Structural and kinematic evolution of the Yukon-Tanana upland tectonites, east-central Alaska: A record of late Paleozoic to Mesozoic crustal assembly

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ABSTRACT

The Yukon-Tanana terrane, the largest tectonostratigraphic terrane in the northern North American Cordillera, is polygenetic and not a single terrane. Lineated and foliated (L-S) tectonites, which characterize the Yukon-Tanana terrane, record multiple deformations and formed at different times. We document the polyphase history recorded by L-S tectonites within the Yukon-Tanana upland, east-central Alaska. These upland tectonites compose a heterogeneous assemblage of deformed igneous and metamorphic rocks that form the Alaskan part of what has been called the Yukon-Tanana composite terrane. We build on previous kinematic data and establish the three-dimensional architecture of the upland tectonites through kinematic and structural analysis of more than 250 oriented samples, including quartz c-axis fabric analysis of 39 samples.

Through this study we distinguish allochthonous tectonites from parautochthonous tectonites within the Yukon-Tanana upland. The upland tectonites define a regionally coherent stacking order: from bottom to top, they are lower plate North American parautochthonous attenuated continental margin; continentally derived marginal-basin strata; and upper plate ocean-basin and island-arc rocks, including some continental basement rocks. We delineate three major deformation events in time, space, and structural level across the upland from the United States–Canada border to Fairbanks, Alaska: (1) pre-Early Jurassic (>212 Ma) northeast-directed, apparent margin-normal contraction that affected oceanic rocks; (2) late Early to early Middle Jurassic (>188–185 Ma) northwest-directed, apparent margin-parallel contraction and imbrication that resulted in juxtaposition of the allochthonous tectonites with parautochthonous continental rocks; and (3) Early Cretaceous (135–110 Ma) southeast-directed crustal extension that resulted in exposure of the structurally deepest, parautochthonous continental rocks. The oldest event represents deformation within a west-dipping (present coordinates) Permian-Triassic subduction zone. The second event records Early to Middle Jurassic collision of the arc and subduction complex with North American crust, and the third event reflects mid-Cretaceous southeast-directed crustal extension. Events one and two can be recognized and correlated through southern Yukon, even though this region was affected by mid-Cretaceous dextral shear along steep northwest-striking faults. Our data support a model of crustal assembly originally proposed by D. Tempelman-Kluit in which previously deformed allochthonous rocks were thrust over parautochthonous rocks of the attenuated North American margin in Middle Jurassic time. Approximately 50 m.y. after tectonic accretion, east-central Alaska was dissected by crustal extension, exposing overthrust parautochthonous strata.

INTRODUCTION

The Yukon-Tanana terrane, the largest tectonostratigraphic terrane in the northern North American Cordillera, was originally defined as an assemblage of rocks containing a strong L-S (lineated and foliated) tectonite fabric in contrast with adjacent rocks (e.g., Coney and Jones, 1980). Early studies showed that the Yukon-Tanana terrane includes rocks that have distinctly different geologic histories (e.g., Churkin et al., 1982; Foster et al., 1985; Aleinikoff et al., 1987), leading Hansen (1990a) to suggest that the terrane be considered as polygenetic rather than as a single coherent crustal entity. Structural studies of these tectonites show that they record multiple deformations, and their characteristic L-S fabric formed at different times (e.g., Hansen et al., 1991; Dusel-Bacon et al., 1995). Thus we refer to these rocks as the Yukon-Tanana composite terrane. Widespread mid-Paleozoic to Mesozoic magmatic crystallization and metamorphic cooling ages (Mortensen, 1992) indicate that this was an important period in the assembly of this large tract of crust. Despite evidence of a complicated polyphase history, however, some workers, on the basis of geochemical and isotopic characteristics, treat the Yukon-Tanana composite terrane as a uniform assemblage with a simple geologic history (e.g., Gehrels et al., 1990, 1991; Mortensen, 1992; Nelson and Mihalynuk, 1993; Mihalynuk et al., 1994). Although geochemical or isotopic tracers provide useful information about crustal origin and average mantle-separation ages of their continental rocks, these data do not explain how crust is assembled, or reassembled.

Our goal is to understand the late Paleozoic to Mesozoic assembly of east-central Alaska as recorded by L-S tectonites of the Yukon-Tanana upland, east-central Alaska (referred to hereafter as the upland tectonites, on the basis of their geographic exposure in the Yukon-Tanana upland). The upland tectonites compose a heterogeneous assemblage of deformed igneous and metamorphic rocks that together form the Alaskan part of what has been called the Yukon-Tanana composite terrane. We document the polyphase history recorded within the L-S tectonites and establish a structural framework within which pressure-temperature-time (*P-T*-t) and geochemical data can be examined. We build on the kinematic data base initiated by Hansen et al. (1991) and establish the three-dimensional architecture of the upland tectonites through kinematic and structural analysis of more than 250 oriented samples, including quartz c-axis fabric analysis of 39 samples. From these data we define kinematic domains and determine temporal relations within and between domains. This kinematic framework, coupled with published thermobarometric and thermochronometric studies, allows us to

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constrain the geometric and temporal stacking order of the tectonites, and to identify contractional versus extensional relations within and between the kinematic domains through time.

Although we are ultimately interested in understanding the spatial and temporal domains within all of the upland tectonites, we begin our analysis in the eastern Eagle-Tanacross region (Figs. 1 and 2). After establishing a structural framework for that region, we extend our discussion to specific areas to the west. Published thermobarometric and thermochronometric data allow us to refine the geologic history of the entire upland and correlative tectonites in Canada (Fig. 1).

BACKGROUND

The Yukon-Tanana upland consists of moderately dissected hills and mountains that escaped regional glaciation. The metamorphic bedrock comprises a mass of lower greenschist to amphibolite facies L-S tectonites, intruded by Mesozoic and Tertiary granitoids and overlain by klippen of oceanic rocks (Seventymile terrane) (e.g., Foster et al., 1994). Our term *upland tectonite* is generally synonymous with Yukon-Tanana terrane of older literature, but we introduce this new nomenclature to emphasize the heterogeneous character of this association of crystalline rocks. For clarification we refer to specific terrane designations where appropriate; however, we use the term *assemblage* because terrane has implications that may not be appropriate. Early workers recognized a stacking order among the tectonites, rocks of continental affinity being at the base and oceanic-arc rocks being at high structural levels (e.g., Coney et al., 1980). Initially, these rocks were interpreted as a single structural package because they display pronounced L-S tectonite fabrics, which inhibit identification of primary structures and lithology. Therefore, early studies focused on determining the age of ductile deformation, with interpretations ranging from Paleozoic (e.g., Dusel-Bacon and Aleinikoff, 1985) to Cretaceous (e.g., Nokleberg et al., 1989). Despite their apparent structural similarity, kinematic and thermochronometric studies within the upland tectonites revealed significantly different tectonic histories (e.g., Hansen, 1990a; Hansen et al., 1991; Pavlis et al., 1993; Dusel-Bacon et al., 1995). Lithologic divisions (Churkin et al., 1982) correspond, in general, with metamorphic, kinematic, and temporal domains, illustrating that these rocks are not a single tectonic entity with a common history.

Upland tectonites are divisible into five distinct packages (Fig. 2) on the basis of lithology and geologic history (e.g., Churkin et al., 1982; Hansen et al., 1991): (1) oceanic volcanic and sedimentary rocks of the Seventymile assemblage; (2) tectonites of oceanic and marginal basin origin in the Taylor Mountain assemblage; (3) tectonites derived from siliciclastic marginal-basin strata composing the Nisutlin assemblage; (4) paragneiss and peraluminous orthogneiss of continental affinity (herein referred to as the orthogneiss assemblage); and (5) tectonized parautochthonous continentally derived metasedimentary rocks of the Chena River and Fairbanks subterranes.

Seventymile rocks (Fig. 2), correlative with the Slide Mountain terrane in Canada (Fig. 1) (Harms et al., 1984), include weakly metamorphosed greenstone, Mississippian to Triassic metasedimentary rocks, and serpentinized peridotite (Foster, 1992; Foster et al., 1994). They are interpreted as disrupted mid-Paleozoic to lower Mesozoic oceanic crust (Harms, 1986; Coney, 1989; Roback et al., 1994) and parts of an upper Paleozoic oceanic arc (Nelson et al., 1989). Rocks of the Seventymile assemblage are generally not penetratively deformed.

Tectonites of the Taylor Mountain assemblage, correlative with the Teslin and Anvil assemblages in Yukon (Hansen, 1990a), consist of high-P amphibolite facies garnet-amphibolite, biotite ± hornblende ± garnet gneiss and schist, marble, quartzite-metachert, and pelitic schist, and small bodies of hornblendite, metadiabase, pyroxenite, and serpentinized peridotite (Dusel-Bacon et al., 1995). Slide Mountain and Teslin rocks are broadly correlative, differing mostly in crustal level of deformation and grade of metamorphism (Hansen, 1990a; Wheeler and McFeeley, 1991). We regard the Seventymile and Taylor Mountain assemblages as sharing protolith types, but differing in crustal level of deformation. The Taylor Mountain assemblage yields latest Triassic to Early Jurassic metamorphic cooling ages, and they are intruded by the postkinematic Taylor Mountain batholith (titanite U-Pb age of 212 Ma) (Hansen et al., 1991; Dusel-Bacon et al., 1995).

The Nisutlin assemblage (Birch Hill and Butte Yukon-Tanana composite subterranes east of Fairbanks; Pavlis et al., 1993), interpreted as tectonized marginal-basin strata (Tempelman-Kluit, 1979), includes a sequence of greenschist facies siliciclastic metasedimentary rocks, felsic to mafic metavolcanic rocks, and marble. Limited biostratigraphic data indicate that protoliths are in part Devonian to Mississippian and contain Early Pennsylvanian to Early Permian and Late Triassic conodonts (Tempelman-Kluit, 1979; Mortensen, 1992; Dusel-Bacon et al., 1993; Foster et al., 1994). Metavolcanic rocks are Devonian in age (U-Pb ages, J. N. Aleinikoff and W. J. Nokleberg, 1989, unpublished data, cited in Dusel-Bacon et al., 1993; Smith et al., 1994).

The orthogneiss assemblage (also called the Lake George subterrane of the Yukon-Tanana composite terrane, Robinson et al., 1990; Pavlis et al., 1993; Dusel-Bacon et al., 1995) consists of pelitic schist and gneiss, quartzite, and minor amphibolite that have been intruded by Devonian to Mississippian peraluminous granitoids (now augen orthogneiss). Granitoids show Precambrian U-Pb inheritance and yield εNd values consistent with derivation from cratonal North American basement (Aleinikoff et al., 1981, 1986; Mortensen, 1992; Helsop et al., 1995; Dusel-Bacon and Aleinikoff, 1996). In general, these tectonites yield Early Cretaceous cooling ages (Rb-Sr, $^{40}Ar/^{39}Ar$, hornblende, biotite, muscovite; e.g., Hansen, 1990a; Hansen et al., 1991; Pavlis et al., 1993).

Strata of the Fairbanks subterrane of the Yukon-Tanana composite terrane are interpreted as deposited within a continental margin setting, correlative with Selwyn basin strata in Yukon, and hence parautochthonous to North America (Murphy and Abbott, 1995).

Generally, massive Late Triassic to Early Jurassic granitoids (e.g., Taylor Mountain batholith and Mount Veta pluton, Fig. 3) only intrude rocks of the Seventymile, Taylor Mountain, and Nisutlin assemblages over the entire upland (Foster, 1992). These bodies represent arc granitoids within an oceanic or marginal-basin setting and have been correlated with the Stikinia arc on the basis of Pb isotopes (Aleinikoff et al., 1987; Dusel-Bacon et al., 1995).

Mid-Cretaceous plutons, generally massive, intermediate in composition, and corundum-normative, are most abundant in the central upland; they intrude each of the tectonite assemblages, and display mylonitic textures only along major high-angle faults (Foster et al., 1994). Latest Cretaceous to early Tertiary plutons intrude primarily the northwestern upland, are generally felsic (including some two-mica granites), and form small massive plutons that have well-developed contact aureoles (Dusel-Bacon et al., 1989, 1993). Post-mid-Cretaceous, northeast-striking, high-angle faults disrupt the upland locally; left-lateral offset along most faults is relatively minor (Griscom, 1979), but dip-slip movement may be significant in preserving high-level assemblages (Newberry et al., 1995; Solie et al., 1995).

