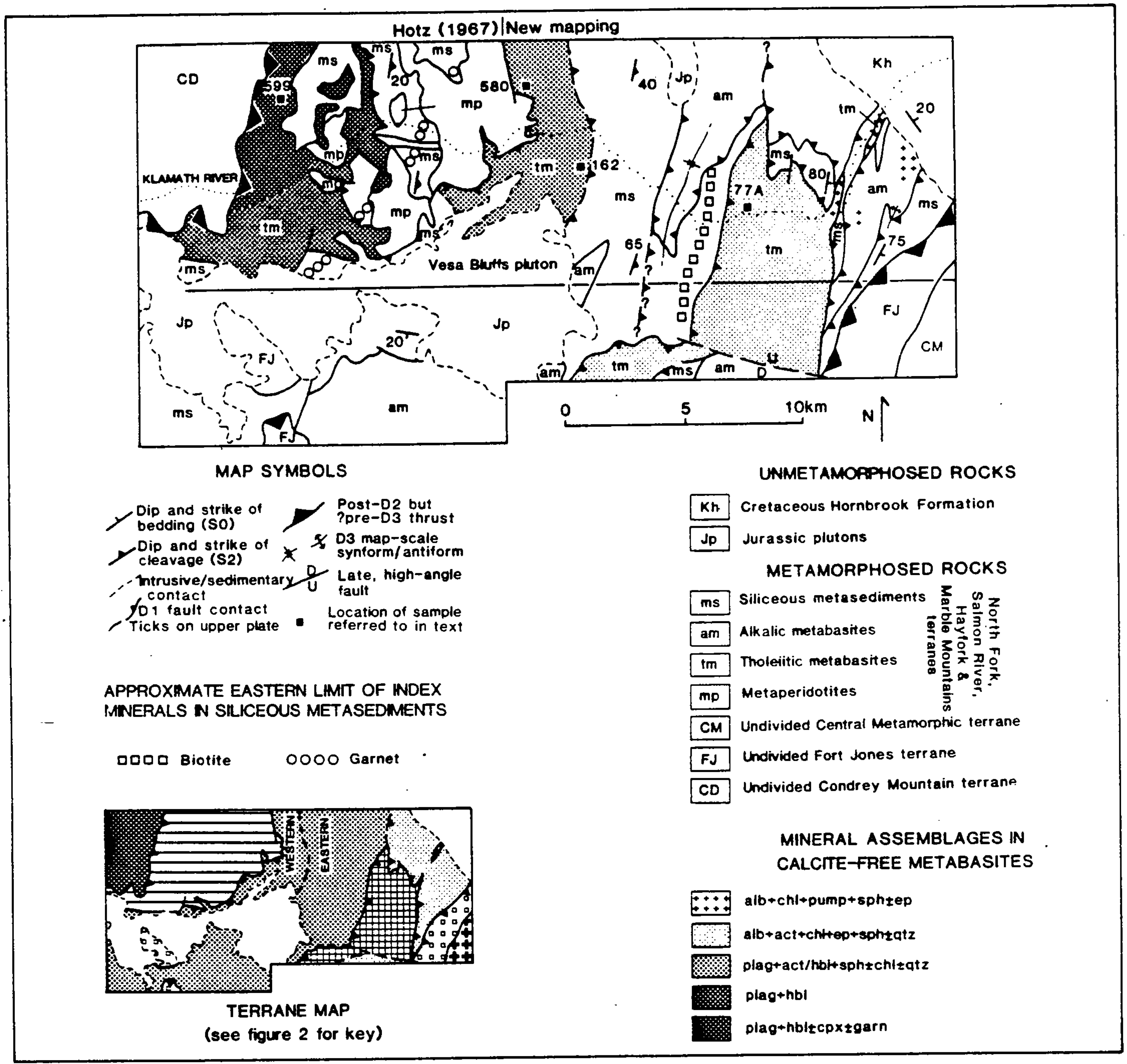

Figure 3—Simplified geologic map of the study area, emphasizing the distribution of metamorphic protoliths and progressive mineral change in calcite-free metabasites. Inset at lower left shows the major lithotectonic subdivisions of the area.

metabasites) are calcite-free and contain more diverse mineral assemblages than do the calcite-bearing metabasites (Fig. 4). Metasedimentary rocks also display progressive mineral changes across the study area. The following discussion of metamorphism is based on progressive mineral changes observed in calcite-free metabasites and siliceous metasediments (summarized in Figs. 3, 4).

The North Fork terrane is the least metamorphosed of the TrPz belt terranes and contains relict, premetamorphic textures and minerals. Examples include well-preserved radiolaria and fusulinids in cherts and limestones and relict palagonite, calcic plagioclase, augite, and hornblende in volcanic rocks. Cleavage is developed only in argillaceous lithologies. Metamorphic assemblages in calcite-free metabasites (Fig. 4) indicate subgreenschist facies metamorphism, a lower grade than recognized by Hotz (1979) and Kays and Ferns (1980).

The Salmon River terrane consists entirely of tholeiitic basalt and diabase. Original textures are again well preserved (e.g., chilled pillow rims and ophitic textures). Relict igneous augite is preserved only in the eastern portion of the terrane; westward augite is replaced by actinolite. Very rarely, albite and actinolite define a weak,

