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Tertiary Tectonics of the Border Ranges Fault System, Chugach Mountains, Alaska: Deformation and Uplift in a Forearc Setting

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The Border Ranges fault system (BRFS) locally separates supracrustal Upper Cretaceous-Tertiary rocks of the Cook Inlet/Matanuska Valley forearc basin on the Peninsular terrane from metamorphosed Cretaceous subduction complex rocks of the Chugach terrane to the south. This 5- to 10-km-wide zone of concentrated deformation along the inboard edge of southern Alaska's accretionary prism has suffered a protracted history, beginning with its inception as a "megathrust" by Early Cretaceous time and continuing into early Tertiary time, when it was transected by a system of steeply arcward dipping normal- and dextral-slip faults. Based on detailed geologic mapping, structural analysis, metamorphic mineral assemblage data, and K-Ar and fission track geochronology, the Tertiary history of displacements along a central part of this forearc fault system has been divided into several phases of deformation. These include a Paleocene phase of regional uplift of the forearc basin together with block faulting along the BRFS to rapidly uplift and subaerially expose low-grade metamorphic rocks of the subduction complex (Upper Cretaceous Valdez Group) within 15 Ma of their inferred underplating at deep structural levels of the accretionary prism. Continued normal-separation faulting along the BRFS in late Paleocene/early Eocene time to further uplift the subduction complex was recorded by deposition of a syntectonic alluvial fan system (Chickaloon Formation) across the BRFS and along the southern margin of the forearc basin. A third, mid Eocene, increment of normal-separation faulting along the BRFS juxtaposed greenschist facies fabrics of early Eocene age in the subduction complex against the Chickaloon Formation. This latter uplift event predated intrusion of early late Eocene (~43–48 Ma, zircon fission track minimum ages) felsic dikes into the present terrane-bounding fault and was accompanied by no more than a few tens of kilometers of dextral-slip faulting along the BRFS, a conclusion that does do not accord with recent suggestions for thousands of kilometers of displacement along that fault system in early-middle Tertiary time, based on paleomagnetic data. Field observations in the study area indicate that the great oroclinal bend of southern Alaska is postearly Eocene and possibly prelate Oligocene in age. A final period of deformation in middle to late Tertiary time was marked by periods of minor north-south contraction of the forearc basin and by local reverse-slip reactivation of earlier faults. Fission track age data on apatite indicate rapid cooling and probably uplift of both subduction complex and adjacent parts of the forearc basin in Miocene time (~17–24 Ma). Episodic uplift of the subduction complex, either locally by normal-separation faulting along its "backstop," or by a more regional uplift also affecting the adjacent forearc basin, overlapped in time or closely followed discrete pulses of large-scale sediment underplating along the Gulf of Alaska subduction margin. This coincidence suggests that major pulses of sediment underplating along southern Alaska's convergent margin may have led to isostatic uplift of its "critical-taper" accretionary prism, an uplift that was in part accommodated by normal-separation faulting along its mechanical backstop.

INTRODUCTION

The relationship between plate tectonic interactions and orogenic events recorded in the geology of the continent remains a controversial and poorly understood subject [e.g., *Beck*, 1984, and papers therein]. Research into this complex problem is commonly hindered by uncertainties in Mesozoic and older plate reconstructions and the necessity for a detailed chronology of on-land structural events. An important subtopic in convergent margin tectonics is the nature of "backstop" fault systems along the inboard edge of accretionary prisms [e.g., *Page*, 1970; *Karig and Sharman*, 1975; *Davis et al.*, 1986]. Specifically, what role do they play in accommodating relative plate motions, in the dynamics of accretionary prisms, and in the uplift of deep-level metamorphic rocks? How important is strike-slip faulting along these boundaries in the structural development of forearc regions? This paper will address these questions along a central part of southern Alaska, where the Peninsular, Chugach, and Prince William terranes comprise elements of a south facing arc-trench system of Late Cretaceous and Paleogene age (Figure 1).

The Border Ranges fault system (BRFS) locally separates a forearc basin sequence (on the Peninsular terrane) from rocks inferred to have been deposited in a subduction accretionary complex (Chugach terrane) and is thus analogous to the Coast Range fault system of California [*Page*, 1981; *Jayko et al.*, 1987]. In the north-central Chugach Mountains the BRFS is here defined as a 5- to 10-km wide zone of closely-spaced faults of Mesozoic and Tertiary age that cut and locally separate rocks of the Chugach and Peninsular terrane. This zone of concentrated deformation began its history as a late Mesozoic system of north dipping thrusts [e.g., Pavlis, 1982], but in early

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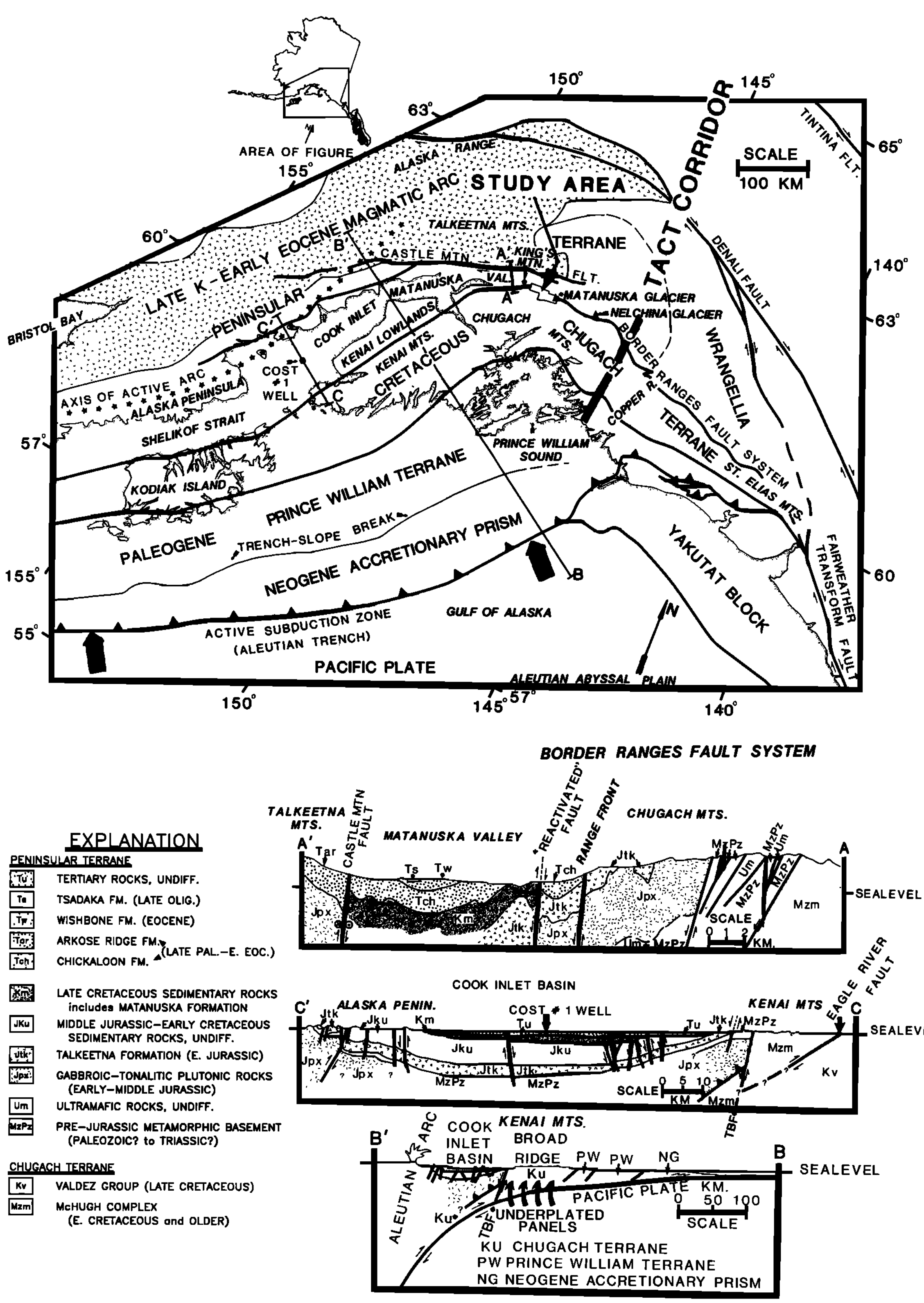

Fig. 1. Index map and generalized cross sections of a central part of southern Alaska. Cross sections have no vertical exaggeration and, except for B-B′, are at enlarged scales relative to map. Area of Late Cretaceous/early Eocene magmatic arc taken from *Wallace and Engebretson* [1984] and *Csejtey et al.* [1978]. Cross section A-A′ is adapted from *Clardy* [1974] and *Pavlis* [1983], B-B′ from *Pavlis and Bruhn* [1983], and C-C′ from *Fisher and Magoon* [1978].