Previous studies demonstrated that the upland tectonites, and correlative rocks in Yukon, record two distinct phases of ductile deformation: a pre-Early to Early Jurassic and an Early Cretaceous event. Early deformation is dominantly contractional with evidence of dextral strike-slip shear preserved locally in Yukon. The Early Cretaceous deformation records crustal extension in eastern Alaska and dextral strike-slip in southern Yukon (Hansen et al., 1989, 1991; Pavlis, 1989; Pavlis et al., 1993). Our data illustrate that the upland tectonites also variably record Early to Middle

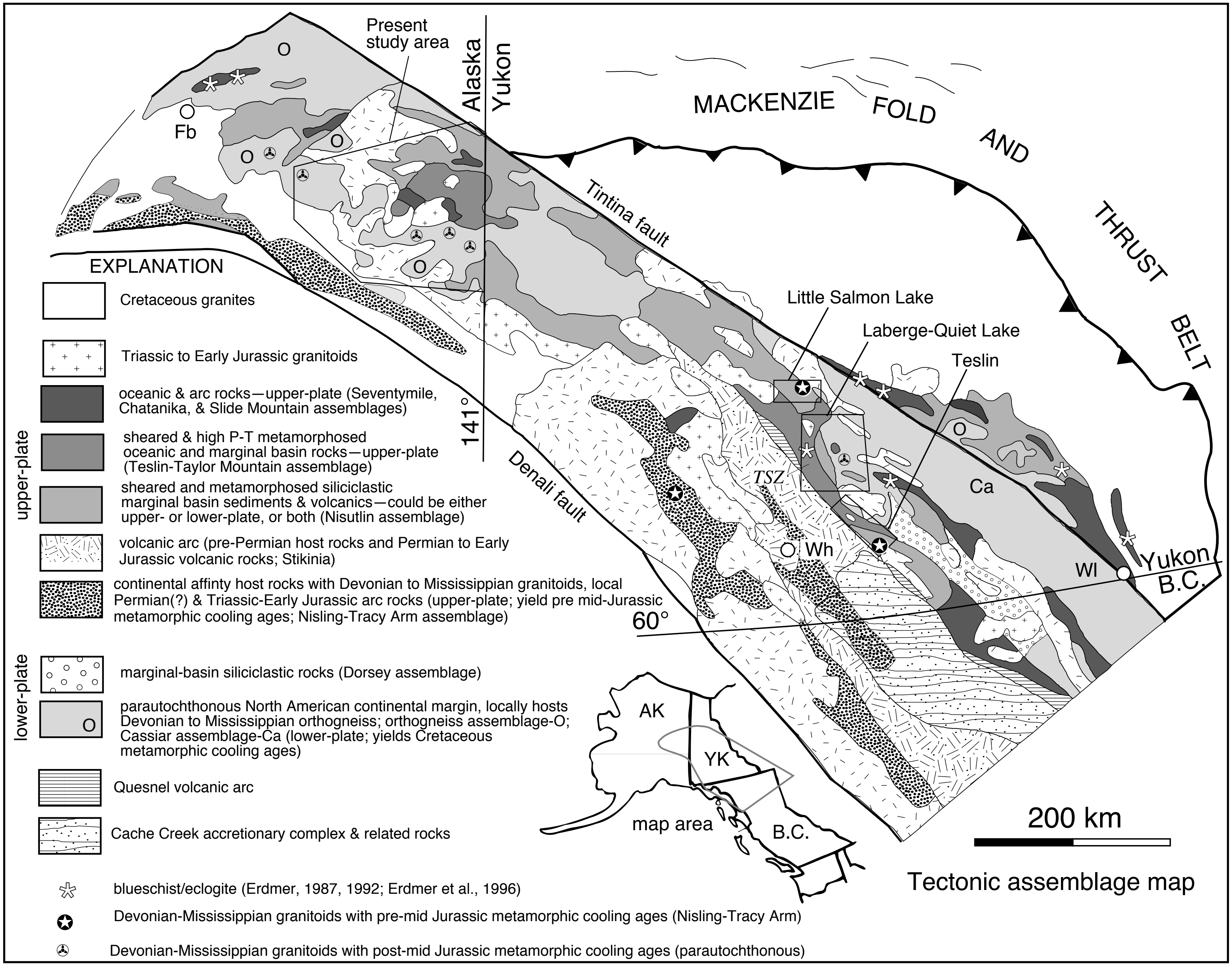

Figure 1. Simplified tectonic assemblage map (modified from Hansen et al., 1991, and data sources listed therein). Abbreviations: Fb—Fairbanks, Wh—Whitehorse, Wl—Watson Lake, TSZ—Teslin suture zone (see text for explanation). Unlabeled area around Fairbanks is alluvium and unlabeled area north of Denali fault in Alaska comprises various terranes not discussed in this paper. Inset map shows location of detail.

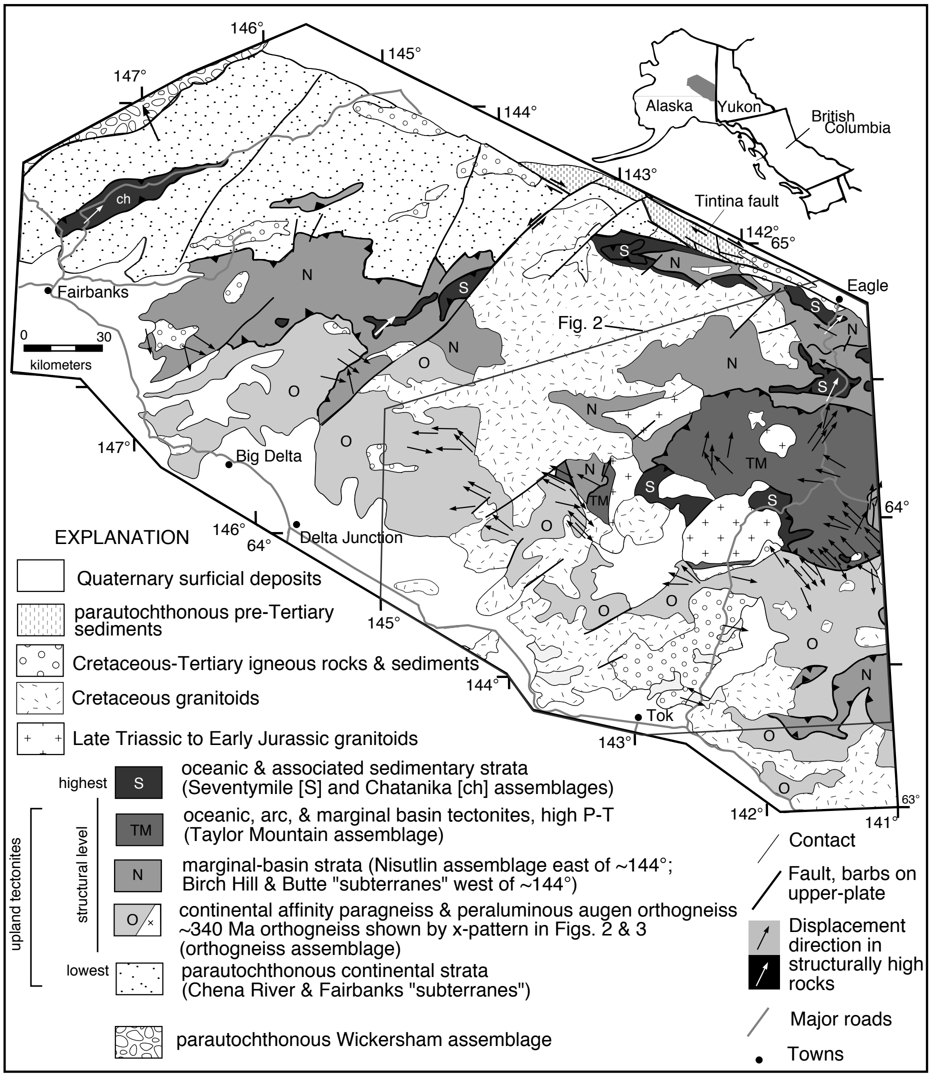

Figure 2. Simplified tectonic assemblage map of the Yukon-Tanana upland (modified from Foster, 1992; Pavlis et al., 1993; Dusel-Bacon et al., 1995, and data sources therein) and kinematic data. Kinematic data west of 145° are from Pavlis et al. (1993); data east of 145° are from Hansen et al. (1991) and this study. Inset shows location in Alaska; irregular box shows area of Figure 3.

Jurassic deformation that is kinematically distinct from the previously recognized deformations.

STRUCTURAL AND KINEMATIC RELATIONS

Scope of This Study and Methods of Analysis

We describe the structural relations in four main areas; from east to west, these are (1) the eastern Eagle-Tanacross quadrangles; (2) Mount Warbelow; (3) Molly Creek; and (4) the southeast Big Delta quadrangle (Figs. 2, 3, and 4). The eastern Eagle-Tanacross region, the largest and best exposed, preserves three distinct kinematic domains. Data from the other regions allow us to extend the spatial limits of these three domains, and they provide additional evidence for the geometric, kinematic, and temporal relations between the domains. The southeast Big Delta area allows close spatial correlation with published kinematic and thermochronometric data to the west.

Lithologic contacts generally parallel foliation (S), which dips moderately to gently and describes open to gentle upright warps with east-west axial traces (Cushing and Foster, 1984; Foster et al., 1985, 1994). These warps affect each of the assemblages and therefore they formed late with respect to final structural juxtaposition. Local preservation of the structurally highest rocks of the Seventymile assemblage is likely due to their position in broad synformal warps. Similarly, the deepest structural level that has orthogneiss assemblage is best exposed in the core of broad antiformal warps.

The tectonites contain monoclinic or triclinic fabrics composed of foliation (S), elongation lineations (Le), textural asymmetries, and locally, mesoscopic folds. Compositional layering and alignment of platy minerals define S; rodded quartz, smeared or crenulated mica, and elongate or aligned feldspar or amphibole define Le. Le (X axis) is contained within S (XY plane).

Because the upland tectonites comprise a mass of L-S tectonites, in order to understand their evolution we delineated structural domains as defined by Le orientation and associated shear-sense indicators. Because S dips gently to moderately throughout the upland, and because Le is within S, Le orientation can be represented by a line in map view. We determined Le distribution from published maps, unpublished U.S. Geological Survey field notes, and our field measurements. We examined rocks for kinematic indicators in the field after carefully determining that tectonite exposures were structurally in situ and not affected by frost heaving. We collected oriented samples for microstructural analysis using methods described by Hansen (1990b).

Kinematic Indicators

Mesoscopic, microscopic, and petrofabric kinematic indicators viewed within the motion plane (XZ) of the upland tectonites allow us to define kinematic domains.

Microstructures. Fabric asymmetry within the motion plane records the direction of tectonic transport during ductile deformation (e.g., Eisbacher, 1970; Berthé et al., 1979; Hanmer and Passchier, 1991). No asymmetric fabrics indicative of noncoaxial strain were observed in the YZ plane. Mesoscopic and microscopic motion-plane asymmetries used in this study include asymmetric folds with fold axes perpendicular to Le; shear bands (Platt and Vissers, 1980); rare rotated clasts; type I and II S-C fabrics (Lister and Snoke, 1984); mica and amphibole fish; asymmetric pressure shadows; sigma porphyroclasts; obliquity between spaced foliation; and grain-shape–preferred orientation of dynamically recrystallized quartz.

Quartz c-axes. Asymmetric quartz c-axis fabrics also record ductile shear sense. We selected 36 of the most quartz-rich samples for quartz petrofabric analysis, which was carried out optically on XZ and XY sections from each sample using a universal stage (Turner and Weiss, 1963).

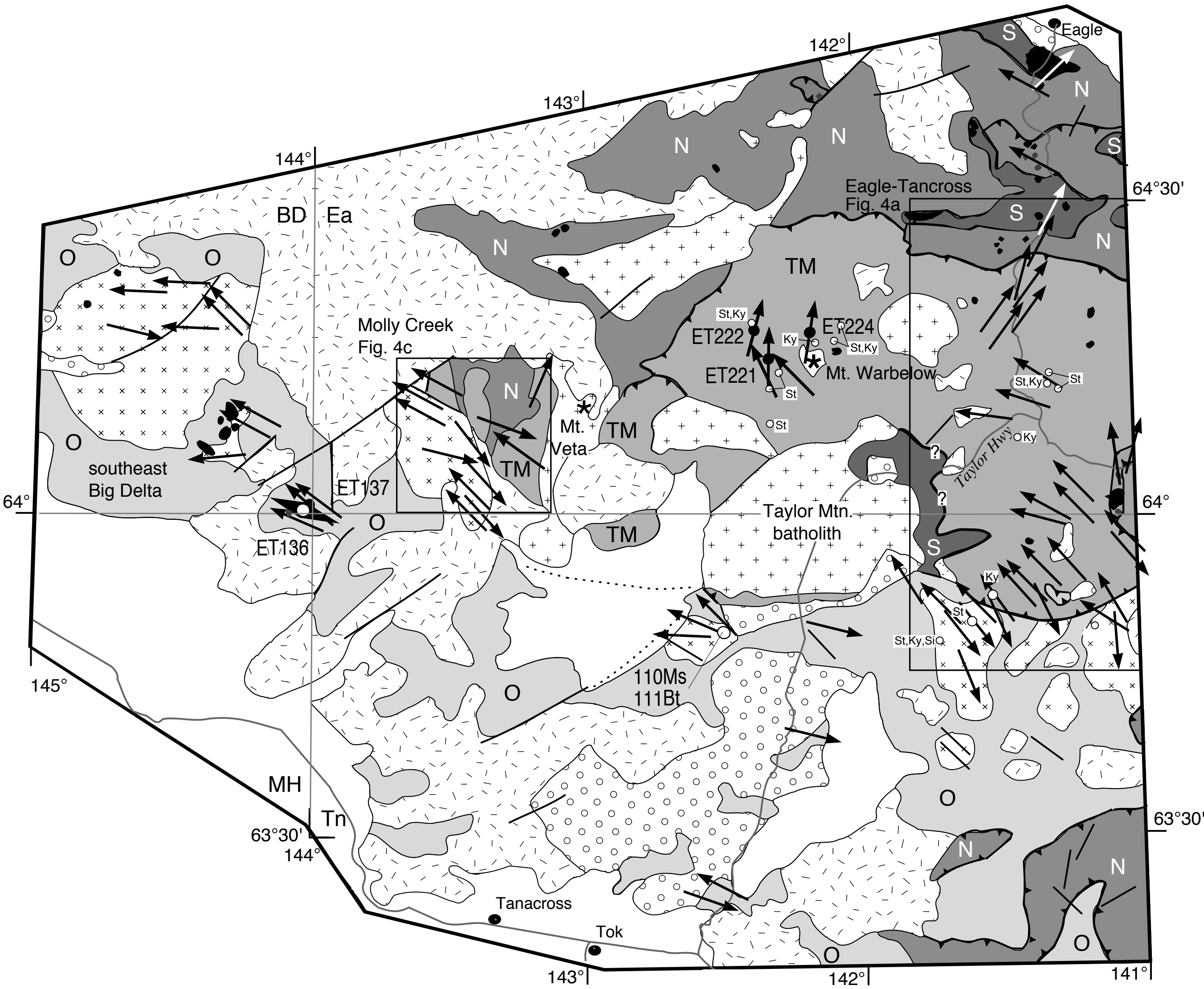

Figure 3. Simplified tectonic assemblage map of east-central Alaska, including parts of the Big Delta (BD), Eagle (Ea), Mount Hayes (MH), and Tanacross (Tn) 1° × 3° sheets (modified from Foster, 1992; Dusel-Bacon et al., 1993, and sources therein) and kinematic data, quartz c-axis localities, and metamorphic cooling ages (see Fig. 4 legend). Additional quartz c-axis locations are shown in Figure 4. Pelitic mineral assemblages shown: Ky—kyanite, Si—sillimanite, and St—staurolite (Dusel-Bacon et al., 1995). Dark gray depicts ultramafic (peridotite or serpentine) bodies. Map units and symbols are the same as in Figure 2.