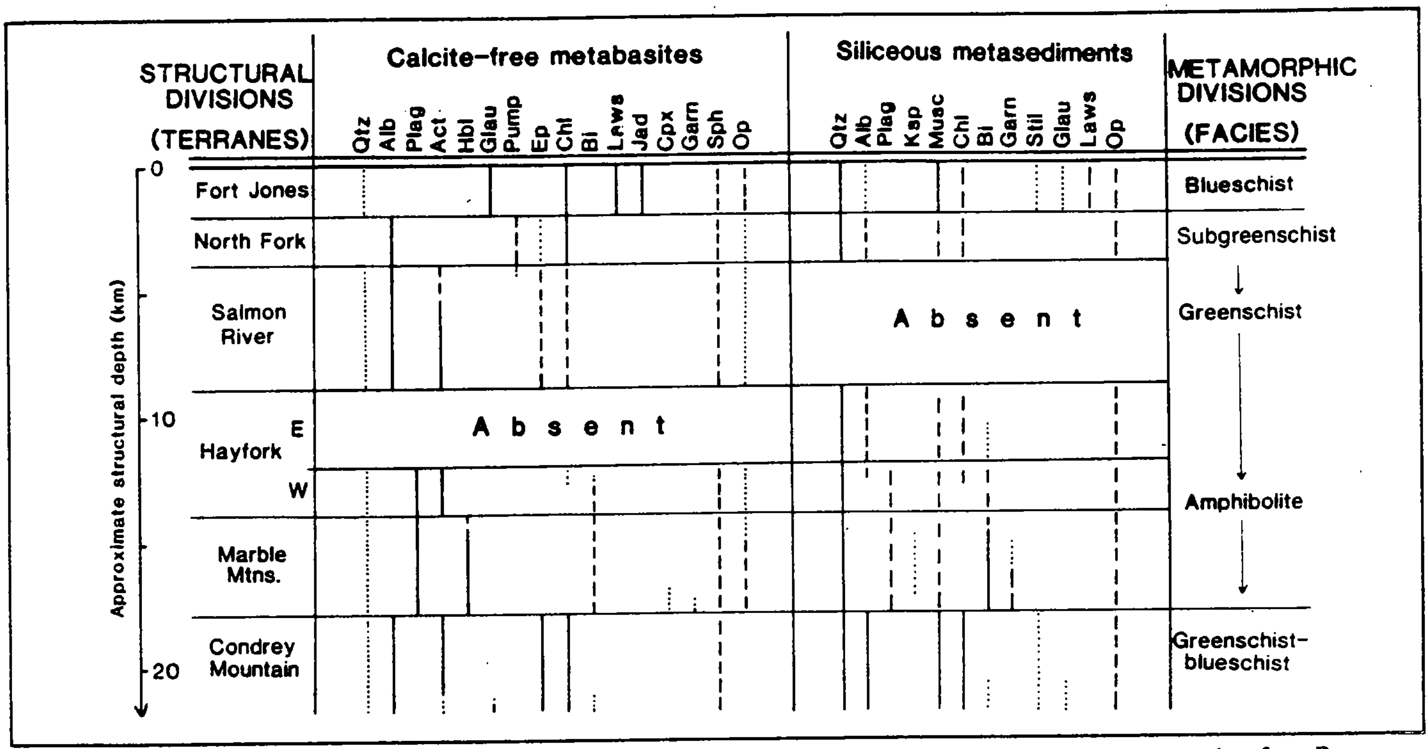

Figure 4—Variation of metamorphic mineral assemblages in the terranes of the area of Figure 3. Fort Jones terrane data from Borns (1980), Marble Mountains and Condrey Mountain terrane data from Hotz (1967). Abbreviations are as follows: Qtz = quartz, Alb = albite, Plag = plagioclase, Act = actinolite, Hbl = hornblende, Glau = glaucophane, Pump = pumpellyite, Ep = epidote, Chl = chlorite, Bi = biotite, Laws = lawsonite, Jad = jadeite, Cpx = non-jadeitic clinopyroxene, Garn = garnet, Sph = sphene, Op = opaques, Ksp = alkali feldspar, Musc = white mica, Stil = stilpnomelane.

planar fabric in zones a few centimeters wide, but for the most part the rocks are unfoliated. Mineral assemblages and the composition of metamorphic plagioclase and amphibole in the Salmon River terrane (Figs. 4, 5) indicate greenschist-facies metamorphism.

Traces of biotite first appear in metasediments of the eastern Hayfork terrane. In the western Hayfork terrane, static metamorphic textures overprint volcaniclastic bedding in calcite-free metabasites. In contrast to the Salmon River terrane metabasites, the metamorphic amphibole is actinolitic hornblende and the feldspar a calcic plagioclase (Fig. 5), indicative of transitional greenschist-amphibolite-facies conditions (Liou et al, 1974).

Hotz (1967) defined three metamorphic zones in rocks corresponding to the Marble Mountains terrane based on the pleochroic color of metamorphic hornblende in metabasites. Mineral assemblages and plagioclase and amphibole compositions in Marble Mountains terrane metabasites (Figs. 4, 5) indicate amphibolite facies metamorphism, a higher grade than Hayfork terrane metabasites. The occurrence of garnet and clinopyroxene in metabasites, and garnets in metasediments in the lowest structural levels of the Marble Mountains terrane mark the metamorphic culmination of TrPz belt rocks in the area of Figure 3. The TrPz belt is thrust (Hotz, 1979) over the structurally and metamorphically distinct Middle to Late Jurassic greenschist-blueschist-facies rocks of the Condrey Mountain terrane (Figs. 3, 4; Hotz, 1967, 1979; Helper, 1983).

Contact Metamorphism

The Vesa Bluffs pluton is one of a number of calc-alkaline plutons of latest Middle and earliest Late Jurassic age that intrude terranes of the Klamath Mountains (Hotz, 1971; Davis et al. 1978; Irwin, 1981; Wright and Sharp, 1982; Allen et al, 1982). The contact metamorphic aureole of the Vesa Bluffs pluton is generally no more than 200 m (650 ft) wide. Contact metamorphism is clearly later than regional metamorphism, a fact that is most apparent where the pluton has intruded greenschist- and blueschist-facies rocks. For example, within the contact aureole, eastern Hayfork terrane metasediments are upgraded to biotite hornfelses and greenschist-facies Salmon River terrane metabasites are upgraded to hornblende-plagioclase granofelses. In the Fort Jones terrane, glaucophane is replaced by intergrowths of albite and chlorite, and lawsonite is replaced by clinozoisite (Borns, 1980).

Discussion

With the exception of local retrograding, no evidence for more than one episode of regional metamorphism is seen in the rocks of the North Fork, Salmon River, Hayfork, and Marble Mountains terranes. Although outcrop of calcite-free metabasites and siliceous metasediments is discontinuous across the North Fork, Salmon River, Hayfork, and Marble Mountains terranes (Fig. 3), consideration of the metamorphic assemblages in each terrane (Fig. 4) suggests that metamorphic grade increases steadily westward (and down-structure) across these terranes. The fact that metamorphism overprints the

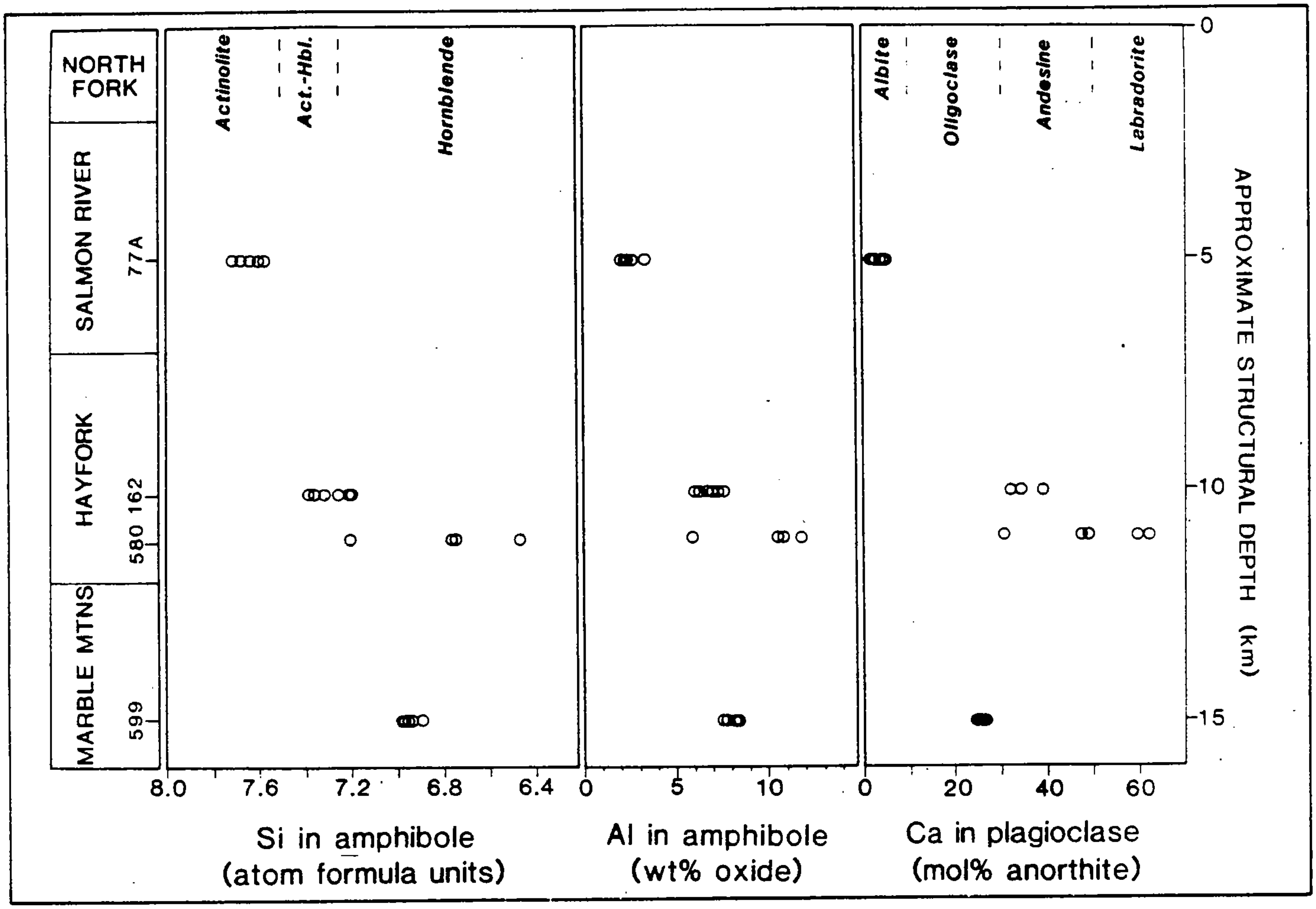

Figure 5—Variation in composition of metamorphic amphibole and feldspar in the Salmon River, Hayfork, and Marble Mountains terranes. See Mortimer (1984) for analyses.

terrane boundaries is significant because it requires that by the time of metamorphism, the four terranes had to have been juxtaposed. Additionally, the observed westward increase in grade rules out *major* tectonic disruption of the four terranes subsequent to regional metamorphism (cf. Hill, this volume).