Tertiary time was transected by a system of steeply arcward dipping oblique-slip faults. The lithological contrast between crystalline basement rocks of the Peninsular terrane to the north and metasedimentary rocks of the subduction complex to the south suggests that the BRFS has functioned as the mechanical backstop of the accretionary prism as it has thickened and widened southward throughout much of late Mesozoic and Tertiary time [e.g., *Pavlis and Bruhn*, 1983]. The study area for this paper is located in the northern Chugach Mountains about 100 km west of the Trans-Alaska Crustal Transect (TACT) corridor (Figures 1, 2). This region is of special interest because exposures of Paleogene Chickaloon Formation of the Cook Inlet forearc basin and uppermost Cretaceous subduction complex rocks of the Valdez Group are both deformed within the BRFS, providing a unique record of that fault system's Tertiary history. This record indicates that episodes of normal-separation faulting and dextral strike-slip faulting, either alone or in combination with one another, have resulted in localized uplift and erosion of the accretionary complex and in a present juxtaposition of deep-level metamorphic rocks against supracrustal sedimentary rocks of the forearc basin. In addition, at least two periods of regional uplift have affected the forearc basin, the second of which occurred in Neogene time after the forearc had switched from a regime of horizontal extension to one of compression.

In this paper, structural relationships and K-Ar and fission track geochronology are used to divide the multistage history of displacements along the BRFS into several discrete tectonic events. Because their timing is well constrained, these events can be confidently compared with deformations in other parts of the arc-trench system and to Tertiary plate motion reconstructions for the Pacific Basin. This multistage history is described chronologically below, and in some detail, with the intent of reporting important new constraints from an especially informative and previously poorly known part of the fault system and synthesizing those data with the results of other workers to obtain for the first time a unified picture of the kinematic development of the BRFS in Tertiary time. In terms of regional tectonics the most significant findings are, first, that the early Tertiary history of the BRFS includes no more than a few tens of kilometers of dextral slip, an observation that does not accord with recent proposals of thousands of kilometers of early to middle Tertiary displacement along that fault zone. Second, field relationships in the study area document a post-early Eocene age for oroclinal bending of southern Alaska. Two main points are made in the context of general forearc tectonic processes. First, components of strike slip along this backstop fault system seem to have been related to partial mechanical coupling between underriding and overriding plates during times of strongly oblique convergence. Second, repeated episodes of dip-separation faulting along the inboard edge of the accretionary prism, with or without an accompanying regional uplift of the adjacent forearc basin, probably resulted from isostatic uplift in response to major pulses of sediment underplating.

TECTONOSTRATIGRAPHY

Peninsular Terrane

The Peninsular terrane generally dips moderately northward, exposing deep structural levels of a Lower–Middle Jurassic island arc sequence along its southern edge (Figure 1, A-A′ and C-C′). The oldest rocks in the study area consist of a pre-Jurassic sequence of siliceous, pelitic, and calcareous metasediments and metabasites that have been regionally metamorphosed and deformed in the epidote amphibolite facies [*Pavlis*, 1983; *Little et al.*, 1986]. The arc complex consists of Lower to Middle Jurassic gabbroic, tonalitic, and locally ultramafic plutonic rocks, parts of which intrude both the metamorphic sequence, and also overlying marine andesitic flows and tuffs of the over 4-km-thick Talkeetna Formation of Lower Jurassic age [*Pessel et al.*, 1981; *Pavlis*, 1983; *Burns et al.*, 1983; *Burns*, 1985; *Flynn and Pessel*, 1984]. Conspicuous by their absence are up to 6 km of Middle Jurassic/Upper Cretaceous marine clastic and carbonate rocks which overlie the Talkeetna Formation in more northern parts of the Peninsular terrane [e.g., *Detterman and Reed*, 1980; *Grantz*, 1960; *Fisher and Magoon*, 1978] (Jku, Figure 1, C-C′). Upper Cretaceous and Paleogene sedimentary rocks of the Cook Inlet-Matanuska Valley forearc basin [*Burk*, 1965; *Moore and Connelly*, 1979] are represented in the north-central Chugach Mountains by the Matanuska and Chickaloon formations, respectively. The turbiditic Matanuska Formation unconformably overlies the Talkeetna Formation and contains Albian-Maastrichtian age marine fossils [*Grantz*, 1964]. The Chickaloon Formation locally disconformably overlies the Matanuska Formation and consists of nonmarine conglomerate, sandstone, mudstone, and locally coal of late Paleocene/early Eocene age [*Wolfe et al.*, 1966; *Triplehorn et al.*, 1984; *Little*, 1988].

Chugach and Prince William Terranes

The Chugach terrane and more outboard Prince William terrane (Figure 1) form the uplifted and subaerially exposed part of southern Alaska's wide accretionary prism and consist of complexly deformed oceanic deposits offscraped against the continental margin by subduction in Cretaceous to early Tertiary time. In south-central Alaska the Cretaceous Chugach terrane can be divided into two lithotectonic assemblages of locally overlapping age [e.g., *Nilson and Zuffa*, 1982]. The McHugh Complex [*Clark*, 1973] and its correlatives consist chiefly of Triassic/Lower Cretaceous chert-argillite, greenstone, graywacke, and minor marble and serpentinite deformed into broken formation and argillite-tuff-chert matrix melange [*Connelly*, 1978; *Pavlis*, 1982; *Nelson et al.*, 1986]. These brittlely dismembered ophiolitic rocks are metamorphosed in the prehnite-pumpellyite (and locally blueschist) facies and have been interpreted as subducted oceanic lithosphere and trench-slope sediments [e.g., *Decker*, 1980; *Winkler et al.*, 1981]. The more coherent Valdez Group to the south and its correlatives are an upper Campanian-Maastrichtian age trench-fill turbidite sequence [*Moore*, 1973a; *Nilson and Zuffa*, 1982] that has been thrust beneath the McHugh Complex along the north dipping "Eagle River thrust" (Figure 1, C-C′). In the study area, where the Valdez Group consists chiefly of a monotonous slope or basinal sequence of dark gray pelitic phyllite, this thrust has been rotated to steeper angles by a later event of kilometer-scale chevron folding (Figure 2, location 6; Figure 3, D-D′).

Outboard and structurally beneath of the Chugach terrane, the Prince William terrane consists of complexly folded and faulted trench-fill turbidite sequences and local basaltic pillow lavas of early Paleogene age (Figure 1, C-C′). In Prince William Sound this accreted belt includes Paleocene to lower middle Eocene rocks of the Orca Group that are coeval in age with forearc

