[*Dear Authors: I have very much enjoyed reading your paper even though I don't understand some of the structural nuances you discuss. Your big-picture interpretation is very interesting. I have edited the paper for sense, consistency, GSA style and format, etc. I hope you find the editing useful. Sincerely, Mary Eberle***]**

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Deformation history of the Yolla Bolly terrane at Leech Lake Mountain, Eastern belt, Franciscan subduction complex, California Coast Ranges

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ABSTRACT

The roles of volume loss, coaxial versus noncoaxial flow, and blueschist exhumation in subduction-related accretionary wedges are still poorly understood. In our study at Leech Lake Mountain in the Eastern belt of the Franciscan subduction complex, we focus on these subjects. In the specific example of the Franciscan, the tectonic significance of the boundary between the Eastern and Central belts remains controversial. The Leech Lake Mountain area in northern California is situated immediately above this boundary and, therefore, appears to be of crucial importance for understanding aspects of the tectonic evolution of the Franciscan.

The structural development at Leech Lake Mountain is characterized by three deformational events. D_2 produced the regional cleavage (s_2) during blueschist-facies metamorphism. D_2 is the only entirely ductile deformation event and was associated with accretion-related internal stacking within the Yolla Bolly terrane. The s_2 cleavage is folded by F_3 folds, which are overturned to the west. Spacing of a related s_3 cleavage is generally at the decimeter scale, but locally is spaced at the centimeter scale.

The s_2 and s_3 cleavages, and F_3 folds, are overprinted by tight to open F_4 folds at the decimeter to map scale. Map-scale F_4 folds are largely upright, whereas small-scale F_4 folds are either upright or overturned to the east.

Our finite-strain analysis relates deformed lengths to original lengths in the rock and thus provides an absolute reference frame, which allows us to detect deformation-related volume changes. Absolute finite-strain data from 20 samples support earlier studies indicating that the development of the moderately dipping s_2 cleavage was accompanied by pronounced volume loss, averaging 36%. The directions of the principal finite-strain axes are scattered; therefore, we calculated a tensor average of the data. The principal stretches of the tensor average are $S_X : S_Y : S_Z = 1.06 : 0.91 : 0.66$, indicating that the accumulation of ductile strain was characterized by subvertical shortening, which was largely compensated for by volume loss and not by orthogonal extension. Evidence for noncoaxial deformation in our samples is limited, indicating that the accumulation of ductile strain was largely coaxial.

Our preferred tectonic interpretation is that accretion and blueschist-facies metamorphism of the Yolla Bolly terrane at Leech Lake Mountain occurred during D_2 under an almost coaxial deformation regime. During and after D_2, the rocks were considerably exhumed and were telescoped by D_3 top-to-the-west out-of-sequence thrusts at shallow-crustal levels. In the Leech Lake Mountain area, D_3 thrusting juxtaposed the Eastern and Central belts along the Red Mountain fault and cut out the lower tectonic units of the Eastern belt. The difference in the degree of peak metamorphism between the Eastern and Central belts is modest, indicating that displacement at the Red Mountain fault was not large. We propose that D_3 out-of-sequence thrusts attenuated the metamorphic and stratigraphic section across the entire Franciscan and overlying Great Valley forearc. The final D_4 event produced large-scale folds. All three events resulted from horizontal shortening. There is no evidence for a major phase of horizontal extension, which might have aided exhumation of the Eastern belt blueschists. Modest tectonic exhumation was due to vertical ductile shortening during D_2.

Keywords: accretionary wedge, deformation, folds, Franciscan complex, graywacke, strain.

INTRODUCTION

It is widely accepted that the Franciscan subduction complex (commonly shortened to just Franciscan) represents an accretionary wedge that formed above an eastward-dipping subduction zone (e.g., Hamilton, 1969; Ernst, 1970). In the northern California Coast Ranges, the Franciscan has been divided into three northwest-trending stratigraphic and lithotectonic belts, which are, from east to west the Eastern, Central, and Coastal belts (Bailey et al., 1964; Berkland et al., 1972; Blake et al., 1988) (Fig. 1). The structural relationship between the Eastern and Central belts is, however, still poorly understood owing, at least in part, to intense disruption by the San Andreas fault system (Wakabayashi, 1992). For example, Worrall (1981) and Blake and Jayko (1983) regarded the boundary between the Central and Eastern belts as a major fault, the Red Mountain fault, but Seiders (1991) mapped Franciscan conglomerate units that strike across this boundary without apparent offset.

The Eastern belt is the structurally uppermost part of the Franciscan and is well known for its regionally coherent high-pressure and low-temperature rocks. A major debate in the Eastern belt is whether synconvergence Late Cretaceous to early Tertiary normal faults can (Platt, 1986; Jayko et al., 1987; Harms et al., 1992) or cannot (Ring and Brandon, 1994, 1997, 1999) be mapped in the upper parts or directly above this unit. Advocates favoring a major phase of extensional deformation have identified the Coast Range fault zone and the associated Del Puerto Canyon shear zone (Fig. 1) as the fundamental structures that aided exhumation of Franciscan high-pressure rocks. However, this view has been challenged by Ring and Brandon (1994) who mapped kinematic data from the Coast Range fault zone that do not support a normal-slip interpretation. They inferred that this prominent structure was formed as an out-of-sequence thrust, probably due to eastward tectonic wedging as proposed by Wentworth et al. (1984) and Unruh et al. (1995). No intra-Franciscan normal faults have been mapped so far. Ring and Brandon (1999) presented the first absolute finite-strain data from the Eastern belt, which are also incompatible with a major phase of regional extension. According to their study, solution–mass-transfer (SMT) deformation involved subvertical shortening, which was largely balanced by mass-loss volume strain and not by horizontal extension.

Another controversial aspect of Franciscan geology is whether oblique subduction at the Franciscan margin (Engebretson et al., 1985) caused margin-parallel displacements. Jayko and Blake (1993) proposed that Early Cretaceous to middle Eocene oblique subduction led to 600–1000 km of dextral, margin-parallel offset in the Franciscan Complex and Great Valley Group.

Herein, we report on a structural and strain study in the Leech Lake Mountain area of the Eastern belt. We believe that this area is crucial for understanding aspects of the tectonic development of the Eastern belt and also aspects of the boundary between the Eastern and Central belts. The aims of this paper are twofold: (1) to unravel the structural history of the Leech Lake Mountain area and (2) to quantify ductile deformation in Franciscan metagraywacke. Both aspects of this paper complement earlier structural studies in the northern Coast Ranges (e.g., Suppe, 1973; Worrall, 1981; Jayko and Blake, 1989; Ring and Brandon, 1999) and may contribute to a better understanding of the role that horizontal contraction and horizontal extension played in the tectonic evolution of the Franciscan.

