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Direction and shear sense during suturing of the Seven Devils/Wallowa terrane against North America in western Idaho: implications of large scale west-directed thrusting along the western Idaho suture zone

Luther M. Strayer
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Direction and shear sense during suturing of the Seven Devils/Wallowa terrane against North America in Western Idaho: implications of large scale west-directed thrusting along the Western Idaho Suture Zone

By

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B.A. Macalester College, 1984

Presented in partial fulfillment of the requirements for the degree of
Master of Science
University of Montana
1989

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Direction and shear sense during suturing of the Seven Devils/Wallowa terrane against North America in Western Idaho: implications of large scale west-directed thrusting along the Western Idaho Suture Zone (100 pp.)

Director: Donald W. Hyndman

A northeast-dipping 1.5-km-thick mylonite near Dworshak Dam marks the suture zone between Precambrian North America and the Seven Devils/Wallowa terrane in western Idaho. It formed under amphibolite facies conditions from quartz diorite containing apparently synplutonic mafic and synkinematic pegmatite dikes of the Kamiah plutonic complex. Mylonitic lineations and fold axes have a mean plunge of 48° toward 056°, nearly down the dip of the mylonitic foliation. Shear sense, given by offset of late-stage cross cutting pegmatites, is consistently top-to-the-southwest, reverse-slip, parallel to the mylonitic lineation. Folds formed by progressive folding of the mylonitic foliation, approach sheath-fold geometry. Axial planes and fold limbs are nearly parallel to the mylonitic foliation. Transposition of mafic dikes into near concordance with the foliation by simple shear requires high values of shear strain, and suggests that cumulative top-to-the-southwest, reverse-slip displacement across the mylonite zone is at least 27 km, likely more than 80 km. This caused by underthrusting or tectonic wedging of the Seven Devils/Wallowa terrane with respect to North America.

The western Idaho suture zone is defined by a thin (5-25 km) deformed and/or mylonitic belt of mafic granitoid rocks, with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, $r_i = 0.706$, suggesting they mark the boundary between oceanic and continental crust. Previous attempts to document the sense of movement on the suture zone have been inconclusive or contradictory.

Recent models that address Idaho's miogeoclinal gap, the missing Jurassic accreted terranes, and the origin of Quesnellia, combined with isotopic evidences, suggest that the western Idaho suture zone formed as a near vertical strike-slip boundary. The gross orientation of the "plane" of the suture suggests that structural styles change from being characterized by near-vertical tectonics south of the Slate Creek area, to westward directed thrusting on the Clearwater culmination of the WISZ, north of Slate Creek.

The change in structural style is proposed to be caused by the insertion of the northern Seven Devils/Wallowa terrane as a tectonic wedge into North America: above the Archean basement, and beneath the sediments of the east-west trending, Late Proterozoic Central Montana Trough.
Preface

This thesis is composed of two parts. Part I is a complete manuscript that was submitted to Geology with D.W. Hyndman, J.W. Sears and P.E. Myers as co-authors. It was accepted (4/89), pending revisions and was resubmitted in modified form soon after. Part I is the core of this thesis, based on field work and collected data.

Part II is an effort to relate and integrate the deformation recorded in the Orofino/Ahsahka area to the whole western Idaho suture zone, and in turn to relate that deformation to Idaho and Montana. The conclusions reached in Chapter IV of Part II are speculative and based on models. They serve to focus attention on a few of the many enigmatic aspects of the western Idaho suture zone.

List of Acronyms

CC        Clearwater Culmination
CMT       Central Montana Trough
MDB       Montana Disturbed Belt
MFCR      Middle Fork of the Clearwater River
NFCR      North Fork of the Clearwater River
RRT       Rapid River thrust
SC        Slate Creek
SD/W      Seven Devils/Wallowa terrane
SFCR      South Fork of the Clearwater River
SP        Sapphire Plate
SR        Salmon River
WISZ      western Idaho suture zone
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Part I

Chapter I

Direction and shear sense during suturing of the Seven Devils/Wallowa terrane against North America in Western Idaho

Introduction

The boundary between western allochthonous terranes and continental North America is marked by the western Idaho suture zone (WISZ) (Fleck and Criss, 1988; Strayer et al., 1988). It trends generally north-south near the western edge of the Idaho batholith in western Idaho. In the Orofino area, the map pattern of the mylonitic suture zone bends nearly 90° toward the west, before it is covered by Columbia River Basalt (Fig. 1-1).

Lithologic contrasts across the WISZ were first studied by Hamilton (1963); the apparently exotic Seven Devils and Riggins groups are juxtaposed against Precambrian North America (Lund and Snee, 1988). Jones et al. (1977), using faunal and lithologic similarities, correlated the Seven Devils/Wallowa terrane with the displaced Wrangellia terrane of southern Alaska. Sarewitz (1983), however, showed that whereas faunal and paleomagnetic evidence indicate that the two terranes may have formed near each other, lithologic, geochemical and stratigraphic evidence suggest that they are from different tectonic settings.

The WISZ follows a distinct isotopic boundary between
FIGURE 1-1. Geologic sketch map of the western Idaho suture zone area. Initial $^{87}\text{Sr} / ^{86}\text{Sr}$ isotopic ratio 0.706 line is nearly coincident with physical boundary (WISZ) between Precambrian North America (east) and the accreted terranes (west). RRT, Rapid River Thrust; O, Orofino; K, Kamiah; L, Lowell; R, Riggins; M, McCall. Diagonal line pattern is Kamiah plutonic complex; horizontal lines pattern is Idaho batholith. Miocene Columbia River Plateau Basalts not shown.
rocks with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of <0.704 in accreted terranes to the west, and >0.706 in the continental lithologies (Armstrong et al., 1977; Fleck and Criss, 1985). In the area around Orofino, and around the Dworshak Dam near Ahsahka, the zone marks sharp contrasts in lithology, with mylonitic mafic plutonic rocks on the outboard side and mylonitic quartz-rich metasedimentary rocks, perhaps of the Belt Supergroup (Heitenan, 1962), on the inboard side of the suture zone.

Previous attempts to document the sense of movement on the suture zone have been inconclusive or contradictory (c.f. Lund, 1984; Bonnichson, 1987; Strayer et al., 1987; Aliberti and Manduca, 1988). Where WISZ tectonites are exposed in the McCall area, about 190 km south of Orofino, nearly vertical to east-dipping mylonitic foliation contains a mylonitic lineation plunging down-dip (Manduca and Aliberti, 1988), but no distinct sense of displacement has been established. In the Rapid River area, south of Riggins and west of the suture, Aliberti and Wernicke (1986) interpreted east-southeast movement of the Seven Devils terrane against the craton, based on "strain analysis on deformed volcanic breccias." Lund (1984) and Lund and Snee (1985) in the area about 30 km northeast of Riggins, propose the movement direction on the WISZ was "convergent right-lateral transcurrent," and modelled after a "flower structure." They argue strike-slip movement because the suture is straight and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio gradient is sharp, and uplift because of rapid cooling implied by the $^{40}\text{Ar}/^{39}\text{Ar}$ data (Lund and Snee, 1988). Myers (1982) described top-to-the-west deformation,
ubiquitous shearing, shear folds, and mylonites near the Browns Creek fault which separates the cratonic terrane to the east from the outboard Blacktail block in the Harpster area. Along the South Fork of the Clearwater River, tonalitic and granodioritic plutons appear to have intruded synkinematically along the near-vertical suture boundary (Hoover et al., 1985). The present study is the first to document the kinematics of the WISZ mylonites based on well-exposed rocks within the mylonite zone.

**Unsheared Lithologies**

The 95-80 Ma Kamiah plutonic complex (KPC; Rb-Sr and \(^{40}\)Ar/\(^{39}\)Ar determinations by Fleck and Criss, 1985; Snee et al., 1987) lies west of the Western Idaho Suture Zone, near Kamiah, Idaho. The complex consists of quartz diorite, tonalite, and minor granodiorite with steeply dipping synplutonic basaltic dikes and late-stage pegmatitic dikes. All these lithologies become progressively deformed northeastward toward the suture. The dikes provide important kinematic and strain markers within the mylonite near Orofino.

Rocks of the KPC have initial \(^{87}\)Sr/\(^{86}\)Sr ratios of less than 0.704 (Armstrong et al., 1977; Fleck and Criss, 1985), and they have chemical and isotopic characteristics comparable to modern calc-alkaline arc magmas (Hyndman, 1983; Fleck and Criss, 1985). The unsheared quartz diorite contains euhedral to subhedral, apparently magmatic epidote, suggesting that the pluton crystallized at depths as great as 25 km (Zen and Hammarstrom, 1984; Zen, 1985).
The numerous basaltic dikes in the unsheared quartz diorite are subvertical but have no regular trend. Mutually intrusive relations indicate that they are synplutonic. Rounded masses of basalt surrounded by quartz diorite also suggest they crystallized at the same time as the quartz diorite. The subvertical initial orientation permits quantification of the minimum amount of strain in the quartz diorite in the mylonite zone.

