Backflow and margin-parallel shear within an ancient subduction complex

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ABSTRACT

Lineated and foliated tectonites of the Teslin suture zone, Yukon, represent the deep-seated part of a west-dipping subduction complex that formed seaward of western North America in Permian-Triassic time. The tectonites were progressively underplated onto the hanging-wall plate during B-type subduction. With continued subduction and underplating, the boundary between the hanging wall and subduction channel migrated oceanward, resulting in "growth" of the hanging-wall plate at depth. These tectonites preserve a progressive record of backflow, dextral margin-parallel shear, and downflow within the subduction channel. Early Jurassic A-type subduction of the leading edge of western North America resulted in eastward overthrusting of the tectonites as a coherent block onto North American strata. These tectonites provide empirical evidence that backflow, margin-parallel displacement, and downflow can all occur within the deeper parts of subduction zones.

INTRODUCTION

It has long been thought that a major proportion of the sediments involved in subduction are not recycled to the mantle, but instead become incorporated into the accretionary prism landward of the trench (Seeley et al., 1974; Karig and Sharman, 1975). Understanding of duplex-thrust styles of structural accretion is growing (e.g., Sample and Fischer, 1986); however, geologists have yet to address the styles of deformation and accretion and, therefore, the kinematic paths of rocks at depths of $\geqslant$10–30 km within subduction complexes. An understanding of the material paths deep within the subduction environment is necessary to facilitate modeling of subduction complexes (Shreve and Cloos, 1986; Cloos and Shreve, 1988) and to elucidate tectonic uplift of eclogite- and blueschist-facies rocks (Ernst, 1975; Cowan and Silling, 1978; Karig et al., 1980; Cloos, 1982; Pavlis and Bruhn, 1983; Platt, 1986).

The deep-seated subduction environment is difficult to study along modern convergent margins. Seismic reflection studies, which have successfully imaged large-scale structures at shallow crustal levels (e.g., McCarthy and Scholl, 1985), show poor resolution at depths greater than 5–10 km below the sea floor. Furthermore, seismic signals can best resolve large-scale, low-angle reflectors. Detailed study of drill cores has allowed direct observation of small-scale deformation features and enabled an understanding of deformation mechanisms, but drilling typically samples depths of only 0.5–1.0 km. Deeper crustal levels of subduction zones are outside the limits of standard seismic and drilling techniques; therefore, study of these zones is limited to modeling and examination of the exhumed parts of ancient subduction margins. Yet, the deep-seated subduction environment is difficult to study in the rock record because these rocks either are not exposed or have been deformed by more recent tectonic processes.

Despite these complexities, the Teslin suture zone, Yukon, preserves a 1000-km^2 coherent package of lineated and foliated (L-S) tectonites that were underplated onto the base of the hanging-wall plate below the brittle-ductile transition within a west-dipping, B-type (cf. Bally, 1981) Permian-Triassic subduction complex; the tectonites were exhumed as a coherent block in Early Jurassic time as a result of A-type subduction of the western edge of North America (Hansen, 1989, 1991). Tectonites, which represent the leading edge of North American continental crust (tectonites of the Cassiar terrane), underwent high-P/T metamorphism as a result of A-type subduction. these tectonite fabrics preserve a record of subduction-zone displacement under high-P/T ductile deformation conditions, and they have implications for deep-seated subduction-zone dynamics. In this paper I review the material paths predicted for deep-seated subduction-zone dynamics and present evidence that tectonites of the Teslin suture zone record underplating, backflow, margin-parallel flow, and downflow in the subduction-zone environment.

FLOW PATTERNS IN SUBDUCTION ZONES

The subduction-channel model (Shreve and Cloos, 1986; Cloos and Shreve, 1988) provides a quantitative theoretical framework that unifies most of the principal concepts of subduction-zone dynamics. This model assumes the same basic mechanisms for all convergent plate margins that have achieved a quasi-steady state (10–20 km/m.y. subduction for 20 m.y.). The model components consist of an oceanic footwall block, a hanging-wall block, and an intervening subduction channel in which sediment deforms as an approximately viscous material (Fig. 1). The hanging-wall block is composed of an accretionary prism and the crystalline block at the front of the overriding plate. Footwall material is either subducted and recycled to the mantle, or it is mechanically transferred to the hanging-wall block by underplating at the top of the subduction channel.