FRANCISCAN SUBDUCTION COMPLEX

The Franciscan, the overlying Great Valley forearc, and the Sierra Nevada batholith of northern and central California represent a long-lived subduction complex that fringed the western margin of California from the Late Jurassic through the Paleogene (Cowan and Bruhn, 1992). Arc-derived volcaniclastic sediments form the dominant lithology of the Franciscan and are interpreted as offscraped and tectonically **[***Authors: for clarity, I think it is best to use “tectonically” (as opposed to “magmatically”) with “underplated” here, especially as the next sentence deals with magmatic rocks. There are so many kinds of underplating these days. OK?***]**underplated trench and near-trench deposits (Dickinson, 1970; Dickinson et al., 1982). Mafic and keratophyric rocks and radiolarian chert are locally abundant and are considered to be fragments of seamounts and oceanic plateaus (Hamilton, 1969; Tarduno et al., 1985; McPherson et al., 1990). The basement to the Upper Jurassic and Cretaceous forearc sedimentary rocks of the Great Valley Group is the Jurassic Coast Range ophiolite. The Franciscan is separated from the overlying Coast Range ophiolite and the Great Valley Group by the Coast Range fault zone (e.g., Bailey et al., 1970; Ernst, 1970; Ingersoll, 1979; Dickinson and Seely, 1979), which juxtaposed zeolite-facies to incipient prehnite-pumpellyite–facies rocks (Dickinson et al., 1969) of the forearc with Franciscan high-pressure rocks.

In the northern Coast Ranges, the stratigraphic age and the degree and age of metamorphism and deformation generally increase structurally upward toward the east across the Coastal, Central, and Eastern belts. The Coastal belt, including the Yager terrane of Underwood and Bachmann (1985), is the westernmost and structurally lowest belt. It is built up by variably deformed sandstone and shale, including local mélange units, with minor basalt, limestone, and chert. Rocks were metamorphosed under zeolite-facies conditions (Blake et al., 1988). Except for pelagic rocks, fossils suggest a Paleocene to Miocene age for the Coastal belt (Blake and Jones, 1974; Blake et al., 1988).**[***Authors: This sentence leads the reader to wonder what age is suggested by "pelagic" rocks. (Do you mean "pelagic fossils"?)***]**

The Central belt lies inboard and east of the Coastal belt. The belts are separated by the Coastal belt thrust, which has been interpreted by Ring and Brandon (1997) as a top-to-the-west-southwest thrust juxtaposing the higher-grade Central belt (maximum pressure ~6–8 kbar, Terabayashi and Marayuma, 1998)**[***Authors: Spelling? Maruyama in References]** against the underlying weakly metamorphosed Coastal belt, thereby cutting out 15–20 km of section. If an original dip of 15°–20° for the Coastal belt thrust is assumed, the metamorphic hiatus would indicate a displacement of 40–80 km. The Central belt contains coherent graywacke, but also shale-matrix mélange that includes blocks of metagraywacke, greenstone, and chert, as well as exotic blocks (the so-called knockers) of higher-grade blueschist, amphibolite, and eclogite (Bailey et al., 1964; Blake et al., 1988; Wakabayashi, 1990). Rare fossils from the mélange matrix indicate Tithonian–Valanginian (latest Jurassic–Early Cretaceous) ages for the eastern part of the Central belt, whereas Albian–Coniacian (Late Cretaceous) fossils are present in graywacke slabs and accreted limestones in the west (Blake and Jones, 1974; Maxwell, 1974; McDowell et al., 1984). Fine-grained jadeitic pyroxene, lawsonite, and aragonite are widespread in both graywacke and shale-matrix mélange (Blake et al., 1988; Underwood et al., 1988; Terabayashi and Marayuma, 1998) **[***Author: Maruyama in references]**and suggest deep burial (~25 km) of the Central belt.

The Eastern belt constitutes the structurally highest part of the Franciscan (Fig. 1). The term *Eastern belt* is generally used to refer to a distinctive imbricated sequence of several thick, gently dipping, fault-bounded units, each of which contains a relatively coherent internal stratigraphy (Suppe, 1973; Worrall, 1981). The faults that bound these units appear to be postmetamorphic (Suppe, 1973; Cowan, 1974; Platt, 1975; Worrall, 1981). Metamorphic grade is lawsonite-albite or blueschist facies, as indicated by widespread lawsonite and aragonite and more localized glaucophane and jadeite (e.g., Ernst et al., 1970; Blake et al., 1988; Ernst, 1993). In the northern Coast Ranges, the two main units of the Eastern belt are the Yolla Bolly terrane and the structurally higher Pickett Peak terrane (Blake et al., 1988). The terranes are separated by the Sulphur Creek fault (Worrall, 1981) (Fig. 1). The Pickett Peak terrane is further subdivided into the South Fork Mountain Schist and the underlying Valentine Springs Formation (Worrall, 1981). Maximum temperatures in the South Fork Mountain Schist were ~400 °C, whereas in the Valentine Springs Formation, they were between ~250 and ~310 °C (Jayko et al., 1986; Tagami and Dumitru, 1996). Maximum metamorphic pressure was ~6–9 kbar for the entire Pickett Peak terrane (Blake et al., 1988). The Yolla Bolly terrane comprises three fault-bounded units, which are, from bottom to top, (1) the broken formation of Devils Hole Ridge, (2) the Hammerhorn Ridge unit and, (3) the Chicago Rock mélange (Blake and Jayko, 1983). In the Yolla Bolly Mountains, metamorphic conditions in these units were 6–8 kbar, suggesting 23–30 km of burial, and between 125 and 200 °C (Jayko et al., 1986; Bröcker and Day, 1995). The Taliaferro metamorphic complex (Taliaferro, 1943; Suppe and Armstrong, 1972), which occurs within the Chicago Rock mélange, is stratigraphically older than the rocks of the Yolla Bolly terrane and has a higher metamorphic grade (8–9 kbar and 250–300 °C; Suppe, 1973) than the Yolla Bolly terrane. Therefore, and because of the isotopic ages that we subsequently discuss, **[***Authors: Is there a better way to inform the reader of your intentions. GSA doesn’t like to cross-reference with “below” or “above” because after laying out the paper with the figures, what was below may end up physically “above” and vice versa.***]** we do not regard the Taliaferro metamorphic complex as part of the Yolla Bolly terrane.

Isotopic ages from the Eastern belt indicate a protracted history of high-pressure metamorphism, followed by slow cooling in the Late Cretaceous and earliest Tertiary (Suppe and Armstrong, 1972; Lanphere et al., 1978; McDowell et al., 1984; Mattinson, 1988; Dumitru, 1989; Tagami and Dumitru, 1996). The oldest metamorphic ages of 165–150 Ma are from blueschist-, eclogite-, and amphibolite-facies blocks (Coleman and Lanphere, 1971; Nelson and DePaolo, 1985; Mattinson, 1988). The Taliaferro metamorphic complex also yielded ages of ca. 150 Ma (Suppe, 1973). The Pickett Peak terrane underwent regional high-pressure metamorphism at ca. 130–125 Ma (Lanphere et al., 1978). High-pressure metamorphism of the upper part of the Yolla Bolly terrane occurred at ca. 120–115 Ma (Peterman et al., 1967;**[***Authors: Date? 1963 in Refs. and elsewhere in text.***]** Mattinson, 1986). These metamorphic ages are in accord with Berriasian–

Valanginian (earliest Early Cretaceous) ages of scarce fossils from structurally equivalent parts of the Yolla Bolly terrane. However, rocks from structurally lower units, like the pre–high-pressure metamorphism gabbro intrusion at Ortigalita Peak in the southern Diablo Range, have U-Pb ages indicating peak metamorphism at 92 Ma (Mattinson and Echeverria, 1980). Cenomanian *Inoceramus* (Blake et al., 1988) from lawsonite- and aragonite-bearing shale and sandstone from the Hull Mountain area, which have a structural position similar to that of the Ortigalita Peak gabbro, corroborate metamorphism extending into the early Late Cretaceous.