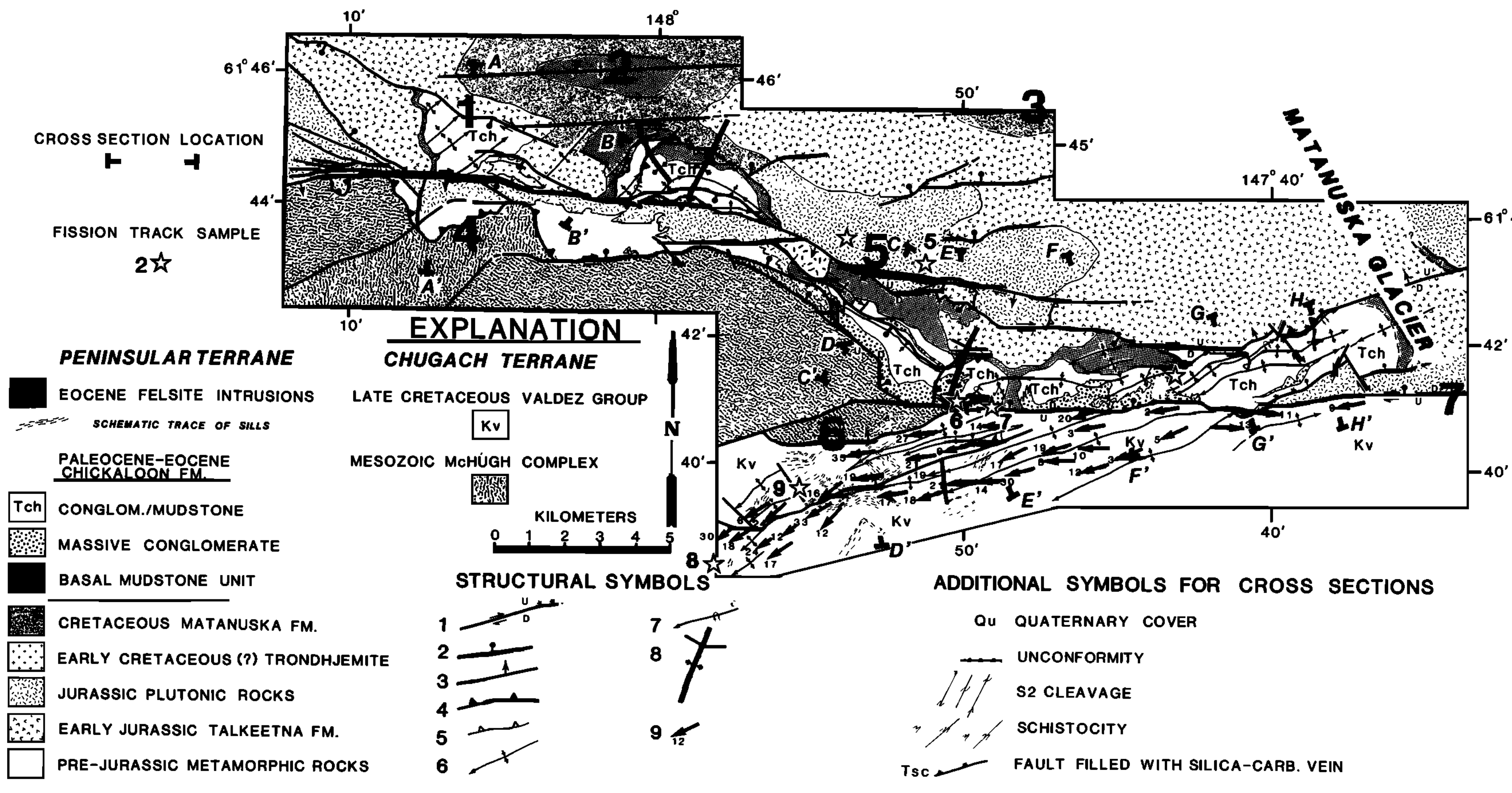

Fig. 2. Simplified geologic map of detailed study area (area of map shown in Figure 1). Numbered stars indicating fission track sample locations are keyed to Table 1 and Figure 13. Bold numbers refer to locations mentioned in text. Explanation of structural symbols: 1, fault, ornamented where intruded by silicic dikes; 2, normal-separation fault; 3, reverse-separation fault; 4, thrust fault; 5, decollement fault; 6, axial trace of fold; 7, overturned fold; 8, axial trace of fault-bend megakink; and 9, mean trend and plunge of L_2 intersection lineation in the Valdez Group (means of 10–40 measurements in selected structural domains). Map simplified from *Little* [1988] and *Burns et al.* [1983].

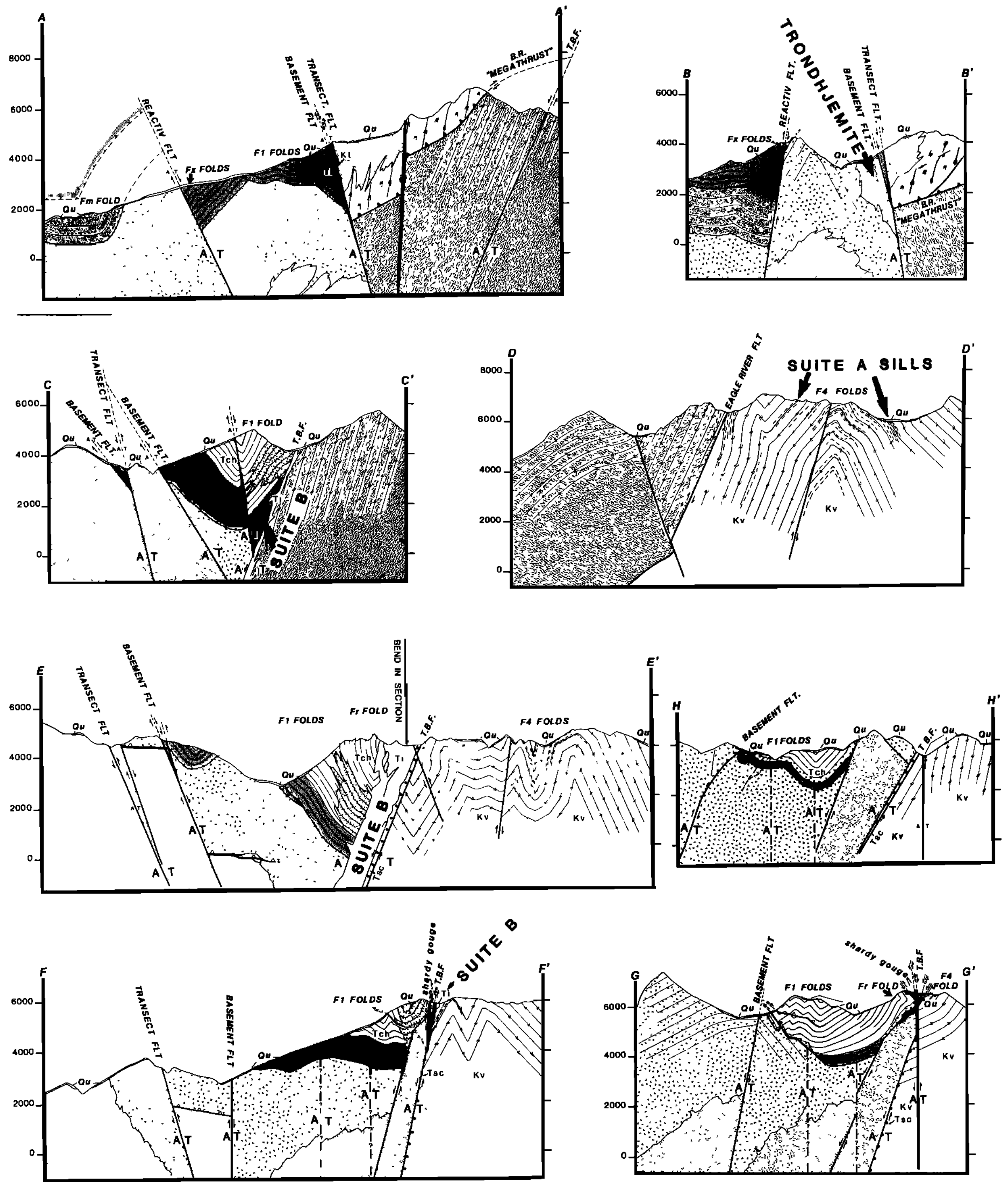

Fig. 3. Structural cross sections for map of Figure 2. For explanation of symbols and map patterns, see Figure 2. Vertical elevations in feet above mean sea level. No vertical exaggeration. Scale enlarged from that of Figure 2 to show detail.

basin deposits of the Chickaloon Formation [*Helwig and Emmet*, 1981; *Plafker et al.*, 1985]. On Kodiak Island, the Prince William terrane includes the Paleocene Ghost Rocks Formation and also the Sitkalidak Formation, the latter constrained by fossils to be Eocene and/or lower Oligocene in age [*Byrne*, 1982, 1986].