We measured a minimum of 250 c-axes in each section, unless noted. Data from both sections are shown with c-axes rotated into a single equal-area, lower-hemisphere composite plot (n > 500) with the XZ plane as the perimeter circle. We attempted to achieve coverage both regionally and with respect to structural domains. The c-axis fabrics from each sample (Fig. 5) indicate that Le is an elongation lineation (i.e., that it is parallel to X) because the fabric girdle for each sample intersects S normal to Le (Behrmann and Platt, 1982).

Quartz c-axis patterns are a function of intracrystalline slip mechanism, temperature, water content, strain rate, deformation path, and total strain (Fig. 5kk; Tullis et al., 1973; Nicolas and Poirer, 1976; Lister and Hobbs, 1980; Hobbs, 1985; Law, 1990). Asymmetric single-girdle fabrics can form as the result of noncoaxial component of strain, the sense of asymmetry recording the sense of bulk noncoaxial shear (Fig. 5ll), whereas fabric symmetry indicates bulk pure shear (Fig. 5mm; Schmid and Casey, 1986). Because c-axis plots record finite strain history, the complete fabric diagram could be a result of several nonunique strain histories. For example, a bulk coaxial fabric could record a single coaxial flattening event, or two sequential, coplanar but opposite vergence, noncoaxial ductile shear deformations. Quartz slip systems also show a relative temperature dependence, that is, low temperature basal <*a*> slip, rhombohedral <*a*>, prism <*a*>, and the rarely observed prism <*c*> slip at progressively higher temperatures (Fig. 5kk;

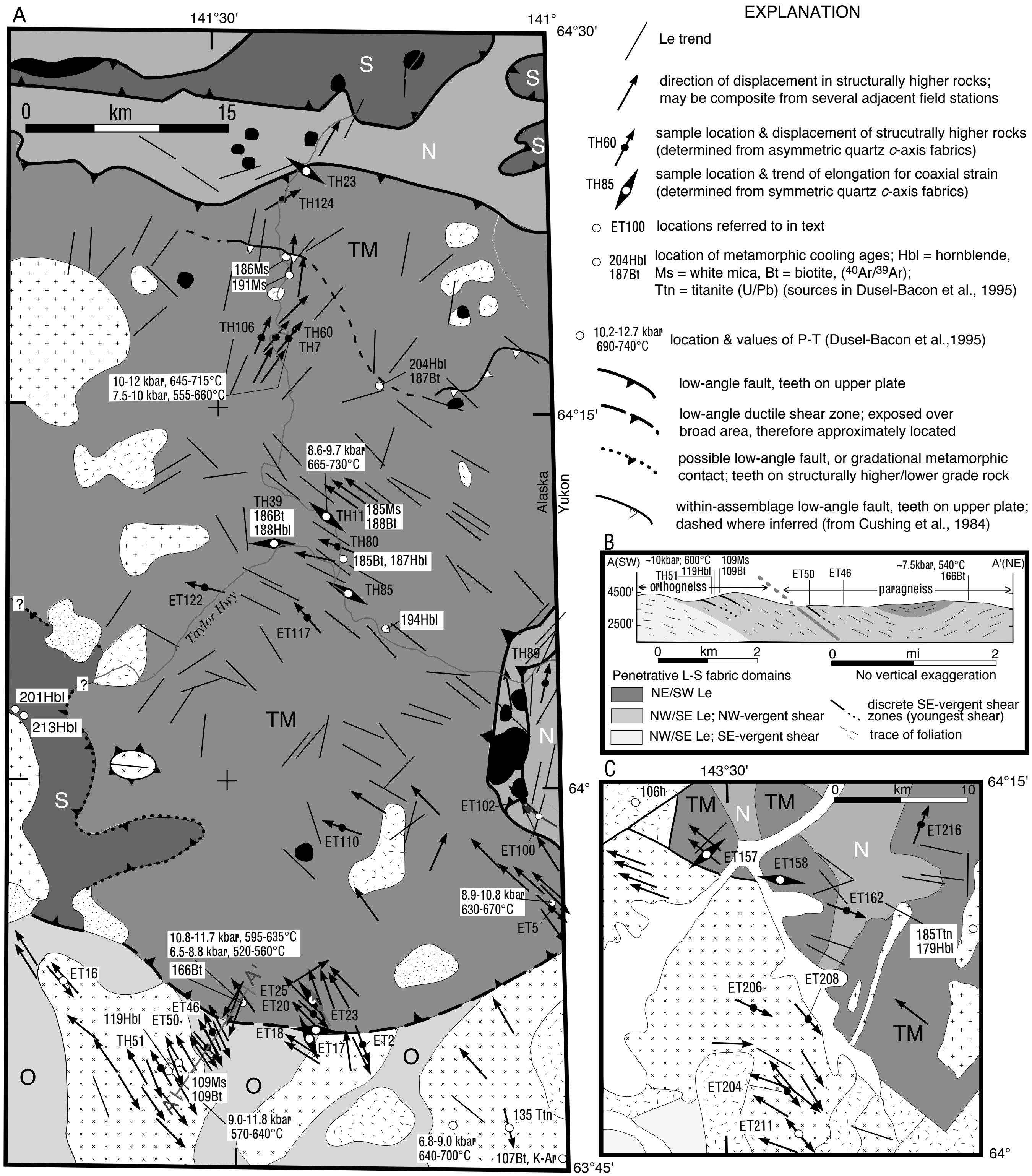

Figure 4. Geologic and kinematic maps of the regions identified in Figure 3. (A) Eastern Eagle and Tanacross map area. (B) Cross section A–A′ in southeast corner of A; note that the patterns in B are structural facies (legend shown), not lithologic units, and the scale is not the same as that in A. (C) Molly Creek region. Units are the same as in Figures 2 and 3. Pressure-temperature and age data from Dusel-Bacon et al. (1995) and sources therein.

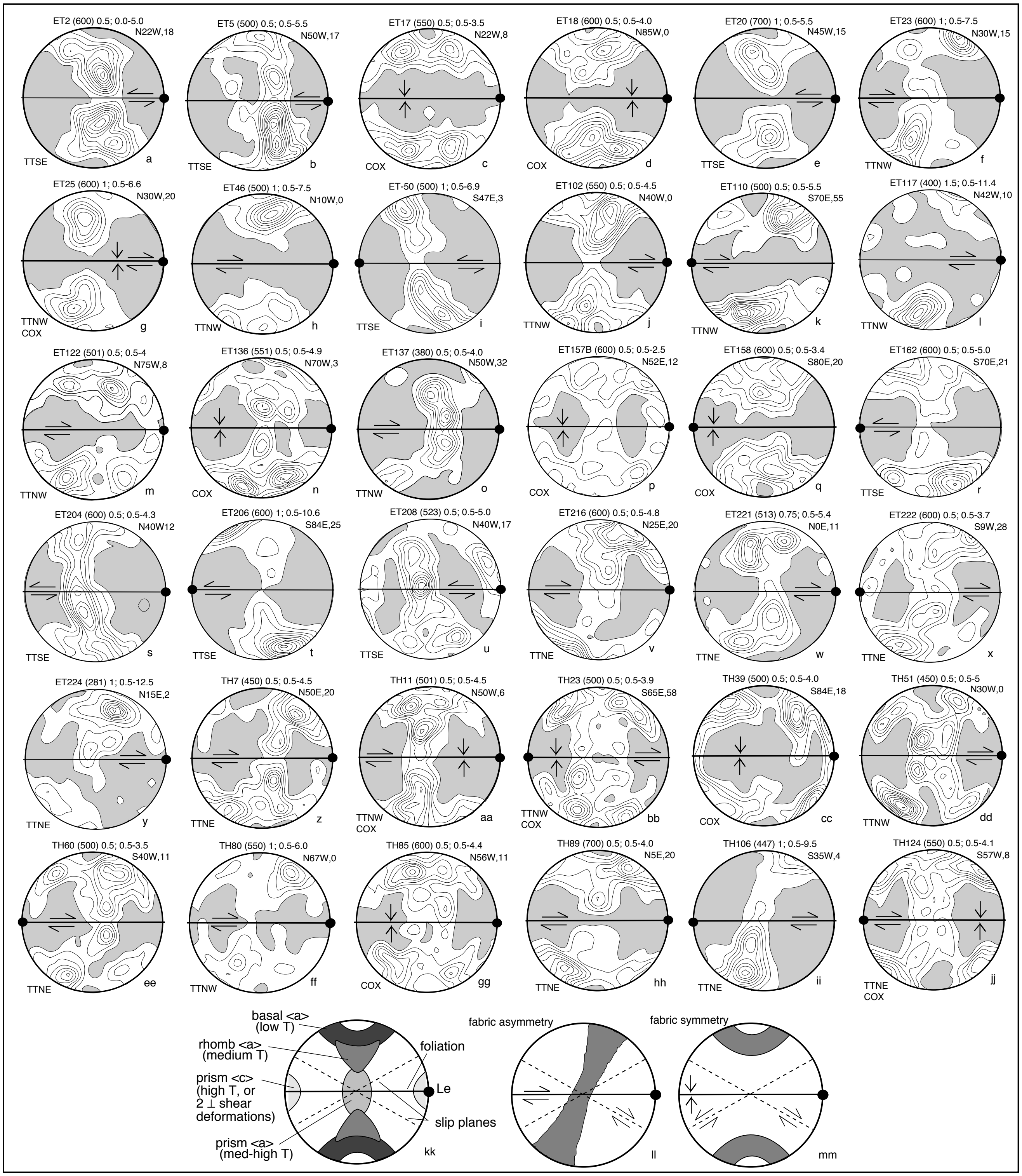

Figure 5. (a–jj) Equal-area, lower-hemisphere stereonet projections of quartz c-axis petrofabrics viewed within the motion plane (plane normal to S, which contains elongation lineation Le); sample locations in Figures 2 and 3. Foliation shown by horizontal line, Le shown by dot; gray marks pole free (<0.5%) region; arrows show shear sense interpreted from fabric asymmetry (noncoaxial) or fabric symmetry (coaxial shear). Data at top right of each diagram includes: sample number, number of c-axes measured (in parenthesis), contour interval (%), range of contour values (%), and trend and plunge of Le. Letters in the lower-left corner give interpreted shear sense in geographic terms: TTNE—top-to-northeast; TTNW—top-to-northwest; TTSE—top-to-southeast; COX—coaxial shear; no shear-sense determined. Plots were contoured using STEREOPLOTII (Mancktelow, 1993). (kk) Lower-hemisphere stereoplot showing the location of quartz c-axes with respect to foliation and elongation lineation corresponding to different active slip systems (modified from Schmid and Casey, 1986). (ll) Asymmetric fabric indicative of simple shear or high strain; (mm) symmetric fabric indicative of coaxial shear.

Hobbs, 1985). Prism <*c*> slip occurs at high-temperature subsolidus conditions (Jessel and Lister, 1990), although it might also be activated under greenschist facies conditions as a result of polyphase shear (Oliver, 1996).

Eastern Eagle-Tanacross Region

Our most detailed analysis focuses on the eastern Eagle-Tanacross region, which is relatively well exposed, has a low volume of Cretaceous granitoids, and is accessible along the Taylor Highway (Fig. 4). The Taylor Mountain assemblage dominates the area; the Seventymile and Nisutlin assemblages are exposed in the north, east and west, and the orthogneiss assemblage is exposed in the south.

The Seventymile assemblage is in fault contact with structurally lower rocks, except east of the Taylor Mountain batholith, where Seventymile greenstone, metachert, and phyllite may grade into higher grade Taylor Mountain rocks (Figs. 2 and 3). As discussed by Dusel-Bacon et al. (1995), this contact is shown as a fault in many recent papers; however, Foster (1969) noted that the contact could be either a gradational metamorphic contact or a structural contact.

The Nisutlin–Taylor Mountain contact consists of a regionally extensive low-angle brittle-ductile thrust fault (Foster et al., 1985). Structural interleaving of ultramafic, Taylor Mountain, and Nisutlin rocks near the international border at 64°N indicates the local complexity of this contact (Fig. 4). The contact as exposed along the Taylor Highway is marked by a 1–3-km-wide (map view) moderately south dipping fault zone (Foster et al., 1985). Displacement on the fault zone postdates penetrative ductile shear of the Taylor Mountain and Nisutlin assemblages. A 186 ± 2 Ma ^{40}Ar/^{39}Ar muscovite plateau age from an undeformed dike that crosscuts tectonite foliation of the Taylor Mountain assemblage (Cushing et al., 1984; Cushing, 1984) establishes a minimum age for ductile deformation. Evidence for the timing of fault juxtaposition of Taylor Mountain tectonites above Nisutlin tectonites is provided by a biotite plateau age of 187 ± 2 Ma from actinolite-biotite schist formed within a shear zone that is parallel to the south-dipping thrust fault (Cushing et al., 1984).

The nature of the Taylor Mountain–orthogneiss assemblage contact is controversial (see discussion in Dusel-Bacon et al., 1995), in part because of poor exposure, yet it is a critical line of evidence in the tectonic history. If the orthogneiss assemblage is structurally above the Taylor Mountain assemblage, it provides evidence for major Early Cretaceous contraction within the upland (Nokleberg et al., 1989; Mortensen, 1992). However, if Taylor Mountain assemblage is structurally above the orthogneiss assemblage, then evidence for Early Cretaceous contraction in this part of the upland diminishes (Hansen, 1990a; Hansen et al., 1991). If the Taylor Mountain assemblage grades stratigraphically downward into the orthogneiss assemblage with no significant discontinuity (e.g., Mortensen, 1992), then these two tectonic units would appear to share a common tectonic history. Early Middle Jurassic metamorphic cooling ages from the Taylor Mountain assemblage and mid-Cretaceous cooling ages from orthogneiss assemblage (e.g., Hansen et al., 1991) are difficult to reconcile with an upper plate orthogneiss position. Structural and kinematic data presented in the following favor a lower plate position for the orthogneiss assemblage, and a lack of stratigraphic continuity between the orthogneiss and Taylor Mountain assemblages.