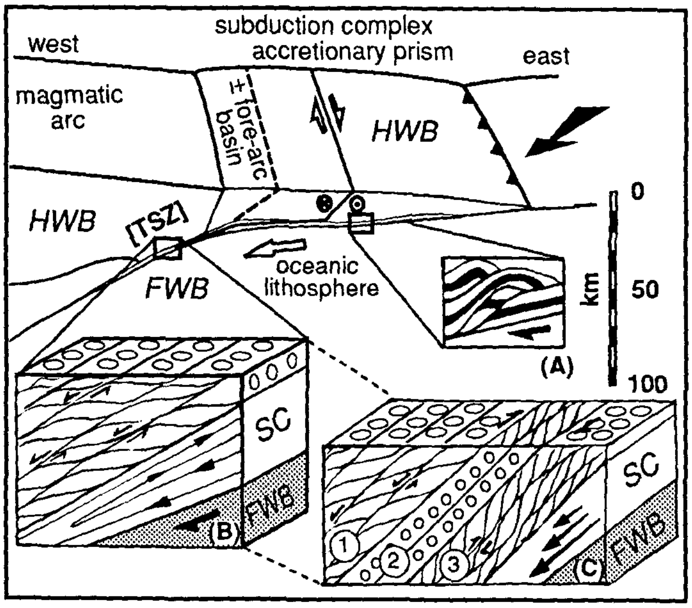

Figure 1. Schematic block diagram of oblique convergent margin; subduction channel (SC) forms zone of transfer between footwall block (FWB) and hanging-wall block (HWB). Subduction-related, margin-parallel, strike-slip faults can dismember hanging-wall block as result of oblique convergence; circled dot and circled x indicate motion out of and into plane of diagram, respectively. [TSZ]—location of Teslin suture zone. Expanded views of (A) thrust-style underplating during downflow, (B) normal-style underplating during backflow, and (C) underplating during progressive (1) backflow, (2) margin-parallel flow, and (3) reverse flow, and resultant trenchward migration of subduction channel.

The subduction-channel model predicts that material which is carried to depth within the subduction channel, but is not recycled to the mantle, can be underplated to the base of the hanging-wall block. Material can also be removed from the base of the hanging-wall block by subduction erosion (Scholl et al., 1980; von Huene, 1984). Subduction erosion can occur locally within a subduction complex at the same time accretion occurs elsewhere (Cloos and Shreve, 1988). Eroded material either can be recycled to the mantle or can be underplated at a new location along the base of the hanging-wall block.

Because subduction zones are dynamic systems, the locations of the hanging-wall block, the material in the subduction channel, and the footwall block are transitory. The subduction channel is a shear zone. Structural vergence across the boundaries of this shear zone should reflect the relative displacement of the footwall and hanging-wall blocks with respect to the adjacent material in the subduction channel. In the case of downflow, vergence across both boundaries will be reverse, or trench vergent (Fig. 1C, stage 3). Where there is backflow, shear across the structurally lower boundary between the subduction channel and the footwall block will be reverse, whereas shear across the structurally higher boundary between the subduction channel and the hanging-wall block will produce apparent normal, or hanging-wall-down, displacement (Fig. 1B). In the case of margin-parallel displacement, shear sense along both boundaries of the subduction channel should be compatible and reflect the bulk displacement sense along the margin.

Material underplated to the base of the hanging-wall block within the ductile-flow regime may preserve noncoaxial fabrics compatible with the sense of displacement between the hanging-wall block and the immediately adjacent material in the subduction channel. If material is underplated to the hanging-wall block during downflow, structurally lower material within the subduction channel will be flowing at a faster rate than the structurally higher material nearer the hanging-wall block; therefore, fabric asymmetries in tectonites underplated to the base of the hanging-wall block should record reverse shear sense (Fig. 1C, stage 3). Structures of reverse type are documented from higher levels in the accretionary complexes where deformation occurs at <300 °C (e.g., Cowan, 1985; Platt et al., 1985; Moore et al., 1985; Sample and Fischer, 1986).