Border Ranges Fault System As a Composite Boundary

The BRFS is a profound structural boundary that has suffered a protracted history of superimposed faulting and folding. Most previous studies of the BRFS have emphasized its late Mesozoic inception as a north dipping "megathrust" between the overriding Peninsular terrane and the underthrust McHugh Complex to the south (Figure 1). Previous work in the north-central Chugach Mountains [e.g., *Pavlis*, 1982; *Pavlis et al.*, 1987] indicates that this fault system was active by ~103–124 Ma, when a near-trench suite of trondhjemitic-tonalitic plutons were intruded into cataclastically deformed rocks on both its hangingwall and footwall. Probable vestiges of late Mesozoic thrust faults are locally exposed in the study area, where a fault that dips gently northward places Jurassic plutonic rocks of the

Peninsular terrane above the McHugh Complex (Figure 2, loc. 4; Figure 3, A-A´). Early Cretaceous uplift and erosion on the hangingwall of the Border Ranges megathrust is also suggested by the above-described omission of Middle Jurassic/Lower Cretaceous rocks locally along the southern edge of the Jurassic arc complex. Elsewhere in the north-central Chugach Mountains the crystalline roots of the arc complex are complexly dismembered within a several kilometer-wide zone of densely spaced, gently to moderately north dipping faults [*Pessel et al.*, 1981; *Pavlis*, 1982]. These faults and related prehnite-pumpellyite facies cataclastic rocks probably represent a zone of distributed brittle faulting that together comprised the original Border Ranges megathrust [e.g., *Pavlis*, 1982].

The fault that presently separates the Peninsular and Chugach terranes in the eastern and central parts of the study area truncates the Border Ranges megathrust, the Eagle River thrust, and the Chickaloon Formation, and is clearly Tertiary in age (Figures 2 and 4). This fault dips steeply to the north, has a south-side-up sense of dip separation, and is one of many generally east-west striking oblique-slip faults that offset older thrust faults and dominate the present structural grain of the BRFS (Figure 4). Because it separates the Peninsular and Chugach terranes throughout most of the study area, this major fault is here referred to informally as the "terrane-bounding fault" (TBF). On the basis of unconformities, postfaulting dikes, and other structural age constraints, the polyphase Tertiary tectonic history of the BRFS can be divided into four main periods of deformation: latest Cretaceous/Paleocene, Paleocene/early Eocene, early Eocene/late Eocene, and post-late Eocene. The first of these is recognized only in Cretaceous rocks of the Chugach terrane subduction complex.

Latest Cretaceous to Paleocene Deformation: Emplacement and Dynamothermal Metamorphism (M_1) of the Valdez Group

The Valdez Group and its correlatives were imbricated within a seaward verging system of thrust faults and emplaced against the continental margin in latest Cretaceous or early Paleocene time [*Moore*, 1973b; *Plafker et al.*, 1977]. Structural and metamorphic studies of these rocks on Kodiak Island have documented their folding, faulting, and slaty cleavage development within a thrust-duplex system prior to intrusion of ~60 Ma plutons and indicate that the turbidites were underplated to the base of the accretionary prism at ~7- to 12-km depth [e.g., *Sample and Fisher*, 1986; *Sample and Moore*, 1987; *Fisher and Byrne*, 1987; *Sample*, 1987]. Although similar thrust faults have probably duplicated the Valdez Group in the study area, they remain undetected there because of a lack of mappable subunits and a later intense overprint of dynamothermal metamorphism (M_2, below).

The oldest recognizable foliation in the Valdez Group in the study area is a slaty cleavage, S_1, which may have formed during underplating of the Valdez Group at relatively deep levels of the accretionary prism [*Little*, 1988]. Subsequent tight folding during M_2 in early Eocene time has obscured the original orientation of this cleavage in the detailed study area. Near the Nelchina Glacier (Figure 1), however, S_1 is relatively undeformed and dips moderately to steeply north [*Little*, 1988]. Near location 6 in Figure 2 and locally in other regions above the Eagle River fault, S_1 is strongly overprinted on rocks of the McHugh Complex, a relationship similar to that described for the correlative Uganik thrust and Uyak Complex on Kodiak Island [e.g., *Moore*, 1978]. A single calcite marble bed near location 7 (Figure 2) and rare fine-grained metasandstone beds elsewhere form discontinuous markers that are subparallel to S_1, suggesting that those beds may have been isoclinally folded during development of that cleavage. S_1 is a domainal cleavage parallel to a strong dimensional alignment of white mica and chlorite grains and also thin light and dark colored compositional laminae, <1–3 mm thick (Figure 5*b*). This tectonic striping is defined by alternation of quartz-rich microlithons and phyllosilicate-rich cleavage domains, a differentiated metamorphic layering that probably developed from water-enhanced diffusional mass transfer of quartz, calcite, ± albite away from the cleavage domains coupled with neocrystallization of white mica + chlorite within those domains [e.g., *Williams*, 1972; *Beach*, 1979; *Knipe*, 1981]. Metamorphic crystallization of micas and pressure solution of 5- to 10-mμ diameter quartz grains in these phyllites suggest that S_1 formed during low-grade metamorphism (M_1) at relatively deep levels of the accretionary prism, probably at temperatures greater than 150°C [e.g., *Frey et al.*, 1980; *Rutter*, 1983; *Hoffman and Hower*, 1979].

Paleocene to Early Eocene Deformation

Regional Uplift of the Forearc Basin and Block Uplift of the Subduction Complex

The unconformity at the base of the Chickaloon Formation records regional uplift of the forearc basin and faulting and uplift of the accretionary prism soon after emplacement of the Valdez Group. Nonmarine sedimentary rocks of the upper Paleocene-lower Eocene Chickaloon Formation unconformably overlie a block-faulted and eroded basement of the Jurassic arc complex and also locally the Cretaceous subduction complex [*Little*, 1988]. In the study area, steeply north dipping faults having up to several kilometers of normal separation bring up deeper arc basement rocks to the south (Figure 6). Where the Chickaloon Formation overlies Maastrichtian marine rocks of the Matanuska Formation along the northern edge of the study area, the concordant nature of this unconformity suggests that compression and folding did not accompany regional uplift, faulting, and withdrawal of marine waters from the forearc basin. Detailed studies of the provenance of detritus in the Chickaloon Formation along the southern edge of the forearc basin, including cobbles of Upper Triassic and Mesozoic (possibly Jurassic and Cretaceous) age radiolarian chert (C. D. Blome, personal communication, 1985), clearly indicate their local derivation from erosion of adjacent rocks of the Chugach terrane [*Little*, 1988]. A similar stratigraphic sequence of the Chickaloon Formation to that present in the detailed study area unconformably overlies both the McHugh Complex and Valdez Group near the Nelchina Glacier [*Little*, 1988]. This isolated exposure of polymictic conglomerate, lithic sandstone, and mudstone records uplift and subaerial exposure of Valdez Group phyllites within 15 Ma of their inferred deposition, subduction, thrust emplacement, and low-grade metamorphism in latest Cretaceous or earliest Tertiary time. Near the Nelchina Glacier, this rapid Paleocene uplift was probably accomplished at least in part by latest Cretaceous-Paleocene block faulting similar to that documented in the detailed study area (Figure 6).

Renewed subsidence of the forearc basin and continued uplift and erosion of the subduction complex in late Paleocene/early Eocene time are recorded by deposition of the Chickaloon For-

