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A mid-crustal contractional stepover zone in a major strike-slip system, North Cascades, Washington

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Abstract—The segmentation of strike-slip faults at the Earth's surface is well known, but the geometry of these faults in the mid-crust is poorly understood, as are the intervening stepover zones. A mid-crustal example of a segmented strike-slip fault is present within the >500-km-long Ross Lake fault system where the NW-striking Twisp River fault zone and Gabriel Peak tectonic belt occur as overlapping, left-stepping, dextral strike-slip shear zones. The contractional stepover between these structures is occupied by the Black Peak batholith, which is riddled by ductile shear zones that are typically 0.5–1.5-m thick and are restricted to the stepover. Gently to moderately NW-dipping, reverse-slip ductile shear zones in the center of the stepover strike at a high angle to the Twisp River fault zone and Gabriel Peak tectonic belt and lie in an appropriate position to transfer most of the displacement between the strike-slip segments.

The orientation of the reverse-slip ductile shear zones relative to the strike-slip segments is broadly similar to that of folds and thrusts in upper-crustal stepovers. The stepover width is relatively large, however, in comparison to many active stepovers. Emplacement of the Black Peak batholith across an originally narrower stepover or bend in the fault system may have created a rigid buttress and subsequent deformation jumped to the mechanically weak southwest margin of the body. Because plutons are commonly intruded into strike-slip zones, such partitioning of later displacements may be widespread.

INTRODUCTION

STRIKE-SLIP faults are commonly segmented at shallow crustal levels (e.g. Wallace 1973, Segall & Pollard 1980, Aydin & Nur 1982, 1985, Aydin & Schultz 1990) where slip is typically transferred between fault segments by a zone of distributed extensional or contractional deformation. The type of deformation (extensional vs contractional) in the stepover zone depends upon the sense of slip on the strike-slip segments and the direction of the step between them. In the upper crust, the styles of deformation in the stepover include pull-apart basins or push-up structures between the principal strike-slip segments (e.g. Crowell 1974, Sylvester 1988), or a series of faults that form strike-slip duplexes between the principal fault segments (Woodcock & Fischer 1986). A related style is a major S- or Z-type bend in the principal fault with accompanying minor faults and folds (e.g. Crowell 1974). These upper-crustal structural styles have all been observed in different orogens, but much less is known about the three-dimensional form of stepover zones at mid-crustal and greater depths.

A fundamental question is how far downward fault jogs penetrate the ductile part of the crust. Some workers suggest that segments coalesce downward into a single fault or narrow fault zone (e.g. Clayton 1966, Sharp & Clark 1972), a relationship duplicated by experimental models of 'wrench faulting' where basement faults propagate upward into en échelon Riedel shears that display a helicoidal geometry (Naylor *et al.* 1986). Other evidence, however, suggests that surface fault geometries extend at least to the base of the seismogenic regime and may continue considerably farther downward (e.g. Reasenberg & Ellsworth 1982, Sibson 1986, ten Brink & Ben-Avraham 1989). Most studies have concentrated on the geometry of dilational stepovers and on such problems as whether associated pull-apart basins sole into subhorizontal detachments (e.g. ten Brink & Ben-Avraham 1989). Few workers, however, have addressed the geometry and kinematics of the deeper levels of contractional stepovers, the subject of this paper.

The Cretaceous and Paleogene Ross Lake fault zone in the North Cascades of Washington and southwestern British Columbia (Fig. 1) provides an example of a segmented strike-slip system where individual segments extend to mid-crustal levels without merging. The contractional stepover zone between these segments is occupied by a large pluton which is strongly deformed by distributed ductile shear zones. These ductile shear zones probably serve the same role as folds and thrusts in shallow contractional stepovers and have implications for the geometry and interaction of segmented faults in the mid-crust.

ROSS LAKE FAULT ZONE

The NW-striking Ross Lake fault zone is an ~10-km-wide, >500-km-long system of fault zones that forms the northeastern boundary of the mainly Mesozoic crystalline core of the North Cascades (Figs. 1 and 2) (Misch 1966, Miller & Bowring 1990). This fault system forms both a major lithological boundary that has been interpreted as a terrane boundary (e.g. Tabor *et al.* 1989) and a metamorphic discontinuity. A pre-Upper Cretaceous oceanic assemblage (Napeequa unit of the Chelan Mountains terrane) lies southwest of the fault zone and

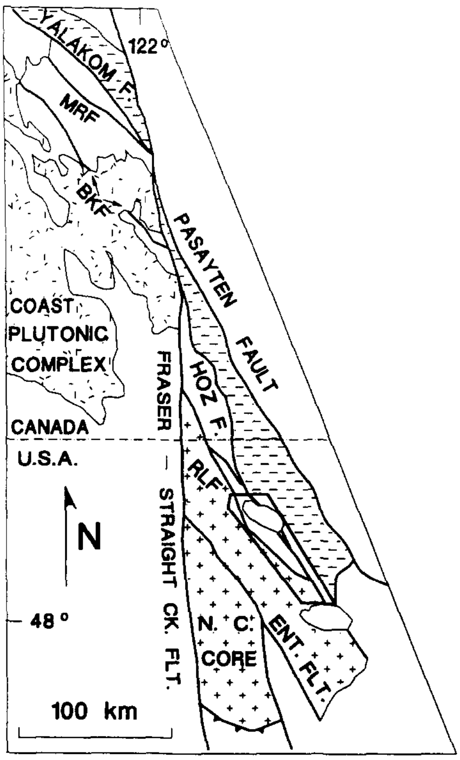

Fig. 1. Map emphasizing the location of major Cretaceous and Paleogene high-angle faults in northern Washington and southwestern British Columbia. Box shows location of Fig. 2. BKF = Bralorne–Kwoiek fault; ENT. FLT. = Entiat fault; HOZ. F. = Hozameen fault; N.C. CORE = crystalline core of the North Cascades; MRF = Mission Ridge fault; RLF = Ross Lake fault; dash pattern = Methow basin and its correlative the Tyaughton basin. Note that the Fraser–Straight Creek fault offsets the other high-angle faults. The Hozameen fault and Yalakom fault are generally considered to be correlative, whereas the Ross Lake fault has been correlated with both the Bralorne–Kwoiek fault and Mission Ridge fault; all are thus considered part of the Ross Lake fault system according to the original definition of Misch (1966).

Jurassic and Cretaceous shallow marine and subaerial clastic and volcanic rocks of the Methow basin (Methow terrane) occur to the northeast (Fig. 2). Metamorphic grade is mainly mid- to upper amphibolite facies on the southwest (metamorphic $T > 650°C$ and P as high as 9 kbar) within the oceanic terrane and decreases to sub-greenschist facies on the northeast within the Methow terrane. In the intervening area along part of the fault zone are fault-bounded lenses of intermediate metamorphic grade that have protoliths typical of the Methow terrane.

The Ross Lake fault zone has a complex, protracted history. The kinematics of the initial juxtaposition of the oceanic assemblage against the Methow basin have been obscured by intrusion of plutons, ranging in age from 91 to 48 Ma, into the fault zone. Furthermore, early formed pre-Late Cretaceous structures have been strongly overprinted by several phases of Paleogene displacement. Latest Cretaceous and younger motion was dominantly dextral strike-slip, although Paleocene thrusting and an Eocene component of normal slip occurred in parts of the fault zone (Miller & Bowring 1990).