Two Le populations are found in the eastern Eagle-Tanacross region (Fig. 4). A domain of northeast (to north-northeast) Le is confined to the Taylor Mountain and Nisutlin assemblages, and is present locally within the Seventymile assemblage. Northwest Le is present at the deepest structural level of the Taylor Mountain assemblage and occurs in the orthogneiss assemblage, locally along the contact between Nisutlin and Taylor Mountain assemblages, and at the base of some Seventymile klippen. Notably, intrusive bodies, including Late Triassic plutons, lack tectonite fabrics, with the exception of the peraluminous orthogneiss units.

Le orientation changes as a function of local and regional structural level. Both northeast and northwest Le are present at ET100, an ~10-m-high tectonite exposure that dips gently south (Fig. 4). Here Le trends northeast at the top of the outcrop but northwest at the base, where asymmetric folds and sheared quartz veins record top-to-the-northwest shear. Regionally, northeast Le is preserved at high structural levels within the Taylor Mountain assemblage (Fig. 4A). Northeast Le is also preserved structurally high in the axis of an open synform near the contact between Taylor Mountain and orthogneiss assemblages (Fig. 4B), and northwest Le occurs structurally low within antiformal warps.

Because the two domains are defined by Le it is difficult to envision how both domains might have formed in a single deformation event. Thus the question becomes how many deformations are represented, and how are the deformations related in time and space? Determination of shear sense within each domain allows us to address these questions.

Northwest-trending slickenside lineations (Lss) are present along brittle faults at the top of the Nisutlin assemblage (where it underlies the Taylor Mountain assemblage), and northeast Le is internally penetrative. Within the same outcrop, penetrative Le formed earlier than spaced, less-penetrative Lss; early formed brittle structures would be erased by younger ductile shear.

Northwest Lss is developed locally along brittle fault contacts between the Seventymile Nisutlin assemblages, and northwest Le is developed at the deepest exposed structural level within the Taylor Mountain assemblage. Penetrative northwest Le is developed throughout orthogneiss assemblage tectonites—neither northeast Le nor northeast Lss have been observed in these tectonites.

Shear-Sense Indicators. Shear sense for the eastern Eagle-Tanacross region varies spatially (Fig. 4) and can be divided into four regions, from north to south.

1. Along the Taylor Highway north of 64°15′S, the shear sense generally dips gently and defines broad west-trending warps; the Taylor Mountain and Nisutlin assemblages display a penetrative northeast Le. Shear-sense indicators are difficult to find in these rocks, probably due to their fine-grained polymineralic nature, but where present, they record top-to-the-northeast shear. Asymmetric double- or single-girdle quartz c-axis fabrics also show top-to-the-northeast shear (TH7, TH60, TH106; Fig. 5, z, ee, and ii). Kinematic indicators are rare in the fault zone between the Taylor Mountain and Nisutlin assemblages exposed along the Taylor Highway. However, TH124 (Fig. 5jj) displays a slightly asymmetric double-girdle quartz petrofabric reflecting a component of top-to-the-northeast shear, and TH23 (Fig. 5bb) shows a slightly asymmetric double-girdle c-axis fabric indicating a component of top-to-the-northwest shear. These quartz fabric data and top-to-the-northeast microstructures indicate that displacement within the boundary zone was both top-to-the-northeast and top-to-the-northwest. Because both the Taylor Mountain and Nisutlin assemblages contain northeast Le, we interpret them to have shared top-to-the-northeast deformation. Evidence for top-to-the-northwest shear is localized along the contact, as is northwest Lss, and thus we interpret top-to-the-northwest shear as younger than the penetratively developed top-to-the-northeast shear.

2. The Taylor Mountain assemblage between 64°15′ and 63°55′N displays top-to-the-northwest shear at more than 25 stations. Quartz c-axis stereo plots of ET110, ET117, ET122, and TH80 show fabric asymmetry indicating top-to-the-northwest shear consistent with microstructural kinematic indicators (Figs. 3a and 4, k, l, m, and ff). Quartz c-axis fabrics TH11, TH39, and TH85 show relatively symmetric fabrics with girdles perpendicular to Le (Fig. 5, aa, cc, and gg), confirming that the northwest Le is an elongation lineation.

3. Microstructures and quartz c-axis fabrics from the Nisutlin assemblage near the international border at ~64°N record top-to-the-northeast and top-to-the-northwest shear, depending on structural level. TH89 displays a quartz fabric asymmetry indicating top-to-the-northeast shear (Fig. 5hh) at structurally high levels, whereas structurally low ET102 yields an asymmetric fabric recording top-to-the-northwest shear, confirming field kinematic interpretations (Fig. 5j).

4. Kinematic indicators are best developed or preserved south of 63°55′ (Fig. 4). This region, which includes the contact between the tectonites of the Taylor Mountain and orthogneiss assemblages, records four different shear directions: top-to-the-northeast and rare top-to-the-southwest, top-to-the-northwest, and top-to-the-southeast shear. We sampled across the Taylor Mountain–orthogneiss assemblage contact in four swaths; in each area, northeast Le is preserved at higher structural levels than northwest Le.

The westernmost traverse through the contact zone is the most detailed; northeast Le-bearing garnet-biotite gneiss and mica quartz schist are preserved in the axis of a gentle, upright, northwest-trending synform with northwest Le-bearing pelitic rocks on either limb (Fig. 4B). S-C fabrics and mica fish show top-to-the-southwest shear parallel to northeast Le. On the limbs of the synform, S-C fabrics, microstructures, and quartz c-axis fabrics variably record top-to-the-northwest and top-to-the-southeast shear. Top-to-the-northwest shear is recorded on the northern limb and at structurally high levels on the southern limb. Top-to-the-southeast S-C fabrics are preserved at the structurally deepest exposed levels of the southern limb (Fig. 4b). Quartz c-axis fabrics (ET46, ET50, and TH51) show top-to-the-northwest shear (Fig. 5, h, i, and dd). TH51 has a double girdle with faint asymmetry; the asymmetry could reflect a small component of noncoaxial top-to-the-northwest shear having a large component of coaxial shear, or a combination of top-to-the-northwest and top-to-the-southeast shear. Both explanations are reasonable and possible given that strain can be partitioned into locally dominant coaxial and noncoaxial shear, and considering that the region underwent both top-to-the-northwest and top-to-the-southeast shear. The region north of, and including, TH51 records dominantly top-to-the-northwest shear, although discrete top-to-the-southeast shear zones cut penetratively developed top-to-the-northwest fabrics, indicating that top-to-the-southeast shear is younger than top-to-the-northwest shear (Fig. 4B). South of TH51 top-to-the-southeast shear dominates. Shear sense is not directly correlative with lithology; top-to-the-northwest shear is preserved in the metasedimentary and metavolcanic rocks as well as the orthogneiss; both top-to-the-northwest and top-to-the-southeast shear are recorded in the orthogneiss (Fig. 4B). On the basis of lithology, we interpret the northeast Le-bearing garnet-mica gneiss and schist in the synform axis as the Taylor Mountain assemblage, and the northwest Le-bearing pelitic schist as the orthogneiss assemblage. This interpretation is consistent with lithologic mapping of Foster (1970, 1976). Therefore, as elsewhere, the Taylor Mountain assemblage contains both northeast and northwest Le, and the orthogneiss assemblage records both top-to-the-northwest and top-to-the-southeast shear. Because the tectonites in both the Taylor Mountain and orthogneiss assemblages contain northwest Le, but only the Taylor Mountain assemblage contains a northeast Le, we propose that the top-to-the-northwest shear fabric represents a tectonic contact between the two assemblages, and that top-to-the-northwest deformation was responsible for their juxtaposition. It is also possible that the two assemblages could have been juxtaposed during top- to-the-northeast shear and then locally overprinted by top-to-the-northwest shear such that top-to-the-northeast shear within the orthogneiss assemblage was completely overprinted by top-to-the-northwest shear. However, the requirement that top-to-the-northeast shear be everywhere overprinted only within the orthogneiss assemblage seems coincidental, and thus we favor the former interpretation.

Temporal relations between the top-to-the-northeast and top-to-the-northwest shear events are best recorded ~5–10 km to the east of section A–A′ (Fig. 4A). In this area, a tectonite lozenge of clinozoisite-chlorite gneiss preserves top-to-the-northeast S-C fabric. The lozenge is enclosed in northwest Le-bearing pelitic schist (ET20). The northeast Le gneiss lozenge hosts a quartz vein (ET23) that itself bears northwest Le and yields an asymmetric top-to-the-northwest quartz c-axis girdle (Fig. 5f). The enclosing northwest Le tectonites also record top-to-the-northwest shear, as shown by microstructures and by quartz petrofabric in ET20 (Fig. 5e). Therefore, top-to-the-northeast shear affected the lozenge, which became incorporated into a top-to-the-northwest shear zone, at which time a quartz vein in the lozenge deformed ductilely, reflecting top-to-the-northwest shear. Adjacent tectonites also contain northwest Le but record symmetric quartz petrofabrics (ET17, ET18, and ET25) indicative of coaxial finite strain (Fig. 5, c, d, and g). ET25 shows a slight fabric asymmetry reflecting top-to-the-northwest shear (Fig. 5g). The history gained from quartz petrofabrics is consistent with independent kinematic data acquired at ET2 and ET16.

Temporal relations between top-to-the-northwest and top-to-the-southeast shear can be discerned at ET2. Here, peraluminous augen orthogneiss forms a sill-like sheet in gently northwest-dipping metasedimentary host rocks; we collected ~30 samples at 10 stations along a detailed transect (~250 m) normal to structural thickness. Although Le trends consistently northwest, both top-to-the-northwest and top-to-the-southeast shear fabrics are recorded in outcrop and in thin section. As in the western section, top-to-the-northwest shear dominates to the north, in the structurally high part of the section, and top-to-the-southeast shear dominates to the south, structurally lower in the section. A quartzite petrofabric records top-to-the-southeast shear (ET2, Fig. 5a). Although no sharp division is observed between domains of opposite shear, less-penetratively developed top-to-the-southeast shear bands cut, and are therefore younger than, more penetratively developed top-to-the-northwest fabrics in a schistose tectonite.

At ET16, about 10 km west of line A–A′ (Fig. 4A), well-developed S-C fabrics in peraluminous augen orthogneiss consistently indicate top-to-the-northwest shear. However, the main tectonite fabric is folded by tight, northeast-trending folds that are asymmetric to the southeast, indicating top-to-the-southeast shear. Similar temporal relations are documented along the international boundary near ET5 (Fig. 4). Here metasedimentary and metavolcanic tectonites could belong to the Taylor Mountain assemblage and/or the orthogneiss assemblage. The foliation dips gently northeast and Le trends northwest. Field and microstructures record top-to-the-southeast shear. The quartz c-axis diagram for ET5 shows top-to-the-southeast shear (Fig. 5b). To the north, structurally higher, two additional stations record top-to-the-southeast shear. Yet farther north, we observed top-to-the-northwest shear. Temporal relations between top-to-the-northwest and top- to-the-southeast shear at this location are unconstrained.

In summary, the distribution of kinematic domains with respect to tectonic packages and structural level provides clues about how each domain formed (Fig. 6). In the eastern Eagle-Tanacross region, three main deformation fabrics are recognized. (1) Top-to-the-northeast fabrics (and rare top-to-the-southwest fabrics) occur within the structurally high oceanic and siliciclastic marginal-basin strata (Seventymile, Taylor Mountain, and Nisutlin assemblages); they are least developed in low-grade rocks (Seventymile) and best developed in high-grade rocks (Taylor Mountain). (2) Top-to-the-northwest fabrics occur along brittle (Lss) and ductile (Le) fault zones between lithotectonic packages. (3) Top-to-the-southeast fabrics dominantly cut the structurally low orthogneiss assemblage rocks. Mid-Cretaceous granites crosscut all of