A direct maximum age limit on this metamorphism is provided by fossils in the North Fork terrane; the youngest well-constrained radiolarian ages in the area of Figure 3 are Pliensbachian (194 to 200 m.y.; Jones, personal communication). If the 168 to 177 m.y. K-Ar ages on igneous hornblende from the western Hayfork terrane of the southern Klamath Mountains (Fahan, 1982) are applicable to correlative rocks in the study area, then metamorphism is confined to have taken place in a very short time; the minimum age limit of regional metamorphism is given by the 164 ± 5 m.y. K-Ar (hornblende) age from the Vesa Bluffs pluton in the area of Figure 3 (Lanphere et al, 1968), which intrudes the regionally metamorphosed rocks.

Evidence that this is a low-pressure metamorphic event include (1) the absence of mineral assemblages indicative of pumpellyite-actinolite facies (Coombs et al, 1976) or albite-epidote amphibolite facies (Liou et al, 1974; Apted and Liou, 1983); (2) presence (in the western Hayfork terrane) of the assemblage calcic plagioclase + actinolitic hornblende ± chlorite indicative of low-pressure greenschist-amphibolite transitions (i.e., below the intersection of the chlorite-out and epidote-out reactions in Fig. 6; Liou et al, 1974; Liou and Ernst, 1979); and (3) low Na(M4) contents of metamorphic amphibole in the buffering assemblage of Brown (1977) that are similar to Na contents of amphiboles from other low-pressure regimes (Fig. 7; Brown, 1977).

The P-T regime of this Middle Jurassic event can be crudely defined by a comparison with experimental phase equilibria studies on natural basaltic systems (Fig. 6). The low-temperature end of the P-T path defined in Figure 6 is constrained by the pumpellyite-bearing assemblages in the North Fork terrane and the upper end by the sporadic occurrence of clinopyroxene-bearing amphibolites in the Marble Mountains terrane.

In summary, two temporally and spatially separate regional metamorphic events can be recognized in the terranes of the TrPz belt in the northeastern Klamath Mountains. These are (1) Late Triassic, high-pressure, blueschist-facies metamorphism restricted to the Fort Jones terrane and (2) Middle Jurassic, low-pressure, subgreenschist to amphibolite-facies metamorphism superimposed on the North Fork, Salmon River, Hayfork, and Marble

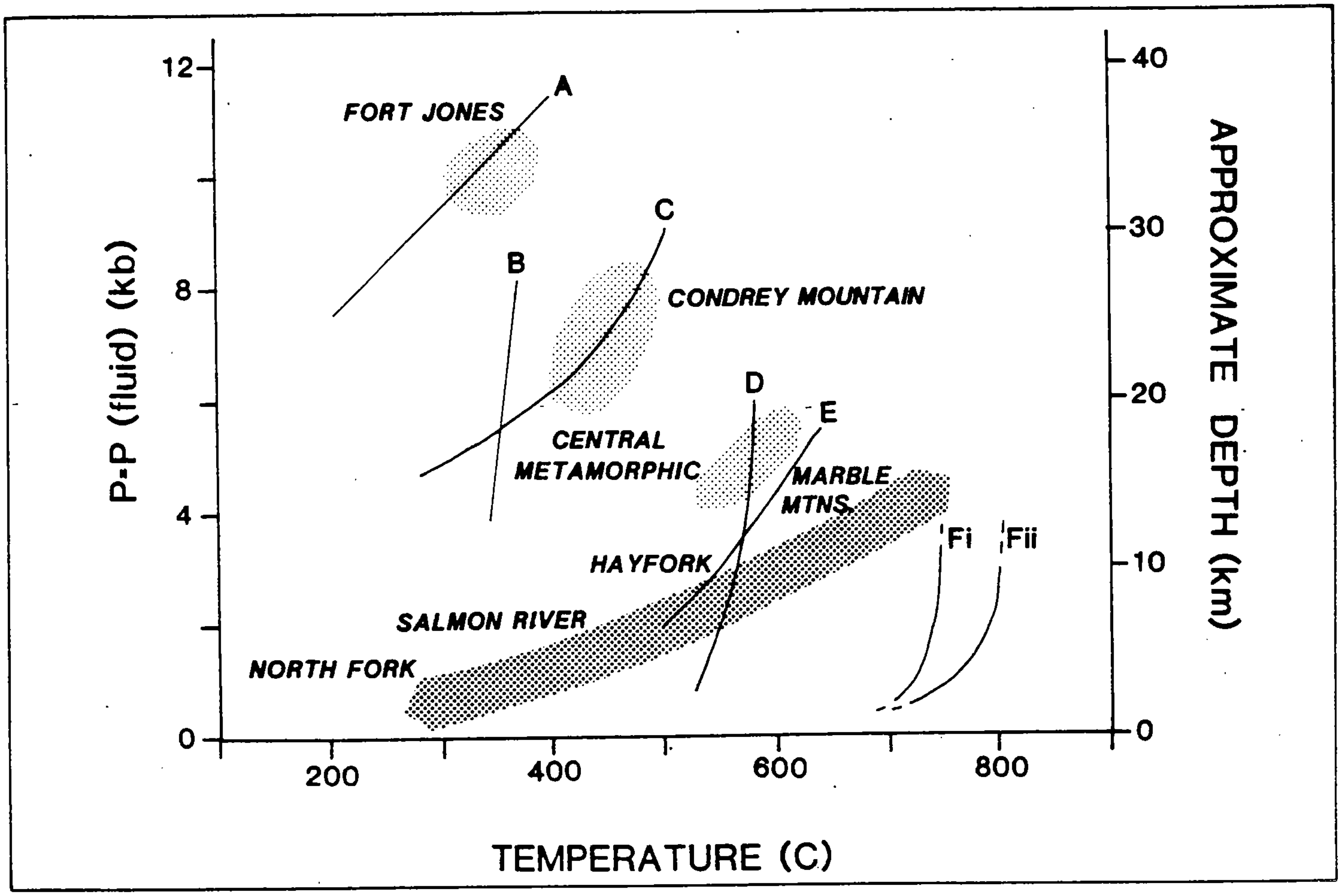

Figure 6—Approximate inferred P-T conditions for regional metamorphic events in the Klamath Mountains, constrained by experimentally determined metabasite phase equilibria. Data for Fort Jones terrane from Borns (1980). Lines A–F represent the following. A: impure jadeite in (Newton and Smith, 1967); B: pumpellyite out (Nitsch, 1971); C: glaucophane composition field (Ernst, 1979); D: chlorite out, QFM buffer (Liou et al, 1974; Apted and Liou, 1983); E: epidote out, QFM buffer (Liou et al, 1974; Apted and Liou, 1983); F: clinopyoxene in i) HM buffer, ii) QFM buffer (Spear, 1981). The Condrey Mountain terrane contains glaucophane but no lawsonite or jadeite (Hotz, 1967; Coleman et al, 1983); parts of the Central Metamorphic terrane contain albite-epidote amphibolite facies assemblages (Hotz, 1977; Cashman, 1980).

Mountains terranes. The Vesa Bluffs pluton intruded and contact metamorphosed all these terranes in latest Middle Jurassic time.