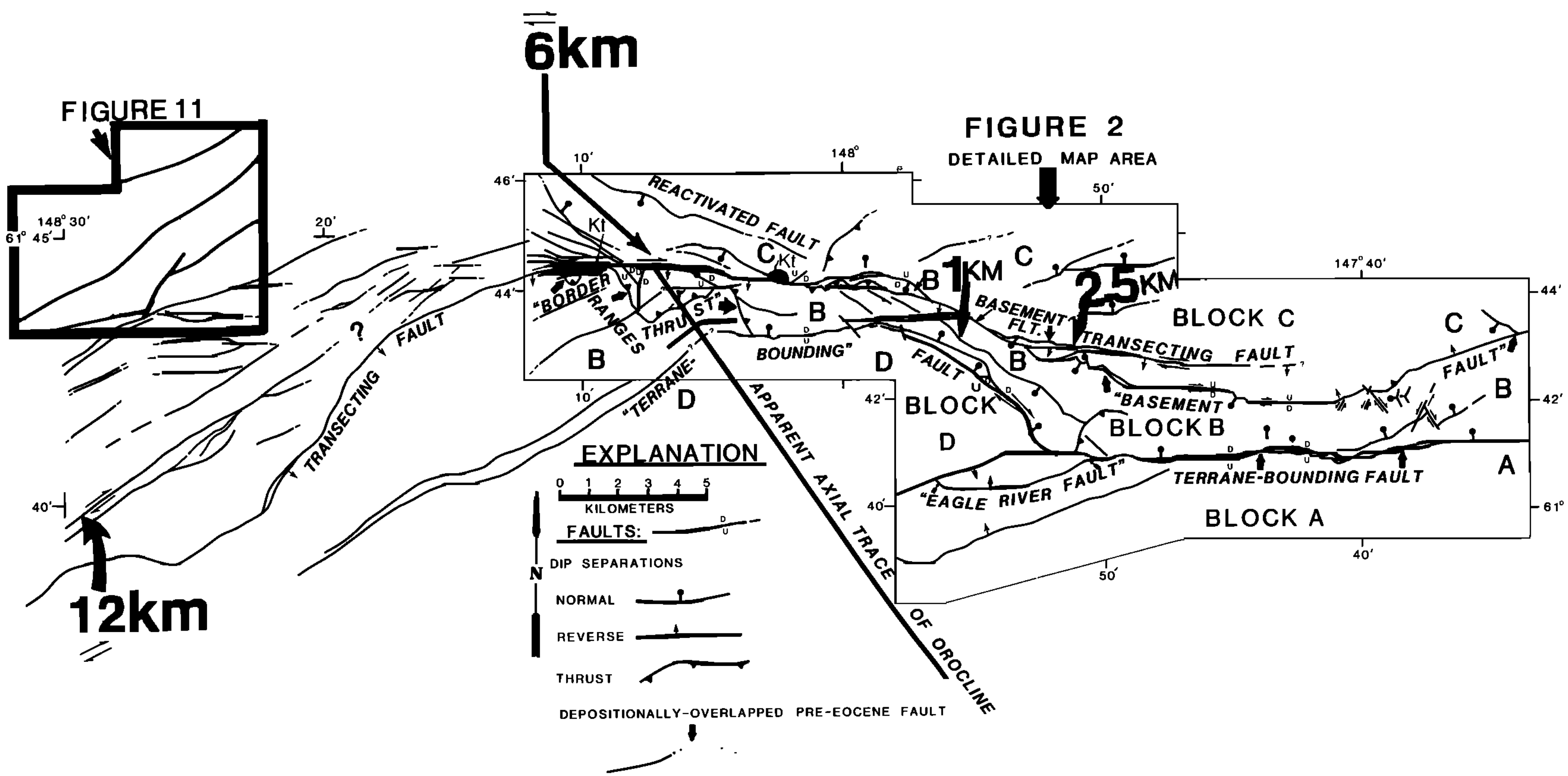

Fig. 4. Map showing major fault traces and senses of dip separation along a central part of the Border Ranges fault system. Simplified from *Little* [1988], *Burns et al.* [1983], and *Little et al.* [1986]. Mapped dextral strike separations are shown adjacent to appropriate fault trace. Half-circles labeled Kt schematically depict displaced portions of a trondhjemite stock. Southeastward trend of orocline axial trace inferred by connecting deflection in BRFS with similar deflection of the Contact fault system separating the Chugach and Prince William terranes in Prince William Sound region [e.g. *Winkler and Plafker*, 1981].

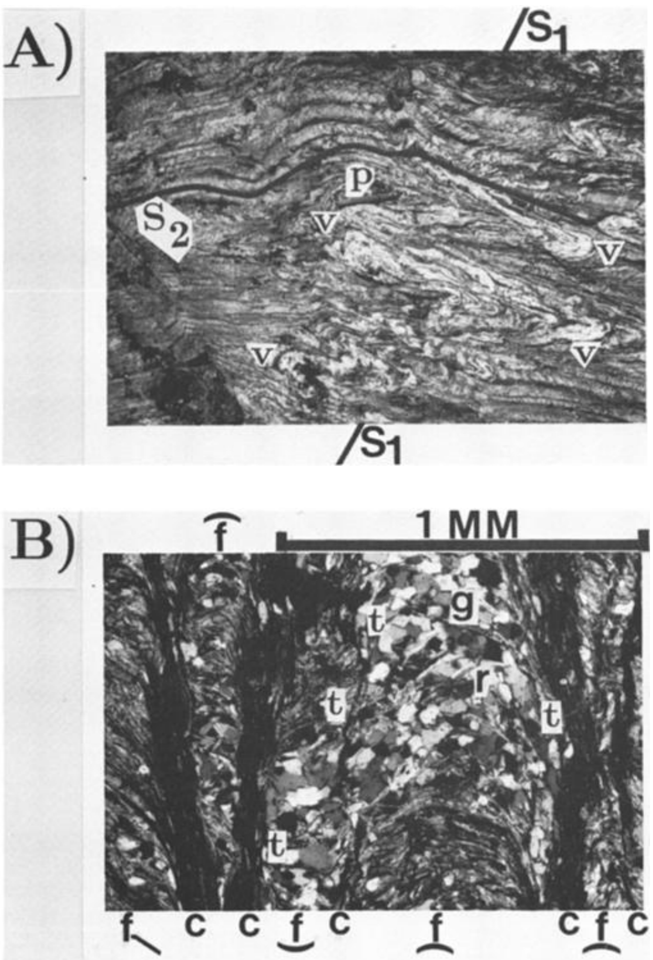

Fig. 5. (*a*) Photograph of Valdez Group showing relationship between S_1 cleavage, early quartzose segregation veins, spaced S_2 crenulation cleavage, and F_2 folds. Vs are located near the hinges of tight F_2 folds of light-colored quartzose segregation veins that are subparallel to S_1. Note crenulation folds of the striped S_1 fabric and axial planar disposition of S_2 crenulation cleavage with respect to F_2 folds. Pencil, p, is 15 cm long. (*b*) Photomicrograph of Valdez Group phyllite showing domainal slaty cleavage (S_1) deformed by crenulation cleavage (S_2). Note alternating quartz- and phyllosilicate-rich laminae along S_1 (subparallel to base of photo). Cs denote S_2 cleavage domains which are enriched in white mica, chlorite, and epidote, and opaques relative to crenulation-folded microlithons (fs). S_2 cleavage domains coincide with the attenuated limbs of crenulation microfolds and locally truncate (t) quartz-rich laminae of the S_1 fabric. Note annealed granoblastic texture (g) in the hinge of tight F_2 crenulation fold. The symbol r is to the right of two recrystallized blades of white mica in that hinge. Crossed nichols.

mation as a northwardly prograding, syntectonic alluvial fan deposit [*Little*, 1988]. At this time additional increments of normal separation accumulated along basement block faults in the BRFS to involve lower parts of the Chickaloon Formation and uplift an adjacent source terrain in the Cretaceous subduction complex to the south [*Little*, 1988].

Dynamothermal Metamorphism (M_2) Affecting the Subduction Complex

At about the same time the Chickaloon Formation was being deposited across supracrustal levels of the BRFS, a dynamothermal metamorphic event and intense ductile deformation affected deeper levels of the Cretaceous subduction complex. During this event a spaced crenulation cleavage, S_2, overprinted both the Valdez Group and adjacent rocks of the McHugh Complex, generally at a high angle to the earlier slaty cleavage, S_1 (Figure 5*a*). Microstructural observations such as those in Figure 5*b* indicate that pressure solution of quartz and calcite during M_2 resulted in local dissolution and truncation of the S_1 fabric and concentration of relatively stable minerals along the S_2 cleavage domains [e.g., *Gray*, 1979; *Gray and Durney*, 1979; *Swager*, 1985]. The synkinematic nature of M_2 is suggested by growth of chlorite pressure fringes around tremolite porphyroblasts that grew during M_2 and by neocrystallization of epidote and white mica preferentially along S_2 cleavage domains. On the other hand, annealed, strain-free grains of granoblastic-polygonal quartz and recrystallized white mica in the axial region of isoclinal crenulation folds indicate that the thermal peak of M_2 locally outlasted deformation (Figure 5*b*). Experimental data indicates that albite + chlorite + epidote + actinolite/tremolite bearing M_2 mineral assemblages in mafic/pelitic rocks of the Valdez Group and McHugh Complex [*Little*, 1988] formed in the lower greenschist facies, probably at temperatures in the range of 300–450°C [*Liou et al.*, 1985; *Cho and Liou*, 1988]. Coarse-grained white mica growing along S_2 in phyllite of the Valdez Group has a late Paleocene/early Eocene K-Ar age of 56.9 ± 3.4 Ma and is interpreted as the time that the rocks cooled below 300-400°C, soon after the thermal peak of M_2 [*Little*, 1988].