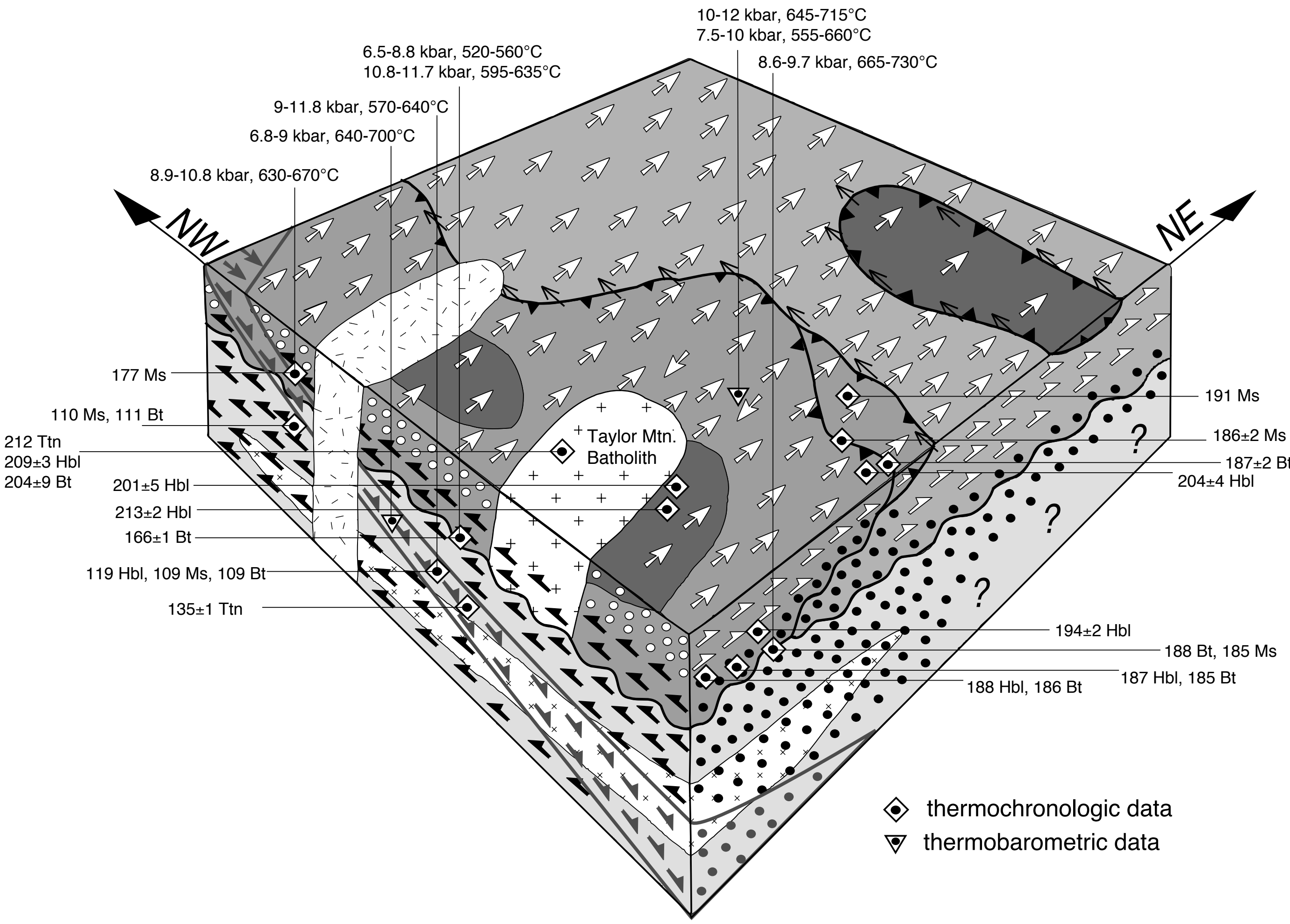

Figure 6. Schematic block diagram of the upland tectonites looking north; cut away northeast and northwest faces illustrate the distribution of kinematic domains with respect to lithologic packages. Map patterns are the same as in Figures 2–4. Heavy black lines mark faults; teeth indicate brittle fault, wavy line indicates ductile shear. Stick arrows represent brittle deformation (Lss); arrow shows upper plate displacement. Large arrows and circles represent penetrative ductile shear and displacement direction of structurally high rocks; white—top-to-the-northeast (and local top-to-the-southwest) shear; black—top-to-the-northwest shear; gray—top-to-the-southeast shear. The effects of late east-trending upright open folds are removed. Thermochronologic and thermobarometric data are from sources given in Dusel-Bacon et al. (1995).

the upland tectonites. Top-to-the-northeast shear is the oldest of the three shear deformations, and top-to-the-southeast shear is the youngest. Top-to-the-northeast fabrics have nowhere been observed to affect the orthogneiss assemblage.

Mount Warbelow

Mica schist, marble, quartzite, and hornblende-biotite schist of the Taylor Mountain assemblage are exposed in the Mount Warbelow area. The foliation dips gently, and Le trends north-northeast and northwest (Fig. 3). We spot sampled eight locations across ~200 km^2. Field, microstructural, and petrofabric data all indicate top-to-the-northwest and top-to-the-north-northeast shear (Figs. 2 and 5, w, x, and y). We interpret this region as one of spatial overlap of top-to-the-northeast and top-to-the-northwest ductile shear; we have no age relations from this area.

Molly Creek

The Molly Creek area, just west of Mount Veta (Figs. 3 and 4C), preserves evidence for similar geometric and temporal relations among the three domains documented in the eastern Eagle-Tanacross region, and it affords another view of the top-to-the-southeast shear. The structurally highest tectonites contain northeast Le, and a quartz c-axis fabric records top-to-the-northeast (ET216, Fig. 5v). Structurally lower tectonites show northwest Le and top-to-the-northwest. Quartz c-axes from ET157, a (chlorite)-garnet-feldspar quartzite, and ET158, a (chlorite)-amphibole-garnet-white mica quartzite, show symmetric girdles reflecting coaxial bulk strain (Fig. 5, p and q). At ET157, different parallel foliations preserve either northeast or northwest Le. The ET157 c-axis diagram (northwest motion plane) shows possible prism <*c*> slip (Fig. 5p; rotation of the data into the northeast motion plane also shows possible prism <*c*> slip). Although prism <*c*> slip is interpreted to occur at high temperatures (i.e., granulite facies, Jessel and Lister, 1990), it can occur at greenschist facies conditions as a result of consecutive and coplanar, but perpendicular, shear events (Oliver, 1996). ET157 shows no evidence of high-temperature shear, but northeast Le and northwest Le preserved in different foliations probably record consecutive, coplanar, perpendicular shear events. Thus we favor this explanation for the prism <*c*> fabrics. Top-to-the-northeast shear probably predates top-to-the-northwest shear on the basis of relations described from the eastern Eagle-Tanacross area.

Peraluminous orthogneiss records both top-to-the-northwest and top-to-the-southeast ductile shear as defined by S-C fabrics. Top-to-the-southeast shear occurred, at Molly Creek, along a more localized, discrete shear zone than the earlier, more penetratively developed top-to-the-northwest fabrics, indicating that top-to-the-southeast shear postdated top-to-the-northwest shear. Here top-to-the-southeast shear, compared with top-to-the-northwest shear, probably represents higher localized strain, and/or it occurred at a shallower crustal level. Top-to-the-southeast shear is documented at ET206 in the field (S-C fabrics), in thin section, and through c-axis fabrics from a deformed quartz vein (Fig. 5t). The c-axis fabric shows a strong single girdle marked mostly by basal <*a*> slip, indicative of low-temperature shear (i.e., greenschist facies). At ET208, extremely well-developed S-C fabrics and small (l < 1–3 cm), Le-normal asymmetric folds that deform the S-C fabrics indicate that top-to-the-southeast displacement here was likely accompanied by local high strain. A quartz petrofabric diagram from this location displays a single asymmetric girdle (Fig. 5u). To the south at ET211, top-to-the-northwest S-C fabrics occur in peraluminous orthogneiss within both upper and lower plate positions with respect to a gently northeast-dipping top-to-the-southeast shear zone. These top-to-the-southeast tectonites typically display transitional ductile-brittle character. The quartz petrofabric of ET204 records top-to-the-southeast shear (Fig. 5s). Orthogneiss within the upper level of the top-to-the-southeast shear zone is locally chloritized. Graphitic quartzite ET162 records low-*T* (basal <*a*>), top-to-the-southeast shear (Fig. 5r).

In summary, the Molly Creek area hosts each of the three kinematic domains recognized to the east. Here top-to-the-northeast shear occupies the highest structural level; top-to-the-northwest shear fabrics overlap spatially with top-to-the-northeast shear fabrics locally; and top-to-the-southeast shear fabrics overprint top-to-the-northwest fabrics and occur in a zone within the top-to-the-northwest domain. As in the eastern Eagle-Tanacross region, the orthogneiss assemblage records only top-to-the-northwest and top-to-the-southeast shear.

Southeast Big Delta

Our work in the southeast Big Delta area focused on three locations (Fig. 3). At the southernmost locality, field and microstructural data from gently dipping schist and orthogneiss consistently record top-to-the-west-northwest shear. S-C orthogneiss fabrics at ET136 record top-to-the-northwest shear. Quartz petrofabrics from ET136 and ET137 show symmetric and top-to-the-west-northwest asymmetric girdles, respectively (Fig. 5, n and o). In both cases, prism, rhombohedral, and basal <*a*> slip are represented, indicating that top-to-the-northwest shear occurred at moderately high temperature. ET136 records bulk coaxial strain (perhaps with a slight top-to-the-northwest noncoaxial component) that could result from coaxial deformation, or from sequential colinear top-to-the-northwest and top-to-the-southeast shear.

To the northwest, peraluminous orthogneiss and quartz-mica schist and gneiss dip gently in many directions. Ultramafic to mafic rocks, locally foliated and marked by a variably developed Le, are structurally above the orthogneiss and host rocks; north-northeast to northeast Le, marked by amphibole, occurs structurally high within the ultramafic rocks (not shown in Fig. 3). Structurally deeper, toward the contact with the orthogneiss, Le trends northwest to west, and top-to-the-northwest shear is recorded by field and microstructures. Farther to the northwest, peraluminous orthogneiss displays top-to-the-northwest and top-to-the-west S-C fabrics. Evidence for local top-to-the-east-southeast shear is also preserved. On the basis of lithologic and kinematic similarity with relations documented to the east, we interpret the ultramafic rocks as klippen correlative with the Taylor Mountain or Seventymile assemblages. Thus, the structural and kinematic evolution determined for the Mount Warbelow, Molly Creek, and southeast Big Delta regions appear to be consistent with that of the eastern Eagle-Tanacross region.

***P-T* and Cooling Histories**

Published thermobarometric and thermochronometric data (U-Pb titanite, ^{40}Ar/^{39}Ar hornblende, white mica, and biotite; see Dusel-Bacon et al., 1995, for references) constrain the physical conditions and the time of deformation within each domain (Figs. 4 and 6). Although *P-T* and thermochronometric data were collected within the structural-kinematic framework described herein, interpretation of the data must be undertaken with caution because kinematics, *P-T,* and cooling age data cannot be unequivocally correlated to a unique time window. Thermometric data record peak temperature, barometric data generally record pressure that accompanied peak temperature, and thermochronometric data record when a specific mineral lattice closed for a particular isotopic system, a process largely dependent on temperature. Shear zones anastomose and can vary in thickness and strain intensity as a function of total strain, lithology, preexisting fabrics, crustal level, and other variables. As a result, polydeformed tectonites may preserve variable age relations dependent on the dynamothermal conditions (e.g., peak temperature, length of time at peak temperature, kinetics of reactions, strain history) that affected a specific tectonite sample. With these cautions in mind, thermobarometric and thermochronometric data can place important constraints on the tectonic evolution of the upland tectonites.

Top-to-the-northeast shear occurred under high *P-T* conditions prior to or during the Late Triassic to Early Jurassic (Fig. 6). Evidence for this conclusion comes from TH7 and TH60, which contain top-to-the-northeast fabrics and yielded *P-T* conditions of 10–12 kilobars, 645–715 °C, and 7.5–10 kilobars, 555–660 °C, respectively (Dusel-Bacon et al., 1995). Because these samples only record top-to-the-northeast shear—the oldest deformation in the area—the *P-T* conditions recorded probably accompanied top-to-the-northeast shear. The top-to-the-northeast tectonites record cooling through ~500 °C at 204 Ma (hornblende) and through ~350 °C at 191 Ma (white mica). Moreover, top-to-the-northeast shear predated intrusion and cooling of the massive Taylor Mountain batholith, which cooled through ~600 °C at 212 Ma and ~500 °C at ca. 209 Ma (titanite and hornblende, respectively). Thus, this deformation occurred, at least in part, prior to 209 Ma, and likely prior to 212 Ma. Therefore, these cooling ages do not necessarily date the age of deformation, but rather reflect postkinematic cooling.

Top-to-the-northwest tectonites also record high *P-T* conditions, and they cooled through about 300 °C by Middle Jurassic time (Figs. 4a and 6; Dusel-Bacon et al., 1995). *P-T* data from four samples from within the top-to-the-northwest shear domain yield high *P-T* conditions ranging from 520 to 730 °C and 6.5 to 11.7 kilobars. Each of these samples are from the Taylor Mountain–orthogneiss assemblage contact zone. *P-T* constraints from two structurally deep orthogneisses yield 570–700 °C and 6.8–11.8 kilobars (Figs. 3A and 5). Top-to-the-northwest tectonites yield cooling ages from hornblende- biotite pairs of 188 and 186 Ma at high structural levels, and 177 Ma (white mica) and 166 Ma (biotite) at deeper structural levels. High-level cooling ages probably more closely bracket cessation of deformation, whereas deep-level cooling ages reflect posttectonic crustal cooling. This minimum age constraint on ductile deformation is similar to the 187 Ma $^{40}Ar/^{39}Ar$ biotite age from the south-dipping brittle-ductile shear zone that places the Taylor Mountain assemblage above the Nisutlin assemblage (Cushing, 1984; Cushing et al., 1984). These workers interpreted biotite to have formed during fault-zone formation and therefore to date imbrication along this zone. Lss and kinematic data from the fault zone indicate top-to-the-northwest thrusting, consistent with shear sense preserved in the L-S tectonites. Therefore, tectonites affected by top-to-the-northwest shear cooled more quickly at high structural levels relative to deeper structural levels, and the upper structural levels cooled through their blocking temperatures at about the same time that displacement along intra-assemblage and inter-assemblage fault zones waned. The Taylor Mountain batholith records cooling though ~600 °C at 212 Ma and through ~300 °C at 204 ± 9 Ma (Dusel-Bacon et al. 1995). Presumably, the base of the Taylor Mountain batholith records northwest shear, although the region is not exposed.

The timing of top-to-the-southeast shear is constrained by titanite, hornblende, white mica, and biotite cooling ages of 135, 119, 109, and 109 Ma, respectively (Figs. 4A and 6). Top-to-the-southeast tectonites cooled from ~500 °C to 300 °C in 10 m.y. Quartz in many top-to-the-southeast tectonites shows microscopic textures indicative of low-temperature plasticity, including strong undulatory extinction, ragged grain boundaries, and subgrain growth. The lack of annealed textures, together with relatively fast cooling rates, indicates that ductile shear accompanied, rather than predated, cooling (Hansen and Oliver, 1994). Thus, the metamorphic cooling ages closely approximate the time of top-to-the-southeast ductile shear.

A peraluminous orthogneiss with the older top-to-the-northwest fabric that was sampled in a lower plate position relative to a top-to-the-southeast shear domain yielded white mica and biotite cooling ages of 110 and 111 Ma, respectively (Fig. 6). Although it contains earlier-formed top-to-the-northwest shear fabrics, the rock probably cooled through the white mica and biotite blocking temperatures during tectonic denudation related to top-to-the-southeast shear. Thus, the preserved kinematic fabrics and cooling ages reflect different events because top-to-the-northwest shear fabrics formed at temperatures above the Ar/Ar blocking temperatures for muscovite and biotite, and the rocks remained buried until the top-to-the-southeast event.