In the southern part of the Ross Lake fault zone, the Twisp River fault zone and the central section of the Gabriel Peak tectonic belt were interpreted by Miller & Bowring as overlapping strike-slip segments (Fig. 2). The ~10-km-wide stepover zone between these shear zones is occupied by the mid-Cretaceous Black Peak batholith. This batholith was apparently intruded across a stepover or a major bend in the contact between the oceanic terrane and the Methow basin and deformed during subsequent movements. Microstructures and metamorphic assemblages (upper greenschist to amphibolite facies) in mylonites associated with the strike-slip segments and in the stepover zone record deformation at depths below the brittle–ductile transition and presumably within the mid-crust.

TWISP RIVER FAULT ZONE AND GABRIEL PEAK TECTONIC BELT

The Twisp River fault zone, together with the North Creek fault to the northeast, is a splay of the Foggy Dew fault zone (Fig. 2). The Twisp River fault zone extends northwestward for ~ 15 km from its intersection with the Foggy Dew fault zone, where it is about 1 km wide, to its termination at the Black Peak batholith (Fig. 2). The area of the intersection with the batholith is poorly exposed, although there is some suggestion that the Twisp River fault zone narrows toward the Black Peak as shown in Fig. 3. The fault zone juxtaposes the polydeformed Twisp Valley Schist of the oceanic assemblage against a homoclinal sequence of pre-Upper Cretaceous arkoses and volcanic and volcaniclastic rocks of the North Creek Volcanics, which are probably part of the Methow terrane. Local mylonitic tonalitic gneisses in the fault zone may be derived from the Paleocene Oval Peak batholith (Miller & Bowring 1990). Mylonitic foliation in the Twisp River fault zone has a nearly vertical dip, the stretching lineation is subhorizontal, and kinematic indicators record dextral strike-slip.

The Gabriel Peak tectonic belt is a >70-km-long shear zone that can be considered in terms of three sections from northwest to southeast (Fig. 2). In the northern and central sections, the tectonic belt places mylonitic Black Peak batholith against the oceanic assemblage and Cretaceous and Paleogene orthogneisses of the Skagit Gneiss. Intrusion of the batholith obliterated the contact between the oceanic assemblage and the Methow basin. A narrow screen of the oceanic assemblage also occurs in the southern section where it separates the Oval Peak batholith from the Skagit Gneiss (Miller & Bowring 1990).

The Gabriel Peak tectonic belt curves from a strike of ~310° in the southern and part of the central section to a more northerly orientation in the northern section. Dips are mostly moderate to steep (50–75°) to the northeast in the central and northern sections where a stretching lineation plunges gently north (Figs. 3 and 4). Kinematic indicators are ambiguous in the far north, but consistently demonstrate dextral strike-slip in the central section. A significant transition occurs from the central to southern sections, as the stretching lineation changes gradually from subhorizontal to down dip (Fig. 4), and movement changes from dextral strike-slip to SW-directed thrusting (Fig. 2). This transition occurs directly across strike from the termination of the Twisp River fault zone.

The age of ductile deformation in part of the Gabriel Peak tectonic belt is reasonably well bracketed. In the southern section, thrusting occurred between ~ 65 and 57 Ma with some earlier motion likely (Miller & Bowring 1990). The central dextral strike-slip section was probably active at about 65–68 Ma (Hoppe 1984, Miller & Bowring 1990), but the lower and upper bounds to deformation are poorly bracketed. The northern section was active before, during(?) and after emplacement of a deformed pluton which resembles a distinctive Paleocene (~60 Ma) leucocratic orthogneiss in the southern section (Haugerud *et al.* 1991). Ductile deformation preceded brittle E- to ENE-striking cross faults with left-lateral separation (Figs. 2 and 3) that elsewhere offset rocks that are as young as 50 Ma.

The magnitude of strike-slip on the Twisp River fault zone and Gabriel Peak tectonic belt, as well as the Ross Lake fault system as a whole, is unknown because the different structural levels on either side of the system preclude correlation of piercing points. Displacement for the fault system is likely to be large (more than tens of km) in view of its great length and the major lithological and metamorphic contrasts across it. Furthermore, Umhoefer *et al.* (1989) have estimated ~150 km of dextral slip on the Yalakom fault, one of the structures within the system in British Columbia that is probably the offset continuation of the Hozameen–North Creek fault (Monger 1986) (Fig. 1).

BLACK PEAK BATHOLITH

The dominantly tonalitic and granodioritic, mid-Cretaceous (88–91 Ma, U/Pb zircon; Hoppe 1984, S.A. Bowring written communication 1990) Black Peak batholith is mylonitized on the southwest within the Gabriel Peak tectonic belt, whereas on the northeast it intrudes the low-grade North Creek Volcanics. This intrusion lies across the projection of the Twisp River fault zone (Fig. 2). The eastern part of the pluton may have crystallized near the roof of the body (Adams 1964), as the country rocks (North Creek Volcanics) are lower grade than elsewhere and altered screens of the oceanic assemblage are intruded by a heterogeneous series of porphyritic bodies of the batholith a short distance southwest of the Twisp River fault zone. Hornblende barometry also confirms relatively shallow (≤3 kbar) levels of emplacement (Miller *et al.* in press).

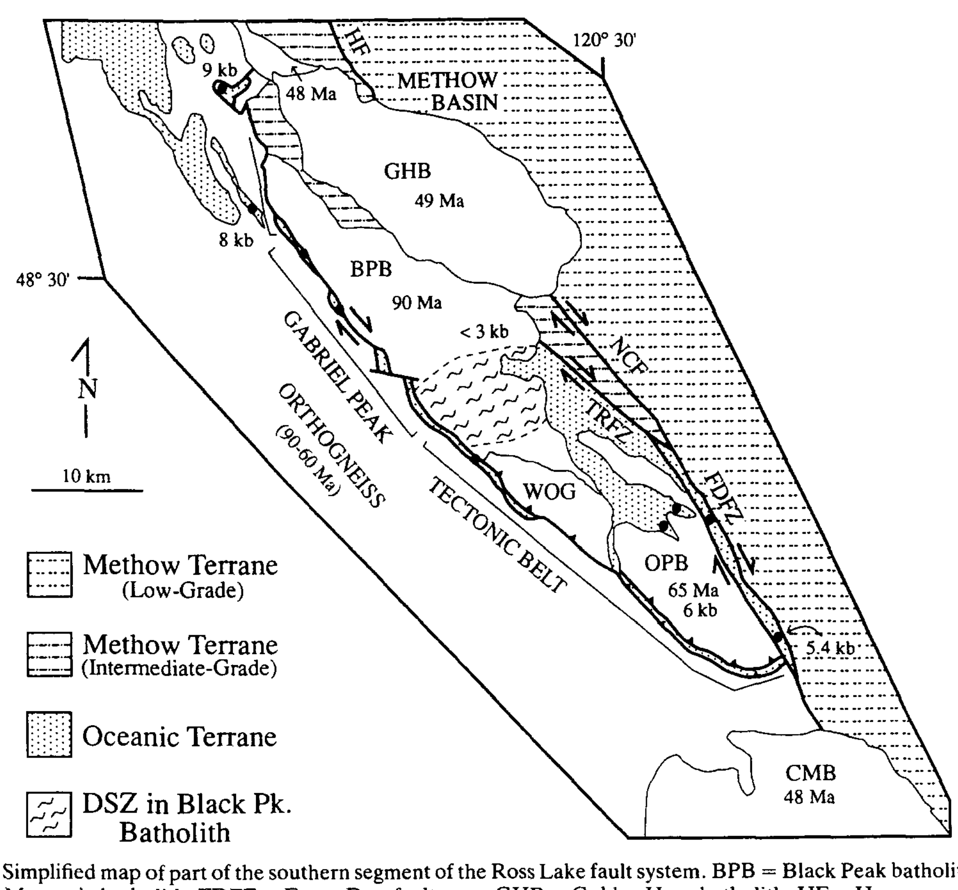

Fig. 2. Simplified map of part of the southern segment of the Ross Lake fault system. BPB = Black Peak batholith; CMB = Cooper Mountain batholith; FDFZ = Foggy Dew fault zone; GHB = Golden Horn batholith; HF = Hozameen fault; NCF = North Creek fault; OPB = Oval Peak batholith: WOG = War Creek orthogneiss, a variably foliated, Late Cretaceous (S.A. Bowring written communication 1992) tonalite to trondhjemite gneiss. Brackets indicate locations of southern, central, and northern sections of the Gabriel Peak tectonic belt. Pressures for plutons are based on hornblende barometry, whereas others are metamorphic pressures. Solid circles are locations where garnet zoning profiles indicate an increase in pressure during metamorphism (Miller *et al.* in press).