Granodioritic pegmatite dikes, the latest stage of the pluton magmas, crosscut all other lithologies. Within the shear zone these felsic dikes form strain markers and are deformed to varying degrees. Their relatively small degree of strain makes them useful indicators of the sense of shear. In individual outcrops they range from undeformed planar dikes to thoroughly sheared augen trains in the mylonitic foliation. Thus these pegmatite dikes were injected throughout the deformation of the shear zone; mylonitic deformation took place while the KPC was near magmatic solidus temperature conditions compatible with amphibolite-facies mineralogy outlined below.

**Mylonitic Deformation**

The quartz diorite of the KPC becomes progressively more strained as the shear zone is approached. Anastomosing minor shear zones are scattered through this area. In the Orofino-Ahsahka area, the zone of mylonitic deformation is about 2 km wide. In the spectacular exposures around the Dworshak Dam, the quartz diorite, basaltic dikes, and pegmatite dikes have all been strongly sheared.
Mafic dikes appear as shear folded mafic bands with axial planes that are concordant to the mylonitic foliation. Where synkinematic pegmatitic dikes crosscut the earlier mafic dikes they are, in all cases, offset across the sheared mafic dikes with a top-to-the-southwest sense of shear (Fig. 1-2). Strain was therefore concentrated in the fine-grained mafic dikes to a greater extent than in the quartz diorite host.

Shearing at near-solidus temperatures in the quartz diorite was accompanied by recrystallization in the amphibolite facies. Features such as quartz ribbons, recrystallized mosaics of plagioclase and quartz, and strained plagioclase suggest that mylonitic deformation was solid-state (Paterson et al., 1989). The stable metamorphic mineral assemblage is hornblende - plagioclase ($\text{An}_{30}$) ± biotite - quartz. The high-temperature nature (Simpson, 1985) of the mylonite would inhibit development of mica "fish" with the stair-stepping asymmetry of a type II S-C mylonite (Lister and Snoke, 1984). Rare mica "fish" show the same top-to-the-southwest sense of displacement, documented, as discussed above, by deformation on the macroscopic scale.

Structure: Orientation and Symmetry

Mylonitic foliation, the dominant structural feature in the area near the Dworshak Dam, has a mean orientation of 116°/54°NE (Fig. 1-3c). Lying within the mylonitic foliation is a variably developed mylonitic stretching lineation made up of biotite, hornblende, and feldspars. The mylonitic and fold-hinge lineations plot with almost identical means (Fig. 1-3a) on the
FIGURE 1-2. a: Outcrop photograph of transposed mafic dike. Dike is virtually parallel to mylonitic foliation and contains stretched inclusion of quartz diorite. Late-stage pegmatitic dikes crosscut sheared mafic dikes and are consistently offset in a top-to-southwest sense by simple shear. b: Shear strain, $\gamma$, is calculated using cotangents of $\alpha$ and $\alpha'$. Note competency contrast between mafic (M) and plutonic material (QD) indicated by the less intense shearing of pegmatite (P) within quartz diorite inclusion.
FIGURE 1-2b.
stereonet, consistent with large shear strain. The mean of the combined fold hinge/mineral lineation plunges 48° toward 056° (Fig. 1-3b). Throughout the sheared quartz diorite, mylonitic foliation, mafic dikes, and pegmatites have been progressively refolded isoclinally (e.g., Platt, 1983); axial planes of these folds are parallel to the overall mylonitic foliation. Fold hinges have been progressively rotated toward the elongation or slip direction with geometries approaching those of sheath folds, stretched in the plunge direction with apparently no consistent strike-slip movement. Such refolding of the mylonitic foliation requires shear strain $\gamma \geq 20$ (Skjernaa, 1980).

The parallel orientation of fold hinges and lineation, combined with the consistent top-to-the-southwest sense of shear indicated by the offset pegmatites and by mica "fish," indicates that the latest movement on this segment of the suture is top-to-the-southwest, implying northeast-directed underthrusting.

Symmetry relations exhibited in a large quarry adjacent to the Dworshak Dam show clear evidence of displacement directly down plunge. The combination of strong two-fold fabric symmetry as viewed perpendicular to the lineation (Fig. 1-4a), and lack of symmetry as viewed down the lineation (Fig. 1-4b), indicates overall monoclinic fabric and that movement was dominantly simple shear, parallel to the lineation. The amount of pure shear is unknown.

Superimposed upon the ductile deformation fabrics are small, very late-stage, vertical to southwest-dipping, high-angle reverse shear zones. They cross cut all structural features in the area, range from about 4-20 cm wide,
FIGURE 1-3. a: poles to mylonitic foliation (n = 147) with mean strike and dip of 116°/54°NE. b: Equal-area stereonet projection of mineral lineations (n = 70) with mean direction of 46°/056°. c: fold hinges (n = 14) with mean direction of 47°/058°.
and span the full range from ductile to brittle behavior. Throughout the quartz diorite these shears are generally regularly spaced at intervals of about 30-50 m, and consistently show southwest-side-up sense of displacement. They do not appear to play any significant part in the large-scale displacement in the Dworshak Dam area, although they would have the effect of rotating all of the structural data to a steeper northeast dip and plunge.

**Displacement Estimate**

Displacement can be estimated on this segment of the WISZ by measuring the angular transposition of the basaltic dikes outside the shear zone to nearly parallel to the mylonitic foliation. This assumes that the synplutonic basaltic dikes (pre-Columbia River Basalt) from outside and within the shear zone are indeed the same dikes. Although the unsheared dikes cannot be followed continuously into the shear zone because of discontinuous exposure, synplutonic characteristics are found in both occurrences and regional mapping indicates that the mylonitic quartz diorite of the Ahsahka area is continuous with the northwest-trending unsheared quartz diorite body north of Kamiah (Hietanen, 1962; P. E. Myers, in prep.). Petrographic work and chemical study (Hyndman, unpubl. data) suggest that the mylonitic and pristine quartz diorite are compositionally identical and differ only in texture. The basaltic dikes in the shear zone are finely foliated, and consist almost exclusively of recrystallized hornblende and plagioclase, and minor epidote. Minerals in the unsheared and sheared quartz diorite in and adjacent to the suture zone have virtually identical compositions as determined by
FIGURE 1-4. Outcrop photographs showing symmetry relations of pegmatitic dikes from quarry adjacent to Dworshak Dam. a: Looking perpendicular to mylonitic lineation direction; northeast-dipping foliation is well developed and shows monoclinic symmetry. b: (90° from 4a) In down-plunge direction foliation is poorly defined and pegmatites poorly oriented. Note: vertical lines are 9-cm-diameter drill holes.
The displacement model requires that the subvertical dikes outside the shear zone are rotated into near parallelism with the mylonitic foliation within the shear zone. Close investigation of the angular relation between the sheared mafic bands (dikes) and the mylonitic foliation reveals that the angle is as great as 3°. However, in most cases this angle is less than 1° and, in fact, appears parallel to the surrounding foliation (Fig. 1-5). Because large differences in inferred amount of displacement are associated with small angular differences in such calculations, an angle of 3° between the displaced mafic band and the shear zone gives a conservative minimum estimate of displacement (See Fig. 1-6). Shear strain $\gamma$ is given by:

$$\gamma = \cot \alpha' - \cot \alpha,$$

(1)

where $\alpha$ = the initial angle between a basaltic dike and the shear zone, and $\alpha'$ = the final angle between the sheared dike and the shear zone (Ramsay, 1967). For example, where $\alpha = 42^\circ$ and $\alpha' = 3^\circ$, $\gamma = 18$.

Displacement $D$ is given by:

$$D = \int_0^L \gamma \, dx$$

(2)

over the thickness of the shear zone (Ramsay, 1970). The mapped width of the WISZ mylonite is approximately 2 km and the mean plunge is 48°, so the thickness of the shear zone is 1.5 km. This yields a minimum estimate of displacement across the shear zone of 27 km. However, using the more common angle $\alpha'$ of 1°, shear strain $\gamma$ would equal 56 and the inferred
FIGURE 1-5. Mafic bands in mylonitic quartz diorite that have been crosscut by late-stage pegmatite dike. Bands are actually two limbs of northeast-plunging fold with its axial plane parallel to mylonitic foliation. Although foliation appears to be locally parallel to mafic bands, there is small angular difference ($\alpha'$) ranging from $1^\circ$ to $3^\circ$ (field of view about 0.75 m).
Shear Strain $\gamma = \cot (\alpha') - \cot (\alpha)$

Displacement $= \int_{D}^{x} \gamma \, dx$

**FIGURE 1-6.** Large scale displacement model shows an unsheared, nearly vertical mafic dike, transposed to within a small angle $\alpha'$ of the shear zone. Shear strain $\gamma$ is calculated using $\alpha$ and $\alpha'$. Displacement is calculated by integrating $\gamma$ over the thickness of the shear zone.
displacement would be 84 km. Progressive refolding of the mylonitic foliation, as noted above, requires $\gamma \geq 20$ (angles $\alpha'$ of less than 2.7°), or a minimum displacement of 30 km.