We concur with others (e.g., Mattinson, 1988) that the range of metamorphic ages from the Eastern belt is probably related to protracted accretion and high-pressure metamorphism. The Central belt would fit into this picture of sequential and protracted accretion and high-pressure metamorphism.

Exhumation of the Eastern belt to shallow-crustal levels occurred during the latest Cretaceous and earliest Tertiary, as indicated by apatite and zircon fission-track dating (Dumitru, 1989; Tagami and Dumitru, 1996), by the recognition of reworked blueschist-facies clasts in conglomerates deposited in a Late Cretaceous trench-slope basin (Cowan and Page, 1975), and by the occurrence of unmetamorphosed Paleocene and Eocene strata resting unconformably on high-pressure Franciscan rocks (Page and Tabor, 1967; Berkland, 1973). The fact that thrusting of the Eastern and Central belts onto the Coastal belt did not cause pronounced metamorphism of the latter indicates that considerable exhumation of the Eastern and Central belts must have occurred before the earliest Tertiary.

GEOLOGY AND MAP-SCALE STRUCTURE OF LEECH LAKE MOUNTAIN

The Leech Lake Mountain area is part of the western Yolla Bolly terrane and lies directly above the Red Mountain fault (Fig. 2). We mapped an area in detail at the contact between the Hammerhorn Ridge unit and the structurally overlying Chicago Rock mélange (Figs. 3 and 4). The units are juxtaposed along the Chicago Camp fault. The Hammerhorn Ridge unit consists of coherent graywacke and intercalated radiolarian chert and mudstone. The graywacke is medium to coarse grained, and bedding is defined either by the intercalation of mudstone or by parallel alignment of dark shale chips. Rare sedimentary structures include graded bedding and cut-and-fill structures; the Hammerhorn Ridge unit also includes lenses of conglomerate and pebbly mudstone. Four diabase sills are exposed along the crest of Leech Lake Mountain, and two sills occur farther to the south (Fig. 3). The diabase sills were intruded preferentially along contacts between chert and chert and between chert and graywacke; the sills range in thickness from a few meters to 70 m. Chilled margins at the upper and lower contacts of the sills, and contact-metamorphic zones in the host rock, indicate an intrusive origin.

The Chicago Rock mélange contains blocks and slabs of graywacke, metabasalt, serpentinite, radiolarite, and rare marble. Mélange units also occur north of Leech Lake Mountain and display variable degrees of shearing. Tectonically intercalated within the Chicago Rock mélange is a slice of the Taliaferro metamorphic complex (Suppe, 1973) (Fig. 2). Graywacke of the Chicago Rock mélange was also intruded by Ti-rich alkaline diabase sills and dikes (Jayko, 1984). One of these dikes yielded a ^{39}Ar/^{40}Ar hornblende age, which has been interpreted as an intrusion age (Weinrich et al., 1997). Because the diabase intruded into the trench fill and because the time span for underthrusting of Eastern belt rocks is on the order of 1–2 m.y. (Ring and Brandon, 1999), the age of 119 Ma can only be slightly older than the time of accretion and high-pressure metamorphism of the rocks of the Chicago Rock mélange at Leech Lake Mountain.

Irregular bodies of serpentinite were mapped at several localities at Leech Lake Mountain. The serpentinite preferentially occurs along the Chicago Camp fault. It is strongly sheared and contains blocks of graywacke and gabbro (Fig. 3A). A metasomatic zone of several decimeters is developed along the contact between graywacke and serpentinite and is characterized in the graywacke by a change in color (from dark gray to light gray) and a marked decrease in grain size.

The map-scale structure of the Leech Lake Mountain area is dominated by late, largely upright folds, which we refer to as F_4 folds (see next section). Figure 2 shows that the Leech Lake Mountain area largely represents the northwestern limb of a large upright F_4 antiform, as indicated by the general northeast dip of s_0, s_2, and s_3 (Fig. 5). The F_4 antiform is cut by a later, steeply southwestward inclined, reverse fault. Suppe (1973) originally mapped this fault, and we name it according to his work the Leech Lake–Ball Mountain fault.**[***Authors: GSA prefers to use an en-dash (–) in place of a slash when joining multiword items.***]** This fault crosscuts the Coast Range fault zone to the east-southeast (Suppe, 1973, his Fig. 8). Figure 2B shows that F_4 folds also deform the Red Mountain fault (which**[***Authors: Change OK?***]** would therefore probably be a D_3 structure). The Red Mountain fault crosscuts the Chicago Camp fault (**[***Authors: Change OK?***]**which would therefore be a D_2 fault). Both faults largely contour along irregularly shaped ridges, suggesting that they are shallowly dipping structures (see Jayko and Blake [1989] for more on **[***Authors: Addition OK?***]**the Red Mountain fault). The puzzling occurrence of the higher-grade Taliaferro metamorphic complex within the Chicago Rock mélange might be due to D_2 or pre-D_2 thrusting and subsequent isoclinal folding of the contact, or it may represent a sedimentary intermixed block (wildflysch) that was exposed in the forearc before ca. 120 Ma.

METHODS OF DEFORMATION ANALYSIS

Internal-Rotation-Axis Method

The internal-rotation-axis (IRA) method of Cowan and Brandon (1994) was applied to deduce the average direction and sense of shear from asymmetric folds formed during D_3 and D_4. The principal idea behind the IRA method is that progressive, noncoaxial deformation produces certain symmetry fabrics in fault zones (i.e., asymmetric folds), which provide information about the direction and sense of bulk shear because of their orientation and geometry (Fig. 6). An important assumption is that the final deformational fabric has a monoclinic symmetry, defined by a so-called mirror plane (Cowan and Brandon, 1994). The fold axes are regarded as internal rotation axes (Means et al., 1980) and are subdivided into *S* and *Z* **[***Authors: See next query. Should the S and Z be italics here also?***]**folds, depending on the relative sense of rotation when viewed in the down-plunge direction of the fold axis. All folds are converted to a common *Z***[***Authors: Should the Z be italics when it refers specifically to sense of rotation, Z-transformed axes, and synoptic Z-axis? It seems that italics would be correct, so I have so changed the Z and the S as well–but see following section with *S* for principal stretches.***]** sense of rotation and are referred to as**[***Authors: Should this phase read “as having”?***]** *Z*-transformed axes. Because directions of plunge will either be upward or downward, the data have to be depicted on the upper and lower hemispheres of a stereogram. The *Z*-transformed axes are expected to lie on a plane representing the shear plane in which they formed and are distributed in two groups, separated from each other by the mirror plane. The *Z*-transformed axes should cluster around a maximum, which is considered to represent the average *Z*-axis and is called the synoptic *Z*-axis (SZA). The SZA can be determined by calculating the Fisher mean of all *Z*-transformed axes and is expected to correspond to the pole of the mirror plane. A slip vector can be determined from the intersection of the shear plane (average girdle of *S* and *Z* axes) and the mirror plane. The slip vector is interpreted to indicate the average direction and sense of tectonic transport of the hanging wall relative to a fixed footwall (Cowan and Brandon, 1994) and can be inferred from the position of the SZA by using the right-hand rule.