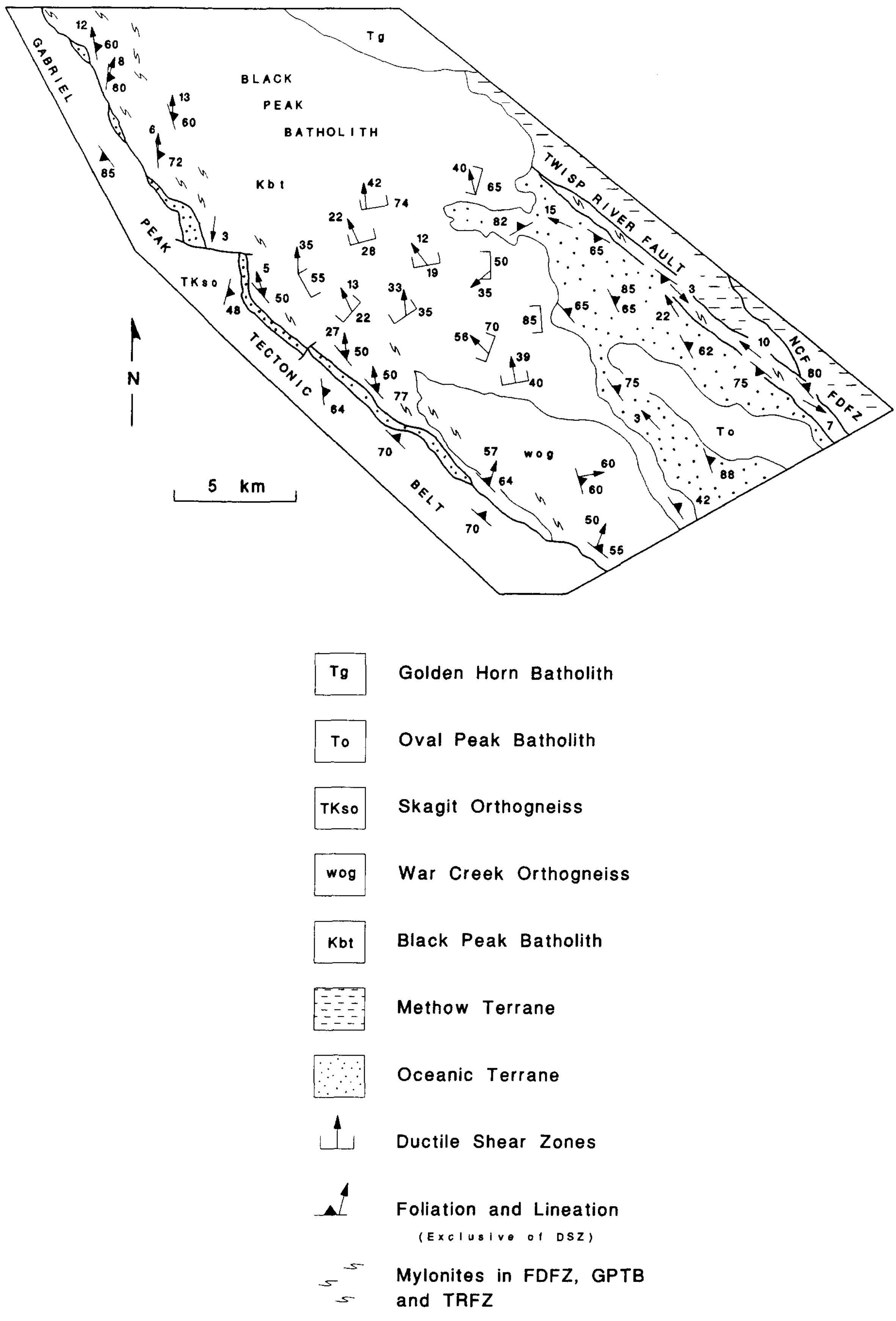

Fig. 3. Map emphasizing the stepover between the Twisp River fault zone and Gabriel Peak tectonic belt.

Structural patterns within the Black Peak batholith vary considerably away from the Gabriel Peak tectonic belt. Large parts of the pluton show only a weak to moderately strong magmatic foliation. In the southern part of the batholith, solid-state foliation of variable intensity is typically parallel to the NW strike of the Ross Lake fault zone and the crystalline core of the North Cascades as a whole. Ductile shear zones pervade the overlap zone between the Twisp River fault zone and the central section of the Gabriel Peak tectonic belt, but are rare elsewhere. Many of these shear zones strike NNE–SSW to E–W at a high angle to the tectonic belt and Twisp River fault zone (Figs. 3 and 5a). This orientation is anomalous for both the Ross Lake fault zone and the entire crystalline core.

SUMMARY OF EVIDENCE FOR AND AGAINST A STEPOVER

The major evidence that the Twisp River fault zone and the central section of the Gabriel Peak tectonic belt are overlapping segments of the same dextral strike-slip structure includes the following:

(1) the Twisp River fault zone and central section of the Gabriel Peak tectonic belt are both dextral strike-slip shear zones;

(2) they have a nearly identical strike (~310°) that is at about 10–15° to several other major shear zones (North Creek fault, Hozameen fault, Foggy Dew fault zone) within the Ross Lake fault zone (Fig. 2);

(3) the fundamental break between the oceanic terrane and the Methow terrane steps to the west from the Twisp River fault zone to the north end of the Black Peak batholith (Fig. 2);

(4) abundant ductile shear zones occur in the Black Peak batholith in the overlap zone between the Twisp River fault zone and Gabriel Peak tectonic belt, but are rare elsewhere in the batholith;

(5) the kinematics of the Gabriel Peak belt change in the overlap segment (Figs. 2 and 4);

(6) the strike of mylonitic foliation in the Gabriel Peak tectonic belt changes to the north of the overlap segment (Fig. 3).

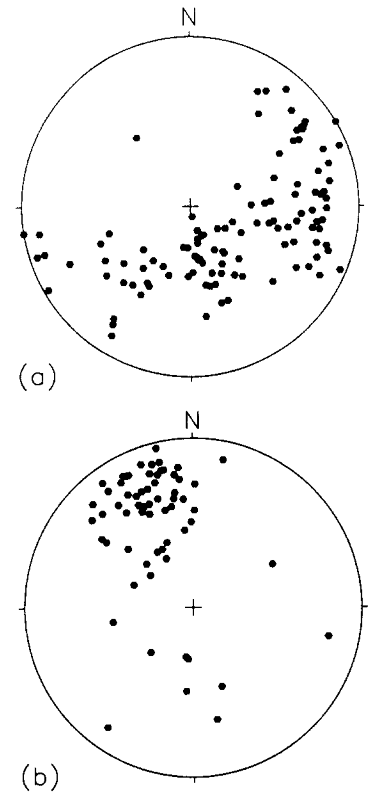

Fig. 5. Structural data from the ductile shear zones. (a) Stereographic plot of poles to mylonitic foliation (113 points). (b) Stereographic plot of stretching lineations in mylonites (63 points).