Folding that accompanied development of S_2 reflects an intense ductile flattening of the subduction complex in late Paleocene-early Eocene time. About 5–10 vol % of the Valdez Group consists of 1- to 3-cm-wide quartzose veins that are subparallel to S_1 and also contain calcite + albite ± white mica ± chlorite. Most of these segregation veins were emplaced during or after M_1 and prior to M_2. F_2 folds are polyharmonic, occurring both as crenulation microfolds of the S_1 fabric and as mesoscopic folds of the segregation veins (Figure 5*a*). Folded veins are tight to isoclinal, commonly boudinaged, and have a class 1C geometry characteristic of homogeneously "flattened" parallel folds [*Ramsay*, 1967]. Profile exposures consistently indicate a minimum layer-parallel shortening due to buckling in the range of 75–90%. S_2 is axial planar to the folded veins and contains a lineation, L_2, parallel to the hinge lines of crenulation folds. This intersection lineation between S_1 and S_2 is also subparallel to the long axes of boudinaged segregation veins and plunges gently to the east-northeast or west-southwest (Figure 2, symbol 9; Figures 7*a* and 7*c*). S_2 in the study area today dips moderately to steeply to the north-northwest or south-southeast (Figures 7*b* and 7*d*), but was probably subhorizontal before its involvement in later kilometer-scale chevron folding (Figure 3, E-E′). That the Eagle River thrust is subparallel to S_2 in adjacent rocks (Figure 3, D-D′) suggests that S_2, like the thrust, originally dipped gently to the north or northwest. The disposition of boudin axes subparallel to L_2 and elongation of chlorite pressure fringes perpendicular to that lineation suggest a north-south direction of maximum finite extension within that originally gently dipping foliation.

Local swarms of 1- to 5-m-wide dacitic dikes and sills intrude and locally crosscut S_2 cleavage surfaces in both the Valdez Group and McHugh Complex (e.g., Figure 3, D-D′). These leucocratic intrusions, which here are referred to as suite A, contain up to 2% phenocrysts of (now altered) amphibole or biotite and 2-30% phenocrysts of Ca-oligoclase or Na-andesine

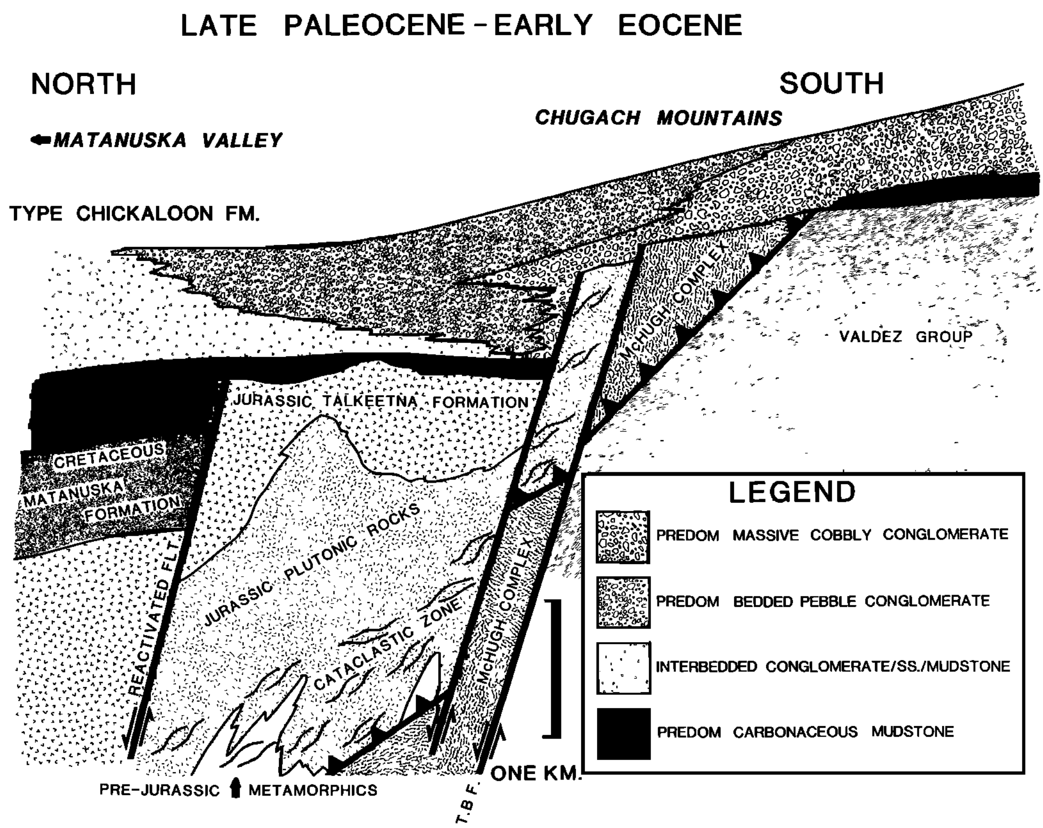

Fig. 6. Schematic cross section across the study region in Paleocene/early Eocene time summarizing stratigraphic and structural relationships of the Chickaloon Formation to its basement. Note predepositional to syndepositional age (with respect to the Chickaloon Formation) of north dipping normal-separation faults.

± minor quartz in a microcrystalline to fine-grained groundmass. Some sills consist of medium-grained, equigranular tonalite and all are altered by the assemblage albite + sericite + calcite + chlorite ± epidote. Separates of hornblende from a dike in the Valdez Group and biotite from a hornfels in the McHugh Complex yield K-Ar dates of 57.2 ± 3.5 Ma and 52.1 ± 3.2 Ma, respectively [*Little*, 1988]. Based on the crosscutting relations and available K-Ar age data, dike intrusion closely followed or possibly accompanied attainment of peak metamorphic temperatures during M_2. Other silicic dikes intruding the subduction complex in adjacent parts of the central Chugach Mountains typically have K-Ar ages of ~53–50 Ma [e.g., *Mitchell et al.*, 1981; *Winkler et al.*, 1981].

A similar Paleocene-early Eocene sequence of regional metamorphism, S_2 cleavage development, and synkinematic to postkinematic intrusion of silicic plutons has been reported in the Valdez Group and its correlatives throughout southern Alaska [e.g., *Sample and Moore*, 1987; *Mitchell et al.*, 1981; *Pavlis*, 1985; *Wallace*, 1981; *Pickthorn and Silberman*, 1984; *Plafker et al.*, this issue]. Considered together, these occurrences seem to define a regional belt of high T/P metamorphism increasing in grade and depth of exposure eastward to a culmination east of the Copper River [*Hudson and Plafker*, 1982]. Where available, constraints on the timing of M_2 in these different areas as inferred from K-Ar and Ar-Ar dating consistently fall in the range of 60–50 Ma [e.g., *Hudson and Plafker*, 1982; *Sisson et al.*, this issue]. Upper Cretaceous and lower Tertiary rocks of the accretionary prism are widely intruded by tonalitic-granitic plutons that, as a general trend, yield progressively younger K-Ar ages from ~60–47 Ma [*Hudson*, 1983] in an eastward direction around the rim of southern Alaska. Interpretation of some of these "near-trench" plutons as anatectic melts of metasedimentary rocks in the subduction complex coupled with the occurrence of basaltic pillow lavas of similar age in parts of the Prince William terrane have led people to infer that an oceanic spreading ridge was subducted beneath the continental margin [e.g., *Marshak and Karig*, 1977; *Moore et al.*, 1983] or that there was a temporary cessation in subduction which allowed isotherms to rise through the structurally thickened accretionary prism [*Hudson et al.*, 1979].