Conclusions

Mylonitic rocks of the Kamiah plutonic complex deformed in the western Idaho suture zone in the Orofino/Ahsahka area lie just outboard of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio transition of 0.706. The orientation of mylonitic lineation and shear-fold axes, as well as large-scale symmetry relations, indicate that the movement occurred in a northeast-southwest direction. Offset of late-stage pegmatites across sheared basaltic dikes demonstrates that the relative sense of shear is top-to-the-southwest. At least 27 km and more likely at least 84 km of simple-shear displacement is necessary to transpose the originally subvertical basaltic dikes to within 3° and commonly 1° of the mylonitic foliation. At least 30 km of displacement is indicated by the sheath-like geometry of the folds which require $\gamma \geq 20$. Regardless of the figure used, major southwest-directed thrusting is indicated in the suture. These findings are consistent with the style shown by accretionary terranes in British Columbia (Price, 1986) which are emplaced as tectonic wedges into continental North America.
References Cited in Part I


Fleck, R.J., and Criss, R.E., 1988, Location, age, and tectonic significance of the Western Idaho Suture Zone (WISZ) and its relation to the Idaho batholith: Geological Society of America Abstracts with Programs, vol. 20, no. 6, p. 414.


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Part II

Implications of large-scale, west-directed thrusting along the western Idaho suture zone: the Orofino/Ahsahka area.

west-central Idaho

Chapter I

Previous work and origin of the WISZ

Introduction

In part two of this thesis I attempt to show the regional implications and significance of at least 27 and more likely >80 km of top-to-the-southwest, continental-scale thrusting of North America over the Seven Devils/Wallowa (SD/W) terrane, as developed in part one of this study. However, before developing an integrated model for the western Idaho suture zone (WISZ) (Fig. 1-1), I first outline the broad tectonic framework of eastern Washington and Oregon, and western Idaho, in order to define the necessary ingredients and parameters for a valid model.

Constraints and Previous work

Any model must take into account the location of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio ($r_i$) contour of 0.706 (Armstrong et al., 1977; Fleck and Criss, 1985; Criss and Fleck, 1987) (Fig. 2-1), interpreted as defining the boundary between the edge of the Precambrian crust ($r_i < 0.704$) and the accreted terranes ($r_i > 0.706$) docked in Phanerozoic time. Of specific interest is the close spacing of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio ($r_i$) contours of 0.704 < $r_i$ < 0.708 (Criss and Fleck,
FIGURE 2-1. Approximate location of the initial \(^{87}\text{Sr}^{86}\text{Sr}\) ratio \((r_i)\) line for \(r_i = 0.706\) from Armstrong et al., (1977) and Criss and Fleck (1987). The location of the suture (WISZ) is from locating the various "suture zone plutons" along the respective rivers and creeks (Lund, 1984; Hamilton, 1969, Manduca, 1988, Morrison, 1969, Myers, 1982). NFCR; North Fork of the Clearwater River, MFCR; Middle Fork of the Clearwater River, SFCR; South Fork of the Clearwater River, SC; Slate Creek, SR; Salmon River, LSR; Little Salmon River. O; Orofino, Ka; Kamiah, Ko; Kooskia, H; Harpster, R; Riggins, M; McCall
FIGURE 2-2. Location of the initial $^{87}\text{Sr}^{86}\text{Sr}$ ratio ($r_i$) line for $r_i = 0.704$, 0.706, and 0.708 (after Criss and Fleck, 1987), with respect to the location of the suture (WISZ). The close proximity of the isotopic contours indicates that the WISZ was an initially vertical boundary.
1987). The contours fall on either side of the physical location of the suture. Plutons having $r$, values between 0.704 and 0.708 lie within a narrow, 5 to 25 km "tectonic zone," the low and high values indicating oceanic and continental source rocks, respectively (Criss and Fleck, 1987). The short distance (<5 km) in which source rock affinities change indicates that the oceanic-continental boundary is sharp and near vertical (Hoover et al., 1985; Manduca, 1988), (Fig. 2-2).

Plausible models must also address the abrupt transition across the WISZ from Proterozoic Belt sediments to the Seven Devils/Wallowa arc terrane (Hietenan, 1962; Hyndman and Talbot, 1976; Hamilton, 1963, 1978; Myers, 1982; Lund, 1984); the distinctive belt of Paleozoic slope and rise sediments characteristic of most of the Cordillera, is missing (Sears and Schmidt, 1986; Wernicke and Klepacki, 1988, Fig. 1). Similarly, Wernicke and Klepacki, (1988) propose that during the Early Jurassic, the western margin of North America consisted of a long belt of terranes, accreted to the miogeoclone, extending from northern British Columbia to central California. Today, however, in the area of eastern Washington and Oregon, and western-central Idaho, this belt is missing. After the Early Jurassic and before the Late Cretaceous, the Jurassic terrane and the block of miogeoclinal North America to which it was accreted was somehow removed, leaving the craton exposed to the docking Wrangellia terrane.

The Seven Devils/Wallowa terrane has, by two estimates, undergone 60° ±29° (Wilson and Cox, 1980) and 66° ±21° (Hillhouse et al., 1982) of
clockwise rotation since the Jurassic, of which at least 45° of rotation occurred prior to 50 Ma. Any model that addresses the origin of the WISZ must take these data into account; it must afford some mechanism that permits large rotations about a vertical pole (Hillhouse et al., 1982).

Origin of the continental boundary marked by the WISZ

Several lines of evidence indicate that the suture may have originally been a near vertical, strike-slip fault zone.

1. The abrupt isotopic and geochemical change in source rock affinities (Armstrong et al., 1977; Fleck and Criss, 1985), is interpreted to be a result of the side-by-side occurrence of chemically distinct basement terranes (Lund, 1984) along a near vertical boundary (Hoover et al., 1985).

2. The apparent doubling of the miogeocline in the area of the Cassiar platform along the British Columbia-Yukon border, combined with the apparent lack of the miogeoclinal assemblage in western Idaho, suggests that the rocks of the Cassiar platform may have been removed from western Idaho along a strike slip fault system (Sears and Schmidt, 1986), similar to those recognized in northwestern Canada and Alaska (Gabrielse, 1985).

3. Similarly, the belt of Jurassic accreted terranes that was along the western margin of the Cordillera in Paleozoic and early Mesozoic time, is apparently doubled in Canada (Wernicke and Klepacki, 1988; Sears and Schmidt, 1986). The Stikine terrane, which lay between and linked the Sonomia and Quesnellia terranes during the Jurassic (Wernicke and Klepacki, 1988), now lies outboard of the Quesnellia terrane. It appears to have been
removed from the area of eastern Washington and Oregon, and western Idaho, and translated north along strike-slip faults.

Two models that address the removal of the miogeocline-Stikine block and thus the creation of the sharp, originally near-vertical continental boundary of WISZ are discussed below.

**Occlusion Model**

Wernicke and Klepacki (1988) proposed that the Stikine terrane, which occupied eastern Washington and Oregon, and western Idaho, was squeezed out of that position by the collision of Wrangellia between 160 and 130 Ma.

In this scenario the Stikine terrane effectively acts as a watermelon seed, being squeezed out to the north by the convergent "thumb" of Wrangellia and the "finger" of the continent (Wernicke and Klepacki, 1988, Fig. 4). The allochthonous Stikine-miogeocline block is a fault slice which is bound on either side by faults of opposite sense, that merge to form the suture as the terrane is translated away. This zone between the "thumb," the "finger" and the trailing edge of the allochthonous "seed," has been called, "the zone of occlusion" (Aliberti, 1988, Fig. 35c) (Fig. 2-3); the Stikine terrane was occluded from the suture zone by the collision of the Wrangellia terrane.
FIGURE 2-3. Cartoon depicting the kinematics of Wernicke and Klepacki's (1988) zone of occlusion (ZOO) model for the removal of the Stikine terrane from western North America. Pin indicates that there is no movement after the terrane is occluded.
Problems arise with this model when the amount of displacement of the Stikine block and the Cassiar platform is considered. The northward occlusionary displacement of the Stikine block should end after the suturing of Wrangellia. This can be illustrated by pressing a small ball of clay with a finger. Clay is displaced only as long as the finger is pressing and it stops when the finger stops (docks). Given the size of the Columbia embayment, it seems unlikely that filling it with Wrangellia would displace Stikinia and the Cassiar platform as far north as the B.C.-Yukon border (1800 km). The likely resting place for any terrane occluded from the WISZ would be beneath the Columbia River Basalts in Washington (Aliberti, 1988).

**Strike-slip model**

Sears and Schmitt (1986, 1987) proposed a simpler and more plausible model for the origin of the near vertical boundary of the WISZ; it calls upon familiar strike-slip faulting to remove the Stikine/Cassiar block from the U.S. northward to its present location in Canada on the Yukon-B.C. border.