Strain and Rotation Analysis

Twenty samples from Leech Lake Mountain (18 fine- to medium-grained metagraywacke and two metasiltstones) have been used to quantify finite strain, which accumulated during D_2 (see subsequent discussion). In the field, the graywacke showed variable development of a spaced s_2 cleavage. Usually no linear fabric was visible in hand sample. Textural observations and strain measurements were made by using thin sections cut in two principal planes, *X*-*Y* and *X*-*Z*. Only in a few cases textural observations in *Y*-*Z* sections have been made. We use *X*, *Y*, and *Z* to refer to the maximum-extension, intermediate-strain,**[***Authors: “strain” OK?***]** and maximum-shortening directions.

Petrographic evidence indicates that deformation was accommodated by mechanisms such as fracturing and solution– mass transfer. Note that solution–mass transfer (SMT) is also referred to as diffusive mass transfer (McClay, 1977). The graywacke is, in part, composed of first-cycle volcanogenic sediment. Monocrystalline grains of volcanic quartz and plagioclase show little to no undulose extinction, deformation laminae, or deformation twinning. Polycrystalline quartz grains show evidence of undulose extinction and crystal-plastic deformation. These grains probably represent metamorphic detritus because the microstructures have no systematic orientation and monocrystalline quartz shows no evidence of dislocation activity. This view is further supported by the presence of nonrecrystallized fibers on many of the detrital grains. The dominance of SMT deformation is consistent with metamorphic temperatures (see the metamorphic data already discussed**[***Authors: Change OK? If not, please indicate what section specifically that you want to refer the reader to.***]**), which were below the 300 °C threshold needed to activate dislocation mechanisms in quartz (Küster and Stöckhert, 1997).

Quartz and, to a lesser degree, feldspar are truncated by thin selvages composed of insoluble minerals. The selvages, dark brown to black and rich in opaque minerals and micas, are interpreted as insoluble residues formed during solution–mass-transfer processes (Durney, 1978; Beach, 1979). The selvages can be regarded as planes of finite flattening, which formed perpendicular to *Z* (Ramsay and Huber, 1983). Directed fibrous overgrowths, composed of quartz and, to a lesser extent, chlorite and phengite, mantle quartz and feldspar grain boundaries oriented at a high angle to cleavage. The high silica content of the phengite suggests that the fibers formed during maximum-pressure conditions (Ring, 1996). The fibers are considered to record extensional strains that accumulated during SMT deformation. In *X*-*Y* and *X*-*Z* sections, fibers are generally straight, as are tiny fibers due to flattening strain that occur in *Y*-*Z* sections.**[***Authors: Editing of preceding sentence OK?***]** In *X*-*Z* sections, fibers are commonly subparallel to the trace of cleavage. We assume that the fibers track the incremental deformation history of the rock, whereas the cleavage represents the accumulation of finite strain in the rock. The parallelism between fibers and cleavage indicates coaxial strains during SMT deformation (Feehan and Brandon, 1999; Ring and Brandon, 1999). However, in a few samples, curved fibers occur that result from complex displacements around large, closely spaced quartz and feldspar grains. The curved fibers record localized, heterogeneous, noncoaxial deformation. On the sample scale, the localized noncoaxial deformation commonly averages out for an approximate coaxial bulk deformation.

Our study employs the PDS (projected dimension strain), the mode, and the SMT-fiber**[***Authors: Changes OK? I didn’t see why MODE or FIBER would need to be capitalized.***]** methods for measuring absolute strains and internal rotations by using detrital quartz grains from sandstones deformed by the SMT mechanism. Details of these methods have been given elsewhere (Brandon et al., 1994; Feehan and Brandon, 1999; Ring and Brandon, 1999). Traditional methods, such as the R_f/ϕ method**[***Authors: Please explain R_f/ϕ in parentheses. ***]**, are not suitable because the grains did not deform as passive markers but rather by truncation and precipitation along grain boundaries. The principal stretches are designated as $S_X > S_Y > S_Z$, where S = final length/initial length (note that *S* [in italics and capital letters] refers to the principal stretches, whereas s [in small letters, no italics] refers to foliation).**[***Authors: Good explanation—thanks!***]**

The PDS method is used to measure the amount of shortening produced by dissolution of grain boundaries. The method utilizes the fact that for SMT deformation, the dimensions of detrital quartz grains remain unchanged in the *X* direction. Therefore, the grain diameter in the *X* direction provides a record of the original size of the grain and thus supplies an absolute reference frame. Ring and Brandon (1999) showed that the detrital quartz grains in sandstones from the Great Valley Group, which are unaffected by SMT deformation, have an average stretch of ≈1. The grain fabrics produced by deposition and compaction are characterized by the development of a weak preferred orientation in grain shape. The PDS method, however, is based on the average projected dimension of the grains, not on their orientations. Numerical simulations indicate that deposition and compaction effects are generally not important as long as the initial grains have aspect ratios less than 3:1 (Brandon and Feehan, unpublished data), **[***Authors: We don't like to cite unpublished data that are not in a repository somewhere. Can you turn this into a personal communication with a year?]** which is commonly the case for sandstones (Paterson and Yu, 1994; **[***Authors: Please supply Paterson and Yu for Refs.***]**Ramthun et al., 1997). Thus, the PDS method provides a specific measure of those strains resulting from the SMT mechanism, assuming, of course, that the rock was not significantly affected by intragranular-deformation mechanisms.

The mode method is used to determine the extensional strains recorded by fiber overgrowths. If SMT deformation is not accompanied by crystal-plastic mechanisms, the modal percentage of fibers in a rock is directly related to the absolute extensional stretch in the rock. Fiber modes are most easily measured in *X*-*Z* sections. For unidirectional fibers, the maximum stretch S_X is related to the modal fraction of fiber (m) by the relationship $S_X = (1 - m)^{-1}$.

Given absolute strains, the volume stretch S_V (final volume/initial volume) is equal to the product of the principal stretches ($S_X \cdot S_Y \cdot S_Z$). Because our methods are focusing entirely on the loss of mass to grains and the amount of mass locally precipitated, the estimates of S_V only represent the mass-transfer component of the volume strain.

The SMT-fiber method is used to quantify the internal rotation by using the angular relationship between the fiber overgrowths and cleavage. The degree of noncoaxiality can be represented by an average kinematic vorticity number. As defined by Means et al. (1980), the kinematic vorticity number is a dimensionless ratio of the internal rotation rate over the stretching rate. The average corresponds to the ratio calculated by assuming a steady deformation (where the ratio is constant throughout deformation). We use the modified kinematic vorticity number (W^*_{m}) of Ring and Brandon (1999), which accounts for volume strains.

As we subsequently show, the directions for the principal stretches show some scatter. The variability in orientations probably reflects local variations in deformation and also random errors in our measurements. Thus, we have found it essential to calculate averages for our data (Table 1). As discussed by Brandon (1995), it is not appropriate to average the stretches, principal directions, and internal rotation measurements separately. The data must be averaged in tensor form to ensure that the orthogonality of the axes is preserved and that the magnitudes and directions of the principal stretches are correctly associated. In this study, tensor averages were calculated by using the Hencky method where only the stretch tensor is needed (see Appendix B of Brandon [1995] for details about the method).