During backflow, material within the subduction channel flows upward along the arcward side of the channel (Cowan and Silling, 1978; Cloos, 1982). Therefore, apparent normal shear would be expected along the boundary between the hanging-wall block and the subduction channel, and some of the underplated material should record apparent normal displacement (Fig. 1B).

Margin-parallel flow may be predicted for obliquely convergent margins where the subduction complex is subjected to both dip-slip and strike-slip displacements, and tectonic slivers of the hanging-wall block may be translated laterally (Fig. 1; for a review, see Jarrard, 1986). If margin-parallel shear zones sole into the subduction channel (Hansen, 1988), the shear zone between the hanging-wall block and the subduction channel would also undergo margin-parallel displacement (Fig. 1C, stage 2). Evidence for margin-parallel displacement could easily be destroyed by subsequent dip-slip displacements during continued convergence, unless successive underplating and resultant trenchward migration of the boundary between the hanging-wall block and the subduction channel result in preservation of earlier accreted material (Fig. 1C, stage 3). In addition, further underplating and extension may result in flattening, and therefore destruction, of earlier formed noncoaxial fabrics. A change from dip-slip to strike-slip elongation lineation in underplated tectonites may be one of the few ways to recognize the root zones of subduction-related margin-parallel shear zones (Fig. 1C).

The *P-T* conditions that accompanied flow and underplating may be deduced from synkinematic mineral assemblages; these may include early high-*P*/*T* relicts overprinted by assemblages from lower metamorphic facies, indicating that rocks traveled up the subduction channel from great depth (e.g., Cloos, 1982). Similarly, the character of the accreted material (brittle or ductile), will reflect the mechanical, and therefore thermal, conditions of flow and accretion. Hence, *P-T* conditions recorded in underplated material will depend upon the thermal regime of the specific subduction-zone environment, as well as the individual displacement path of a specific tectonite package.

TECTONITES OF THE TESLIN SUTURE ZONE

The Teslin suture zone, which forms the fundamental boundary between North American strata and terranes accreted to the northern North American Cordillera since the Late Triassic (Hansen, 1989), lies structurally above rocks of the (par)autochthonous Cassiar terrane, which is the westernmost edge of the Permian-Triassic margin of North American continental crust (Tempelman-Kluit, 1979; Wheeler et al., 1988; Hansen, 1990). The following discussion is summarized from Hansen (1988, 1989, 1991).

Extending from northern British Columbia to east-central Alaska, the Teslin suture zone and related rocks form a belt of high-*P*/*T* metamorphic tectonites of oceanic affinity with local eclogite and blueschist blocks (Fig. 2). The tectonites record dynamothermal metamorphism within a west-dipping, Permian-Triassic B-type subduction complex outboard of western North America. These tectonites were thrust eastward as a coherent package in Early Jurassic time as a result of A-type subduction of the leading edge of North American continental crust. Cassiar strata were locally ductilely deformed and imbricated under high-*P*/*T* conditions along east-vergent shear zones during A-type subduction. Following collision, Cassiar strata cooled slowly as a result of erosion. Both the Teslin and Cassiar tectonites are dissected by mid-Cretaceous dextral strike-slip faults and plutons (e.g., d'Abbadie fault zone, Fig. 3).