Metamorphism in the Southern TrPz Belt

Metamorphic relations in the TrPz belt 100 km (60 mi) to the south are somewhat different. There the Fort Jones terrane (Stuart Fork Formation) was, until recently, thought only to have been metamorphosed to the greenschist facies (Davis et al, 1965). Whole-rock K-Ar ages of 148, 158, and 245 m.y. were reported for the Fort Jones terrane by Lanphere et al (1968). Recently, rare relict lawsonite and glaucophane has been found in Fort Jones terrane rocks in the central Klamath Mountains (Jayko and Blake, 1984; Blake, personal communication, 1984) demonstrating an older high-pressure event in these rocks. The other TrPz belt terranes are metamorphosed to subgreenschist or greenschist facies, and local metamorphic gradients are spatially related to plutons (Fahan, 1982). Well-preserved radiolaria in the North Fork, Hayfork, and Rattlesnake Creek terranes (Irwin et al, 1978) demonstrate

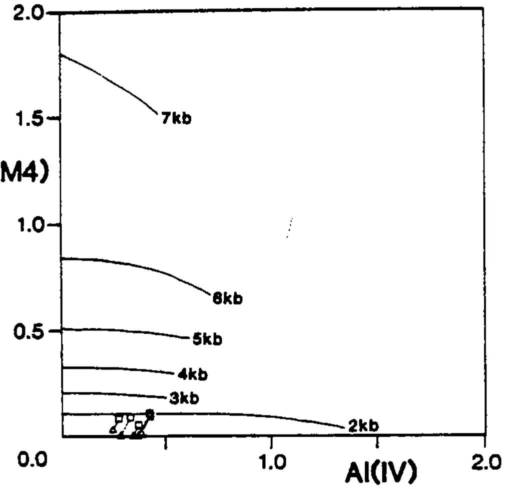

Figure 7—Amphibole compositional data from sample 77A plotted on the Al(IV) versus Na (M4) diagram of Brown (1977). Squares are analyses recalculated with full stoichiometric allocation of ferric iron; triangles are analyses recalculated with all ferrous iron (Papike et al, 1974).

that these metasediments were never metamorphosed to high grades.

The major differences in metamorphic grade between the northern and southern TrPz belt can be ascribed to two factors: (1) lateral thermal gradients during Middle Jurassic regional metamorphism such that higher grades were never regionally attained in the southern Hayfork and Rattlesnake Creek terranes, and (2) more extensive greenschist-facies recrystallization during Middle to Late Jurassic pluton intrusion in the southern TrPz belt than in the north. Jayko and Blake (1984) ascribe the obliteration of blueschist mineralogies in the Fort Jones terrane to a greenschist-facies overprint synchronous with pluton intrusion. Jurassic thermal events may also help explain the spread of whole-rock K-Ar ages in the southern part of the Fort Jones terrane.

STRUCTURE

An approximately 18 km (11 mi) section (structural thickness) of the TrPz belt is exposed in the area of Figure 3. Extreme lithologic heterogeneity, almost total absence of coherent stratigraphy, and general lack of facing directions and structural overprints in the rocks hinder identification and correlation of deformation events with any reasonable degree of certainty. Nonetheless, the case can be made that the North Fork, Salmon River, Hayfork, and Marble Mountains terranes have shared a common structural (as metamorphic) history since their mutual juxtaposition in Middle Jurassic time. Almost all deformation in the Fort Jones terrane is Triassic in age (Borns, 1980) and is not dealt with in this paper.

D1—Inter- and Intraterrane Faulting

At the surface, the faults bounding the terranes are steep to shallow east-dipping zones generally between 20 and 100 m (70–300 ft) wide, containing rock slices from contiguous terranes. Regionally they map out as low-angle, thrust-like faults (Irwin, 1966; Fig. 2 of this paper). The terranes are also internally faulted such that originally coherent stratigraphy is destroyed. This is especially obvious in the North Fork terrane where radiolarian cherts of different ages are mutually juxtaposed (Mortimer, 1984) and in the North Fork and Hayfork terranes where lenses of competent (volcanic) lithologies have become isolated in a matrix of argillaceous metasediments. Portions of the terranes are thus melanges (definition of Hsu, 1968). Argillaceous matrices are absent from the other terranes and most of the North Fork terrane but the style of faulting throughout the area is similar to melange deformation, with older rocks juxtaposed on younger and vice versa. The structural condition of most of the terranes is such that they are probably best described as "broken formations" (Hsu, 1968); the lithologic integrity of individual terranes being preserved despite extensive internal disruption.

Chaotic faulting is thus responsible for the inter- and intraterrane juxtaposition of North Fork, Salmon River, Hayfork, and Marble Mountains terrane lithologies prior to their shared regional metamorphism and is interpreted to be the earliest recognizable deformation in the area. Although specific cross-cutting relationships are observed (e.g., truncation of North Fork terrane faults at the Salmon River terrane boundary; Fig. 3), the general style of faulting between and within terranes is similar, and all this deformation is grouped under a single, nonpenetrative deformation event designated D1.

D2—Flattening and Isoclinal Folding

Throughout the area of Figure 3 a flattening foliation, axial planar to rare isoclinal folds, is variably developed. It is manifested as a penetrative slaty cleavage in argillites, a weak penetrative cleavage in marbles and siliceous argillites, pinch-and-swell structure in cherts, and micaceous cleavage in schists. Low-grade metabasites are not penetratively deformed but most amphibolite-facies metabasites are well foliated and lineated (Hotz, 1967, 1979). Correlation of the flattening fabrics is based on the fact that the flattening foliation is everywhere defined by prograde regional metamorphic minerals (Fig. 4) that probably formed during the same metamorphic event (see above). The flattening fabric in all four terranes can therefore be attributed to the same (synmetamorphic) deformation, designated D2 (with flattening fabric S2).

Isoclinal folding accompanied S2 formation, but the extent of folding is difficult to assess. Where seen together in outcrop, S0 (bedding) and S2 are almost always parallel (see also Fig. 8). S2 is parallel to the axial planes of rare 10 cm (4 in.) amplitude isoclinal folds in marble of the Hayfork and Marble Mountains terranes. In ribbon cherts of the North Fork and eastern Hayfork terranes, bedding and cleavage dip east with cleavage sometimes slightly steeper than bedding (Fig. 9a). Of the 15 facing directions found (using radiolarian age sequences, graded volcaniclastic beds and pillows), 4 were overturned (one each in the North Fork and Salmon River terranes and two in the Hayfork terrane; Mortimer, 1984) implying overturning though on an unknown scale.

Kays and Ferns (1980), working in the Marble Mountains terrane north of the area of Figure 3, interpret D1 faulting to be synchronous with metamorphism, D2 isoclinal folding, and axial planar cleavage development. Although D1 faults and D2 cleavage are indeed subparallel throughout the study area, cleavage was not observed to be better developed near faults. Thus the interpretation of a D2 cleavage superimposed on already disrupted rocks (albeit shortly after D1) is preferred.

D3—Open Folding

Postmetamorphic centimeter to 10 m (.4 in–30 ft) scale, open to tight, upright to overturned, north-south trending folds affect S0 and S2 in metasediments. No overprints were found that might suggest more than one postmetamorphic mesoscopic folding, and the folds are here loosely grouped in a single deformation event, D3. The extreme variability in style is in part a function of rock type; argillites and thin-bedded sediments are crenulated and crumpled on a cm scale (Fig. 9b). Thicker bedded sediments, including ribbon cherts, show meter scale buckling, and massive siliceous argillites fold on a larger scale still. Unfoliated metabasites and metaperidotites do not show recognizable mesoscopic folds. Where best developed, in the ribbon cherts of the North Fork terrane,