STRUCTURAL HISTORY

Bedding (s_0) is present in sedimentary rocks of the Yolla Bolly terrane (Suppe, 1973; Worrall, 1981) and is characterized by the presence of sedimentary structures. On the basis of overprinting criteria, we distinguish three major deformation events, which we designate D_2, D_3, and D_4 according to Jayko and Blake (1989). The latter authors also recognized an earlier D_1 event, which only affected the rocks of the overlying Pickett Peak terrane. Three folding events are already visible on the map and the cross section in Figure 2. Chert layers are isoclinally folded about southeast-plunging F_2 axes, and these axes were folded about north- to northeast-trending F_3 axes. The map-scale pattern is dominated by doubly-plunging F_4 folds, which refold F_2 and F_3 folds. In general, bedding, foliation planes, and thrust faults dip to the northeast at a moderate angle. These directional features are**[***Authors: Change OK? “This” did not have an obvious one-word antecedent.***]** attributed to large-scale, tight F_4 folding about northwest-trending axes.

D_2 Structures

A first cleavage (s_2), which deforms bedding, is developed in metagraywacke, mudstone, and metachert and represents the first and also the regional deformational fabric in the Yolla Bolly terrane. The s_2 cleavage in the study area is expressed as a disjunctive spaced cleavage at the millimeter to centimeter scale in metagraywacke, a more penetrative slaty cleavage in mudstone, and a semipenetrative cleavage in shale horizons in chert. Mesoscopically, the parallel alignment of shale chips and flattening of quartz mainly defines s_2. In thin sections of fine- to medium-grained metagraywacke, the cleavage is defined by subparallel, discontinuous, and anastomosing seams (selvages). In general, s_2 parallels s_0, and both planar structures dip moderately to the northeast (Fig. 5); their poles lie on a great circle, however, a fact that indicates folding of these planar structures.

The major map-scale structure associated with D_2 is the Chicago Camp fault. Graywacke is strongly brecciated at the contact, which is locally decorated by pods of serpentinite. According to Jayko and Blake (1989, p. 388), movement along this fault occurred prior to D_2. Although the Chicago Camp fault is deformed by D_2 structures locally, our observations suggest that this contact mainly formed during D_2. Our lines of reasoning are as follows: (1) The s_2 cleavage is parallel to the Chicago Camp fault. (2) Serpentinite developed a crude, gently east-dipping s_2 cleavage subparallel to the Chicago Camp thrust. Locally, cataclastic zones associated with Riedel structures developed in the immediate vicinity of the Chicago Camp fault. (3) Axial planes of large-scale, tight to isoclinal F_2 folds in chert are generally subparallel to the Chicago Camp thrust.

The upper and lower Taliaferro faults of Suppe (1973) separate the Taliaferro metamorphic complex from the Chicago Rock mélange to the east of Leech Lake Mountain. These faults are locally decorated with lenses of serpentinite and, farther to the east, are folded by a north-trending F_3 fold. According to Suppe (1973), the Chicago Rock mélange developed a synmetamorphic cleavage during thrusting at the Taliaferro faults, which we correlate with s_2. However, structures that developed during maximum (pre-D_2) metamorphism in the Taliaferro metamorphic complex are cut by the two thrusts. Therefore, we propose that the upper and lower Taliaferro faults are D_2 structures.

D_3 Structures

A second, spaced cleavage (s_3) is locally developed in metagraywacke and chert. Spacing between s_3 planes ranges from a few centimeters to several decimeters. The s_3 cleavage is only locally developed, and where it occurs, it is weaker and less penetrative than s_2. Therefore, s_2 is referred to as the regional (or main) cleavage. The s_2 planes are crenulated by s_3 and folded by F_3 folds, to which s_3 is axial planar. The cleavage is defined by the rotation of phyllosilicate grains into s_3 planes (Jayko and Blake, 1989). F_3 axes plunge gently to the northwest and F_3 axial planes and s_3 planes **[***Authors: OK?***]**dip moderately to the northeast (Fig. 5). The absence of growth of metamorphic minerals and fiber overgrowths associated with s_3 suggests that D_3 occurred at shallow-crustal levels.

Map-scale D_3 structures are inclined to recumbent, tight to isoclinal folds in chert. These F_3 chert folds have northeast- to north-trending axes (Fig. 2). The Red Mountain fault (Fig. 2) also appears to be a D_3 structure because it is postmetamorphic and because D_3 structures are prominent (and, in part, pervasive) directly above the Red Mountain fault. Asymmetric F_3 folds with amplitudes and wavelengths ranging from a few centimeters to several decimeters are common in chert directly above and below the Red Mountain fault and were analyzed in six outcrops (Fig. 2) to deduce aspects of the kinematic history of the Red Mountain fault.

Kinematic Analysis of F_3 Folds

F_3 axes in the vicinity of the Red Mountain fault are organized into groups of *S* and *Z* asymmetry and define a mirror plane and a gently north-northwest-dipping average girdle (Fig. 7A). The inferred slip vector plunges to the west, suggesting a top-to-the-west sense of tectonic transport. We infer that this is the sense of shear at the Red Mountain fault and possibly also at other D_3 faults in the vicinity of Leech Lake Mountain. Top-to-the-west tectonic transport would be compatible with the generally northeast-dipping F_3 axial planes in the Leech Lake Mountain area and also with fault-slip data of Ring and Brandon (1997) from the Red Mountain fault farther north.

D_4 Structures

D_4 caused tight to open, largely upright folds, which developed at the decimeter to map scale. No new cleavage formed during D_4. F_4 axes and axial planes show some scatter, as is expected for folds that developed at shallow-crustal levels. Mesoscale F_4 axes tend to plunge to the north, and their axial planes dip to the northwest (Fig. 5).

Map-scale D_4 structures include the northwest-trending Yolla Bolly antiform within the Hammerhorn ridge unit, and tight folds with west-northwest–trending axes in chert (Fig. 2). The Yolla Bolly antiform is truncated by the southwest-dipping Leech Lake–Ball Mountain fault (Fig. 2; see also Suppe, 1973, his Fig. 8).

Kinematic data from this fault indicate southwest-side-up movement along a southwest-dipping reverse fault (Fig. 3C), which is compatible with qualitative data from Suppe (1973).

Kinematic Analysis of F_4 Folds

Axes of mesoscopic F_4 folds close to the Yolla Bolly antiform define a north-dipping girdle with an inferred slip vector indicating a top-to-the-east-southeast sense of overturning, which is in accord with the steeply northwest-dipping axial planes of F_4 folds (Fig. 7B).

STRAIN AND ROTATION ANALYSIS

The major goal of the strain and rotation analysis was to shed some light on the accretion and especially the exhumation history of the Eastern belt. The questions we address here include the following: (1) Is subvertical shortening in the rocks, as indicated by the moderately dipping s_2 cleavage, balanced by subhorizontal extension? (2) Are there significant strains perpendicular and/or parallel to the Franciscan margin? (3) Was deformation strongly noncoaxial. Absolute finite-strain analysis helps to answer questions 1 and 2; the quantification of the degree of noncoaxiality sheds light on question 3. If, as we have already noted, subhorizontal noncoaxial extensional deformation has exhumed the Franciscan high-pressure rocks, then we should find pronounced extensional strains and a noncoaxial component of deformation. If oblique subduction was accommodated by margin-parallel shear in the Franciscan, then we should find extensional strains parallel to the Franciscan margin.