After the Jurassic collision of the Sonomia, Stikinia, and Quesnellia terranes, the western coast of North America had a sinuous trace, the Cassiar platform forming a large promontory, with the Stikine terrane outboard. During the late Jurassic, the Wrangellia superterrane docked
FIGURE 2-4. Model for the removal of the Cassiar platform and Stikinia from North America by strike-slip faulting. a: Late Jurassic. b: Cretaceous. c: Late Cretaceous. d: Present.
Cassiar platform transported north
Wrangellia juxtaposed against craton

US/Canadian border
subduction zone

Cassiar Platform
Stikinia
Quesnellia
Wrangellia
Sononia

Cretaceous
~118 Ma

FIGURE 2-4b.
Renewed convergence activates Lewis and Clark "zone"

US/Canadian border

Lewis + Clark "zone"

subduction zone

Cassiar platform

Stikinia

Quesnellia

Wallowa/Seven Devils terrane

igneous arc

Sononia

Late Cretaceous

~82 Ma

FIGURE 2-4c.
FIGURE 2-4d.
against the Jurassic accreted terranes (Fig. 2-4a). Convergent activity is inferred to have been disrupted in middle Cretaceous time, followed by a period of right-lateral strike-slip faulting, which trimmed the Cassiar platform from the craton and translated it and Stikinia northward (Fig. 2-4b). By late Cretaceous time, the strike-slip movement is once again replaced by convergence of Wrangellia against the newly exposed craton. By the latest Cretaceous, a left-lateral transform develops along the Lewis and Clark zone (Talbot and Hyndman, 1973; Sears et al., 1987) (Fig. 2-4c) which offsets the WISZ at least 100 km (Armstrong et al., 1977), causing the "zag" in the $r_i = 0.706$ contour. Post-Mesozoic extension widens the Great Basin and northern Cordillera, disrupting the probable small-circle trace of the strike-slip boundary (Fig. 2-4d).

Discussion

Both these models would create the near-vertical strike-slip boundary shown by the isotopic evidence, and remove the Stikine-miogeocline block from western Idaho. Each model can also account for the moderate (45°) clockwise rotation of the SD/W terrane. Wernicke and Klepacki (1988) do this by maneuvering the colliding terrane into the Columbia embayment around a southern pole of rotation from Albian (110-103 Ma) through earliest Late Cretaceous time (103-95 Ma). In their model, Sears and Schmitt (1986, 1987) do not address the paleomagnetic data. Late Cretaceous right-lateral strike-slip faulting could, due to fault drag, cause clockwise rigid-body rotations on the rocks adjacent to the fault, thus satisfying the paleomagnetic
criteria.

The two models differ, also, in their treatment of the final location of the Stikine-miogeocline block. As outlined above, it is unlikely that the displaced block would be translated the necessary 1800 km to its present location via the occlusion model. However, large displacements (on the scale of a thousand km) due to strike-slip faulting have been documented for the northern Cordillera (e.g. Tempelman-Kluit, 1979; Gabrielse, 1985). Although neither model has been proven yet, throughout the following work, it is assumed that the Late Cretaceous, strike-slip model of Sears and Schmitt (1986, 1987) formed the initially sub-vertical continental boundary now marked by the WISZ.
Chapter II

Six transects across the suture

Introduction

The trace of the WISZ is defined by a thin zone of deformed plutonic rocks that range in age from roughly 80-90 Ma (K-Ar and $^{40}$Ar/$^{39}$Ar determinations on hornblende; Criss and Fleck, 1987, Fig. 18). Previous attempts to document the sense of movement on the suture zone within these deformed rocks have been inconclusive or contradictory (e.g. Lund, 1984; Bonnichsen, 1987; Strayer et al., 1987; Fleck and Criss, 1988; Aliberti and Manduca, 1988). Both vertical (Lund and Snee, 1988; Aliberti, 1988; Manduca, 1988) and thrust geometries (Morrison, 1969; Myers, 1982; Strayer et al., 1987; Bonnichsen, 1987) have been suggested to account for the deformation within the suture. In an effort to explain the gross orientation of the suture from McCall to Orofino, I noted the location of the "suture zone plutons" (defined as the linear, foliated granitiod rocks, that are sandwiched between continental lithologies along most of the WISZ (e.g. Hamilton, 1963, 1969; Myers, 1982; Lund, 1984; Bonnichsen, 1987; Manduca, 1988)), and I also noted the orientation of any foliations and lineations within those units. Along the southern WISZ the suture seems to have a near-vertical to eastward dip as indicated by foliation, but it appears to "roll-over" to an eastward dip on the northern extent of the suture.
FIGURE 2-5. a: Reference map showing the western Idaho suture zone (WISZ), the Rapid River thrust (RRT). Refer to figure 2-1 for town and river names. Cartoon diagrams 2-5b (north) and 2-5c (south) illustrating the orientation of the "plane" of the suture across six transects. The top of the rectangular boxes is a combined cross section/fold line, as in orthogonal projection; cross sections should be viewed with this line oriented horizontally.
FIGURE 2-5b.
FIGURE 2-5c.
In the following text I review the geometry of the WISZ, integrating the available structural data of the recent workers along the length of the suture. Six transects roughly across strike of the suture, from McCall to Orofino are investigated in order to develop a three-dimensional model of the suture’s orientation as it is traced from south to north (Fig. 2-5). Finally, a possible cause for the change in the orientation and structural style along the trace of the suture is considered.

The McCall area

Manduca (1988) studied an area in the New Meadows-McCall area which straddles the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio ($r$) boundary of $r < 0.704$ and $r > 0.706$ (Fig. 2-5c). Although primarily an examination of Sr and O isotope systematics across the suture, the study includes a large body of structural data from within the suture zone mylonites; it does not include kinematic analysis.

Three major north-south trending complexes are defined in the McCall area: the western Hazard Creek complex (HCC), composed primarily of deformed [mylonitic?] epidote-bearing tonalite, the Little Goose Creek complex (LGCC), a mylonitized porphyritic biotite granodiorite (Kuntz 1988), and the eastern Payette River complex (PRC), which consists of large tonalite and granodiorite bodies (Manduca, 1988). These complexes have $r_s$ of $< 0.704$ and $> 0.706$, for the HCC, and PRC respectively, with the LGCC showing a fairly wide range of intermediate values (0.7045 to 0.7097), "indicating that the isotope boundary is a mixing phenomenon" (Manduca, 1988). The tonalitic LGCC is also a zone of mylonitic deformation: a suture
zone pluton. It corresponds to a narrow zone of mylonitized intrusive rocks which contain abrupt changes in $r_1$ (Criss and Fleck, 1987), that extends north to Orofino. Age dates from the three complexes have been obtained using U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ systems. The Jack's Creek pluton in the HCC yields a U-Pb date of 118±5 Ma and an $^{40}\text{Ar}/^{39}\text{Ar}$ date of 95.1±3 Ma from hornblende from the same sample (Manduca 1988), with the younger $^{40}\text{Ar}/^{39}\text{Ar}$ date interpreted to reflect slow cooling or reheating of the intrusive. The mylonitic LGCC is dated preliminarily at 111±5 Ma, using the U-Pb system and an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 87 Ma (Manduca 1988). The PRC yields a poorly constrained U-Pb age of about 90 Ma, an $^{40}\text{Ar}/^{39}\text{Ar}$ age from hornblende of 81±4 Ma (Manduca 1988) and a K-Ar age from biotite of 65±2 Ma (Armstrong et al., 1977). On the easternmost side of the PRC, the Trail Creek granite, a two-mica granite correlated with the Idaho-Atlanta batholith which yields K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dates ranging between 69 and 77 Ma (Lewis et al., 1987; Lund and Snee, 1988).

Manduca (1988) recognized some mylonitic deformation in all three of the above complexes, but showed that the most intense mylonitic deformation is centered in the LGCC.

In the western portion of the HCC, the foliation, interpreted to be due to primary flow, is varaibly developed with no regular trend and no lineation. This foliation becomes more regular towards the east as the LGCC is approached, and it changes orientation from shallow east dipping (50 to 70°) to steeply east dipping (80 to 90°) (Manduca, 1988).
Adjacent to the strongly mylonitic LGCC, in the eastern-most portion of the HCC there is a strong mylonitic fabric which trends north-south and dips 80° east; it has numerous ductile folds whose axes parallel the mineral lineation which defines the transport direction. These folds are reported to have axial planes which parallel the mylonitic foliation and steep plunges (down the dip of the foliation) are common. Lineations defined by aligned hornblende, feldspar, streaked biotite and quartz plunge almost directly down dip, towards the northeast (Manduca, 1988).

Bonnichsen (1987), in and just south of the New Meadows area, showed more moderately east dipping fabrics, with foliations ranging from 35° to 82°E, and one, 53°E listed in the [Little] Goose Creek complex east of New Meadows.

The Riggins area

Hamilton (1963), in the Riggins area (Fig. 2-5c), recognized the Seven Devils and Riggins groups as island arc lithologies in contact with continental rocks in a zone of shearing (e.g. Hamilton, 1969). Lund (1984), just north of this area, correlated the greenschist-grade Seven Devils Group which lies below the Rapid River thrust (RRT) to the structurally higher, amphibolite-grade Riggins Group, above the RRT. The Pollock Mountain fault (PMF), which is structurally higher than, and part of the RRT system, roots into a steeply dipping mylonite zone to east (Aliberti, 1988, Fig. 2). This combined with the abrupt changes in lithology and $^{87}\text{Sr}/^{86}\text{Sr}$, defines the location of the suture. Hyndman and Talbot (1976, stop 8) locate the suture in a gradational
zone along the Salmon River, between the Riggins Group and the metasedimentary rocks of the continental basement to the east. Onasch (1987) however, did not recognize the PMF, and shows the RRT and rocks of the hanging-wall cutting across this vertical sheared zone, which corresponds to the location of Criss and Fleck's (1987) $r_i = 0.706$ contour; indicating that the suture lay farther east than the 0.706 contour.