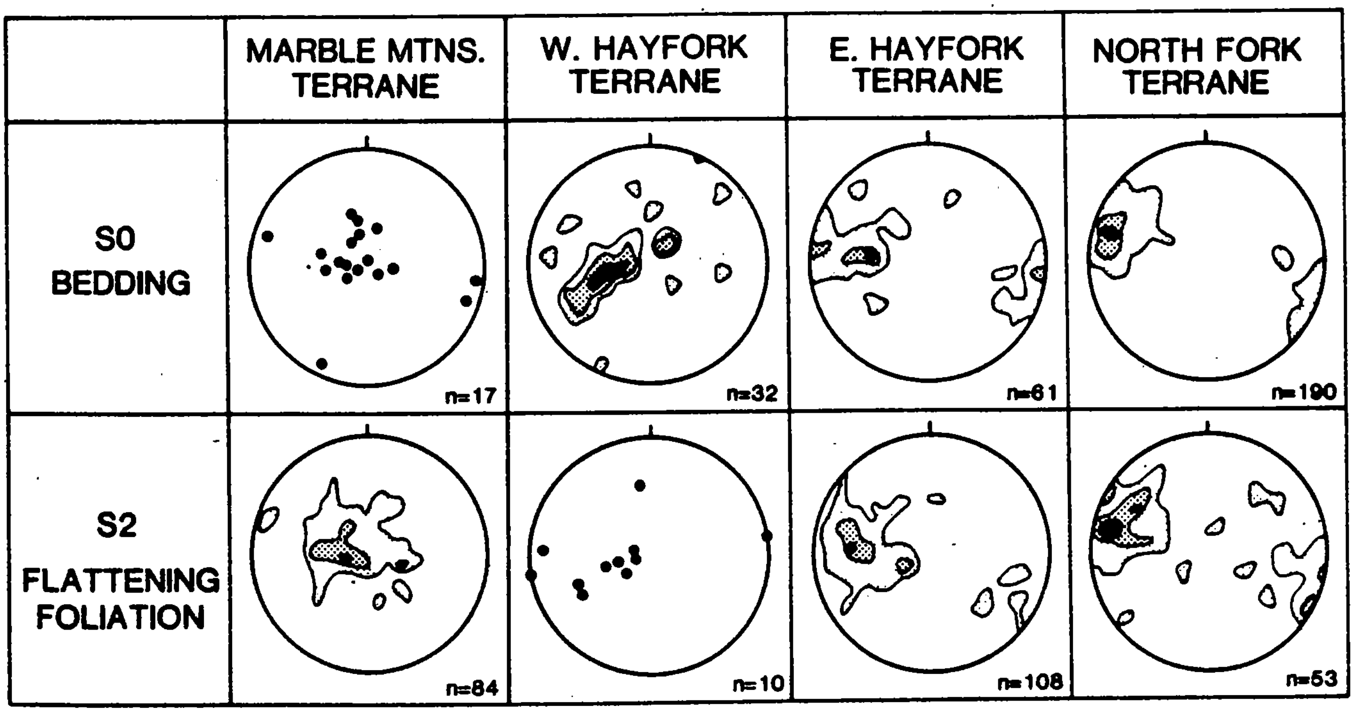

Figure 8—Equal-area stereonets of poles to planar fabric data from the area of Figure 12. Marble Mountains terrane data from Hotz (1967). Contours at 2, 6, and 10% per 1% area.

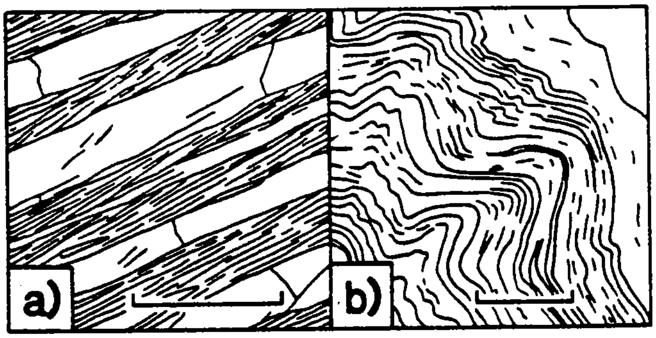

Figure 9—(a) Bedding/S2 cleavage intersection in ribbon chert of the eastern Hayfork terrane, (b) F3 folds in interbedded marble, volcaniclastic rocks, and argillite (S2 parallel to bedding) of the western Hayfork terrane. Scale bars are 10 cm (3.9 in.) long.

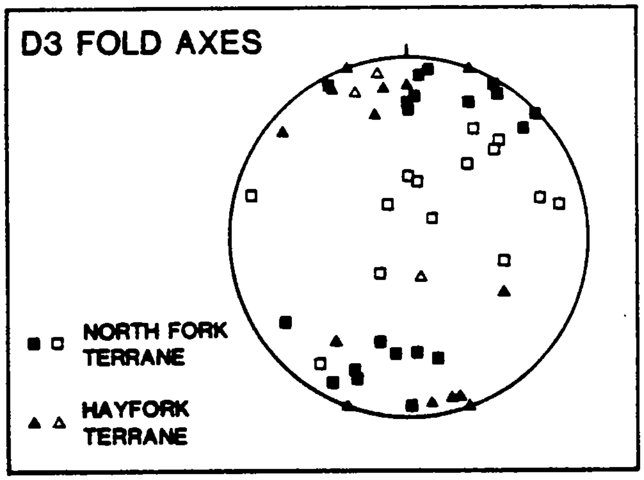

Figure 10—Equal-area stereonet of D3 fold axes from the North Fork and Hayfork terranes. Open symbols are axes measured within 50 m (160 ft) of major volcanic outcrops. Closed symbols are axes measured from the central portions of metasediment outcrops.

the folds are seen in outcrop to be noncylindrical. Some scatter in the north-south trends of fold axes can also apparently be accounted for by strain heterogeneity resulting from the proximity of volcanic rocks (Fig. 10).

A north-south trending upright synform (wavelength approximately 1,500 m [5,000 ft]) in the eastern Hayfork terrane is the best example of a map scale D3 structure (Fig. 3). Other possible examples are folding of the easternmost chert/volcanic contact in the North Fork terrane (Fig. 3) and still smaller synforms and antiforms in metasediments of the North Fork and Hayfork terranes (Mortimer, 1984). Given that certain D1 faults have been demonstrably folded, the apparent steepening and reactivation of other D1 faults can also probably be attributed to D3 deformation.

D4—Regional Tilting and Doming

Evidence for Neogene doming of the northern Klamath Mountains, accompanied by high-angle faulting, has been presented by Barnes and Rice (1983), Coleman and Helper (1983), and Mortimer and Coleman (1984). The gradual change in orientation of S0 and S2 from north-striking and gently dipping in the Marble Mountains terrane to more northeast-striking and steeply dipping in the North Fork terrane (Fig. 5) may be an expression of this doming. This would be consistent with Jurassic structures remaining shallow near the center of the dome and being steepened on its eastern flank.

The unmetamorphosed Upper Cretaceous Hornbrook Formation (Nilsen et al, 1983) unconformably overlies the North Fork and Fort Jones terranes in the area of Figure 3. It contains no mesoscopic folds but has a regional east-northeast dip of some 20 to 30° that was probably acquired during Neogene deformation. All Jurassic structures in the Klamaths basement are truncated by the unconformity, and the Hornbrook Formation thus definitively constrains the age of pre-Neogene deformation and metamorphism in the area of Figure 3 as pre-Late Cretaceous.

GRAVITY MODELING

Some indication of the deep structure of the area is obtained by modeling of Bouguer gravity anomalies (Fig. 11). The interactive computer program GRAVMODEL, developed by Eureka Resources Inc., was used to match the observed gravity profile along the line shown in Figure 2 with those computed for geologically reasonable models. Gravity data were compiled by Eureka from a number of sources including Kim and Blank (1973).

The bodies defined in the preferred gravity model of Figure 11 represent terranes exposed along or near the section line. The densities assigned to the Condrey Mountain and Marble Mountains terranes are from Barnes et al (1982) and the Vesa Bluffs pluton from Hotz (1971); the other bodies are proportional averages of the author's own density measurements and/or published rock densities (Clark, 1966; Hotz, 1977, 1979).

Absolute thicknesses and dips of terranes are not well constrained in this simple gravity model. However, two points that can be made are that (1) instead of maintaining their often steep surface dips, the terrane boundaries must flatten at depth and dip gently east, and (2) the western gravity maximum (over the outcrop of the Vesa Bluffs pluton) is probably best explained by buried high-density metaperidotite bodies in the Marble Mountains terrane (these are common where the terrane is exposed at the surface). No high-angle boundaries between terranes are required at depth. This is in keeping with the regional style of low-angle east-dipping faults seen throughout the Klamaths province (Irwin, 1981).