L-S tectonites of the Teslin suture zone are composed of three protolith lithotectonic assemblages: (1) oceanic strata, including chert, argillite, carbonate, and graphitic siltstone; (2) oceanic crust, including massive to pillowed basalt, gabbro, and ultramafic rocks; and (3) magmatic arc rocks. Teslin tectonites evolved in a zone of noncoaxial strain and are divided into three structural domains on the basis of kinematic history (Fig. 3). From west to east, these are (1) $\mathrm{D_{Nds}}$, a 5–8-km-wide zone of top-to-the-west, or apparent normal, shear; (2) $\mathrm{D_{Dss}}$, a 1–2-km-thick zone of dextral strike-slip shear; and (3) $\mathrm{D_{Rds}}$, a 1–10-km-wide zone of top-to-the-east or apparent reverse shear. Crosscutting relations indicate that motion was initially normal dip slip ($\mathrm{D_{Nds}}$) at a high angle to the trend of the zone under high-*P*/*T* conditions. Displacement progressively evolved to right-lateral translation ($\mathrm{D_{Dss}}$) parallel to the trend of the zone at lower-*P*/*T* conditions. Reverse shear ($\mathrm{D_{Rds}}$) under low-grade metamorphic conditions dominated the last stages of tectonism in the Teslin suture zone. Metamorphism and associated penetrative ductile deformation of the Teslin suture zone and the related tectonites ended before Early Jurassic time, when the tectonites were quickly cooled through 500–300 °C at ~195 Ma (Hansen et al., 1991).

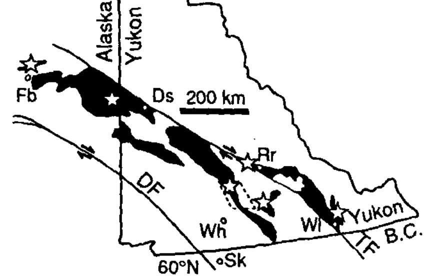

Figure 2. Location map showing distribution (black) of rocks correlative with those of Teslin suture zone (simplified from Hansen, 1991). Stars are eclogite locations. Rocks related to Teslin suture zone are offset in dextral sense along Tintina fault (TF); DF is Denali fault. Towns: Ds—Dawson, Fb—Fairbanks, Rr—Ross River, Sk—Skagway, Wh—Whitehorse, Wl—Watson Lake. Dashed line shows location of Figure 3.