EARLY TO LATE EOCENE DEFORMATION

Dextral Wrench Faulting Along the Border Ranges Fault System

The next major period of tectonic activity along the BRFS is recorded by deformation of the Chickaloon Formation and its fault-juxtaposition against previously deep-seated M_2 metamorphic rocks of the Valdez Group. This deformation included dextral wrench faulting and folding and local pull-apart basin formation. The age of this tectonic event is constrained by the in part lower Eocene depositional age of the Chickaloon Formation and by middle to late Eocene isotopic ages for a posttectonic suite of silicic dikes. These undeformed dikes (suite B, below) intrude long segments of the two faults bounding block B (Figure 4). Two dikes that intrude the faulted boundary between the Cretaceous subduction complex

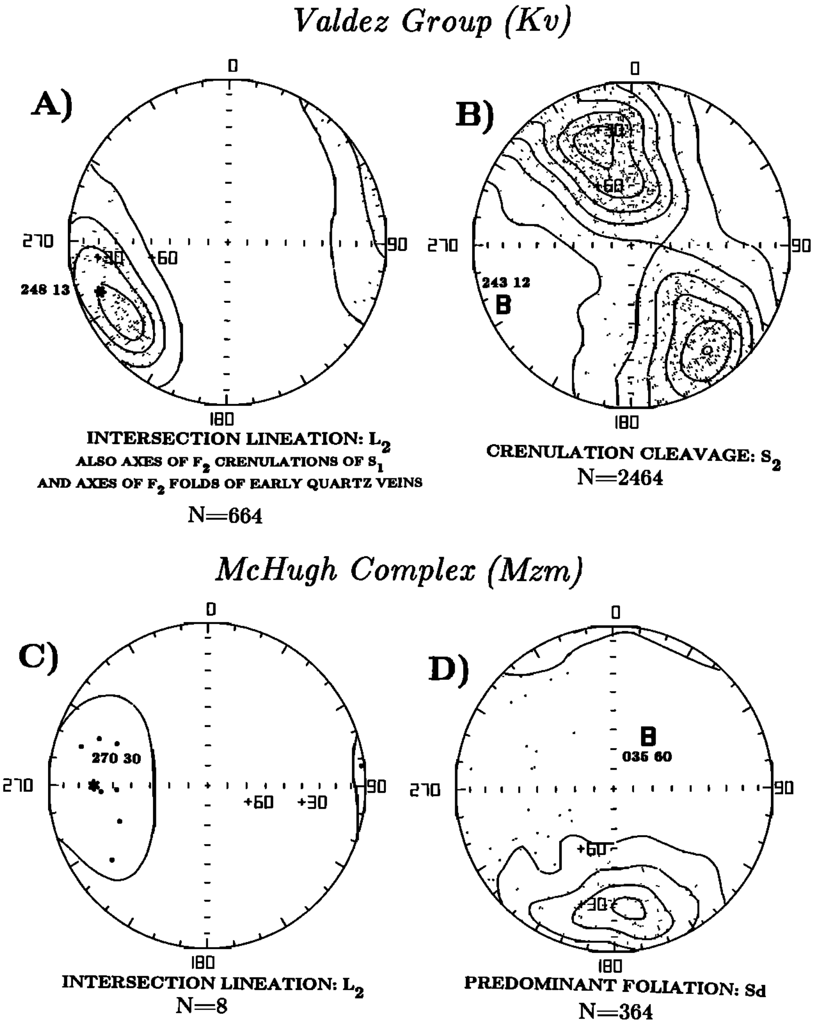

Fig. 7. Contoured lower hemisphere equal-area stereograms of S2 and L2 in the Cretaceous subduction complex (Chugach terrane). Mean values determined by computer using the eigenvalue technique of *Woodcock* [1977]. (*a*) L2 lineations in the Valdez Group defined by the intersection of S1 and S2 (contour intervals: 3.5, 5.8, 8.1, and 10.4 % data/1% area). Asterisk is mean lineation. (*b*) Poles to S2 in the Valdez Group (contour intervals: 1.0, 1.7, 2.4, 3.1, 3.8, and 4.4 % data/1% area). B is best fit β axis to girdled distribution resulting from map-scale F4 chevron folding. (*c*) L2 lineations in the McHugh Complex defined by the intersection of S1 and S2 (contour interval 2.3 % data/1% area). Asterisk is mean lineation. (*d*) Poles to dominant foliation (S2) in the McHugh Complex (contour intervals: 1.2, 3.7, 6.2, and 8.7 % data/1% area), B is best-fit β axis to girdled distribution.

and Paleogene rocks of the forearc basin (Chickaloon Formation) have yielded fission track ages on zircon of ~43 and ~48 Ma (samples 6 and 7 in Figure 2 and Table 1). Petrographically identical dikes crosscut faults that cut and offset en echelon folds in the Chickaloon Formation, and an undeformed ~41 Ma pluton (sample 3) markedly thickens in the axial region of two such anticlines [*Little*, 1988]. These relationships indicate that faulting and en echelon folding occurred together in mid-Eocene time.

A several-kilometer-wide belt of en echelon folding formed during Eocene dextral-slip faulting along the BRFS. Both bedding in the Chickaloon Formation and S2 in the Valdez Group are similarly deformed by a distinctive sequence of en echelon folding events, a correspondence that suggests mutual involvement of both late Paleocene/early Eocene surfaces in the same progressive wrenching event. F1 folds in the Chickaloon Formation consist of parabolic to chevron-shaped parallel folds that recur in wavelengths of 300–600 m (Figure 3, F-F′, G-G′, and H-H′). Similarly spaced and oriented folds in the Valdez Group are chevron or box-shaped (Figure 3, D-D′ and F-F′) and are an F4 generation for those rocks. Open to close folds in both these units have hinge lines that plunge gently either to the northeast or southwest (Figures 8a and 8b) and upright axial surfaces that locally deflect sigmoidally into subparallelism with adjacent faults. These geometric relationships suggest a wrench origin for these folds, as does the occurrence of extensional faults and veins oriented transverse to the hinge lines of these folds. Similarly, computer inversions for the mean deviatoric stress tensor from fault-slickenline data consistently indicate a subvertical σ_2 and a least compressive stress direction, σ_3, that is subparallel to adjacent fold hinges [*Little*, 1988].

A second set of en echelon folds are superimposed across F1 folds in the Chickaloon Formation and F4 folds in the Valdez Group and probably formed during a late increment of the same

TABLE 1. Fission Track Data

Sample	*Latitude* N	*Longitude* W	*Elevation* ft.	*Mineral*	*Fossil Tracks*, $\times 10^6$ t/cm^2	*Induced Tracks*, $\times 10^6$ t/cm^2	*Neutron Dose*, $\times 10^{15}$ n/cm^2	*Age* Ma	2σ, Ma	N, *Grains*	S′	U, ppm
Southern Matanuska Valley Felsite Intrusions (into Km)												
1. 83-LE-KM (DF-5545)	61° 46.58′	148° 29.87′	790	AP	0.044 (184)	0.130 (541)	1.04	21.1	4.6	100	0.047	4.0
83-LE-KM (DF-5546)			790	ZR	2.70 (551)	4.56 (464)	1.04	36.8	4.8	6		140
2. 83-LE-124 (DF-5541)	61° 45.30′	148° 30.12′	4140	AP	0.029 (122)	0.075 (312)	1.04	24.3	6.5	100	0.077	2.3
83-LE-124 (DF-5542)			4140	ZR	3.99 (609)	6.64 (507)	1.04	37.3	4.7	6		200
Northern Chugach Mountains Felsite Intrusion (into Tch)												
3. 84-LE-58 (DF-5538)	61° 41.60′	147° 42.65′	5700	ZR	3.60 (483)	5.41 (363)	1.04	41.3	6	6		160
Northern Chugach Mountains Jurassic Tonalite												
4. 84-CR-46 (DF-5553)	61° 43.33′	147° 54.36′	1950	AP	0.143 (264)	0.417 (772)	1.04	21.2	5.9	100	0.099	13
84-CR-46 (DF-5554)			1950	ZR	6.95 (1513)	2.52 (274)	1.04	170	23	6		80
5. 84-CR-42 (DF-5551)	61° 42.98′	147° 50.62′	5420	AP	0.073 (135)	0.116 (215)	1.04	39.0	12	100	0.098	3.5
84-CR-42 (DF-5552)			5420	ZR	13.1 (1273)	4.32 (210)	1.04	186	29	6		130
Felsite Intrusions into Terrane-Bounding Fault												
6. 84-CR-25 (DF-5548)	61° 41.15′	147° 49.11′	3010	AP	0.028 (117)	0.0943 (393)	1.04	9.3	3.9	100/50[1]	0.014	3.0
84-CR-25 (DF-5549)			3010	ZR	3.73 (518)	4.84 (336)	1.04	47.8	7	6		150
7. 84-LE-96 (DF-5540)	61° 41.10	147° 50.07′	5020	ZR	4.60 (639)	6.65 (462)	1.04	42.9	5.5	6		200
Near-Trench Intrusions into Valdez Group												
8. 84-CR-47 (DF-5555)	61° 38.87′	147° 58.70′	2290	AP	0.026 (49)	0.0940 (174)	1.04	17.5	6.5	100	0.11	2.9
84-CR-47 (DF-5555)			2290	ZR	6.88 (605)	8.59 (378)	1.04	49.6	6.8	6		260
9. 85-LE-16 (DF-5536)	61° 39.58′	147° 54.91′	5390	AP	0.038 (158)	0.141 (586)	1.04	16.8	3.3	100	0.051	4.3
85-LE-16 (DF-5537)			5390	ZR	7.14 (893)	9.38 (586)	1.04	47.3	5.3	6		290

[1] If two numbers are present different numbers of grains were counted for fossil and induced counts: number of fossil grains is first, number of induced grains is second.