P-T conditions of top-to-the-southeast shear are difficult to ascertain because top-to-the-southeast shear postdates early high-temperature events, making it difficult or impossible to be certain that the *P-T* determinations from top-to-the-southeast tectonites record physical conditions that accompanied top-to-the-southeast shear and not the conditions during earlier deformation. *P-T* determinations from adjacent tectonites show high pressure and temperature (top-to-the-southeast fabric: 9–11.8 kilobars, 570–640 °C; northwest Le, no shear sense determined: 6.8–9 kilobars, 640–700 °C) (Figs. 4A and 6). Temperature probably reached ≥600 °C locally during top-to-the-southeast shear because titanite (U-Pb closure *T* of 600 °C; Heaman and Parrish, 1991) records cooling at 135 Ma, unless shearing and ductile deformation substantially lowers the U-Pb blocking temperature of titanite. Lower temperature conditions (<300–350 °C) during top-to-the-southeast shear are reflected locally in the Molly Creek area, ~20 km to the northwest, where minerals record transitional brittle behavior. Thus, top-to-the-southeast shear probably occurred over a range of *P-T* conditions.

Integration of kinematic, *P-T*, and cooling data results in the following conclusions (Fig. 7). (1) Top-to-the-northeast shear, at high *P-T* conditions, occurred prior to 191 Ma and probably prior to 212 Ma, but is now preserved at high structural levels (Seventymile, Taylor Mountain, and Nisutlin assemblages). (2) Top-to-the-northwest shear postdated top-to-the-northeast shear—likely beginning before 188 Ma and waning by ca. 185 Ma. Top-to-the-northwest shear occurred locally at high *P-T* conditions, and placed Seventymile, Taylor Mountain, and Nisutlin assemblages structurally above rocks of continental affinity. (3) Top-to-the-southeast shear that occurred from ca. 135 to 109 Ma resulted in exposure of the structurally deepest parautochthonous continental rocks. Oceanic and marginal-basin rocks are intruded by Late Triassic to Early Jurassic arc plutons, and all assemblages are intruded by mid-Cretaceous plutons.

REGIONAL CORRELATION

Compilation of our data, together with published studies, reveals that the general structural, kinematic, *P-T*, and temporal constraints derived from upland tectonites allow correlation with upland tectonites to the west and with tectonites in western and central Yukon.

Yukon-Tanana Upland

In the western Yukon-Tanana upland north of Fairbanks, Chatanika eclogites are structurally above parautochthonous continental strata correlative with autochthonous North American rocks of the western Selwyn basin, Yukon (Fig. 1) (Murphy and Abbott, 1995). The eclogites record high *P-T* metamorphic conditions (Laird et al., 1984; Brown and Forbes, 1986) and have been correlated with eclogites enclosed in oceanic and marginal-basin tectonites in Yukon (Erdmer, 1987, 1992; Hansen, 1992a, 1992b). Northeast of Big Delta, oceanic rocks are structurally above marginal-basin tectonites. Although few kinematic indicators have been documented, top-to-the-northeast shear structures are reported from the eclogitic and oceanic rocks, and top-to-the-northwest structures are present locally within marginal-basin tectonites, and characterize the parautochthonous Wickersham assemblage (Pavlis et al., 1993) (Fig. 2).

Top-to-the-southeast shear characterizes the contact between the structurally low orthogneiss assemblage and structurally high marginal-basin tectonites west of ~145° (Fig. 2). The contact represents a mid-Cretaceous extensional shear zone on the basis of consistent top-to-the-southeast kinematic data, a sharp transition in metamorphic grade across the zone, and thermochronometric data recording fast mid-Cretaceous cooling of footwall rocks (Pavlis, 1989; Pavlis et al., 1993).

Timing of top-to-the-northeast and top-to-the-northwest shear in the western upland is not well constrained. Top-to-the-northwest shear is younger than top-to-the-northeast shear and older than top-to-the-southeast shear (Pavlis et al., 1993). Muscovite from Chatanika tectonites yielded K-Ar cooling ages of 178 and 166 Ma (Wilson and Shew, 1981). Although excess Ar or Ar loss may be a problem, on the basis of regional upland relations we interpret these muscovite K-Ar ages to reflect cooling following top-to-the-northwest shear, which placed Chatanika eclogite above parautochthonous continental strata. We interpret the top-to-the-northeast shear to predate juxtaposition of eclogite and parautochthonous continental strata.

Thus, the geologic relations illustrated in Figure 7, correlative across the upland, describe a simple stacking order from bottom to top: North American parautochthonous continental margin, to continental marginal-basin strata, to ocean-basin and island-arc rocks. In many regions, oceanic and arc rocks are directly above parautochthonous continental rocks. The regionally consistent stacking order, and the integrated kinematic, *P-T*, and cooling age data provide constraints that must be addressed by any tectonic model.

A model in which the orthogneiss assemblage is thrust over the Taylor Mountain assemblage in Cretaceous time (Foster et al., 1994) is not supported by the data presented here. First, contraction and juxtaposition of the orthogneiss and Taylor Mountain assemblages occurred in Jurassic, not mid-Cretaceous, time. Second, emplacement of the orthogneiss assemblage over the Taylor Mountain assemblage is inconsistent with metamorphic cooling ages. In the case of polyphase

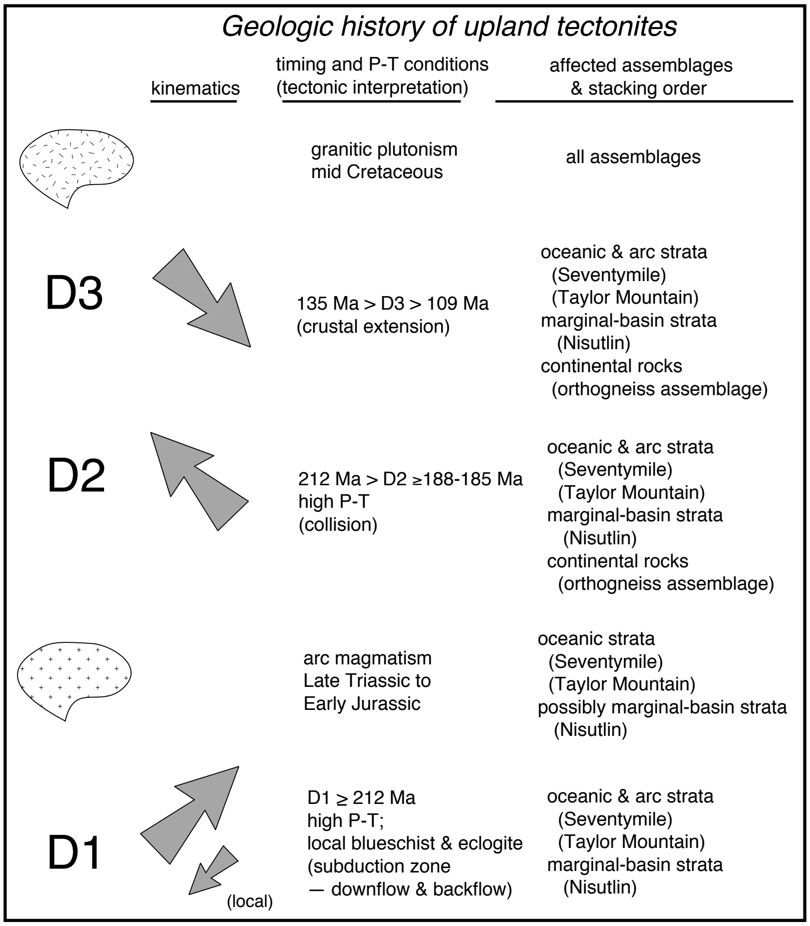

Figure 7. Geologic history of upland tectonites.

deformation and polyphase cooling, tectonites that yield relatively older cooling ages must be structurally high (hanging-wall position), and those that record relatively younger cooling must occupy a low structural level (footwall position) regionally, unless imbrication completely postdates cooling. Third, mid-Cretaceous shearing is top-to-the-southeast, the orthogneiss assemblage being in a lower plate position in the Eagle-Tanacross region and in the western upland.

The model of Mortensen (1992) calls on stratigraphic continuity between the orthogneiss and Taylor Mountain assemblages. This model is inconsistent with our data. Top-to-the-northeast deformation is nowhere documented in the structurally deep (stratigraphically in Mortensen's model) orthogneiss assemblage, yet evidence for this older penetrative shear event is documented in structurally high rocks (stratigraphically high in Mortensen's model); this relationship is difficult to justify within a stratigraphic continuum hypothesis. In addition, Late Triassic–Early Jurassic arc granitoids intrude only oceanic and marginal-basin tectonites (Seventymile, Taylor Mountain, and Nisutlin assemblages), and have nowhere been documented to intrude the orthogneiss assemblage. If all these assemblages represent a continuous stratigraphic section, it is difficult to justify how intrusive rocks would selectively affect younger (and thus higher) and not older rocks. Furthermore, the top-to-the-northwest deformation, shared by the Taylor Mountain and orthogneiss assemblages, constrains the mode of juxtaposition, and metamorphic cooling ages constrain the time of juxtaposition (i.e., late Early Jurassic).

Our data also argue against the Cache Creek enclosure model (Nelson and Mihalynuk, 1993; Mihalynuk et al., 1994), as do broad geologic relations. The Cache Creek enclosure model was developed to address apparent "enclosure" of allochthonous rocks (Stikinia arc, Quesnelia arc, and Cache Creek oceanic strata) by rocks of continental affinity—a "paradox" disregarded in other models (Mihalynuk et al., 1994). Unfortunately, these authors set up a paradox that does not exist; they assumed that continental margin crystalline rocks wrap around the northern end of Stikinia and Quesnelia. This assumption dissipates when one examines geologic and structural histories. There are several problems inherent in this analysis. (1) The authors treat the Yukon-Tanana composite terrane as a single tectonic entity with a singular geologic history, thus disregarding the stacking order of the lithologic units and documented differences in the deformation of the assemblages. (2) Continental margin rocks of the orthogneiss assemblage are parautochthonous to North America, and the Chena River and Fairbanks subterranes are correlative with autochthonous Selwyn basin strata, western Yukon. Therefore neither of these packages of rocks were separated from western North America by an oceanic or back-arc basin in Permian to Middle Jurassic time, as required by the enclosure model. (3) The Nisutlin assemblage, which is composed of continental margin rocks that define the western limb of the proposed enclosure orocline, are separate and distinct from the parautochthonous rocks (e.g., Currie, 1995). Tempelman-Kluit (1979) originally proposed that Nisling rocks may be a rifted fragment of North America, and we know of no data that would argue against this hypothesis, though this is not required by any models. (4) Upland tectonites represent the hinge of the proposed orocline of crystalline rocks in the Cache Creek model; however, the deformation, timing, and crustal conditions documented herein, and correlative across the upland and central Yukon, are not addressed in the context of the model. For example, contrary to statements by Mihalynuk et al. (1994), the effects of the earliest, top-to-the-northeast, shear deformation can be spatially and temporally differentiated from subsequent deformation related to imbrication in late Early Jurassic time (e.g., Hansen, 1992b; data presented herein). The enclosure model also requires top-to-the-northeast and top-to-the-southwest contraction of upland tectonites and correlative rocks in Yukon at ca. 185 Ma (Mihalynuk et al., 1994, Fig. 4C), contrary to our data, which record early top-to-the-northeast shear (not addressed in the enclosure model), followed by locally spatially distinct top-to-the-northwest shear, which waned ca. 185 Ma. Thus the enclosure model addresses a paradox that does not exist, and the *P-T*-t displacement history recorded in the upland tectonites, located within the proposed oroclinal hinge, is inconsistent with the enclosure model.

Correlation with Yukon Tectonites

Hansen et al. (1991) outlined broad similarities in kinematics and cooling ages between the eastern upland tectonites and L-S tectonites within and east of the Teslin suture zone, Yukon, supporting previous correlation of these units (Tempelman-Kluit, 1979). The northwest-striking Teslin suture zone separates parautochthonous ancestral North America from allochthonous terranes (Tempelman-Kluit, 1979). The suture zone is marked by a 10–15-km-wide zone of L-S tectonites that have oceanic and marginal-basin lithologies. Metamorphic grade ranges from mid-greenschist to albite-epidote amphibolite facies and rare eclogite (Erdmer, 1987; Hansen, 1992b). Tectonites are locally intruded by Late Triassic to Early Jurassic plutons. Suture-zone tectonites have been examined within a structural-kinematic and thermochronometric framework in the Laberge–Quiet Lake and Little Salmon Lake areas (Fig. 1).

In the Laberge–Quiet Lake area, tectonites record high *P-T* conditions that reflect subduction-zone metamorphism (Hansen, 1992b), in agreement with *P-T* conditions recorded by the enclosed Permian Last Peak eclogite (Erdmer, 1987; Erdmer and Armstrong, 1989; Erdmer et al., 1996). Tectonites record apparent normal, reverse shear, and strike-slip shear, which are interpreted to record backflow, downflow, and margin-parallel shear, respectively, within a west- dipping subduction zone (Hansen, 1989, 1992a). Following subduction-zone deformation, these rocks, which cooled quickly at ca. 195 Ma, were thrust eastward over parautochthonous continental strata in Early Jurassic time (Hansen et al., 1991; Hansen, 1992b). Parautochthonous North American strata of Cambrian(?) and younger age that host Mississippian peraluminous orthogneisses (Hansen et al., 1989) were ductilely deformed as a result of eastward overthrusting. These rocks cooled slowly through ~500 to 300 °C from ca. 150 Ma to 120 Ma. In mid-Cretaceous time (ca. 110 to 90 Ma), the area was cut by dextral strike-slip faults broadly parallel to the Tintina fault, and intruded by granites. The regional stacking order preserved in tectonites in this region is the same as that documented for the Yukon-Tanana upland-parautochthonous continental strata; Mississippian orthogneiss are structurally deepest (although here they are east of allochthonous rocks in map view), and marginal-basin and oceanic tectonites intruded by arc rocks are at the highest structural level.