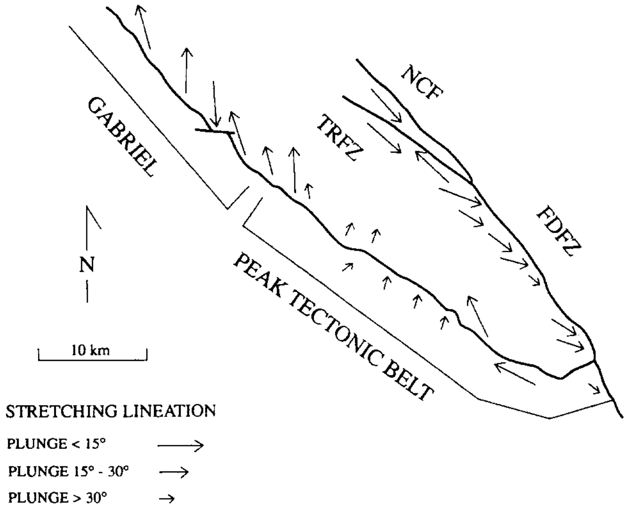

Fig. 4. Sketch map showing lineation patterns in mylonites in the southern part of the Ross Lake fault zone. FDFZ = Foggy Dew fault zone; NCF = North Creek fault; TRFZ = Twisp River fault zone. The central and southern segments of the Gabriel Peak tectonic belt are indicated by half-brackets.

The biggest problem with the stepover model is demonstrating synchronous activity of the two faults in the latest Cretaceous to Paleocene. The initial impression from the map pattern, as noted by Misch (1966), is that the Twisp River fault zone is truncated by the Black Peak batholith and thus did not move after the mid-Cretaceous. Miller & Bowring (1990) pointed out, however, that the Twisp River fault zone is continuous with the Foggy Dew fault zone which strongly deforms the Paleocene Oval Peak batholith and has unequivocally undergone major dextral shear in the Paleogene. It is possible that all of the post-Black Peak movement on the Foggy Dew fault zone was transferred to the North Creek fault and that the Twisp River fault zone is an abandoned earlier structure, but, as discussed by Miller & Bowring (1990), the Paleogene structural style of the Foggy Dew fault zone more closely resembles the Twisp River fault zone than the North Creek fault. Furthermore, the Twisp River fault zone may also deform the Oval Peak batholith (see above). Thus, it seems unlikely that a broad fault zone like the Twisp River fault zone dies out over a short distance without transferring at least some of its slip to another structure. Most probably, either the Foggy Dew and Twisp River fault zones were active in the latest Cretaceous and Paleogene, with the latest slip possibly restricted to the Foggy Dew fault zone and North Creek fault, or all three structures were active at the same time, forming a diverging set of faults. I therefore assume in the following discussion that the Twisp River fault zone and the central section of the Gabriel Peak tectonic belt are en échelon segments of a dextral strike-slip fault and discuss the nature of the stepover zone itself.

DEFORMATION WITHIN THE STEPOVER ZONE

Hundreds of ductile shear zones, typically 0.5–1.5-m thick but locally attaining 10 m in thickness, have been observed within the Black Peak batholith in the stepover zone. The ductile shear zones show significant variation in orientation (Figs. 3 and 5a) and can be divided into three main groups:

(1) ductile shear zones striking NNW to NW and dipping moderately steeply NE, with a gently to moderately steeply N-plunging stretching lineation. These strike subparallel to the Gabriel Peak tectonic belt and are common near the edge of the tectonic belt;

(2) ductile shear zones striking NNE–SSW to E–W at a high angle to the Gabriel Peak belt and Twisp River fault zone and dipping gently to moderately WNW to N, commonly with a nearly down-dip lineation (Table 1). These dominantly dip-slip shear zones are present mainly in the central part of the stepover zone (Fig. 3);

(3) ductile shear zones typically striking between ~170° and 210° and dipping moderately to steeply W. Lineation lies obliquely within the foliation, typically plunging moderately to the NW (Table 1). These oblique-slip shear zones are most abundant in the northeastern part of the stepover zone.

These high strain zones show features typical of ductile shear zones (cf. Ramsay & Graham 1970) in plutonic rocks. Grain size is markedly reduced and mylonites and locally ultramylonites characterize the interiors of the shear zones. Foliation has a sigmoidal trajectory and in the center of the shear zones is orientated sub-parallel to the walls (Fig. 6a). Many have sharp walls as in 'ideal' ductile shear zones and truncate the magmatic and sporadically developed solid-state foliation in the wall rocks. Others have diffuse boundaries and the solid-state foliation in the wall rocks intensifies toward the shear zone and curves into parallelism with that in the shear zone.

The dip-slip ductile shear zones in the center of the stepover zone are typically thicker and their fabric is more intense, on average, than the oblique-slip zones in the northeastern part of the stepover (Table 1). Folds of mylonitic foliation are present in some of the dip-slip ductile shear zones (Fig. 6b) and, in the most intensely foliated zones, hinge lines and stretching lineations are parallel and a new axial-planar, mylonitic foliation is developed. Crenulations of mylonitic foliation occur rarely in the oblique-slip zones.

Microstructures and metamorphic conditions

The ductile shear zones deform tonalites and granodiorites in which biotite is generally the only mafic phase present. Outside of the ductile shear zones most of these rocks record low-temperature alteration marked by chloritization of biotite and the partial replacement of plagioclase by muscovite and epidote. The sporadically developed, weak to moderately strong solid-state foliation is marked by elongate quartz aggregates and aligned biotite. Euhedral, zoned igneous plagioclases define a generally weak magmatic foliation.

Table 1. Summary of dip- and oblique-slip ductile shear zones

Dip-slip shear zones	Oblique-slip shear zones
Strike: NNE–SSW to E–W Dip: gently to moderately WNW to N	Strike: 170–210° Dip: moderately to steeply W
Lineation: nearly down-dip to N or NW	Lineation: lies obliquely within foliation, typically plunging moderately NW
Location: center of stepover	Location: northeast part of stepover
Relatively thick (typically 1–2 m)	Relatively thin (typically ≤1 m)
Intense *L–S* mylonites and ultramylonites	$L < S$ protomylonites dominate; less common *L–S* mylonites and ultramylonites
Extend as planar zones for >30 m before pinching out, or becoming covered	Anastomosing pattern on scale of 5–10 m
Folds of mylonitic foliation in some zones. Hinge line orientations range from nearly perpendicular, to parallel, to stretching lineation; in former orientation, asymmetry consistent with shear sense deduced from other kinematic indicators; in latter orientation, new axial-planar mylonitic foliation is developed.	Local crenulations of mylonitic foliation; development of associated crenulation cleavage
Kinematic indicators are well-developed Kinematics: S- or SE-vergent reverse slip	Kinematic indicators sporadically developed Kinematics: dominantly combination of SE-directed reverse-slip plus sinistral strike-slip

Fig 6. (a) Typical small ductile shear zone in the Black Peak batholith. Note the curvature of foliation in the shear zone and the local development of ultramylonite. This is one of the reverse-slip ductile shear zones in the center of the stepover. Exposed length of pen is 7 cm. (b) Folded mylonitic foliation in a reverse-slip ductile shear zone in the central part of the stepover. Exposed length of pen is 7.5 cm.