Hamilton (1963) describes shear as being important in all metamorphic rocks except some greenstones of the Seven Devils volcanics. This shear fabric is everywhere parallel to compositional layering.

Although shear fabrics are recognized along the length of the WISZ, no studies have indicated the shear sense accompanying these fabrics, especially near the suture. However, it seems likely that the shear fabrics (flaser gniess of, Hamilton 1963, 1969) associated with, and formed in the RRT indicate a general top-to-the-northwest, sense of shear, sympathetic to apparent movement on the thrust. Strain analysis on deformed volcanic breccias indicates that the maximum elongation of the clasts was "down the dip of the foliation (S75°E 80°)" (Aliberti, 1988).

The orientation of the suture in the Riggins area is poorly constrained, but appears to be oriented roughly north-south, and to dip very steeply, near where Elkhorn Creek intersects the Salmon River (e.g. Hamilton, 1969; Hyndman and Talbot, 1976, stop 8; Onasch, 1987, Fig. 2).
The Slate Creek Area

In an effort to correlate the deformation acrosss the zone, Lund (1984), studied a transect that spanned the suture located 24 km north of Riggins and 40 km south of Elk City (Fig. 2-5c). As with previously mentioned segments of the suture, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio transition between plutonic rocks of $r_i < 0.704$, indicating oceanic source, and $r_i > 0.706$, indicating continental source occurs within a relatively narrow (about 5 km wide), northeast-trending, steeply foliated zone of tonalite gneiss (mylonite?) (R.J. Fleck, oral commun., 1982, in Lund, 1984, plate 1). It is the suture zone pluton, which occupies the same "structural position" with respect to the suture as the Little Goose Creek complex, 25 km south in the Riggins area (e.g. Aliberti, 1988: Manduca, 1988), and the Meadow Creek complex (Myers, 1982) 23 km to the north.

Lund (1984) divided the area into eastern and western metasedimentary terranes. The eastern terrane consists of rocks from the Seven Devils and Riggins groups. The western terrane is made up of 3 tectonostratigraphic units (defined by Lund, 1984), which were correlated with the Belt Supergroup and some Paleozoic units. Intruding most of this area are Cretaceous plutons ranging in composition from tonalite to muscovite granite. The earlier (82 Ma) tonalite and granodiorite were interpreted to intrude both terranes after deformation associated with the Rapid River thrust, dated at $<109$ Ma (Lund and Snee, 1988), but prior to the end of deformation. The granites are shown to have intruded after deformation (Lund, 1984).
In the western terrane, the Rapid River thrust, traced northeast from Riggins, is present on the west side of the study area. It places the Riggins Group over the Seven Devils Group along the Rapid River thrust which varies in orientation from shallow west to shallow east dipping (Lund, 1984, Plate 1) on the west and east sides of the terrane, respectively, and appears flat lying in map pattern. Movement on the thrust in this area is indicated to be approximately west-northwest by the orientation and vergence of folds associated with the thrust and east-west oriented cross sections made through the area (Lund, 1984). Folds mapped in the western terrane tend to plunge gently northeast and lie subparallel to the thin zone of foliated tonalite which corresponds to the location of the suture as defined by lithology, r,, and latest deformation.

The eastern terrane consists of a series of continental metasediments of apparent Proterozoic to Paleozoic age. They appear thoroughly intruded by Late Cretaceous age tonalite, granodiorite and granite; the metasediments are preserved as roof pendants of the intrusion (Lund, 1984, Plate 1). She shows a system of east-verging thrusts with an associated duplex preserved in the eastern pendants. Open folds associated with the thrusts appear to trend roughly parallel to the suture, similar to the deformation in western terrane.

The 5 km-wide zone of tonalite contains a "steep schistosity that parallels the suture zone [and] steep southeast-plunging mineral lineations in the plutonic rocks on the west side of the suture (Lund, 1984); fabric in some of
these rocks is lineation-dominated" (Lund and Snee, 1988). However, also note that "because of subsequent plutonism and late-stage uplift processes, no shear indicators have been found along the suture zone that could directly give the relative movement between terranes". This is the same zone that records important late-stage movement on the suture (e.g. Strayer et al., in press; Strayer et al., 1987; Manduca, 1988; Myers, 1982) in other locations.

A detailed micro- and mesoscopic study focusing on the kinematics of this zone is necessary to define the strain, to constrain pure and/or simple shear processes, and most importantly, to demonstrate the direction and sense of displacement on this zone.

The South Fork of the Clearwater River area

Myers (1982), described a shear foliated and lineated, hornblende-bearing tonalite body, the Meadow Creek complex, that lies between Riggins/Seven Devils group rocks and continentally derived metasediments. It is the "suture zone pluton" there, occupying the same structural position as the foliated tonalite of Lund (1984), separating oceanic and continental metasediment terranes (e.g. Manduca, 1988; Strayer et al., 1987). Progressive isoclinal shear-folded pegmatite stringers within the sheared "flaser gneiss" or mylonite of the Meadow Creek complex occurs identically in the mylonitic quartz diorite in the Orofino area (Strayer et al., 1987), and indicates that plutonic activity was coincident with thrust-related movement on both the northern (Hyndman et al., 1988) and southern extents of the suture between Harpster and Orofino.

North of the South Fork of the Clearwater River (Fig. 2-5b) the moderate
to steeply east dipping, Rapid River thrust system is visible again west of the suture. It makes a small acute angle with the Meadow Creek complex east of Harpster (Myers, 1982, plate 1) and appears to merge, or root concordantly, into the mylonitic rocks of the complex; the Rapid River thrust has not been recognized north of this juncture.

The Middle Fork of the Clearwater River area

West of Lowell and east of Kooskie, Idaho the suture cuts the Middle Fork of the Clearwater River (MFCR) (Fig. 2-5b). This part of the suture has not undergone any modern structural or kinematic review since Morrison (1969), prior to recent developments in the definition and location of the WISZ.

Morrison (1969), described a foliated unit that he called the Middle Fork orthogneiss (mylonite?). It outcrops near Swan Creek on the MFCR, and may occupy the same "structural location" as the Meadow Creek complex in the Harpster area and the mylonitic quartz diorite in the Orofino area. The Middle Fork orthogneiss yields K-Ar dates from biotite of 86 Ma (Morrison, 1969), similar to the other dates obtained from the deformed tonalite and quartz diorite "suture zone plutons" (ranging from 90-80 Ma).

Morrison's (1969) study was done prior to the recent understanding of mylonites and their implied simple-shear displacements, and does not include any sense of shear criteria (e.g. Simpson and Schmid, 1983). However, "structural evidence indicates that the white quartzites and schists of the [Ravalli Group?] Quartzite-Gneiss sequence are reverse faulted against the
orthogneiss... suggesting a relatively low angle [east-side-up] reverse fault" (Morrison, 1969). This is analogous to the relation between Belt rocks (Hietenan, 1962) that are thrust over and are structurally above the mylonitic quartz diorite which occupies the suture in the Orofino area (Strayer et al., 1987; 1988).

Morrison (1969), recognized four folding events for the Lochsa/Clearwater area. These he interpreted to range in age from Precambrian for the $F_1$ event, to Cretaceous for the $F_4$ event. Later work in this area has shown that the Precambrian ages may, based on isotopic age determinations from zircon, may actually be from deep crustal rocks from which the magmas may have been derived (Hyndman et al., 1988b, Reid et al., 1979), and that the plutonic rocks of this area are the earlier, more mafic phases of the Idaho-Bitterroot batholith (e.g. Hyndman and Foster, 1988; Hyndman et al, 1988b). Thus, all of the visible deformation in this area likely occurred during the Late Cretaceous.

Small-scale isoclinal, west vergent folds with steep, roughly north-south trending axes, were interpreted by Morrison and Greenwood (1967), to indicate overturned, southwest-vergent, isoclinal recumbent folding on the regional scale. These are Morrison's (1969) $F_1$ folds. The $F_2$ folds are said to deform the axial planar fabric of the $F_1$ folds. The $F_2$ fold axes describe a great circle on the stereonet which appears to define the $F_1$ axial plane: many plunge down the dip of the primary foliation. This "folded" pattern of lineations led them to interpret an $F_3$ event. It may be possible to reinterpret
the orientation of $F_2$ structures as progressive folding of the primary foliation due to top-to-the-southwest simple-shear processes (e.g. Skjernaa, 1980; Platt, 1983). The final folding event is manifest as west-vergent kink folds and "cataclastic shear folds" that are best developed in the Quartzite-Gneiss sequence which has been thrust over the Middle Fork orthogneiss (Morrison, 1969), adjacent to the suture.

Structural relations from where the orthogneiss intrudes an orthoamphibolite body indicate that the foliation in the orthoamphibolite was formed prior to emplacement and deformation of the orthogneiss unit (Morrison, 1969). Similar relationships from xenolith evidence have been observed in the Orofino/Peck area (Davidson et al., 1988).