TIMING AND CORRELATION OF JURASSIC EVENTS

Timing of D1 and D2 is constrained by the same criteria used to date the regional metamorphism; they occurred prior to pluton intrusion at 164 ± 5 m.y. and after the deposition of Pliensbachian sediments in the North Fork terrane and, if correlations with the southern Klamath Mountains are correct, after the 168 to 177 m.y. eruption of rocks in the western Hayfork terrane (Fahan, 1982). D1, D2, and regional metamorphism thus took place in a relatively short time in the Middle Jurassic (Fahan and Wright, 1983). Timing of D3 is more difficult to constrain. Cross-cutting relations between D3 and the Vesa Bluffs pluton are not seen, but open folding definitely occurred after Middle Jurassic metamorphism and before deposition of the Hornbrook Formation in Turonian time (Nilsen et al, 1983). This age range may be narrowed by making assumptions based on regional relationships: Hill (1984, this volume), working near Happy Camp (Fig. 2), has correlated postmetamorphic open folds in the Hayfork, Marble Mountains, Condrey Mountain, and Smith River terranes with each other. This deformation is tightly constrained to be between 145 and 150 m.y. old in the Galice Formation of the Smith River terrane (Harper, 1983) and is generally recognized to be the Nevadan orogeny. The D3 folds in the area of Figure 3 are probably equivalent to these Nevadan folds.

Pluton intrusion at about 164 ± 5 m.y. constrains the TrPz belt metamorphism, plutonism, D1, and D2 to be strictly pre-Nevadan events (cf. Irwin et al, 1978). Many K-Ar mineral ages for TrPz belt rocks do cluster between 144 and 151 m.y. (Lanphere et al, 1968), thus spanning the age of the Nevadan orogeny, but, in the author's opinion, record nothing more than the interval during which TrPz belt hornblendes and biotites were slowly cooling down through their blocking temperatures from pre-Nevadan regional metamorphism. Uplift of the region was complete by Late Cretaceous time as paleosols developed on the metamorphic basement are overlain by the basal beds of the Hornbrook Formation (Nilsen et al, 1983).

SUMMARY, DISCUSSION, AND SPECULATION

Juxtaposition of the North Fork, Salmon River, Hayfork, and Marble Mountains terranes took place along low-angle, east-dipping faults with much inter- and intraterrane disruption (D1) in Middle Jurassic time. Following this, a ductile flattening deformation (D2) synchronous with low-pressure subgreenschist to amphibolite facies regional metamorphism was superimposed on the terranes. A slice of Late Triassic blueschist-facies crust, the Fort Jones terrane, was then thrust over this Jurassic metamorphic package. During latest Middle Jurassic time, the whole of the TrPz belt was intruded by calc-alkaline plutons (Davis et al, 1978; Wright, 1981; Allen et al, 1982). Timing of open folding (D3) is poorly constrained but can reasonably be assigned to the (latest Jurassic) Nevadan orogeny. Upper structural levels of the TrPz belt were exposed at the surface before Turonian time. These events are summarized in Figure 12. The absence of deep high-angle discontinuities (Fig. 10) suggests that major strike-slip faults, recognized elsewhere in the North American Cordillera, are absent in this part of the Klamaths. Thus, apart from regional Neogene doming and minor block faulting, low-angle Jurassic structures are still preserved intact.

The preferred interpretation of the above sequence of Middle and Late Jurassic events is that they took place in a single arc/subduction system. In this model, terrane juxtaposition by low-angle faulting occurred in the high, brittle levels of the subduction zone and was followed by transport to appropriate (though still relatively low-pressure) metamorphic depths. Subsequent events were

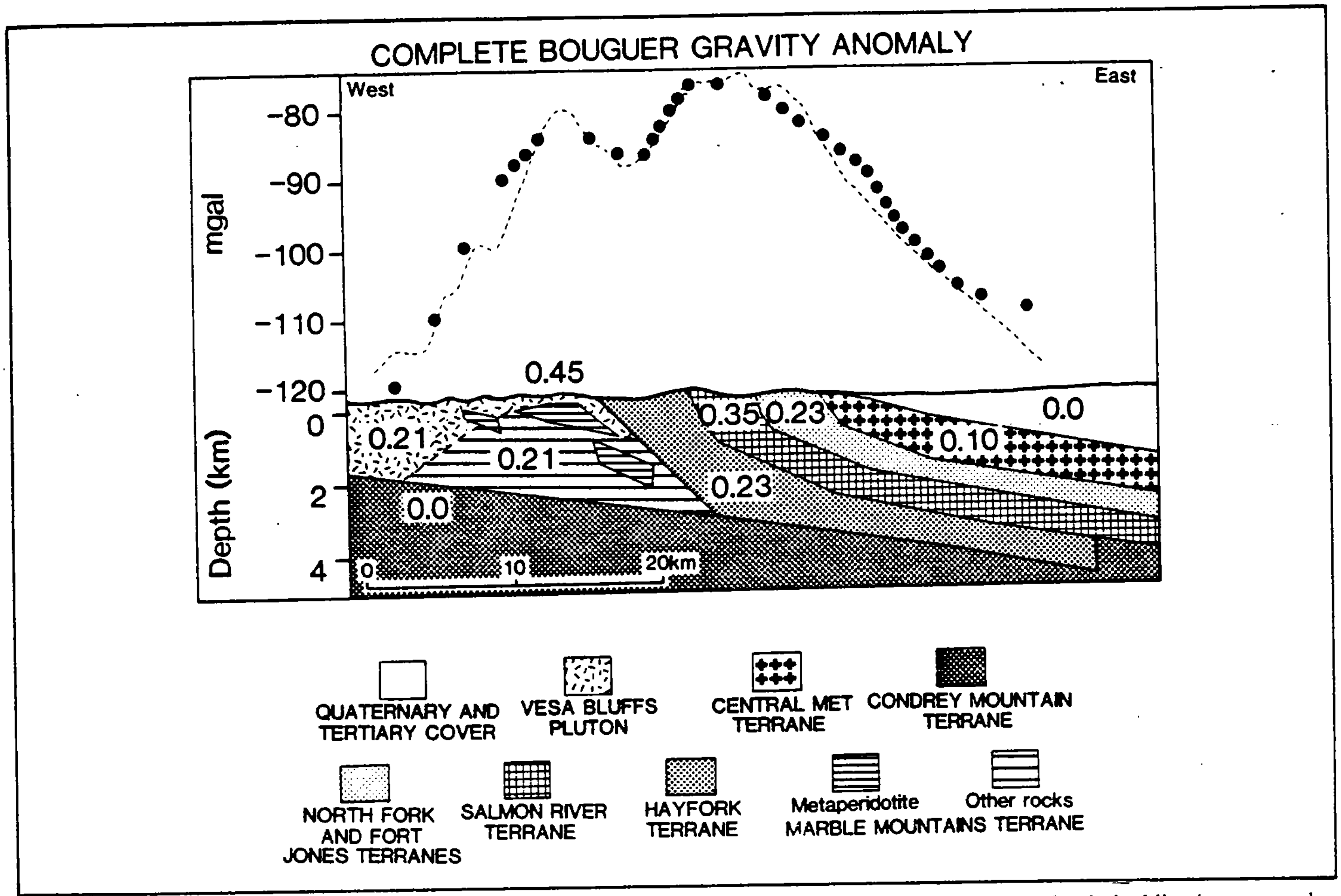

Figure 11—Gravity model along the line shown in Figure 2. Dots are values of the observed gravity anomaly, dashed line is computed anomaly. Numbers are positive density contrasts between the modeled bodies (in g/cc). The contact between the Vesa Bluffs pluton and Marble Mountains terrane cannot be determined using the gravity model; its position in the cross section is therefore questionable.

intra-arc thrusting followed by pluton intrusion, cooling, and uplift to the surface. This particular model is attractive because of its relative simplicity and consistency with current observations and ideas about style of deformation, metamorphic facies, and igneous activity in arc/subduction systems (e.g., Shiki and Misawa, 1982; Ernst, 1974; Ringwood, 1977).