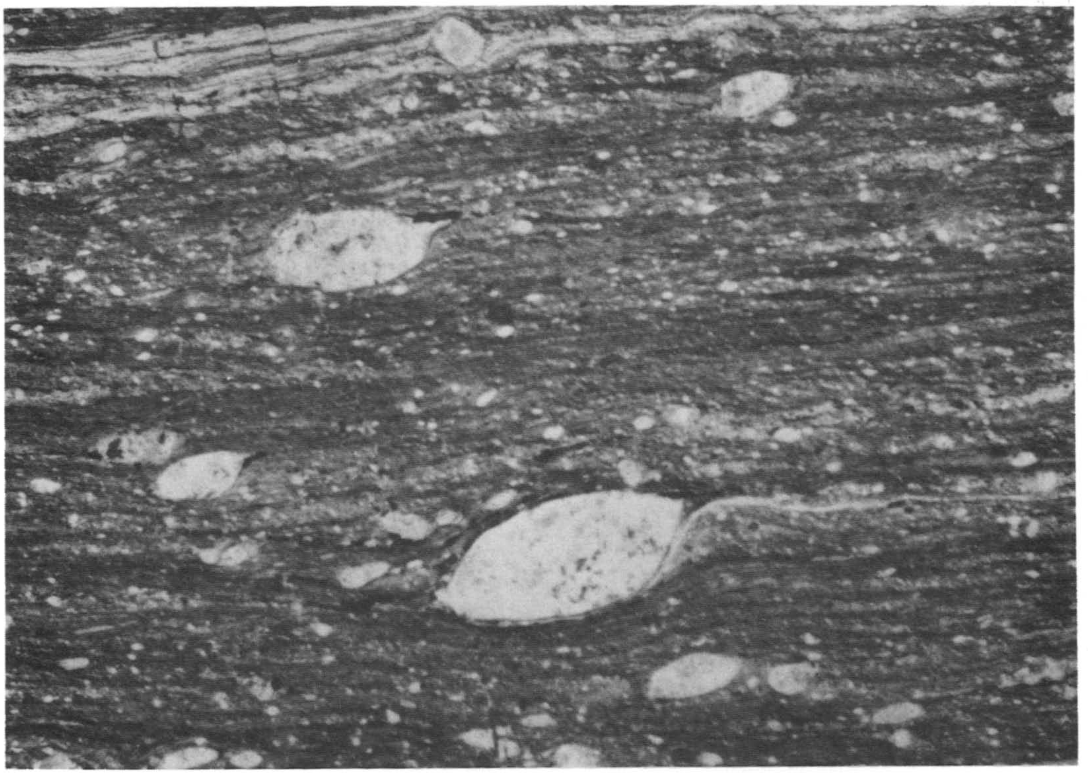

Fig. 7. Photomicrograph taken of the plane orthogonal to foliation and parallel to stretching lineation of a mylonite in a ductile shear zone. Lenticular asymmetric plagioclase porphyroclasts are set in an extremely fine-grained mosaic. Sense of shear is top to the right. Base of figure is 6.6 mm in length.

In the ductile shear zones, microstructures indicative of non-coaxial strain are well developed and include *S–C* fabrics, shear bands, oblique quartz foliations and porphyroclasts with asymmetric tails. These kinematic indicators are in agreement with shear directions determined from the curvature of foliation trajectories. Mylonitic foliation (*S*) is defined by orientated biotite and muscovite, quartz ribbons, and micaceous layers alternating with bands of plagioclase and quartz. *C* surfaces and *C′* surfaces (shear bands) are characterized by intense grain-size reduction, particularly of plagioclase and quartz, and by small, aligned grains of biotite, muscovite and locally chlorite. Aggregates of micas, quartz and plagioclase also define the stretching lineation.

Foliation wraps around plagioclase porphyroclasts that commonly retain their igneous zoning and contain much secondary muscovite and epidote, as in the less deformed rocks. These porphyroclasts are typically bent, display deformation twins, and in some rocks are extensively microfractured. A few samples show recrystallization of fine-grained plagioclase, and core-and-mantle structure is present rarely.

Plagioclase porphyroclasts commonly have asymmetric tails of fine-grained muscovite, and porphyroclasts of kinked, medium-grained biotite and less commonly muscovite have finely recrystallized tails that are aligned in *C* surfaces. Micas also form asymmetric tails on relict euhedral sphene and on strongly bent epidote.

Quartz is generally present as fine- to medium-grained aggregates, many of which form bands of recrystallized ribbons. Subgrains are well developed and in most samples quartz has been dynamically recrystallized to a polygonal mosaic that defines an oblique foliation. In a few mylonites, quartz forms medium-grained porphyroclasts, with variably developed subgrains. Quartz ribbons in the least recovered mylonites consist of large, strongly undulose crystals, with aspect ratios of up to 15:1, that are locally sigmoidally shaped.

In ultramylonites, *C* surfaces are typically the dominant fabric element, but shear bands (*C′*) are also prominent. Plagioclase (Fig. 7), quartz, epidote, sphene and locally biotite form small, asymmetric porphyroclasts. Muscovite is more abundant than in the coarser-grained mylonites.

The typical metamorphic assemblage in the mylonites and ultramylonites, quartz–biotite–muscovite ± epidote ± sphene, is compatible with the greenschist facies and the microstructures are also typical of mylonitic granitoids deformed under upper-greenschist facies conditions (e.g. Simpson 1985). Such conditions are similar to those for mylonites in the Twisp River fault zone (Miller & Bowring 1990) and parts of the Gabriel Peak tectonic belt. Higher temperatures may be recorded in a few mylonites where plagioclase has undergone dynamic recrystallization. In contrast, chlorite is abundant in a few of the oblique-slip ductile shear zones, and these zones show less recovery of quartz than in other mylonites, features compatible with somewhat lower temperatures.

Metamorphic reactions may have played an important role in the evolution of the ductile shear zones. Muscovite is abundant in these zones, but apparently was not a magmatic phase in the Black Peak batholith (Adams 1964). Several workers (e.g. O'Hara 1988, Gibson 1990) have noted that the formation of muscovite by the breakdown of feldspar leads to significant strain softening in mylonitic granitoids. The scarcity of K-feldspar in mylonites relative to less deformed rocks supports this interpretation for the shear zones. It is not clear, however, whether most of the muscovite formed during mylonitization, or during the hydrothermal alteration recorded throughout the batholith. Thus, some combination of early static alteration and reactions during mylonitization resulted in the formation of muscovite at the expense of feldspar and weakened the granitoids.

Kinematic model

The kinematics of many of the ductile shear zones can be readily determined and, overall, provide a consistent picture. The NW-striking, NE-dipping zones in the southwestern part of the stepover zone show the same kinematics as the adjacent Gabriel Peak belt, dextral strike-slip with a component of reverse slip (SSE-vergent). However, lineation in these ductile shear zones generally plunges steeper than that in the tectonic belt, compatible with a larger reverse-slip component. South- or SE-directed reverse-slip is almost invariably indicated for the NE- to E–W-striking dip-slip shear zones in the central part of the pluton. Most of these shear zones record small components of strike-slip; both sinistral and dextral examples are present. Kinematic indicators are not as well developed in the oblique-slip shear zones, but the orientation of the stretching lineation in most of these zones implies that motion was a combination of either normal-slip and dextral strike-slip or reverse-slip plus sinistral strike-slip. Kinematic indicators show that both situations apply, but that the majority of these ductile shear zones experienced the combination of SE-directed reverse-slip plus sinistral strike-slip.