The North Fork of the Clearwater River/Orofino area

The next good exposure of the suture is about 50 km northwest of where it intersects the North Fork of the Clearwater River (NFCR), (Fig. 2-5b): the Orofino-Ahsahka area. Part one of this study provides a structural and kinematic picture of the suture along the North Fork of the Clearwater River (NFCR) at the Dworshak Dam site near Ahsahka. Here I review some of the previous work and interpretations from this area and provide a brief review of the nature and geometry of the suture there.

Hietanen (1962) was the first to complete a detailed petrologic study in western Clearwater County, in the area adjacent to the suture. At that time, however, the suture was unrecognized, and thus much of the deformation in this region is was attributed to forceful intrusion of the Idaho-Bitterroot
batholith and associated metasomatism. Because the well developed foliations and lineations in the mylonitic tonalite and quartz diorite parallel those preserved in the adjacent, concordant, metamorphic rocks, Heitanen (1962) attributed the formation of the mylonitic plutonic rocks to metasomatic replacement or "granitization" of sedimentary rocks. Later work (e.g. Armstrong et al., 1977; Hyndman, 1983, 1988; Zen, 1985; Fleck and Criss, 1985; Snee et al., 1987) has shown that these foliated rocks are of igneous origin. Once this is understood, much can be gleaned from Hietanen's (1962) work as to the nature and timing of deformation.

Hietanen (1962) stated that the "rebuilt" plutonic rocks were stressed during mineral growth, and that "because the linear structure of the plutonic rocks is parallel to the lineation (and second fold axes) of the metasedimentary rocks, the metasomatism [deformation] seems to be contemporaneous with the folding...". These second fold axes which apparently plunge down-dip are the same as those attributed to progressive refolding of the mylonitic foliation in part one of this study, and are interpreted to form during simple shear deformation (e.g. Skjernaa, 1980;
FIGURE 2-6. Diagram illustrating the reorientation of fold axes by progressive simple shearing. Fold axes form initially at a high angle to the transport direction, and are progressively rotated to within near parallelism to the transport direction.
FIGURE 2-7. Figure from Greenwood and Reid (1969), showing the large fold that Hietanen (1962) first mapped. Greenwood and Reid took structural data from the fold and show its axis plunging 55° toward 055°. This is essentially parallel to the orientation of mesoscopic folds within the quartz diorite mylonite about 6 km away at Ahsahka.
Platt, 1983) (Fig. 2-6). The folds (axes are parallel to the mineral lineations) within the mylonitic plutonic rock plunge 48° toward 056° (Figs. 1-3, 1-5). Hietanen (1962) mapped a large, kilometer-scale fold at Orofino (near the suture and initial $^{87}$Sr/$^{86}$Sr ratio boundary), that involves mylonitic plutonic and metasedimentary units, plunging 55° toward 040° (Greenwood and Reid, 1969) (Fig. 2-7). This orientation is close to the fold axes and mineral lineations from within the nearby mylonitic quartz diorite, and strongly suggests that similar styles of deformation occur over a wide range of scales in this area.

Three major lithologic groups occur in the study area. From the southwest toward the northeast they are: 1) quartz-diorite/tonalite mylonite from the Kamiah plutonic complex. 2) mylonitic mafic metasediments (amphibolite, hornblende-biotite gniess, hornblende gniess, biotite gniess (Hietenen, 1962), found within and adjacent to the quartz-diorite/tonalite mylonite. 3) calcisilicate-quartz and amphibolite mylonite. All of these units are concordant to the local foliation (116°/54°NE) and are probably juxtaposed by faults or shears which are obscured by, and parallel, to the foliation. It is also possible that the discontinuous lenses of mafic metasediment are roof pendants that have been completely transposed, parallel to the mylonitic foliation. These mafic metasediments appear similar to Squaw Creek schist (P.E. Myers pers. comm.) and thus may be a northern scrap of the exotic Riggins Group.
An abrupt transition from mafic metasedimentary and plutonic lithologies to quartz-rich (Belt Supergroup) mylonites is northeast of Ahsahka (the Marina and Big Eddy boat ramp) and on the northeast edge of the quarry. This boundary, which lies close to the $0.704 < r_i < 0.706$ boundary for Sr (Armstrong et al., 1977; Fleck and Criss, 1985), may define the suture zone in this area. This does not, however, imply that the suture, the boundary between low $r_i (< .704)$ sheared plutonic rock and continental lithologies, is a distinct and discrete structural feature: it may be locally folded (Hietanen, 1962) into steep plunging isoclines (Greenwood and Reid, 1969), which, combined with the deformed plutons within the suture itself, would make the precise location of the actual break between North America and the Seven Devils/ Wallowa terrane, impossible to determine at outcrop scale.

Discussion

The reader is encouraged to investigate the original works referenced above for the detailed interpretations for the data summarized above. Although specific areas along the suture each show unique deformational features, the WISZ extending from McCall to Orofino and Ahsahka generally shows two deformational styles; vertical tectonic processes to the south give way to west-directed thrusting north of the Slate Creek area. No detailed microstructural or kinematic work has been done on the "suture zone plutons" south of Slate Creek.

The deformational mechanism invoked by Manduca (1988) for the McCall area is that of horizontal shortening or pure shear accommodated by
"flattening vertical transport." This interpretation reflects the inconsistent asymmetry of folds and because the similarity of metamorphic grade across the zone may preclude vertical offset. However, on a field trip through this area led by Manduca for the Hells Canyon Geologic Society (8/87), I observed evidence of fabric and augen asymmetry within the various mylonites which, upon preliminary observation, have consistent west-side-down sense of displacement. In a regime where the fabrics are formed by pure shear or in effect vertical extrusion of the pluton into the suture, one should expect to find opposite fabric asymmetry across the zone that is east-side-up on the western border of the zone and west-side-up on the eastern border of the zone. This does not seem to be the case.

Citing the "subvertical" orientation of the foliated tonalite which lies at the boundary between the eastern and western metasedimentary terranes, combined with the "mirrored geometry" of the the thrust systems in each terrane, Lund (1984) modelled the suture as a zone of "vertical movement at the center with thrust and fold transport that diverged away from the boundary in either direction". This is based on a model of right-lateral, transpressive accretion (Lund and Snee, 1988) of the western terrane against the steep boundary of North America.

Lund (1984), was the first to suggest a "flower structure" geometry for the suture. Aliberti (1988) later interpreted the Pollock Mountain area to the south as half a flower structure. Lund's (1984) is the only study that appears to document the east-vergent, eastern half of the flower structure, as it is
aparently preserved, in roof remanents capping massive plutonic intrusions. In this scenario the "suture zone plutons" are interpreted to involve no simple shear: deformation by vertical flattening seems to prevail (Lund, 1984, 1988; Aliberti, 1988; Manduca, 1988).

No east-verging structures are found on the segment of the suture located between the SFCR and Orofino. Only west-vergent, top-to-the-southwest movement is indicated on either side of the suture north of Slate Creek (Morrison, 1969; Myers, 1982; Strayer et al., 1987, 1988), (Fig. 2-5b).
Chapter III

Integrated geometry of the WISZ

Introduction

The orientation of the suture changes from being dominated by vertical tectonics south of Slate Creek, to top-to-the-west thrusting north of there. This is an important change in the structural style of the suture from that of vertical tectonics in the south (e.g. Lund, 1984; Aliberti, 1988; Manduca, 1988; Lund and Snee, 1988) to that of large-scale, east-over-west thrusting along the northern extent of the WISZ (e.g. Strayer et al., 1987, 1988, in press; Myers, 1982).

On the Slate Creek traverse the suture trends north-northeast, appears to be steeply east dipping, and symmetrically flanked by generally shallow dipping, east- and west-verging thrust systems which may root into the suture. However, just 24 km north, on the SFCR, the style of deformation changes from a zone of symmetric, vertical deformation to a zone of consistent east-side-up movement, along a series of anastomosing, subparallel thrust faults and reverse shear zones. In the Harpster area all pre-Tertiary high-angle structures are found to be reverse faults and shear zones that show east-side-up sense of displacement. These faults and shear zones dip eastward and southeastward 25 to 70°; there are no west-dipping or east-verging structures shown in this area (Myers, 1982, plates 1 & 2). The suture appears to roll over to an eastward dip as it is traced northward from Slate Creek.
The eastward dip of gneissic (shear) foliation and reverse faults is apparently continuous from the Harpster area, north across the Middle Fork of the Clearwater River (MFCR) east of Kooskia. It continues north toward Orofino and Ahsahka, where the dip of the suture is about 55° northeast.

Discussion

The six transects across the suture give a reasonably clear picture of the orientation of the "plane" of the suture as it is traced from from McCall, north to Orofino/Ahsahka. Certain features are present in each of the transects:

1. The presence of deformed, low or transitional Sr r, value plutons within or bordering the suture, which exhibit a penetrative foliation and/or lineation.

2. Radiometric dates on hornblende from the "suture zone plutons" fall between 80-90 Ma by Criss and Fleck, (1987), ranging from 87 Ma in McCall (Manduca, 1988), 86 Ma at Slate Creek (Lund and Snee, 1988) and the MFCR (Morrison, 1969), and 83 Ma near Orofino (Snee et al., 1987).