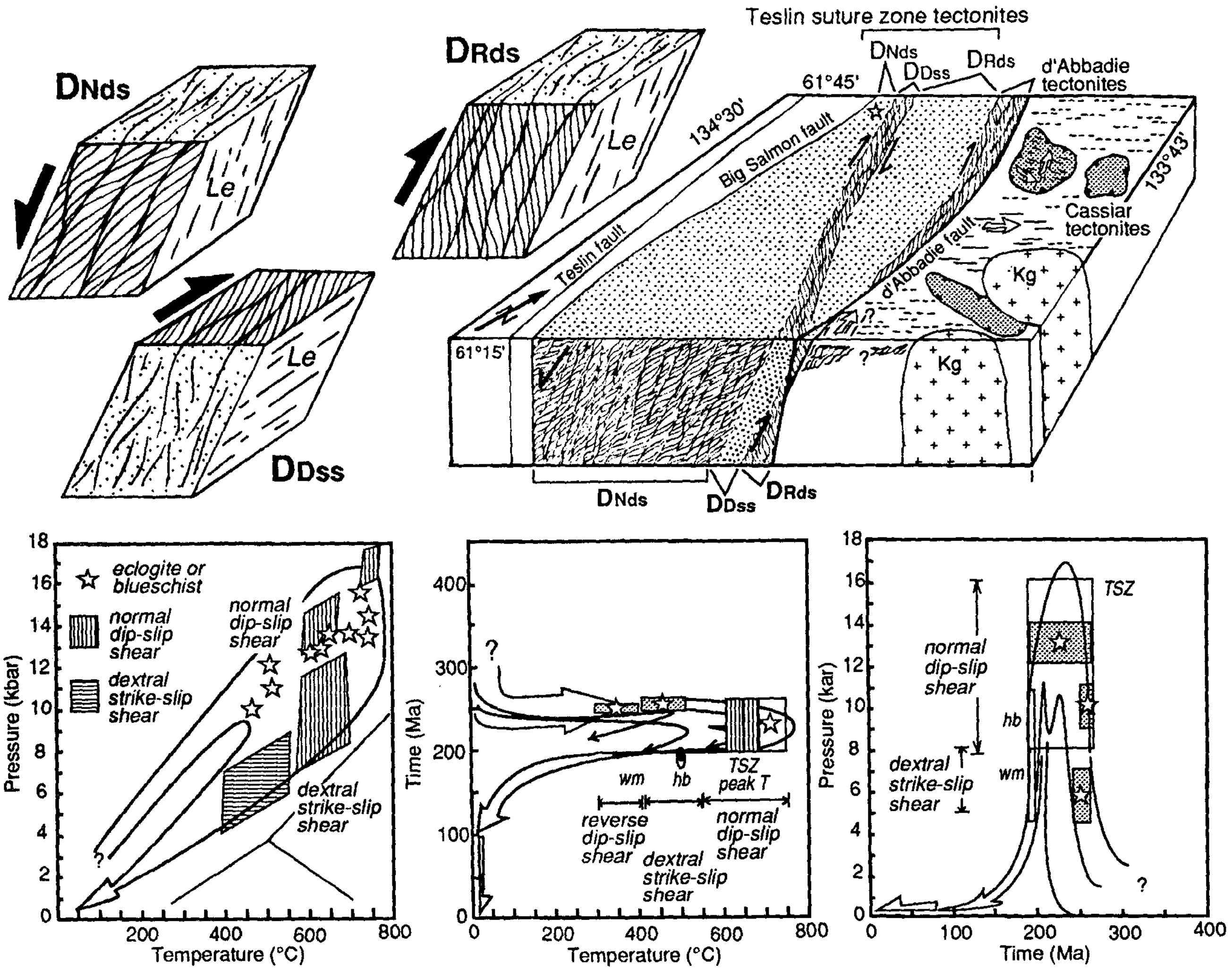

Figure 3. Block diagram of Laberge-Quiet Lake area, Yukon, showing distribution of kinematic domains in Teslin suture zone (TSZ) with accompanying *P-T*, *P-t*, and *T-t* plots (modified from Hansen, 1991), and D_{Nds}, D_{Dss}, and D_{Rds} structural domain kinematic fabrics shown in block diagrams. Le—elongation lineation; Kg—Cretaceous granite; hb—hornblende; wm—white mica.

The *P-T* path for the Teslin tectonites follows a clockwise loop arranged along a trench geotherm; the overall path is similar to prograde paths for circum-Pacific and Alpine-Himalayan high-*P* belts that record subduction-zone metamorphism (Ernst, 1988). The tectonites show a progressive increase in *T* through ~500 °C at ~245 Ma to a maximum of 750 °C, coincident with increased *P* to form blueschist, eclogite, and high-*P* amphibolite. The highest *P* and *T* conditions recorded in D_{Nds} tectonites (575–750 °C and 9–14 kbar) are similar to the conditions derived from structurally enclosed eclogite lensoids that record helical *P-T* paths (Erdmer and Helmstaedt, 1983). D_{Dss} deformation occurred under lower *P-T* conditions (400–550 °C and 5–8 kbar). D_{Rds} tectonites record a peak *T* of ~420 °C and a minimum peak *P* of 3 kbar; the maximum peak *P* may have been higher. Concordant Ar-Ar mineral cooling dates indicate that the tectonites were exhumed quickly (cooled at ~50 °C/m.y.) as a coherent structural block in latest Early Jurassic time. Quartz grains in these tectonites typically show annealed strain fabrics (polygonal grains with flat-field extinction), indicating that exhumation and rapid cooling were not accompanied by penetrative deformation; deformation, therefore, occurred prior to exhumation.