Directions and Magnitudes of the Finite Stretches

The field orientations of the measured finite-strain axes show some scatter (Fig. 3B, Table 1). The maximum shortening axes (Z) plunge steeply to moderately to the south-southwest and, thus, show the same orientation as the poles to the main s_2 cleavage. The maximum extension directions (X) plunge gently and have a maximum in the west-northwest direction. The intermediate-strain axes (Y) plunge moderately to the northeast. The principal directions of the average strain tensor are in accord with the contoured data (Fig. 3B).

The measurements of the modal abundance of fibers in the rock are between 0% to 29% fiber per volume of rock with an average of 19% (Table 1). Therefore, the absolute extensional stretches show a wide scatter and range from 1.00 to 1.41 for S_X. S_Z ranges from 0.50 to 0.87, and S_Y ranges from 0.63 to 1.11. The principal stretches of the tensor average are $S_X : S_Y : S_Z = 1.06 : 0.91 : 0.66$ and indicate that S_X and S_Y are ≈ 1. This surprising result stems from the highly variable orientations of the principal finite-strain axes; the individual strain tensors do not share the same principal directions; see Ring and Brandon (1999) for a fuller description of these unusual results.

The overall deformation at the regional scale records only vertical contraction as indicated by the fact that the average values for S_X and S_Y are close to one. Vertical contraction is balanced by volume-loss strain as discussed subsequently. The average *X* direction trends west-northwest, approximately perpendicular to the Franciscan margin, and indicates that ductile deformation did not accommodate any significant strain perpendicular to the orogen. The average *Y* direction plunges gently to the north-northeast, indicating insignificant horizontal contraction subparallel to the Franciscan belt.

Volume Strain and Strain Type

All analyzed samples have undergone volume loss, which ranges between 18% and 55% (Table 1). On average, ~36% of the rock volume was lost during SMT deformation at Leech Lake Mountain. The volume strain probably occurred largely by the loss of mass from individual detrital grains. At the outcrop scale, there is no evidence of a sink for this missing mass. Modal measurements along line traverses across outcrops show that veins make up no more than 3% by volume of a typical outcrop, with an average about 1%.

In a conventional strain-symmetry plot (e.g., Flinn, 1962; Hsu, 1966; Ramsay and Huber, 1983), strain-magnitude**[***Authors: Should either or both hyphens in this sentence be “versus” for better clarity?***]** data fall in both prolate and oblate fields, with the tensor average indicating slightly oblate strain symmetry (Fig. 8A). However, an interpretation of strain data without any knowledge of volume strain can be misleading, as the position of the plane-strain line is a function of the volumetric stretch (volume gain or loss) (Ramsay and Wood, 1973). Therefore, strain type is best determined by plotting volume strain (S_V) versus the principal stretch in the *Y* direction (S_Y) (Brandon, 1995). Because of the volume loss, the data points shift into the constrictional field, and the tensor average indicates that the overall strain is of constrictional type (Fig. 8B).

Another important aspect of volume strain is highlighted in Figure 8C, where isolines of aspect ratios in the X-Z section are projected into a diagram for the absolute strain values S_V and S_X. Such a diagram illustrates how volume and extensional strains relate to cleavage formation, if cleavage is assumed to be perpendicular to Z and the maximum axial ratio $R_{X\text{-}Z}$ is considered as a proxy for cleavage intensity (Brandon, 1995). S_V and S_X can be regarded as the open and closed components of the deformational system. Therefore, a strain path parallel to S_V would represent a pure volume strain, and a path parallel to S_X would characterize constant-volume plane-strain deformation, where extension in X is balanced by shortening in Z. As has been shown by Brandon (1995) and as is illustrated by the $R_{X\text{-}Z}$ isolines in Figure 8C, the closed-system case requires only half as much strain as the open-system case to produce the same $R_{X\text{-}Z}$ ratio (see arrows in Fig. 8C). The data points in Figure 8C do not plot on either of these strain paths, indicating that deformation apparently involved both closed- and open-system behavior. The highest aspect ratios in our samples are between three and four; however, absolute stretches for this case are less than 1.4. Since this relationship is the same for all data points, it demonstrates that the cleavage intensity is much stronger than would be expected given the low extensional strains and assuming constant-volume deformation.

It is useful to compare the distortional and volume components of the strain as shown in Figure 8D. The natural octahedral shear strain (Γ_{oct}) represents a measure of the average distortional strain caused by the deformation (Nadai, 1963; Brandon, 1995). This measure is zero when $S_X = S_Y = S_Z$ and increases as $R_{X\text{-}Y}$ and $R_{X\text{-}Z}$ increase. In Figure 8D, Γ_{oct} is plotted against the logarithm of S_V. A steady-rate deformation would show on this plot as a path that extended at a constant rate. For coaxial deformation, the distance from the origin is proportional to the amount of work expended in deforming the rock (Nadai, 1963; Brandon, 1995). This diagram shows that the work associated with volume strain varies greatly from sample to sample, but generally exceeds the work associated with distorting the rock. Also note that the tensor averages are centered with respect to the distribution of S_V, but offset on the low side with respect to Γ_{oct}. The reason is that variability in the principal directions at the local scale is averaged out at the regional scale, so that the regional-scale average shows less distortional strain than the distribution of local values would suggest.

Internal Rotation and Strain Regime

Ring and Brandon (1999, their Fig. 3) showed different types of fiber geometries mantling detrital grains obtained by numerical modeling. In the samples from Leech Lake Mountain, the angles of internal rotation (Ω_i) are small, especially when compared to the angle of $\Omega_i = 42°$ for a typical simple-shear deformation as shown in Ring and Brandon (1999, their Fig. 3B). None of the Leech Lake Mountain samples has internal rotation angles larger than 18° (Fig. 9). The degree of internal rotation shows a weak positive correlation with increasing S_X and $R_{X\text{-}Z}$ (Fig. 9, A and B). The amount of volume loss is, in general, highest in samples with the highest degree of coaxial deformation (Table 1).

W^*_m of the individual samples shows considerable scatter, but is, on average, also small (below ~0.35, with only two exceptions, Table 1) and the senses of rotation alternate. The average mean rotation tensor for Leech Lake Mountain shows almost no internal rotation (Table 1). The mean internal rotation axes largely coincide with the *Y* axes of finite strain (Fig. 3B). From the negligible amount of internal rotation on the regional scale, we conclude that the data indicate an overall coaxial strain regime for D_2.

TECTONIC INTERPRETATION AND IMPLICATIONS FOR DEFORMATION IN ACCRETIONARY WEDGES

D_2 occurred before but mainly during peak-metamorphic conditions. Therefore, we infer that it formed during the high-pressure metamorphism that accompanied accretion **[***Authors: Changes OK? I was trying to make the wording more “straightforward.”***]** of the Yolla Bolly terrane to the North American continental margin. Hence the faults resulted from horizontal shortening and are thrusts. The age data of Weinrich et al. (1997) suggest that burial of the rocks at Leech Lake Mountain did not occur before 119 Ma, which would be a maximum age for D_2. D_2 may have continued into the Late Cretaceous or even earliest Tertiary, the time when the studied rocks reached shallow-crustal levels and ductile deformation ceased. The age of ca. 115 Ma for high-pressure metamorphism (see previous discussion**[***Authors: Do you want to specify what section you are referring to here?***]**) is among the oldest in the Yolla Bolly terrane. If it is**[***Authors: Is OK? “Was” seems odd to me.***]** accepted that accretion and high-pressure metamorphism in the Franciscan were sequential and progressed structurally downward with time, the Leech Lake Mountain area can be interpreted to form an originally structurally upper part of the Yolla Bolly terrane.