In addition, most Klamath investigators would agree that a Middle Jurassic arc was constructed across rocks of an already assembled TrPz belt (e.g., Davis et al, 1978; Wright, 1982; Wright and Sharp, 1982; Saleeby, 1983; Fahan and Wright, 1983), their main evidence being the intrusion of plutons. Structural and metamorphic interpretations presented here support such an idea and can be used to infer the specific position of the TrPz belt in the arc/subduction system through time.

ACKNOWLEDGMENTS

I would like to thank Bob Coleman for encouragement and advice throughout this project; Juan de la Fuente, geologist with the Klamath National Forest, for logistical support in the field; and Mel Erskine of Eureka Resource Associates Inc., for assistance with gravity modeling. Earlier drafts of the manuscript were improved by comments from Bob Coleman, Juhn Liou, Elizabeth Miller, Meghan Miller, Mary Donato, and Bruce Hill. Financial support from the Daniel Pidgeon Fund of the Geological Society of London and NSF grant EAR 82-13347 (Coleman)is gratefully acknowledged.

REFERENCES

Allen, C. A., et al, 1982, Comagmatic nature of the Wooley Creek batholith and the Slinkard pluton and age constraints on tectonic and metamorphic events in the western Paleozoic and Triassic belt, Klamath Mountains, N. California (Abs.): Geological Society of America Abstracts with Programs, v. 14, n. 4, p. 145.

Ando, C. J., et al, 1983, The ophiolitic North Fork terrane in the Salmon River region, central Klamath Mountains, California: Geological Society of America Bulletin, v. 94, p. 236-252.

Apted, M. J., and J. G. Liou, 1983, Phase relations among greenschist, epidote-amphibolite, and amphibolite in a basaltic system: American Journal of Science, v. 283A, p. 328-354.

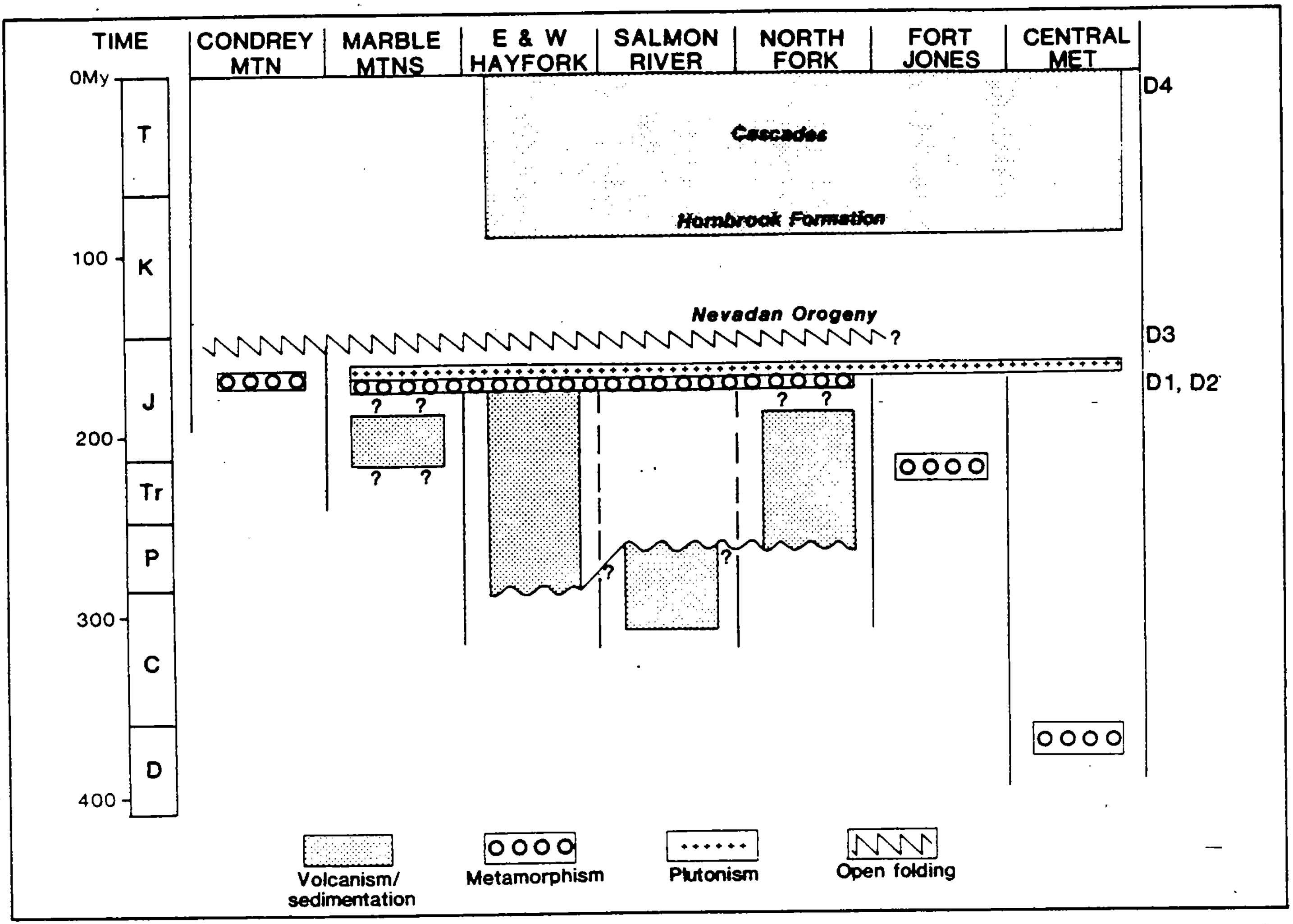

Figure 12—Comparison of the depositional, plutonic, and metamorphic records of seven Klamath terranes. Timescale of Harland et al (1982). Data from Hotz et al (1977), Cashman (1980), Wright (1981), Fahan (1982), Irwin et al (1978), Ando et al (1983), and Hill (1984). Symbols in the right margin indicate the time of the TrPz belt deformation events discussed in the text.

Barnes, C. G., and J. M. Rice, 1983, Titled plutons in the Klamath Mountains (Abs.): Geological Society of America Abstracts with Programs, v. 15, n. 5, p. 314.

______, et al, 1982, Evidence for basal detachment of the western Paleozoic and Triassic belt, northern Klamath Mountains, California (Abs.): Geological Society of America Abstracts with Programs, v. 14, n. 4, p. 147.

Blake, Jr., M. C., et al, 1982, Preliminary tectonostratigraphic terrane map of California: U.S. Geological Survey Open-File Report 82-593.

Borns, D. J., 1980, Blueschist metamorphism of the Yreka-Fort Jones Area, Klamath Mountains, Northern California: PhD Dissertation, University of Washington, 155 p.

Brown, E. H., 1977, The crossite content of Ca-amphibole as a guide to the pressure of metamorphism: Journal of Petrology, v. 19, p. 53–72.

Cashman, S. M., 1980, Devonian metamorphic event in the northeastern Klamath Mountains, California: Geological Society of America Bulletin, v. 91, pt. I, p. 453–459.

Clark, S. P., 1966, Handbook of physical constants: Geological Society of America Memoir 97.

Coleman, R. G., and M. A. Helper, 1983, The significance of the Condrey Mountain Dome in the evolution of the Klamath Mountains, California and Oregon (Abs.): Geological Society of America Abstracts with Programs, v. 15, n. 5, p. 294.

______, et al, 1983, Geologic map of the Condrey Mountain Roadless area, Siskiyou County, California. United States Geological Survey Miscellaneous Field Studies Map MF-1540-A.

Coombs, D. S., et al, 1976, Pumpellyite-actinolite facies schists of the Taveyanne Formation near Loeche, Valais, Switzerland: Journal of Petrology, v. 17, p. 440–471.

Davis, G. A., 1968, Westward thrust faulting in the south-central Klamath Mountains, California: Geological Society of America Bulletin, v. 79, p. 911–934.

______, et al, 1965, Structure, metamorphism and plutonism in the south-central Klamath Mountains, California: Geological Society of America Bulletin, v. 76, p. 933–966.

______, et al, 1978, Mesozoic construction of the

Cordilleran "collage," central British Columbia to central California; *in* Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 2, p. 1-32.