DISCUSSION

P-T-t (time) data indicate that tectonites of the Teslin suture zone were dynamothermally metamorphosed within a Permian-Triassic B-type subduction-zone environment, whereas Cassiar tectonites represent Jurassic A-type subduction tectonism. Regional geologic relations, including structural vergence and spatial distribution of early Mesozoic metamorphic facies and Permian-Triassic arc rocks, indicate that the Permian-Triassic subduction complex dipped westward outboard of western North America (Tempelman-Kluit, 1979; Hansen, 1988). Therefore, the Teslin tectonite fabrics record dynamothermal deformation within the deep-seated part of a Permian-Triassic subduction complex, and the structural and kinematic evolution of these rocks records deep-seated subduction-zone dynamics. These tectonites represent material that was underplated to the base of the hanging-wall block from the subduction-channel shear zone during Permian-Triassic subduction. *P* and *T* constraints and the relative inverted metamorphic gradient preserved by D_{Nds} and D_{Dss} tectonites are consistent with progressive underplating of these rocks to the base of the hanging-wall block during subduction (Peacock, 1987). The Teslin suture zone grew in a trenchward direction (eastward in present-day coordinates) as material was progressively underplated, and the rocks record progressive changes in displacement histories along the boundary between the hanging-wall block and the subduction channel. D_{Nds} tectonites, the structurally highest, represent the oldest preserved material accreted to the hanging-wall block; D_{Dss} tectonites were underplated with continued subduction, and finally D_{Rds} tectonites were underplated.

D_{Nds} tectonites record apparent normal displacement of the hanging-wall block compatible with backflow within the subduction channel. The presence of eclogite lensoids enclosed in D_{Nds} tectonites is predicted by backflow dynamics. D_{Dss} tectonites record dextral displacement, consistent with right-lateral displacement along the boundary between the subduction channel and the hanging-wall block. D_{Dss} fabrics may represent the shallowing of a margin-parallel shear zone into the subduction-channel shear zone, as a result of right-oblique subduction. Structures in the Teslin suture zone record progressive evolution from D_{Nds} to D_{Dss} tectonism. Broad regions of the suture zone containing penetrative D_{Nds} fabrics are crosscut by a 1–2-km-wide shear zone marked by D_{Dss} fabrics. D_{Dss} formation was accompanied by P and T conditions lower than those for D_{Nds} formation, in keeping with the interpretation that dextral displacement dominantly postdated apparent normal-shear deformation. Although strike-slip displacement as recorded by D_{Dss} fabrics dominantly outlasted normal dip-slip displacement, dip-slip *and* strike-slip displacement may have been occurring synchronously in different parts of the subduction complex. Furthermore, D_{Rds} deformation occurred at lower P and T conditions than D_{Dss} deformation, compatible with the interpretations that formation of D_{Rds} dominantly postdated D_{Dss} and that these tectonites record deformation at a higher crustal level within the subduction complex. D_{Nds}, D_{Dss}, and D_{Rds} waned before cooling of the Teslin suture zone at 195 Ma.

The Teslin suture zone represents a tectonite package formed by progressive underplating from the subduction-channel shear zone to the base of the hanging-wall block within the deep-seated part of a B-type, Permian-Triassic subduction complex. The subduction complex formed beneath an east-facing, late Paleozoic–early Mesozoic arc outboard of western North America. Subducted material was, in part, progressively underplated during backflow, margin-parallel flow, and downflow within the subduction channel. With continued subduction and underplating, the boundary between the hanging-wall block and the subduction channel migrated trenchward, resulting in thickening of the hanging-wall block. The tectonites were probably uplifted slowly as a result of continued underplating, although they were not cooled through 350–500 °C until rapid exhumation as a coherent package in Early Jurassic time as a consequence of A-type subduction of the leading western edge of North America beneath the hanging-wall block. These tectonites were underplated during subduction and provide empirical evidence that deep-seated backflow, margin-parallel flow, and downflow all can occur within the subduction-channel shear zone.

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ACKNOWLEDGMENTS

Supported by the Exploration and Geological Services Division of the Department of Northern and Indian Affairs, Whitehorse, Yukon; by National Science Foundation Grant EAR-8715911; and by the Donors of the Petroleum Research Fund, administered by the American Chemical Society. I thank M. Cloos, J. W. Goodge, J. C. Moore, and T. Pavlis for reviews of the manuscript.

Manuscript received June 24, 1991
Revised manuscript received October 7, 1991
Manuscript accepted October 15, 1991

Reviewer's comment

Very important because structurual evidence of backflow in a subduction channel is undocumented previously.

Casey Moore