The overall kinematic pattern for the ductile shear zones is thus one of S- to SE-vergent reverse-slip with a dextral strike-slip component on the southwest side of the stepover and a sinistral component on the northeast side. The reverse-slip ranges from a minor to moderate component on the NW-striking zones, to moderate on the oblique-slip shear zones, to large on the E–W- to NE-striking shear zones. The absence of cross-cutting relations suggests that these shear zones record a single kinematic history.

This kinematic pattern strongly supports the model that the ductile shear zones accommodated the shortening in the stepover zone between two dextral strike-slip segments. The NW-striking, NE-dipping shear zones record dextral strike-slip related to the nearby Gabriel Peak tectonic belt, as well as some shortening. The reverse-slip shear zones in the center of the stepover that strike at a high angle to the Gabriel Peak belt and Twisp

River fault zone lie in the appropriate orientation and position to accommodate much of the shortening within the Black Peak batholith. The oblique-slip ductile shear zones also accommodate shortening within the stepover, although their generally steep dip implies that the magnitude of shortening was relatively minor. The component of sinistral strike-slip is compatible with these shear zones acting as complex oblique ramps in the northeastern margin of the Black Peak batholith as the batholith moved southward.

Some of the reverse-slip zones are orientated clockwise (more E–W) from the perpendicular to the strike of the Gabriel Peak tectonic belt and Twisp River fault zone. Similarly, stretching lineations generally trend clockwise from the strike of the strike-slip faults (Figs. 3 and 5b). This pattern speculatively indicates a component of transpression across the Ross Lake fault zone in agreement with plate motion reconstructions (Engebretson *et al.* 1985) and geologic evidence (Miller *et al.* 1989, Miller 1990), which show that the North Cascades crystalline core was in a transpressional regime while the stepover was active in the early Tertiary. Transpression can also account for the probable synchroneity of reverse-slip on the southern section of the Gabriel Peak belt with at least some of the strike-slip on the central section and in the Twisp River fault zone.

Magnitude of displacement across the stepover

The magnitude of strike-slip accommodated by shortening in the stepover is only loosely constrained. I carried out a reconnaissance study of the displacement on individual shear zones in an effort to provide a semi-quantitative estimate of the minimum shortening within the stepover zone, which, in turn, places some broad limits on the amount of strike-slip transferred across the stepover. I concentrated on the reverse-slip zones as these accommodated most of the shortening.

A relatively well-exposed part of the stepover was studied. It was assumed to be typical of the stepover as a whole, although the distribution of shear zones is clearly heterogeneous. The following were determined in a transect of ~675 m that contains 226.7 m of outcrop: the frequency of occurrence of ductile shear zones; thickness of individual shear zones; and the displacement across individual zones >20 cm in thickness (following techniques of Ramsay & Graham 1970, and Ramsay & Huber 1983). There are 34 such shear zones in the transect (one shear zone >20 cm in thickness per 6.67 m of outcrop), which have a mean thickness of 81 cm. Displacements on 14 shear zones suitable for analysis range from 61 cm to ~16.2 m, and the displacement: width ratios for individual shear zones range from 2.6 to 8.6, with a mean of ~6.2. These ratios are apparently in accord with other studies of deformed plutonic rocks. For example, Yonkee (1992) determined ratios of ~6:1, although such values are likely to be highly variable (e.g. Evans 1990). If it is assumed that the cumulative displacements across the studied interval are representative of the stepover as a whole, then the displacements on the reverse-slip shear zones for the entire stepover (width of ~9.25 km for stepover normal to strike of Twisp River fault zone and Gabriel Peak tectonic belt) are on the order of 6.98 km. Taking an average dip of 24.9° from the measured shear zones, and assuming that the movement was purely dip-slip, this displacement translates into 6.45 km of shortening and 2.66 km of vertical movement across the stepover.

The displacements calculated for individual shear zones and thus, the cumulative displacements, are almost certainly minimum values for the following reasons. (1) Many zones contain ultramylonites in their centers and it was difficult to measure the angle between foliation and shear zone walls. I was conservative in my assignment of angles in order not to overestimate displacement. (2) Numerous shear zones display *S–C* fabrics and some have pervasive shear bands (*C′* surfaces). These presumably are among the most intensely deformed zones, but most were precluded because of difficulties in measuring their displacements. (3) Similar problems are posed by shear zones with folded foliations (Fig. 6b). (4) Some shear zones have poorly defined walls and feather out into domains with *S–C* fabrics. Shortening in domains between shear zones has not been accounted for in this analysis. (5) Small shear zones were not measured. Mitra (1979) has shown that the cumulative displacements on shear zones <1 cm thick within crystalline basement may be considerably greater than those on significantly thicker zones. (6) The smaller components of reverse-slip on the oblique and dextral zones were not taken into account. (7) Even in this relatively well-exposed domain, the most strongly foliated shear zones may have been preferentially weathered out. Thicknesses of several wide shear zones could not be determined because their walls are not exposed.

Regional relations also have implications for the magnitude of displacement across the stepover. Reverse-slip in the stepover requires that deeper structural levels be brought up to the northwest. This observation poses apparent problems as hornblende barometry and metamorphic barometry indicate that the Black Peak batholith almost certainly was intruded at shallower levels (≤3 kbar) than the younger (Paleocene), magmatic epidote-bearing Oval Peak batholith which lies in the footwall to the stepover (Miller *et al.* in press). The latter was emplaced at depths corresponding to about 6 kbar (Miller & Bowring 1990). This problem can be accounted for, however, by the evidence that significant parts of the northeastern core underwent tectonic, or possibly magmatic, loading after 88–91 Ma, the age of the Black Peak batholith (Miller & Bowring 1990, Brown & Walker in press, Miller *et al.* in press). Garnet zoning profiles and thermobarometric data indicate that schists of the oceanic terrane in fault contact with the western margin of the Black Peak batholith record a pressure increase of 1.5–3.0 kbar during metamorphism, with maximum *P* of 6–8 kbar (Miller *et al.* in press), and schists directly northwest of the pluton (Fig. 2) yield pressures of ~9 kbar (Whitney 1992).

In the footwall to the stepover, schists between the

Black Peak and Oval Peak batholith also record a pressure increase during metamorphism, but their maximum values were probably on the order of 2–3 kbar lower than those of schists both southwest and northwest of the Black Peak batholith. These pressure differences speculatively imply vertical displacements of ~6.5–10 km across the stepover, which, utilizing the average dips of the reverse-slip shear zones, corresponds to ~15.8–24.2 km of shortening.

The range from ~7 to 24 km for shortening and, thus, strike-slip transferred across the stepover, is probably reasonable. If displacements were very large (e.g. 100 km or more), then it seems likely that either a major thrust would have formed at the base of the Black Peak batholith or that the shear zones on average would be significantly thicker.

SUMMARY AND SPECULATIONS ON THE MOVEMENT HISTORY OF THE ROSS LAKE FAULT ZONE IN THE AREA OF THE STEPOVER

The Ross Lake fault zone in the vicinity of the stepover zone records a complex sequence of events that are summarized in Fig. 8.