At Little Salmon Lake (Oliver, 1996) (Fig. 1), upper plate tectonites record top-to-the-southwest (apparent normal) and top-to-the-northeast (apparent reverse) directed dip-slip shear, interpreted as having formed within a subduction zone. Dip-slip tectonites are partially overprinted by top-to-the-northwest fabrics. $^{40}Ar/^{39}Ar$ thermochronology and calcite e-twin analysis constrains each of these ductile shear events to pre-190 Ma. Tectonites cooled slowly following northeast-directed folding. The cooling-deformation history recorded within the Little Salmon Lake tectonites is consistent with tectonite formation within a west-dipping subduction complex (Oliver et al., 1995).

Deformation in both these regions is broadly correlative with deformation documented in the upland tectonites, although Early to early Middle Jurassic imbrication of allochthonous rocks was northeast directed in the Laberge–Quiet Lake area and northwest directed at Little Salmon Lake and in the Yukon-Tanana upland of Alaska. These differences may be related to paleomargin orientation. Both regions in Yukon lack evidence of mid-Cretaceous extension, although mid-Cretaceous Rb-Sr and K-Ar cooling ages from Paleozoic orthogneiss in western Yukon could reflect cooling related to extension (Hansen, 1990a). During mid-Cretaceous time, central Yukon was dissected along dextral strike-slip faults and intruded by granitic plutons (Tempelman-Kluit, 1976; Gabrielse and Dobbs, 1982).

Tectonic Synthesis

Although Cordilleran tectonic analysis has focused for many years on terrane identification and distinctions between terranes, identifying links between and among terranes is the next step in understanding crustal assembly processes. The assemblages with which we are concerned, in the interior part of the northern North American Cordillera north of 57°N, are, from east to west (Fig. 1) (1) ancestral North American strata, (2) parautochthonous North American strata—strata displaced by strike-slip faults (orthogneiss assemblage as defined in this paper, and Cassiar and Kootenay terranes of Wheeler et al., 1991), (3) marginal-basin strata (Nisutlin assemblage [within which we include the Nasina assemblage of Wheeler and McFeely, 1991]), (4) oceanic rocks (Slide Mountain, Seventymile, Teslin–Taylor Mountain, and Chatanika assemblages), (5) pre-Permian host rocks, and Permian to Late Triassic and Early Jurassic volcanic-arc rocks (Stikinia), and (6) rocks of continental affinity (Tracy Arm–Nisling assemblage). Each of these assemblages forms a band from ~57°N to central Alaska (Currie, 1995), and each has geologic ties to adjacent assemblages, except the continental assemblages. Parautochthonous North American strata, and Nisling–Tracy Arm assemblages include Devonian-Mississippian plutons (now dominantly orthogneiss) that yield εNd values indicative of continental partial melting (e.g., Aleinikoff et al., 1981, 1986; Bennett and Hansen, 1988; Gehrels et al., 1990; McClelland et al., 1991; Jackson et al., 1991; Samson et al., 1991; Mortensen, 1992; Grant et al., 1996). The Cache Creek and Quesnelia terranes are not discussed in this paper except to outline how our data relate to previous interpretations of Cache Creek–Yukon–Tanana composite terrane interactions. The Cache Creek and Quesnelia terranes are exposed dominantly south of the assemblages we are concerned with and a discussion of these units is outside the limits of the present work.

The geologic, structural, petrologic, and geochronometric data outlined here correlate systematically across the upland and into Yukon. They are consistent with the tectonic model of terrane accretion proposed by Tempelman-Kluit (1979) on the basis of the distribution of lithotectonic assemblages and sequence of structural stacking in Yukon. His model has been modified by local detailed studies, but the original tectonic framework accommodates, and even predicts, the results of more than 15 years of research by a number of workers employing diverse geologic tools. In the model, continental affinity Nisling–Tracy Arm rocks rifted away from the western margin of North America in Devonian-Mississippian time, or shortly thereafter. Prior to, or during rifting, Devonian-Mississippian plutons intruded North American crust, including rocks that were soon rifted from North America. The incipient intervening Anvil ocean separated the Nisling–Tracy Arm assemblage from their parent North America. Slide Mountain–Seventymile assemblages represent Anvil oceanic strata (Harms, 1986; Nelson, 1993), although they have some isotopic similarities to North American marginal basin strata and North America (Nelson et al., 1989; Smith and Lambert, 1995; Roback et al., 1994). The width and shape of the Anvil ocean are unknown. During Early Permian time, the Anvil ocean began to close by west-dipping, right-oblique subduction (present-day coordinates; Hansen, 1989, 1992b) (Fig. 8). The arc, Stikinia, was built in part on oceanic crust (Currie and Parrish, 1993) and in part on crust of continental affinity (Nisling–Tracy Arm; e.g., Rubin and Saleeby, 1991; Jackson et al., 1991). Thus, along-strike variations in marginal basin detritus, isotopic signatures, and magma compositions would be expected. Slide Mountain–Seventymile strata were deformed during west-dipping subduction that closed the Anvil ocean. Low-grade Slide Mountain–Seventymile rocks, imbricated along brittle faults (e.g., Harms, 1986), and Teslin–Taylor Mountain tectonites, metamorphosed and ductilely deformed under high *P-T*, represent Anvil ocean strata that were tectonically transferred from the footwall plate to the hanging-wall plate, at shallow and deep levels, respectively, across the west-dipping convergent margin. Eclogite and high-*P-T* tectonites of the Teslin–Taylor Mountain assemblage are consistent with subduction geotherms and deformation. Nisutlin marginal-basin strata could have been deposited

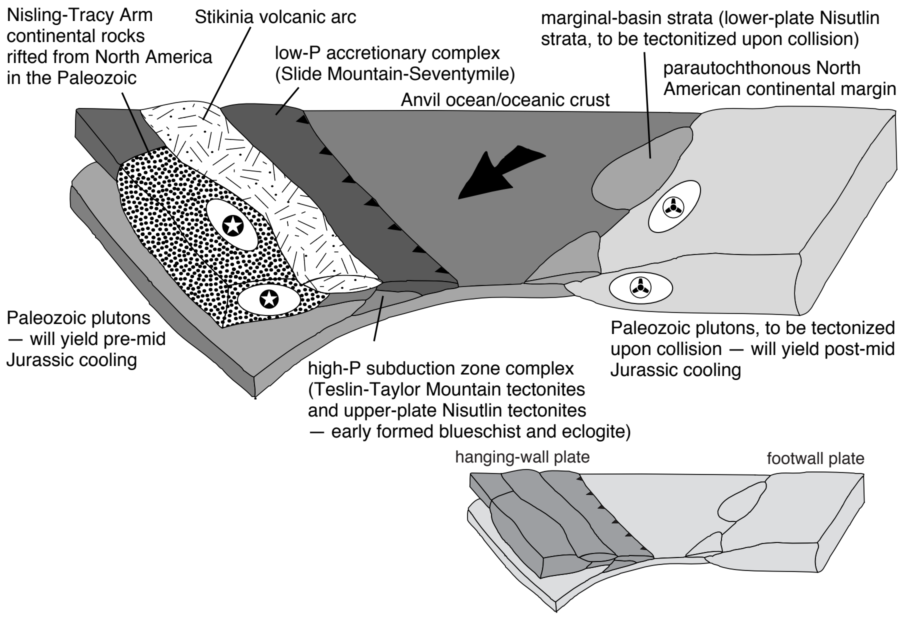

Figure 8. Tectonic model (modified from Hansen et al., 1991); units and symbols as in Figure 1.

adjacent to western North America, or on the opposite side of the Anvil ocean adjacent to the rifted fragment of North America. Either position fits available data. In east-central Alaska near the Yukon border, marginal-basin tectonites record top-to-the-northeast deformation, and in eastern Yukon, Nisutlin tectonites record Early Permian blueschist facies metamorphism (e.g., Erdmer and Helmstaedt, 1983; Erdmer, 1987, 1992). These characteristics suggest an upper plate (outboard of the Anvil ocean) position for these Nisutlin rocks. Farther to the west, however, graphitic schist included in the Nisutlin terrane is thought to grade depositionally and metamorphically into the Chena River sequence (Smith et al., 1994), a lower plate assemblage.

Until recently, there were few direct age constraints on the onset of subduction-zone deformation and metamorphism, but the Last Peak eclogite yields a concordant U-Pb metamorphic zircon date of 268.8 ± 1.5 Ma (Creaser et al., 1996), in good agreement with blueschist cooling ages (256 ± 8 Ma, 267 ± 8 Ma, Rb-Sr, white mica, Erdmer and Armstrong, 1989; ages ranging from 260.0 ± 2.6 to 272.7 ± 2.6 Ma, $^{40}Ar/^{39}Ar$, white mica, Erdmer et al., 1996), interpreted to reflect initial mid Permian subduction of the Anvil ocean (Erdmer and Armstrong, 1989; Hansen, 1992b). The oldest eclogite and blueschist ages constrain the start of subduction because they reflect the early high-*P-T* thermal regime during subduction-zone initiation (e.g., Cloos, 1986; Cloos and Shreve, 1988). Marginal-basin strata that originated on the western side of the Anvil ocean (upper plate convergent margin) might have undergone blueschist metamorphism early in Anvil ocean closure, essentially marking subduction initiation, whereas marginal-basin strata adjacent to North America would likely deform late during Anvil closure.

Permian magmatic-arc activity is documented in rocks (Mortensen, 1992) that we interpret as allochthonous, upper plate, and correlative with the Stikinia arc. An Early Permian sill (276 Ma, U-Pb zircon, titanite) also intrudes a part of the imbricated Slide Mountain sequence, indicating that some imbrication occurred prior to sill emplacement (Harms, 1986). Harms (1986) noted that the nappes and sills were folded along with Late Permian strata. Therefore, contractional deformation began by at least 276 Ma, and continued beyond Permian time, yet predated thrusting of the rocks over parautochthonous Cassiar strata in Jurassic time. Thus, subduction-zone metamorphism, arc magmatism, and contraction of oceanic sediments indicate that during Permian time, the Anvil ocean was in the process of closing.

As the accretionary complex within the upper plate migrated eastward with time, Stikinia arc granitoids locally intruded the subduction complex as well as Nisling–Tracy Arm crust of the upper plate (e.g., Taylor Mountain batholith and Mount Veta pluton [Aleinikoff et al., 1986; Dusel-Bacon et al., 1995] in Alaska, and the Klotassin and Aishihik calc-alkaline suites in Yukon [e.g., Mortensen, 1992; Johnston and Erdmer, 1995]). With continued subduction, the upper plate would have accreted marginal-basin strata from a successively more eastern position, and ultimately overrode western North America. As lower plate marginal-basin strata and North American rocks were pulled into the subduction-collision zone, these rocks were ductilely deformed at depth with top-to-the-east-northeast shear in southern Yukon, and top-to-the-northwest shear in central Yukon and east-central Alaska. The change in displacement from east-northeast–directed margin-normal contraction, to northwest-directed contraction at a low angle to the margin, could reflect a change related to collision, a change in plate motion, or a bend in the western margin of North America. Northwest-directed deformation further imbricated upper plate rocks (Stikinia, Slide Mountain–Seventymile, and Teslin–Taylor Mountain assemblages) and placed them above parautochthonous lower plate rocks (orthogneiss assemblage and Selwyn basin-correlative strata). Ultimately, the entire upper plate was tectonically accreted to the lower plate (North America), which grew laterally and thickened.

The timing of collision is constrained in three regions. In the Laberge–Quiet Lake area, fast cooling of upper plate tectonites at ca. 195 Ma postdates high *P-T* subduction-zone deformation and is interpreted to mark the uplift and cooling of upper plate rocks due to collision; lower plate tectonites, which show top-to-the-east-northeast shear presumably related to collision, were tectonically buried at ca. 195 Ma and cooled slowly through 500 to 300 °C from ca. 145 to 119 Ma (Hansen et al., 1991). Little Salmon Lake upper plate tectonites cooled slowly from ca. 191 to 160 Ma; cooling is interpreted to have resulted from erosional exhumation following collision (Oliver et al., 1995; Oliver, 1996). In east-central Alaska, upper plate tectonites cooling through 500 to 300 °C from 188 to 185 Ma postdated northwest-directed ductile shear, which we interpret as forming during collision.

More than 50 m.y. after northwest-directed collision, upland tectonites in Alaska, and likely in westernmost Yukon, underwent southeast-directed crustal extension resulting in tectonic denudation of parautochthonous strata (Hansen et al., 1991; Pavlis, 1989; Pavlis et al., 1993). Synchronous with this extension, the western North American margin in central and southern Yukon was cut by steep, northwest-striking dextral faults, including the Tintina fault. Dextral displacement and northwestward translation of North American margin rocks and imbricated allochthonous rocks, resulted in dismemberment of the pre-mid-Cretaceous western margin of North America.

Stikinia was also translated to the northwest during mid-Cretaceous time, although paleomagnetic, paleontologic, and geologic evidence indicate that paleolatitudes for Stikinia rocks were concordant with those of ancestral North America during Triassic and Early Jurassic (and Late Permian?) time (e.g., Irving and Monger, 1987; Irving and Yole, 1987; Irving and Wynne, 1990, 1991a, 1991b; Oldow et al., 1989). Northward displacement of Stikinia relative to North America in Cretaceous time following southward Jurassic–Cretaceous movement is consistent with plate-tectonic reconstructions (Engebretson et al., 1985), Middle Jurassic sinistral shear along the Tally Ho shear zone within the Stikinia rocks of southern Yukon (Hart and Radloff, 1990), and other early Mesozoic shear zones of the southern Cordillera (see Oldow et al., 1989, for discussion). The importance of this "yo-yo tectonics" with respect to this study is that in Late Permian through Early Jurassic time, the Stikinia arc and associated upper plate rocks were located at about the same latitude that they are today—forming a band from Fairbanks to ~57°N. Thus, Stikinia apparently collided with North America at about the same location that it is today, and after collision Stikinia was translated to the south during Jurassic–Cretaceous time, and translated north again in Cretaceous time.

IMPLICATIONS

The proposed model incorporates along-strike changes in paleogeography, including the width of the Anvil ocean, the character of the Stikinia arc basement, the shape of the western continental margin of North America (poorly constrained), and local deposition of marginal-basin strata. Therefore, the model predicts a multitude of along-strike (and across-strike) changes in sedimentary facies, intrusive composition and inheritance, and preserved structural level. Despite allowable along-strike differences, there are a few tests of the basic model. Two important tests concern the structural-kinematic, metamorphic, and thermal history of Devonian–Mississippian plutons, and the distribution of Late Triassic–Early Jurassic plutons.