3. Moderate to steeply east/vertical dipping and plunging foliations and lineations within the "suture zone plutons."

4. On the west side of the suture, in all cases, (except perhaps at McCall, where evidence is sparse), the structures show an east-side-up, top-to-the-southwest sense of movement.

These features suggest a Late Cretaceous common origin for the current form of the suture extending from McCall to Orofino/Ahsahka. The essentially coeval period of intrusion for the "suture zone plutons" indicates that the suture was a steeply dipping crustal discontinuity that had the effect of
focusing a curtain of magmatism along its length.

There are, however, some distinct differences in structural style and metamorphism along the length of the WISZ. The major break in structural styles apparently occurs between the Slate Creek and SFCR transects, although the SFCR transect is somewhat transitional in some respects. The features or aspects which differentiate the suture north of the SFCR from that to the south are:

1. Gross orientation of the suture, as defined by $r_i$ and the "suture zone plutons": the trace of the southern WISZ is straight, oriented approximately north-south, and marked by steeply east-dipping to vertical fabrics. The trace of the northern segment forms an east-directed embayment, dominated by moderately east-dipping fabrics.

2. Sense of movement: the southern portion may be symmetrically vergent away from the suture, although only Lund's interpretation of the Slate Creek transect suggests this: east vergent thrusts are not recognized south or north of this transect.

3. The Rapid River and associated thrust systems are not present north of the Harpster quadrangle: it apparently roots (in map and crosssectional views), into the suture about 10 km north of the SFCR.

Along the trace of the suture, from McCall to Orofino, most of the associated metasedimentary rocks are in the amphibolite facies (e.g. Lund, 1984; Myers, 1982; Hamilton, 1963; Hietanen, 1962). The kyanite/migmatite assemblage northeast of the Orofino area near Boehls Butte (Hietanen, 1984), is also
found inboard of the suture on the MFCR (Morrison, 1969), but is not recognized in the area of the SFCR (Myers, 1982) or south of that area. The kyanite/migmatite assemblage may indicate pressures of around 7 kbar, and depths of ≥ 20 km (Hyndman et al., 1988a) for the continental rocks exposed north of the Harpster area (Fig. 2-8). Given the east-over-west (thrust) geometry of this segment of the suture, the structurally underlying footwall rocks in the accreted terrane may have been at least at this depth adjacent to the suture.

The Rapid River thrust system which cuts greenschist facies rocks in the Riggins area, roots into amphibolite-grade rocks of the WISZ toward the north near Harpster. This suggests that deeper
FIGURE 2-8. Phase diagram after Hyndman et al. (1988), showing that pressures of around 7 kbars and depths of >20 km are indicated by the presence of the kyanite-migmatite assemblage found in the hanging-wall of the Clearwater culmination.
FIGURE 2-9. The Clearwater culmination of the western Idaho suture zone, located within the North, Middle and South Forks of the Clearwater River. Only east-side-up, west-directed thrusting is indicated on this segment of the suture.
structural levels are exposed as the suture is traced north. The presence of
the deep-level kyanite/migmatite assemblage north of the SFCR area is
consistent a south plunging geometry. Assuming that the thrusts merge with
the root zone at a constant depth, due to increased plasticity with depth, the
south plunging geometry suggests that deeper levels of the suture are
exposed north of the SFCR.

The deeply exposed nature of the suture, combined with the reverse-slip
or thrust geometry north of Slate Creek suggests that this segment of the
suture is a regional scale, west-vergent, structural and metamorphic
culmination. It is herein named the Clearwater culmination (CC) of the WISZ
because the suture and its west-vergent geometry is exposed along the three
forks of the Clearwater River (Fig. 2-9).

In their discussion of reasons for the preferred location of a culmination in
one place and not another, Boyer and Elliot (1982) noted that a "change in
the ductility of the formations" along the strike of the structure could have the
effect of focussing a culmination. It appears that the continental boundary
marked by the WISZ was initially near vertical, as indicated by the close
proximity of the 0.704/0.708 r contours (Lund, 1984; Criss and Fleck, 1987;
Lund and Snee, 1988). The convergence of the Seven Devils/Wallowa
terrane, due to either transpression (Wernicke and Klepacki, 1988; Aliberti,
1988; Lund and Snee, 1988) or simply normal convergence was apparently
accomodated north of Slate Creek by west-vergent thrusting of the
Proterozoic Belt Supergroup over the converging terrane, as it was accreted
onto or inserted into North America.

This suggests that some important change in rheology, structural fabric and/or composition of the continental crust, may exist between the northern and southern segments of the WISZ. North of Slate Creek this change caused the near-vertical continental boundary to roll over above the Archean basement to an eastward dip in response to resolved east-west directed compression: the root zone of a continental-scale west-directed thrust system.
Introduction

Evidence for the basement discontinuity that may be responsible for the location of the Clearwater culmination of the WISZ may come from the central Montana trough (CMT) (Peterson, 1981), otherwise known as Helena embayment of the Belt basin (Winston, 1986). It is an east-west oriented trough, that subsided during "Precambrian Belt time" but also contains thick Paleozoic and Mesozoic sequences (Peterson, 1981). Independent of any structural interpretations, Winston (1986), defined four "lines" or growth fault zones "based on linear trends of abrupt stratigraphic thickness changes that coincide with local patches of soft sediment deformation." Two of these, the Garnet and Perry lines, mark the northern and southern extent of the trough which is interpreted to be an aulacogen (Precht and Shepard, 1989) (Fig. 2-10).

No western edge of the Belt basin is preserved: the presence of Belt metasediments juxtaposed against the allochthonous Permo-Triassic Seven Devils/ Wallowa terrane indicates that the WISZ is located within the projected boundary of the Proterozoic Belt basin. Assuming the WISZ was originally straight (due to the above-mentioned right-lateral, north-south oriented, strike-slip faulting proposed for the Jurassic by Sears and Schmidt (1986), it would
FIGURE 2-11. Hypothetical relation between the Central Montana trough (CMT), bounded on the north and south by the Garnet and Perry lines, respectively, and the initially vertical and straight WISZ (front-left face of block). Sediments of the CMT (white) are exposed to the convergent Seven Devils/Wallowa terrane, perhaps enabling it to wedge into North America, between the sediments and the Archean basement (x pattern).
intersect at nearly a right angle the east-west trending Central Montana Trough, which Winston (1986) extends through north-central Idaho. The thick succession of Proterozoic through Mesozoic sediments lying unconformably above Archean basement, within the half graben (Schmidt and Garahan, 1986) trough is perhaps the ideal crustal discontinuity: exposing the soft sediments to the "plane" of the suture (Fig. 2-11).

Relation of the WISZ to crustal features in Montana and Idaho

Winston (1986) shows the Garnet line extending as far west as west-central Idaho, and notes that it aligns perfectly with the sharp east-west bend in the $^{87}\text{Sr}/^{86}\text{Sr}$ r$_i$ values of the northern WISZ. In a structural and metamorphic synthesis of the Idaho batholith region, Hyndman et al. (1988) relate the bend in the r$_i$ values to be due to left-lateral displacement on the Lewis and Clark fault zone, the southern-most faults coinciding with the Garnet line. On the southern side of the Central Montana Trough, the Proterozoic Perry line coincides spatially with Late Cretaceous deformation of the southwest Montana transverse zone (Schmidt et al., 1988). It is a major structural feature in western Montana that has been traced as far west as Lost Trail Pass on the Idaho-Montana border (Desmaris, 1978).
FIGURE 2-12. Map showing apparent off-set of the two thrust belts in Montana across the Garnet and Perry lines.
Map patterns

The map patterns of the Clearwater culmination, the Bitterroot mylonite, the leading edge of the Sapphire plate, and the leading edge of the Disturbed belt are similar, pronounced, east directed salients with the apparent left-lateral offsets on the northern margins, and right-lateral offsets to the south, across the Garnet and Perry lines respectively (Talbot and Hyndman, 1973; Hyndman et al., 1975), and align with the Clearwater culmination (Fig. 2-12).

Fold axes and cleavage appear to be offset across the Garnet line, showing left-lateral shear zone geometry (Sears et al., 1987) (Fig. 2-13a,b). The zone was described as "a ductile transform during the growth of the western Montana thrust and fold system" (Sears et al., 1987).