(1) Initial juxtaposition of the oceanic terrane against the Methow terrane occurred before 91 Ma along a fault boundary that was either segmented or marked by a major bend (Fig. 8a). The type of motion along this boundary is unknown but may have been strike-slip, in view of the great length of the fault zone and later well-documented dextral shear. Alternatively, semi-quantitative restoration of nappes exposed to the west of the crystalline core of the North Cascades suggests that the Ross Lake fault zone may represent the 'root zone' of these thrusts (Brandon & Cowan 1985).

(2) The Black Peak batholith intruded a stepover/bend along the terrane boundary (Fig. 8b). It is not known whether the Ross Lake fault zone was active at this time.

(3) The northeastern part of the crystalline core was loaded, as discussed above, either by thrusting (Miller 1990) or by emplacement of diapiric plutons (Brown & Walker in press). This loading can only be bracketed between 90 and 65 Ma, and possibly overlaps with the strike-slip on the central Gabriel Peak tectonic belt and Twisp River fault zone and the reverse-slip on the southern Gabriel Peak tectonic belt.

(4) The Twisp River fault zone and Gabriel Peak tectonic belt experienced dextral strike-slip that was transferred between these structures by the ductile shear zones in the Black Peak batholith (Fig. 8c). Emplacement of the batholith led to an increase in the width of the stepover/bend relative to the original offset of the terrane boundary. The intrusion formed a rigid buttress and subsequent Paleogene (and latest Cretaceous?) movement jumped to the west side of the batholith to the Gabriel Peak belt. This western contact is a mechanically weak boundary between tonalite of the batholith and schist of the oceanic assemblage. Furthermore, emplacement of broadly syntectonic sheet-like intrusions (now orthogneisses) on the southwest side of the schists (Miller & Bowring 1990) probably led to thermal weakening in this zone. On a larger scale, emplacement of the Black Peak batholith across the stepover may have resulted in greater partitioning of strike-slip from the Twisp River fault zone–Gabriel Peak tectonic belt segments to the more easterly North Creek–Hozameen fault (Figs. 2 and 8d). It was probably easier for strike-slip on the Foggy Dew fault zone to the south to be accommodated on the North Creek–Hozameen fault as opposed to the Twisp River fault zone because of the relative difficulty of transferring slip across the stepover in the batholith.

(5) Reverse-slip occurred to the south of the stepover on the southern section of the Gabriel Peak belt, beginning by 65 Ma and ending by 57 Ma. Strike-slip on the central section of the tectonic belt may have begun before the reverse-slip, but the two types of movement are probably in part synchronous as evidenced by the

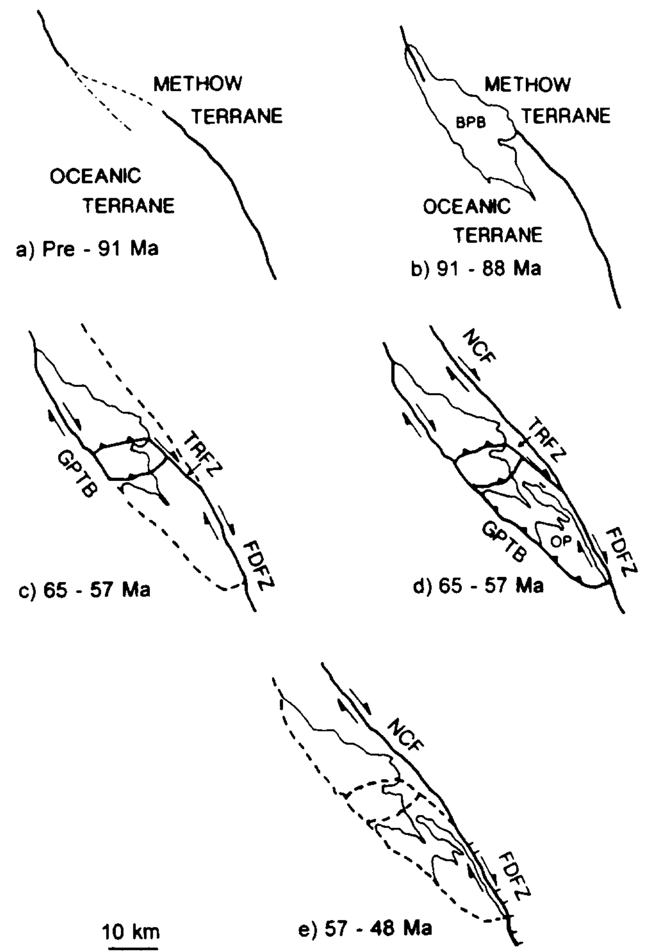

Fig. 8. Diagram illustrating possible sequence of faulting and related plutonism in the southern part of the Ross Lake fault system. See detailed discussion in text. In (a) two possible interpretations of the terrane boundary are illustrated; the dashed line marks a possible bend in the boundary, whereas the dot-dashed line shows an echelon pattern. In (c) and (e), dashed lines are inactive faults. BPB = Black Peak batholith; OP = Oval Peak batholith. FDFZ = Foggy Dew fault zone; GPTB = Gabriel Peak tectonic belt; NCF = North Creek fault: TRFZ = Twisp River fault zone.

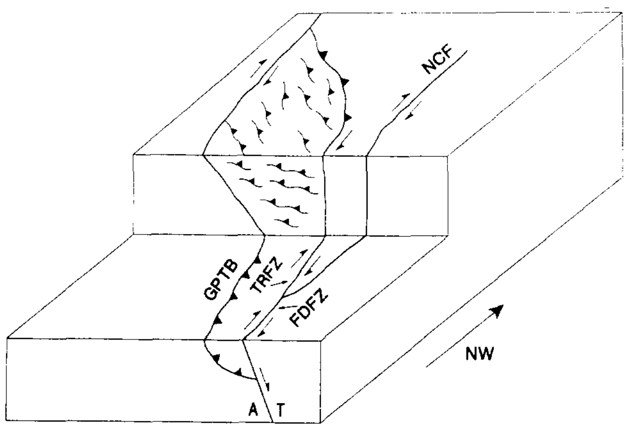

Fig. 9. Schematic block diagram illustrating three-dimensional relationships between faults in the southern part of the Ross Lake fault system. Barbed lines represent ductile shear zones in the stepover between the Gabriel Peak tectonic belt (GPTB) and Twisp River fault zone (TRFZ). A = away, T = toward for movement on the Foggy Dew fault zone (FDFZ). NCF = North Creek fault.

gradual transition from strike-parallel to down-dip stretching lineations (Figs. 3 and 4). In one model (Fig. 8c), the Gabriel Peak tectonic belt originally extended only as far as the stepover zone. The latest Cretaceous–Paleocene transpressive regime then led to the propagation of the Gabriel Peak belt southward during intrusion of the Oval Peak batholith into the footwall of the stepover zone at ~65 Ma (Fig. 8d). At this time, the kinematic pattern was one of SSE-vergent reverse-slip in the stepover (subparallel to the strike-slip segment), SW-vergent reverse-slip in the southern section of the Gabriel Peak tectonic belt, and dextral strike-slip on the central section of the Gabriel Peak belt, Twisp River fault zone, Foggy Dew fault zone and probably the North Creek fault (Fig. 8d). The orientation of these various structures at depth is poorly controlled, but the map pattern is compatible with the speculation that the overall geometry is a complex transpressional flower structure (Fig. 9). This model invokes a master dextral strike-slip fault at depth and implies that the stepover has a wedge shape in three dimensions. Support for such a geometry occurs where the southernmost part of the Gabriel Peak tectonic belt dips under the Oval Peak batholith and merges with, and is truncated by, the Foggy Dew fault zone (Figs. 2 and 9). Farther north, however, the moderately steep dip of the Gabriel Peak belt and near vertical dip of the Twisp River fault zone suggests that any branch line is considerably below the present erosion level, ~15 km if the Gabriel Peak tectonic belt is projected downward at the same dip, unless the tectonic belt has a pronounced listric geometry at depth.