Paleozoic Orthogneiss

Devonian–Mississippian plutons are included within both the lower plate orthogneiss and the upper plate Nisling–Tracy Arm assemblages, and all of the plutons yield εNd values indicative of continental crust. The difference between the two plutonic assemblages is their postcrystallization histories. If the Nisling–Tracy Arm rocks are rifted remnants of the western margin of North American (Tempelman-Kluit, 1979), then Nisling–Tracy Arm and North American strata should have a shared prerift history, but different postrift histories. In Mississippian time, Nisling–Tracy Arm rocks were rifted from North America and stranded on a different plate, shedding detritus into the enlarging basin to the east, which separated them from western North America. In Early Permian time, Nisling–Tracy Arm rocks locally formed the basement for the Stikinia arc, which formed during west-dipping subduction of the Anvil ocean. The Nisling–Tracy Arm assemblage thus resided in an upper plate position relative to the orthogneiss assemblage, which remained part of North America. With continued basin closure, and finally collision in Early Jurassic time, the Nisling–Tracy Arm assemblage, together with the arc and accumulated subduction complex, were thrust over their pre-Pennsylvanian North American counterparts. The Nisling–Tracy Arm assemblage claimed a structurally high position relative to North American strata, which were tectonically buried. Mid-Cretaceous crustal extension resulted in local exposure of North American strata, which yield postaccretion cooling ages. In this scenario, the isotopic signature inherited from plutonic protoliths within these two packages of rocks would be expected to be similar, even though the subsequent structural, metamorphic, and thermal histories of the rocks are different. Without the benefit of integrated kinematic and thermochronologic data, these two assemblages appear to be correlative. In our interpretation, North American rocks of the attenuated margin yield post-Middle Jurassic (mostly mid-Cretaceous) cooling ages and are now at deep structural levels as a result of being overthrust in Early Jurassic time; whereas the Nisling–Tracy Arm assemblage, which has similar pre-Pennsylvanian characteristics, resides at high structural levels and yields pre-Middle Jurassic cooling ages.

Studies from three areas in central Yukon provide an opportunity to examine the Mississippian plutons and their postemplacement kinematic and cooling histories. In the Laberge–Quiet Lake area (Fig. 1), two ca. 355 Ma plutons (now orthogneiss) intrude Cassiar strata (Hansen et al., 1989). Klippen of Teslin–Taylor Mountain and Nisutlin tectonites are structurally above the orthogneiss and their host pelitic metasedimentary tectonites. The orthogneiss and host rocks record top-to-the-east-northeast ductile shear and slow cooling from Late Jurassic to mid-Cretaceous time (Hansen et al., 1991; Hansen 1992b). These rocks are therefore lower plate, parautochthonous North American strata. In the Little Salmon Lake area, an orthogneiss at the highest exposed structural level yields a U-Pb zircon age of 353 Ma, and a biotite $^{40}Ar/^{39}Ar$ cooling age of 215 Ma (Oliver, 1996). The Little Salmon Lake orthogneiss, like the Laberge-Quiet Lake orthogneiss, yields εNd values consistent with North American affinity (Bennett and Hansen, 1988). The Little Salmon Lake orthogneiss displays apparent normal dip-slip shear fabrics (interpreted as subduction backflow; Oliver, 1996), consistent with upper plate tectonites in the Laberge–Quiet Lake area to the south. The orthogneiss and its host rocks are interpreted as upper plate Nisling–Tracy Arm assemblage, consistent with their high structural position and the pre-Middle Jurassic cooling ages.

In the Teslin map area (Fig. 1), 340–350 Ma plutons, locally deformed to orthogneiss, reside at the highest exposed structural level, and yield εNd ratios consistent with North American continental affinity (Stevens et al., 1996; Stevens and Erdmer, 1996; Creaser et al., 1997). Although metamorphic cooling ages are not available in this area, host tectonites are intruded by a massive hornblende-bearing tonalite to quartz diorite pluton with a concordant $^{207}Pb/^{206}Pb$ age of 215 Ma, and a $^{40}Ar/^{39}Ar$ hornblende age of 188 Ma (Stevens et al., 1996). The temporal relations between tectonism and Early Jurassic plutonism are similar to those of the Taylor Mountain tectonites and the Taylor Mountain batholith in east-central Alaska. It is most plausible that the orthogneiss cooled at about the same time as the diorite pluton—in Early to Middle Jurassic time. We interpret these rocks as upper plate Nisling–Tracy Arm, similar to the upper plate interpretation put forward by Stevens et al. (1996).

Parautochthoneity of the inboard orthogneiss assemblage, which is correlated with Kootenay rocks of southern British Columbia (Wheeler and McFeely, 1991), is consistent with the assertion that lower Paleozoic strata of the Kootenay terrane, southern British Columbia, are depositionally linked to and conformable with rocks of the North American miogeocline (Colpron and Price, 1995). The interpretation of parautochthoneity is also strengthened by the recognition of Mississippian magmatism in autochthonous miogeoclinal Cassiar strata east of the Tintina fault. Petrological and geochemical data indicate probable formation within an extensional setting (Mortensen, 1982), consistent with stratigraphic and structural evidence for mid-Paleozoic extension of the Cassiar assemblage (Gordey et al., 1987). Orthogneiss assemblage metabasalt trace element ratios show mid-oceanic-ridge basalt and within-plate geochemical affinities supporting correlation with the pericratonic Kootenay terranes, and suggesting an origin within an attenuated continental margin (Dusel-Bacon and Cooper, 1995). Thus, it is possible that Devonian and Mississippian granitoids that intruded North American marginal-basin strata represent an intrusive component of intermittent early Paleozoic extension (Rubin et al., 1990; Colpron and Price, 1995).

Late Triassic–Early Jurassic Plutons

The Late Triassic–Early Jurassic calc-alkaline plutons, heralded as probable Stikinia (e.g., Aleinikoff et al., 1986), also provide a critical preaccretion link between upper plate assemblages and a distinction from lower plate assemblages. Although the Nisling–Tracy Arm assemblage is geochemically similar to North American strata, it has a different post-Mississippian geologic history than its pre-Pennsylvanian North American counterparts. In addition to the difference in late Paleozoic–early Mesozoic histories outlined here, the Nisling–Tracy Arm assemblage is intruded by Late Triassic–Early Jurassic plutons (e.g., Johnston and Erdmer, 1995), as are the Teslin–Taylor Mountain and Slide Mountain–Seventymile assemblages. In contrast, to date there are no documented examples of Late Triassic to Early Jurassic calc-alkaline plutons intruding the orthogneiss, Kootenay, or Cassiar assemblages in Yukon or Alaska (see Dusel-Bacon et al., 1995). Thus upper plate rocks (Nisling–Tracy Arm, Stikinia, Teslin–Taylor Mountain, Slide Mountain–Seventymile, and locally Nisutlin assemblages) were likely separate from lower plate parautochthonous and autochthonous North American strata in Late Triassic–Early Jurassic time.

Crustal Assembly

The data favor a model in which upper plate assemblages (Nisling–Tracy Arm, Stikinia, Slide Mountain–Seventymile, Teslin–Taylor Mountain, and Nisutlin rocks) are thrust over lower plate rocks of the attenuated North American margin (orthogneiss, Kootenay, and Cassiar assemblages) more than 50 m.y. before crustal extension. Although the crust was extended during top-to-the-southeast shear in the Alaskan upland, central and southern Yukon was dissected by northwest-striking dextral strike-slip faults. The 50 m.y. time gap between crustal thickening and extension, and the synchroneity of extension and dextral translation in Alaska and Yukon, respectively, may place constraints on the mechanism of extension.

Pavlis et al. (1993) proposed three end-member models for mid-Cretaceous upland extension, which are dependent, in large part, on regional timing relations and kinematics: (1) a two-phase model involving Jurassic collision and Cretaceous extension, using the Neogene Hellenic arc as an analog; (2) a syncollisional model, employing the Carpathian Mountains as an analog; and (3) a syncollisional plateau uplift model, extension being driven by gravity spreading, a Himalayan analog. The Carpathian and Himalayan analogs require Early to mid-Cretaceous collision of allochthonous rocks with the North American margin, and near temporal equivalence of contraction and extension. Our data are consistent only with the Hellenic arc analog, although it could also fit a model in which extensional collapse significantly postdates collisional thickening (e.g., Rubin et al., 1995).

The Hellenic arc analog for mid-Cretaceous extension in the upland (Pavlis et al., 1993), based on the Neogene collision and related back-arc extension of the eastern Mediterranean, similar to that proposed by Pavlis (1989), assumes late Paleozoic to Triassic west-dipping subduction followed by Middle Jurassic collision of Stikinia with North America. Following collision, a subduction zone dipping in the opposite direction, beneath North America, formed along the western margin of North America and remained active until the collision of the outboard Peninsular-Alexander-Wrangellia superterrane in mid-Cretaceous time. Initial collision of the superterrane in Early to mid-Cretaceous time resulted in formation of a new subduction zone along the trailing edge of the superterrane. As a result of collision, the Andean margin of North America was isolated from plate convergence, and convergence across the older, inboard subduction zone became slower than the rate of convergence between North America and the outboard oceanic plates, resulting in back-arc spreading due to slab rollback. Subduction rollback, causes in turn, southeast-directed extension in the upland. The biggest problem with the Hellenic arc analog, as pointed out by Pavlis et al. (1993), is the lack of clear evidence for a magmatic arc on North America from latest Jurassic to mid-Early Cretaceous time (e.g., Armstrong, 1988).

Rubin et al. (1995) proposed subduction rollback as a cause for mid-Cretaceous crustal extension within the context of the entire northern circum-Pacific of western Canada, southeast and northern Alaska, and the Chukotka Peninsula, Russia. These workers related rollback to an abrupt change in motion of the subducting Farallon plate at ca. 120 Ma, and coincidental opening of the Canada basin by rifting or by strike-slip faulting. Retreat of the paleo-Pacific margin accompanied opening of the Canada basin, resulting in rollback subduction and subsequent south-directed extension across much of interior Alaska. Either of these models for rollback subduction and subsequent south-directed (southeast-directed) crustal extension are consistent with our data from the upland tectonites; however, synchronous dextral translation along distributed steep northwest-striking faults in central Yukon are predicted by the large-scale plate interactions proposed by Rubin et al. (1995), and might not be expected as a result of superterrane accretion proposed by Pavlis et al. (1993).

Our study of the upland tectonite sheds light on Mesozoic crustal assembly processes in the northern Cordillera. With the recognition of terranes, Coney (1981) proposed that huge volumes of new crust were added to western North America in a very short time (7.23×10^6 km^2 during 165 m.y.). Our data indicate that this volume of new crust might be greatly overestimated. Although a map view of Yukon and Alaska reveals much apparent new crust, much of the new crust forms large thin klippen, and thus represent very little volume. In addition, large tracts of one of the largest previously proposed "accreted terranes"—the Yukon-Tanana composite terrane—is dominantly composed, volumetrically, of the structurally lowest unit composed of North American parautochthonous strata. These rocks are not new to North America; they have simply been "repainted" by allochthonous fragments in Early to Middle Jurassic time, and locally translated along their parent margin. Mid-Cretaceous extension revealed the true nature of the base of the crust as allochthonous "paint" was tectonically denuded and eroded. The chipped allochthonous "paint" exposes the crustal foundation of North American strata. Furthermore, part of the tectonically accreted crust, the Nisling–Tracy Arm assemblage, is also not new to the North American continent, but is simply rifted fragments, now returned, perhaps in a different location, within the parent continent. Thus the volume of continental crust, which is actually new to the North American continent within the north Cordillera, might include only terrain west of the Nisling–Tracy Arm assemblage.

CONCLUSIONS

Integrated kinematic, *P-T*, and thermochronometric data allow us to distinguish allochthonous tectonites from parautochthonous tectonites within the Yukon-Tanana upland. Upland tectonites define a regionally coherent stacking order; from bottom to top, these are the North American parautochthonous continental margin, continental marginal-basin strata, and ocean-basin tectonites locally intruded by arc plutons. We delineate three major deformation events in time, space, and structural level across the Yukon-Tanana upland: (1) pre-Early Jurassic (> 212 Ma), northeast-directed, apparent margin-normal contraction that affected allochthonous oceanic, arc, and marginal-basin rocks; (2) late Early to early Middle Jurassic (>188–185 Ma), northwest-directed, apparent margin-parallel contraction and imbrication that resulted in juxtaposition of the allochthonous tectonites with parautochthonous continental rocks; and (3) Early Cretaceous (135–110 Ma), southeast-directed crustal extension that resulted in exposure of the structurally deepest, parautochthonous continental rocks. These events can be correlated across the upland and through south-central Yukon, although mid-Cretaceous deformation in the Yukon was dominated by dextral translation along steep northwest-striking faults, in keeping with the regional plate kinematics predicted by plate margins and relative plate motions.

The oldest recognized deformation took place within a west-dipping middle Permian–Late Triassic subduction zone, above the Stikinia arc. Deformation variably affected upper plate rocks, including local continental basement to the arc, and oceanic and marginal-basin strata. These upper plate tectonites were locally intruded by Late Triassic to Early Jurassic calc-alkaline arc plutons. They were then thrust over parautochthonous North American strata (lower plate rocks) in Early to Middle Jurassic time. Mid-Cretaceous rollback subduction may have caused southeast-directed crustal extension of the upland region, resulting in tectonic denudation and exposure of the previously overthrust parautochthonous strata.

Prior to Permian subduction, the Anvil ocean formed due to rifting of the western margin of northern North America. The rifted continental fragments have North American geochemical and isotopic fingerprints, although their Pennsylvanian to Late Jurassic histories are very different from those of their North American counterparts. Both packages were intruded by Devonian-Mississippian plutons, but the rifted Nisling–Tracy Arm assemblage came to reside in the upper plate of the convergent margin that brought these assemblages back together, whereas the North American strata reside in the lower plate.

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