______, et al, 1979, Cross section of the central Klamath Mountains, California: Geological Society of America Map and Chart Series, MC-28I.

Donato, M. M., et al, 1982, Geologic map of the Marble Mountains Wilderness, Siskiyou County, California: U.S. Geological Survey Miscellaneous Field Map, MF-1452A.

Ernst, W. G., 1974, Metamorphism and ancient continental margins, *in* C. A. Burk and C. L. Drake, eds., The geology of continental margins: New York, Springer-Verlag, 1009 p.

______, 1979, Coexisting sodic and calcic amphiboles from high-pressure belts and the stability of barroisitic amphibole: Mineralogical Magazine, v. 43, p. 269-278.

Fahan, M. R., 1982, Geology and geochronology of a part of the Hayfork terrane, Klamath Mountains, northern California: MS Thesis, University of California, Berkeley, 127 p.

______, and J. E. Wright, 1983, Plutonism, volcanism, folding, regional metamorphism and thrust faulting: contemporaneous aspects of a major middle Jurassic orogenic event within the Klamath Mountains, northern California (Abs.): Geological Society of America Abstracts with Programs, v. 15, n. 5, p. 272-273.

Harland, W. B., et al, 1982, A geologic time scale: Cambridge, Cambridge University Press, 131 p.

Harper, G. D., 1983, The Nevadan Orogeny—Collapse of a west-facing island arc/back arc/remnant arc complex (Abs.): Geological Society of America Abstracts with Programs, v. 15, n. 5, p. 294.

Helper, M. A., 1983, Deformation-metamorphism relationships in a regional blueschist-greenschist facies terrane, Condrey Mt. Schist, north-central Klamath Mountains, N. Calif. (Abs.): Geological Society of America Abstracts with Programs, v. 15, n. 5, p. 427.

Hill, L. B., 1984, Tectonic and metamorphic history of the north-central Klamath Mountains, California: PhD Dissertation, Stanford University, 248 p.

Hotz, P. E., 1967, Geologic map of the Condrey Mountain quadrangle and parts of the Seiad Valley and Hornbrook quadrangles, California: U.S. Geological Survey Geological Quadrangle Map GQ-618.

______, 1971, Plutonic rocks of the Klamath Mountains, California and Oregon: U.S. Geological Survey Professional Paper 684B, 20 p.

______, 1973, Blueschist metamorphism in the Yreka-Fort Jones area, Klamath Mountains, California: U.S. Geological Survey Journal of Research, v. 1, n. 1, p. 53-61.

______, 1977, Geology of the Yreka Quadrangle, Siskiyou County, California: U.S. Geological Survey Bulletin 1436, 72 p.

______, 1979, Regional metamorphism in the Condrey Mountain Quadrangle, north-central Klamath mountains, California: U.S. Geological Survey Professional Paper 1086, 25 p.

______, et al, 1977, Triassic blueschist from northern California and north-central Oregon: Geology, v. 5, n. 11, p. 659-663.

Hsu, K. J., 1968, Principles of melanges and their bearing on the Franciscan-Knoxville paradox: Geological Survey of America Bulletin, v. 79, p. 1063-1074.

Irwin, W. P., 1966, Geology of the Klamath Mountains province: California Division of Mines and Geology Bulletin 190, p. 19-38.

______, 1972, Terranes of the Western Paleozoic and Triassic Belt in the Southern Klamath Mountains, California: U.S. Geological Survey Professional Paper 800C, p. C103-C111.

______, 1981, Tectonic accretion of the Klamath Mountains; *in* W. G. Ernst, ed., The geotectonic development of California, Rubey v. I: Englewood Cliffs, NJ, Prentice Hall, Inc., 706 p.

______, et al, 1978, Radiolarians from pre-Nevadan rocks of the Klamath Mountains, California and Oregon, *in* Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 2, p. 303-310.

Jayko, A. S., and M. C. Blake, 1984, Geologic map of part of the Orleans Mountain Roadless area, Siskiyou and Trinity Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1600-A.

Kays, M. A., and M. L. Ferns, 1980, Geologic field trip guide through the north-central Klamath Mountains: Oregon Geology, v. 42, n. 2, p. 23-35.

Kim, C. K., and H. R. Blank, Jr., 1973, Bouguer gravity map of California, Weed Sheet: California Division of Mines and Geology, scale 1:250,000.

Lanphere, M. A., et al, 1968, Isotopic age of the Nevadan orogeny and older plutonic and metamorphic events in the Klamath Mountains, California: Geological Society of America Bulletin, v. 79, p. 1027-1052.

Liou, J. G., and W. G. Ernst, 1979, Oceanic ridge metamorphism of the East Taiwan Ophiolite: Contributions to Mineralogy and Petrology, v. 68, p. 335-348.

______, et al, 1974, Experimental studies of the phase relations between greenschist and amphibolite in a basaltic system: American Journal of Science, v. 274. p. 613-632.

Masson, P. H., 1949, Geology of the Gunsight Peak district, Siskiyou County, California: MA Thesis, University of Californis, Berkeley, 74 p.

Miyashiro, A., 1973, Metamorphism and metamorphic belts: New York, John Wiley & Sons, Inc., 492 p.

Mortimer, N., 1984, Petrology and structure of Permian to Jurassic rocks near Yreka, Klamath Mountains, California: PhD Dissertation, Stanford University, 84 p.

______, and R. G. Coleman, 1984, A Neogene structural dome in the Klamath mountains, California and Oregon, *in* T. H. Nilsen, ed., Geology of the Upper Cretaceous Hornbrook Formation, Oregon and California, Society of Economic Paleontologists and Mineralogists, Pacific Section, v. 42, p. 179-186.

Newton, R. C., and J. V. Smith, 1967, Investigations concerning the breakdown of albite at depth in the earth: Journal of Geology, v. 75, p. 268-286.

Nilsen, T. H., et al, 1983, Geologic map of the outcrop of the Hornbrook Formation, Oregon and California: U.S. Geological Survey Open-File Report 83-373.

Nitsch, K. H., 1971, Stabilitatsbeziehungen von Prehnit und Pumpellyit-haltigen Pargenesen: Contributions to Mineralogy and Petrology, v. 30, p. 240-260.

Papike, J. J., et al, 1974, Amphiboles and pyroxenes: characterization of other than quadrilateral components and estimation of ferric iron from microprobe data (Abs.): Geological Society of America Abstracts with Programs, v. 6, p. 1053-1054.

Rawson, S. A., and S. W. Petersen, 1982, Structural and lithologic equivalence of the Rattlesnake Creek terrane and high-grade rocks of the Western Paleozoic and Triassic belt, north-central Klamath Mountains, California (Abs.): Geological Society of America Abstracts with Programs v. 14, n. 4, p. 226.

Ringwood, A. E., 1977, Petrogenesis in island arc systems,*in* M. Talwani and W. C. Pitman, III, eds., Island arcs, deep sea trenches and back arc basins: American Geophysical Union, Maurice Ewing Series 1, p. 311-324.

Saleeby, J. B., 1983, Accretionary tectonics of the north American Cordillera: Annual Review of Earth and Planetary Sciences, v. 11, p. 45-73.

Shiki, T., and Y. Misawa, 1982, Forearc geological structure of the Japanese islands, *in* J. K. Leggett, ed., Trench-forearc geology: Geological Society of London Special Publication 10, p. 63-73.

Spear, F. S., 1981, An experimental study of hornblende stability and compositional variability in amphibolite: American Journal of Science, v. 281, p. 697-734.

Wright, J. E., 1981, Geology and U-Pb geochronology of the western Paleozoic and Triassic subprovince, Klamath Mountains, Northern California. PhD Dissertation, University of California, Santa Barbara, 300 p.

______, 1982, Permo-Triassic accretionary subduction complex, southwestern Klamath Mountains, Northern California: Journal of Geophysical Research, v. 87, n. B5, p. 3805-3818.

______, and W. D. Sharp, 1982, Mafic and ultramafic intrusive complexes of the Klamath-Sierran region, California: Remnants of a Middle Jurassic arc complex (Abs.): Geological Society of America Abstracts with Programs, v. 14, n. 4, p. 245-246.