Accretion was associated with top-to-the-west thrusting of the Chicago Rock mélange onto the Hammerhorn Ridge unit along the Chicago Camp fault (Jayko and Blake, 1989). However, in general, our data indicate that D_2 is characterized by a large degree of coaxial deformation. Brandon and Ring (1998) summarized five quantitative studies of ductile deformation from deeply exhumed accretionary wedges, including the Franciscan, and concluded that flow is almost always coaxial, indicating very low shear coupling on the subduction thrust. These results are at variance with the idea of Cloos and Shreve (1988)**[***Authors: Please supply for Refs.***]** that the Franciscan wedge was characterized by strongly noncoaxial flow.

Our strain data show very low strain magnitudes in the Eastern belt. The fact that the data show no extensional strains parallel to the Franciscan margin suggests no margin-parallel strike-slip movement during D_2 in this part of the Franciscan. As argued by Wakabayashi (1992), the Franciscan conglomerate suits mapped by Seiders (1988, 1991) also do not suggest large-scale strike-slip movements within the Franciscan. Ring and Brandon (1999, p. 82) have shown that coupling between the underthrusting and overriding plate at the Franciscan margin was very low during the accumulation of ductile strain. Low interplate coupling does not favor strike-slip deformation in the forearc (e.g., Jarrard, 1986).

The strain data indicate almost no strain perpendicular to the Franciscan continental margin, suggesting no major displacements normal to the plate margin. Harms et al. (1992) argued that subhorizontal east-west extension during D_2 occurred along the Del Puerto Canyon shear zone, which developed in the upper part of the Yolla Bolly terrane immediately below the Coast Range fault zone. **[***Authors: Editing of next sentence OK?***]**The finite-strain data of this study (which also come from the upper part of the Yolla Bolly terrane) and the finite-strain data of Ring and Brandon (1999) do not supply evidence for either the development of strongly noncoaxial ductile shear zones or for large extensional strains. Ongoing work in the proposed Del Puerto Canyon shear zone shows that the principal finite-strain directions there are also variable and again do not indicate significant extensional strains.

The D_2 event was characterized by pronounced vertical shortening of about 34%, which was balanced by pervasive mass loss of ~36%. Bolhar (1996)**[***Authors: Date? 1997 in Refs. and elsewhere in**

text.*]** estimated that the vertical shortening contributed about 13% (i.e., ~3.5 km) to the exhumation of the blueschist at Leech Lake Mountain (we refer to Feehan and Brandon [1999] for a detailed discussion of the relationship between vertical shortening and exhumation). In general, models addressing deformation in accretionary wedges assume constant-volume deformation, which demands a balance between shortening and extensional strains. We think that it is important to note that the volume loss reported here balanced the shortening strains and, therefore, vertical shortening does not demand horizontal extension.

The pervasive volume strains can be considered as a form of mass loss within the accretionary wedge. SMT deformation included both closed and open exchange involving local precipitation of fiber overgrowths and wholesale loss of mass from the rock. The open-system behavior was apparently related to dissolution and bulk removal of the more soluble components of the rock, probably caused by a large flux of a solvent fluid phase on a regional scale. The closed-system behavior apparently reflects grain-scale transport of the relatively insoluble components of the rock. The presence of Al-bearing phases, such as phengite and chlorite, in the fiber overgrowths is consistent with the very low solubility of Al species in a normal metamorphic fluid. Thus, the extension accommodated by the fiber overgrowths might be best viewed as a closed-system process, perhaps as a wet type of Coble creep (Elliott, 1973).

The D_3 event caused top-to-the-west imbrication. D_3 faults juxtaposed units of different metamorphic grade within the Eastern belt and also the latter with the Central belt. The postmetamorphic D_3 faults occurred at shallow-crustal levels; this depth **[***Authors: depth OK? If not, please add another noun for better clarity.***]**is also indicated by the absence of new mineral growth associated with D_3 structures. Thus, the high-pressure rocks of the Yolla Bolly terrane were substantially exhumed (~10–15 km) before the onset of D_3. Because the Eastern belt reached uppermost crustal levels in the latest Cretaceous and earliest Tertiary, we suggest that D_3 is of Tertiary age.

D_3 largely produced the present tectonic pattern in the Franciscan, characterized by the occurrence of higher-grade (older) units above lower-grade (younger) ones (Suppe, 1973; Cowan, 1974; Platt, 1975; Worrall, 1981). In accord with Jayko and Blake (1989) and Ring and Brandon (1997, 1999), we propose that the D_3 faults resulted from horizontal shortening and are thrust faults. During D_3 thrusting, the Devils Hole Ridge unit was cut out above the Red Mountain fault, indicating that D_3 thrusts are out-of-sequence faults that attenuated the tectonometamorphic section. Given that the difference in maximum burial between the Central belt and the Yolla Bolly terrane in the Leech Lake Mountain area is modest (see the metamorphic data already discussed), displacement at the Red Mountain fault is probably not large. This finding suggests that the lateral extent of the fault is also not large, which in turn, implies that the Red Mountain fault is probably not a continuous fault that separates the Central and Eastern belts over the whole of northern California. This interpretation is in accord with the continuous conglomerate horizons mapped by Seiders (1991) across the boundary between the Central and Eastern belts. Our general interpretation of that belt boundary also implies that both belts were continuous before D_3; therefore, it can be suggested that the Central and Eastern belts represent a largely coherent high-pressure sequence that formed by protracted and sequential accretion during the Cretaceous.

According to Worrall (1981) and Jayko and Blake (1989), movement on the Sulphur Creek fault (Fig. 1), which brought the Pickett Peak terrane above the Yolla Bolly terrane (Blake and Jayko, 1983) and thereby cut out some of the **[***Authors: addition OK?***]**metamorphic section, postdated D_2; therefore we suggest that the Sulphur Creek fault is also a D_3 structure.**[***Authors: preceding editing OK? (Is it you who suggest?) Note: “, suggesting…” is a dangling-participle construction.***]** We envision that many of the postmetamorphic faults in and adjacent to the Franciscan, including the present Coast Range fault zone (Ring and Brandon 1994, 1997), are related to D_3 out-of-sequence thrusting. This interpretation suggests that attenuation of the nappe pile is due to crustal shortening and does not necessarily imply horizontal extension.

The cause for crustal shortening during D_3 might be the accretion of the Coastal belt in the early and middle Tertiary. The weak metamorphism in the Coastal belt suggests that it was accreted at the front of the accretionary wedge and was not underplated at great depths. According to the wedge models of Davis et al. (1983), Platt (1986), and Dahlen and Suppe (1988), frontal accretion should produce horizontal shortening across accretionary wedges. Earlier accretion of the Eastern and Central belts was by underplating, and therefore, preferentially caused vertical shortening.