(6) The latest movement (post-57 Ma, pre-48 Ma) in the southern part of the Ross Lake fault zone is recorded by the oblique-slip (dextral strike plus lesser normal) on the Foggy Dew fault zone. Slip at this time may have largely been restricted to the co-linear (in map view) Foggy Dew fault zone and North Creek fault (Fig. 8e).

COMPARISON WITH ACTIVE STEPOVERS

Segmented faults are common at shallow crustal levels in active strike-slip systems. In the few well-studied late Cenozoic contractional stepovers, such as the Coyote Creek fault, California (Sharp & Clark 1972, Brown *et al.* 1991), Bitter Springs Valley fault, Nevada (Campagna & Aydin 1991), Swan Islands fault zone, western Caribbean (Mann *et al.* 1991) and Jamaica (Mann *et al.* 1985), most of the thrusts and folds are orientated at a high angle to the strike-slip segments (Fig. 10). In the Bitter Springs Valley fault stepover (Fig. 10a), there are abundant steep faults showing reverse-slip, but with significant components of both sinistral and dextral strike-slip (Campagna & Aydin 1991). The strike of structures within this stepover varies considerably, as in the Ross Lake fault zone. The abundance of oblique-slip zones in the stepovers in both the Ross Lake fault zone and the Bitter Springs Valley fault is also noteworthy. In summary, the orientation of most of the reverse-slip ductile shear zones in the Black Peak batholith relative to the strike-slip segments is broadly similar to that for analogous structures in late Cenozoic stepovers. Thus, the ductile shear zones in the Black Peak batholith probably act in the same role as folds and brittle faults in the upper crust in late Cenozoic stepovers.

The presence of this mid-crustal stepover has general implications for segmented strike-slip faults. There is considerable question as to the geometry of segmented faults at depth and whether they merge before reaching mid-crustal levels (see review by Little 1990). The Twisp River fault zone and Gabriel Peak tectonic belt are clearly segmented at these depths and any merger of these structures is well below the present surface as discussed above. It is perhaps noteworthy that the dips are asymmetric, a relationship that is the general rule for extensional stepovers (e.g. Aydin & Nur 1985) and one that presumably also applies to contractional zones. In addition, the combination of reverse- and strike-slip on the Gabriel Peak tectonic belt is reminiscent of the Jamaican (Mann *et al.* 1985) and Bitter Springs Valley fault (Campagna & Aydin 1991) contractional stepovers where both types of slip occur on the same structure.

The stepover in the Ross Lake fault zone does differ somewhat from many active stepovers (see compilation by Aydin & Schultz 1990) in that the spacing between the strike-slip segments is relatively large (~10 km). Active stepovers of comparable magnitude do, however, occur along the Calaveras and Hayward faults, California (~10 km), along part of the Dead Sea System (Aydin & Schultz 1990), and along the North Anatolian fault (Barka & Kadinsky-Cade 1988). The large width of the stepover may result in part from the presence of the Black Peak batholith, as discussed above.

CONCLUSIONS

The stepover within the Ross Lake fault zone shows that segmented strike-slip faults may be important in the

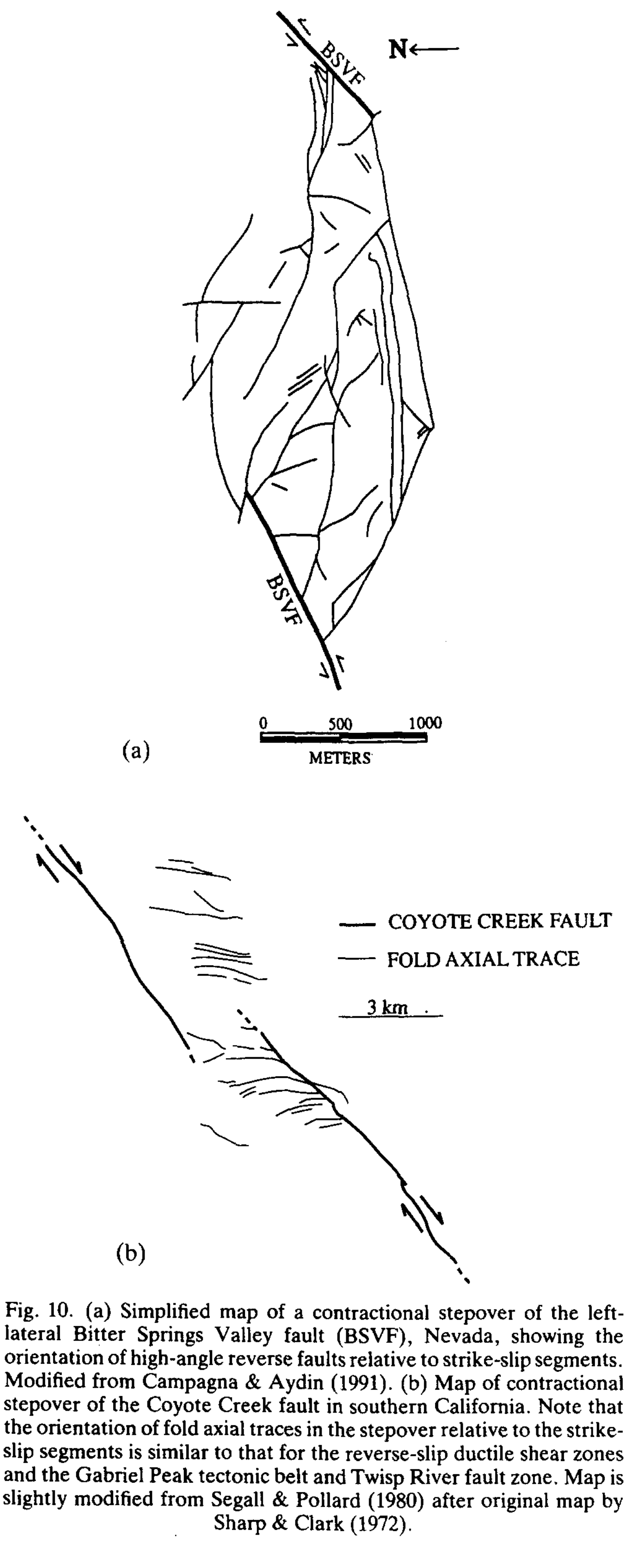

Fig. 10. (a) Simplified map of a contractional stepover of the left-lateral Bitter Springs Valley fault (BSVF), Nevada, showing the orientation of high-angle reverse faults relative to strike-slip segments. Modified from Campagna & Aydin (1991). (b) Map of contractional stepover of the Coyote Creek fault in southern California. Note that the orientation of fold axial traces in the stepover relative to the strike-slip segments is similar to that for the reverse-slip ductile shear zones and the Gabriel Peak tectonic belt and Twisp River fault zone. Map is slightly modified from Segall & Pollard (1980) after original map by Sharp & Clark (1972).

mid-crust and that slip between segments may be transferred by distributed ductile shear zones. Intrusion of the Black Peak batholith into the stepover was important in the partitioning of later displacements. Because plutons commonly intrude strike-slip fault zones (e.g. Hutton 1988), the types of relations described above may occur in other long-lived fault zones.

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