Cretaceous deformation

There is strong evidence for Late Cretaceous deformation across the Central Montana trough. A well developed axial-planar cleavage (Fig. 2-13a) is found within Proterozoic through Mesozoic rocks that are the southward projection of the Purcell Anticlinorium (Sears, 1988). It is intruded by the 82 Ma (K-Ar) Garnet stock (Ruppel et al., 1981), which lies adjacent to the Garnet line. Cordierite found within the metamorphic aureole of the Garnet stock is cleaved (Minnich, 1984). This indicates that the latest movement on the suture near Orofino was roughly synchronous with deformation and intrusion in western Montana.
FIGURE 2-13. Offset of Cretaceous age cleavage (2-13a) and fold axes (2-13b) across the Lewis and Clark zone (Sears et al., 1987; Winston, 1986). The Garnet line bounds the southern extent of the zone.
FIGURE 2-13b.
FIGURE 2-14. Location of thrust features within the Central Montana Trough. The Garnet line appears to bound the WISZ to the north. If the Perry line is extended toward the WISZ, it intersects in the area around Slate Creek.
The east-west oriented, half graben, Central Montana Trough is apparently hinged along the eastern Garnet line to the north and bound by a steep normal fault, to the south at the Perry line (e.g. Schmidt and Garihan, 1986, Figs. 6,8; Sears, 1988). It is possible that the Central Montana trough extended west to the inferred Proterozoic rift and subsequently, affected the location of the Clearwater culmination of the WISZ. The Garnet line certainly appears to bound the northern extent of the culmination and WISZ in the Orofino area, and the Perry line may bound the southern extent of the Clearwater culmination near the Slate Creek-SFCR area (Fig. 2-14). The geometric relation between the location of the Clearwater culmination and the projection of the Central Montana Trough into western Idaho, combined with roughly coeval deformation, metamorphism and plutonism across the zone from western Idaho to the Montana disturbed belt, shows that, like similar Sevier deformation documented in east-central Nevada and western Utah (e.g. Miller et al, 1988) the metamorphism and plutonism of the deep-level hinterland (Idaho and western Montana) is broadly synchronous with cleavage development and deformation to the east; the hinterland acts as a ductile root zone for the shallow thrust system to the east.

Since the deformation in the Montana overthrust belt appears to immediately postdate (Hyndman and Alt, 1987) the 82 Ma locking of the WISZ in the Orofino area, it seems likely that strain was transferred from the WISZ to the thrust systems of Montana (Hyndman et al., 1988a)
Model for tectonic wedging

One striking structural feature may provide a clue to linking the movement of the convergent Seven Devils/Wallowa terrane to thrust deformation in Montana: tectonic vergence. Price (1986) showed that tectonic wedging is often indicated by a pronounced change in tectonic vergence associated with suturing, citing the Quesnellia and Stikine terrane boundaries as examples. In this model, allochthonous suspect terranes are emplaced as wedges between the overlying miogeoclinal rock and the underlying North American basement: an obvious zone for tectonic decoupling. The zone of structural divergence where structures "roll over" to the opposite vergence indicates the approximate "toe" of the wedge (Fig. 2-15). This model uses standard balanced cross-section techniques, such as the orientation of west-dipping surface structures in the hanging wall, to reflect the geometry of the footwall ramp, the inserted wedge.

The pronounced westward structural vergence north of Slate Creek, along the WISZ extends eastward toward the Idaho-Bitterroot batholith (Hyndman and Talbot, 1976); with some minor exceptions, structures show east vergence immediately east of the batholith (Reid et al., 1979). The east vergence extends all the way to the disturbed belt (Hyndman et al., 1975, 1988, Fig. 8). This change from east- to west-dipping structures roughly
FIGURE 2-15. Diagram illustrating tectonic wedging of the Seven Devils/Wallowa (SD/W) terrane into North America. The terrane is inserted between the sediments of the Central Montana Trough and the Archean basement. Thrusts of the Montana disturbed belt (MDB) and from the leading edge of the Sapphire plate (SP) merge at depth below the Idaho Bitterroot batholith (IBB).
coincides with the axis of a broad, southeast trending, open syncline of Lower Belt through Wallace, within which the Idaho-Bitterroot batholith appears to lie in broad concordance (Hyndman et al., 1988, Fig 8; Idaho state geologic map). The WISZ is west of and dips beneath the Idaho-Bitterroot batholith. If the west dipping Sapphire and frontal Montana Disturbed Belt thrusts systems of Montana, also dip beneath the batholith, these faults may merge or at least intersect at depth below the Idaho-Bitterroot batholith and tectonic wedging is the mechanism of deformation where the WISZ intersects the Central Montana Trough in western Idaho. Hyndman et al. (1975) and Hyndman (1983), however, infer that the Montana thrust systems merge with the east-dipping Bitterroot mylonite zone on the east flank of the Idaho-Bitterroot batholith.

The tectonic wedging model is compatible with the lack of basement involvement in the Late Cretaceous deformation within the Central Montana Trough (aside from some slivers, probably from the Dillon block, associated with the resolved strike-slip motion of the southwest Montana transverse zone, e.g. Schmidt et al., 1988, Schmidt and Garihan, 1986). This may indicate that thrusting occurs above basement, where the material within the Central Montana trough may have been decoupled from the Archean basement, perhaps along a decollement at the base of the Belt. There is some evidence, however, of basement involvement near the Idaho batholith (Chase, 1973; Hyndman et al., 1975; Hyndman, 1983), although this may be due thermal effects and vertical drag associated with emplacement of plutons.

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Summary

The Seven Devils/Wallowa terrane arrived at its current latitude either by left- or right-lateral transpression (Lund and Snee, 1988; Wernecki and Klepacki, 1988; Aliberti, 1988) against the sharp, near vertical, continental boundary at around 118 Ma (Lund, 1984; Lund and Snee, 1988). The entire western Idaho suture zone may have initially been a zone of vertical movement. However, west-directed thrusting on the northern WISZ suggests different basement behavior may be responsible for the change in structural style with continued convergence.

The combination of renewed normal convergence at <109 Ma (Lund and Snee, 1988), increased ductility caused by the location of the Kamiah plutonic complex on the suture, and the "soft" Proterozoic through Mesozoic sedimentary sequences of the adjacent Central Montana Trough, may have provided an ideal sub-horizontal discontinuity into which the Seven Devils/Wallowa terrane is wedged above the Archean basement, creating the Rapid River thrust system in the footwall. Continued convergence, wedging, and west-directed thrusting may have delaminated the thick sedimentary sequence from the underlying Archean basement of the Central Montana trough. As wedging, and the subsequent thrusting began north of Slate Creek, on the continental side of the suture, the east dipping WISZ raised deep-level metamorphic assemblages on the west limb of the "batholith syncline" (Hietinen, 1984; Morrison, 1969; Hyndman and Talbot, 1976; Hyndman et al., 1988; Strayer et al., 1988). Continued wedging increased
the thickness of the orogenic pile in west-central Idaho until the east-sloping wedge reached the "critical taper" (c.f. Davis et al., 1983); its subsequent failure and downslope flow may have caused the formation of the east-directed, west-dipping thrust systems of Montana.

The above, tectonic wedge model assumes that simple shear is the mechanism by which crustal thickening occurs. An alternative is possible; tectonic thickening by pure shear. In this case, the margin of the crust is initially "squeezed" from the sides so that thickening is accommodated by vertical flow and flattening. Once the area reaches some critical amount of "orogenic head" it should again fail by outward flow and thrusting. The results should be similar but the root zone implied by the wedging model would not be present. Instead the thrusts should die out at depth toward the center of the thickened area, or reappear as detachments on the east flank of the thickened orogenic welt (e.g. Hyndman, 1983). The presence of the east-dipping, amphibolite grade shear zone marking the WISZ, plunging beneath the batholith, and acting as the root zone to the west-vergent Rapid River thrust suggests that simple shear was the prevalent mechanism for crustal thickening north of Slate Creek.

An additional major contribution to the thickening of the orogenic belt was probably provided by thermal swelling of the lithosphere accompanying rise of mafic magmas and formation of the Idaho batholith (Hyndman, 1983; Hyndman and Foster, 1988).
Conclusion

Offset of late-stage pegmatites across sheared basaltic dikes demonstrates that relative sense of shear is top-to-the-southwest in western Idaho suture zone mylonites near Orofino, Idaho. At least 27 km and more likely at least 80 km of simple-shear displacement is indicated across the 1.5 km thick quartz diorite/granodiorite mylonite. The orientation of mylonitic lineation and shear-fold axes, as well as large-scale symmetry relations, indicate that the movement occurred in a northeast-southwest direction.

The deformational style at Orofino appears to be one of two styles recorded along the length of the WISZ; vertical movement and flattening dominate the southern part and only west-directed thrusting is recorded on the northern part of the WISZ. This area of thrust deformation is called the Clearwater culmination, and it's location may be a result of intersecting the Central Montana trough with the WISZ between Slate Creek and north of Orofino. The soft Proterozoic through Mesozoic sedimentary rocks may have allowed the insertion of the northern Seven Devils/Wallowa terrane as a tectonic wedge into continental North America, perhaps delaminating the overlying trough sediments from Archean basement.

Tectonic wedging combined with thermal swelling from the main- and associated phases of the Idaho-Bitterroot batholith, would have the combined effect of causing the thickening of the crust and its subsequent downslope failure. The result is the foreland fold and thrust belt in Montana, that may or may not root at depth below the batholith and into the suture zone.
Appendix 1

Shear strain calculations for the offset of late-stage pegmatite dikes across sheared mafic bands (see figure 1-2).

Two different methods were used; 1) The cotangent method, where shear strain equals the cotangent of the initial angle between the undeformed pegmatite and the sheared mafic band $\alpha$ is subtracted from the cotangent of the final angle between the deformed pegmatite and the sheared mafic band $\alpha'$ within the band. 2) The slip/width method, which simply divides the amount of offset of the pegmatite in the direction of shearing by the width of the sheared mafic band. In all cases both methods yield similar or identical shear strains except band 4, where the geometry of the system caused some measurement error.

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(angles in degrees, distances in cm)
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