During D_4, the Eastern belt was folded about regional, northwest-trending axes (Fig. 2). Development of the large-scale D_4 synform-antiform structure of the Yolla Bolly Mountains is due to northeast-southwest shortening. The majority of these folds are upright. They are cut by the steeply southwest-dipping, top-to-the-northeast–displacing Leech Lake–Ball Mountain reverse fault. The fact that the Leech Lake–Ball Mountain fault truncates the Coast Range fault zone (Suppe, 1973) supplies further evidence that the present Coast Range fault zone is a D_3 structure.

CLOSING REMARKS

Deformation of the Yolla Bolly terrane at Leech Lake Mountain can be subdivided into three major deformation events, all of which resulted from horizontal shortening. The structural and strain data show no evidence for a major phase of horizontal extension, which might have aided exhumation of the blueschists of the Eastern belt. Our strain data do not corroborate large-scale syn-D_2 strike-slip displacements within the Eastern belt. Vertical ductile shortening during D_2 contributed to exhumation of the blueschist, but was not associated with horizontal extension because vertical shortening was compensated for by mass-loss volume strain. The tectonometamorphic section was attenuated during the postmetamorphic D_3 event, which produced large-scale out-of-sequence thrusts that cut out parts of the tectonometamorphic section.

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Figure 1. Generalized geologic map of northern California and adjacent Oregon (modified from Wakabayashi and Unruh, 1995) and simplified cross section A–A′ through the northern Coast Ranges (modified from Cowan and Bruhn, 1992). Small box indicates area of Figure 2.

Figure 2. (A) Geologic map of the Eastern and Central belt boundary east of Covelo (modified from Blake and Jayko, 1983) showing major thrusts (Chicago Camp fault and crosscutting Red Mountain fault) and axes of three generations of folds (F_2, F_3, and F_4). The Hammerhorn Ridge unit occurs in structural windows. Location of Leech Lake Mountain area (Fig. 3) in the Eastern belt is outlined. (B) Cross section B–B′ illustrating major structural features and cross-cutting relationships between D_2 and D_3 thrusts, large-scale F_4 folding, and late-D_4 top-to-the-northeast Leech Lake–Ball Mountain reverse fault. Note that the D_3 Red Mountain fault is cut by a dextral strike-slip fault.

Figure 3. (A) Geologic map of the Leech Lake Mountain area adapted from Weinrich et al. [*Authors: "et al." OK?***](1997) and Bolhar (1997) showing strikes and dips of bedding (s_0), s_2 and s_3 cleavages, and also strike and dip of finite-flattening plane (*X*-*Y*) and maximum-stretching axes as deduced from finite-strain analysis (see text). Finite-strain axes display a high degree of variability. Orientation of cross section C–C′ (Fig. 4) is also shown. (B) Stereographic projections of finite-strain axes (equal area, lower hemisphere); mean strain tensor (refer to Brandon [1995] for definition); mean internal-rotation tensors (relative sense of rotation is indicated by an arrow) are also shown. *N*—number of measurements. [***Authors: Please explain C.I. contour interval = 3σ.***] (C) Fault-slip data from a late, southwest-dipping fault south of Leech Lake Mountain; principal strain axes are according to method of Marrett and Allmendinger (1990).**

Figure 4. Cross section C–C′ illustrating general structure of Leech Lake Mountain area and crosscutting relationships between F_2 isoclinal folds in chert, D_2 thrusts (including the Chicago Camp fault), and the late-D_4 reverse fault south of Leech Lake Mountain.

Figure 5. Stereographic projections (equal area, lower hemisphere) of structures related to deposition, D_2, D_3, and D_4; bold squares represent mean values; open squares give poles to average circles through data points (π poles). The π poles to bedding, s_2, s_3, and F_3 coincide with the mean for F_4 axes. *N*—number of measurements.[*Authors: please explain the "ratio" notation, i.e., 220.48.***]**

Figure 6. Sketch illustrating the relationship between asymmetric folds and the shear direction and how folds are analyzed kinematically according to the method of Hansen (1971) and Cowan and Brandon (1994). The block above the shear plane represents a ductile shear zone in which asymmetric folds will generally have hinge lines that lie parallel to the shear plane but may have a range of orientations within that plane. In this example, the hinge line of fold 1 is normal to the shear direction, whereas the hinge lines of folds 2 and 3 are oblique to the shear direction. The strike and the downdip direction of the shear plane are used as reference directions within the shear plane. The axis and the sense of asymmetry of each fold are plotted in a lower-hemisphere projection. According to the convention of Cowan and Brandon (1994), the sense of asymmetry is assigned on the basis of the vergence of the fold when viewed in a down-plunge direction. The sense of symmetry for fold 2 is counterclockwise, as indicated by the label "S,"[*Authors: Should the S and Z occurrences in the caption be italics? Somehow the nuances of S and Z are escaping me.***] and the sense of asymmetry for fold 3 is clockwise, as indicated by the label "Z." Because the plunge of fold 1 is zero, the asymmetry is determined on the basis of the arbitrarily designated trend of the fold; fold 1 is assigned a "Z" sense of asymmetry when plotted with a southeastward trend and an "S" sense of asymmetry when plotted with a northwestward trend. The fold axes define a girdle, which parallels the orientation of the shear plane and plot as two distinct "S" and "Z" groups. The shear direction for the shear zone can be determined from the intersection of the shear plane (average girdle of "*S*" and "*Z*" axes)[***Authors: Here it seems that S and Z should be italics. Omit the quotes?***] and the mirror plane.**

Figure 7. Stereographic projections showing internal rotation axes of (A) F_3 and (B) F_4 folds in present coordinates. The left column of stereograms shows the internal rotation axes in a lower-hemisphere projection with the sense of rotation designated as *S* and *Z*. The right two columns of stereograms show the internal rotation axes after conversion to a common *Z* sense of rotation; note that the *Z*-transformed axes can have orientations in both the upper and lower hemispheres. The average direction of the *Z*-transformed distribution is called the synoptic *Z* axis (SZA), and the antipodal direction is called synoptic *S* axis (not shown). The mirror plane for the distribution of *Z*-transformed

directions is defined to be perpendicular to the SZA direction. The slip vector is interpreted to lie at the intersection of the mirror plane and the average girdle. Contours were determined by using the method of Kamb (1959) and are shown at intervals of one times uniform density; *N*—number of measurements. The contour diagrams show the presence of clusters of *Z*-transformed axes for F_3 and F_4.

Figure 8. Finite-strain data: (A) Strain symmetry as illustrated by a conventional Flinn plot. Note that the strain-tensor average plots in the oblate field. (B) Strain type, as indicated by S_V vs. S_Y diagram of Brandon (1995). Note that the data points are dominantly constrictional and that the average of the strain tensor plots in the constrictional field. (C) $R_{X\text{-}Z}$ ratios projected into a S_V vs. S_X plot, indicating that relatively high aspect ratios in the *X-Z* section, which provide a measure of the cleavage intensity, do not correspond to large stretches in *X* when volume strains are considered. (D) Natural octahedral shear strain (Γ_{oct}) plotted against volume strain (S_V), showing that there is no apparent correlation between the strain magnitude and volume loss.

Figure 9. (A) Comparison of internal rotation angles vs. S_X showing increasing angles of internal rotation (Ω_i) with increasing stretch in *X*. (B) Internal rotation vs. $R_{X\text{-}Z}$ showing weak positive correlation between Ω_i and $R_{X\text{-}Z}$.