Decay constant: 7.03×10^{-17}/yr.
σ: standard deviation
S′: standard error of mean (induced counts) in population runs
( ): number of tracks counted
Km, Matanuska Formation; Tch, Chickaloon Formation. Sample numbers correspond to starred sample locations in Figures 2 and 11.

dextral wrenching event. In the Chickaloon Formation, F_2 folds occur on about the same scale as the earlier F_1 folds but have more open interlimb angles and hinge lines that plunge moderately to steeply within a subvertical, north-northeast striking axial plane (Figure 8c). In phyllite of the Valdez Group, similarly oriented folds (F_5) are present in a <1-km-wide belt immediately south of the TBF but are mesoscopic in scale (Figure 8d). In contrast to the early wrench folds, which trend at

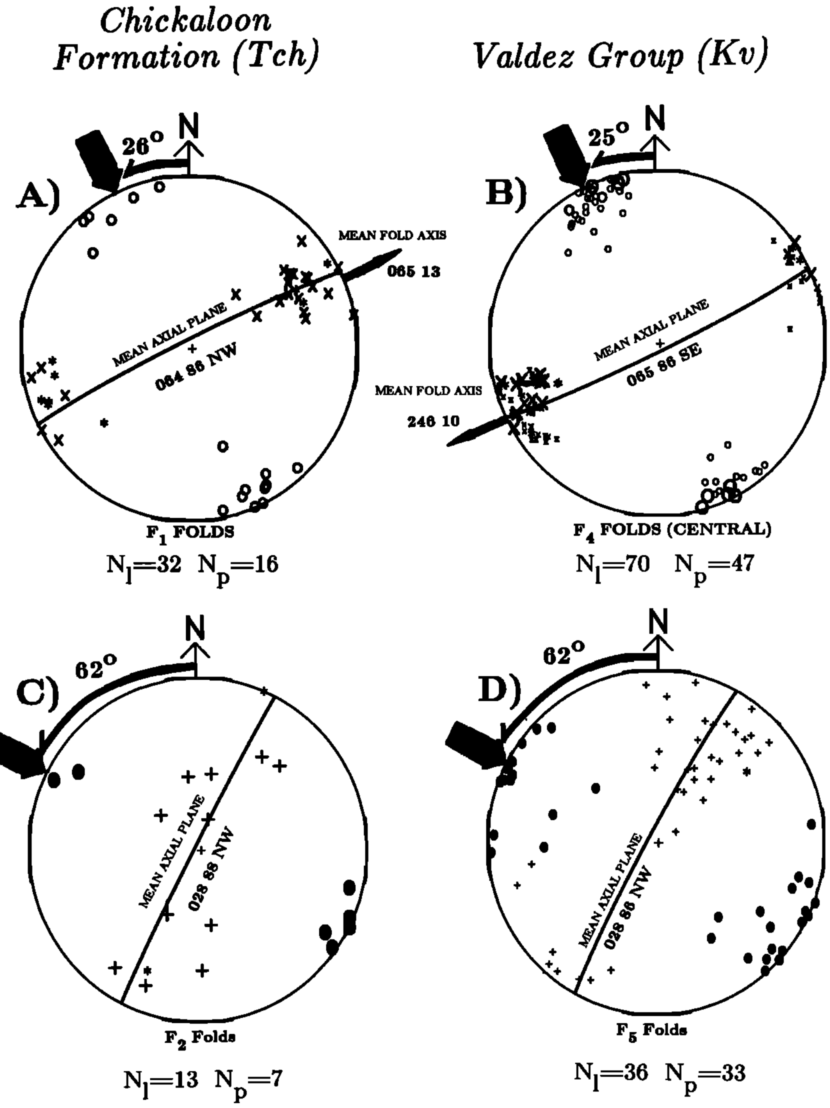

Fig. 8. Lower hemisphere equal-area stereograms showing orientation data for en echelon folds of the Chickaloon Formation and Valdez Group. Crosses and plusses denote early and late fold axes, respectively, whereas circles and solid dots denote corresponding poles to axial planes. Mean orientation of axes (narrow points) and axial planes (girdles) have been calculated by computer using the eigenvalue technique of *Woodcock* [1977]. Axial planes of map-scale folds were constructed from the intersection of the above axes with axial traces taken from detailed geologic mapping in rugged topography. Heavy arrows depict mean horizontal shortening direction. N_l is number of fold hinges; N_p is number of axial planes. Small symbols denote mesoscopic folds, large symbols individual map-scale folds. Each large cross or plus represents the best fit β axis (eigenvector) to a girdled distribution of planar data (bedding or S2) across a single fold hinge and incorporates 14–183 (average about 40) data points. Asterisks denote mean β axes in folded domains containing more than one map-scale fold.

45° or less with respect to the strike of adjacent throughgoing faults, these late-stage folds trend at an angle of ~60°. This orientation and their gently appressed interlimb angle suggest that these late-stage en echelon folds formed during a late increment of divergent (or "transtensional") wrenching along the BRFS [e.g., *Wilcox et al.*, 1973; *Sanderson and Marchini*, 1984]. Transtensional development of the folds is also supported by the common presence of normal-separation faults that cut and axially extend the folds, and by best fit stress tensors inverted from fault-slip data that indicate that σ_2 was vertical and that σ_3 trended subparallel to adjacent F2 fold hinges [*Little*, 1988].

Mapping has shown that many steeply dipping post-Eocene faults in the BRFS are dextral-strike-slip faults. Determination of net strike slip across such faults is in general hindered by a significant component of dip separation and by the lateral heterogeneity or gently dipping attitude of the offset map units. Figure 4 shows fault strands and amounts of mapped dextral-strike separations of moderately to steeply dipping markers locally offset across those faults. As an example, a small trondhjemite stock in the western part of the study area (Figure 3, B-B') is offset with ~6 km of dextral slip across a thin down faulted sliver of the Chickaloon Formation (Figure 4). Farther east, the fault along the southern edge of this sliver cuts and offsets the northern boundary of block B, a fault which there dips moderately to the southeast (Figure 2, location 5). The younger fault has horizontal slickenlines and offsets the older fault ("basement" fault) with ~2.5 km of dextral separation; however part of this separation could be attributed to reverse slip (e.g., Figure 3, B-B′ and C-C′).

Slip criteria associated with the nonplanar character of two throughgoing faults in the BRFS strongly suggest dextral slip along these faults. The "basement" fault along the northern side of block B is so named because it uplifts Jurassic igneous rocks along its northern side. The trace of this fault is segmented into differently oriented strands. Fault segments that dip southwest have a normal separation (Figure 3, E-E′), those that strike east-west are vertical, and those that dip northwest have a reverse separation (Figure 3, H-H′). These differences in type of dip separation are consistent with releasing and restraining bends along a generally east-west striking dextral-slip fault, and slickenlines confirm this interpretation [*Little*, 1988]. In the eastern part of the study area, the TBF is locally subvertical and consists of a complex system of thin fault slices that converge downward to form a "flower structure" [e.g., *Christie-Blick and Biddle*, 1985] (Figure 3, G-G′). This fault zone makes an abrupt right-stepping bend in the central part of the study area (Figure 2). Along this bend, the margins of block B dip toward each other and downdrop a narrow pull-apart graben (Figure 3, C-C′). This graben is dismembered by oblique-normal faults that do not extend outside of the bend area and accommodate an east-west extension in that region (Figure 4). Similarly, late Eocene silicic dikes that intrude the TBF reach their maximum width (up to 250 m) in and just to the east of the right-stepping bend (Figure 3, E-E′). The amount of extension across the pull-apart graben is consistent with as much as 4 km of strike slip along the east-west striking "master" fault segments [*Little*, 1988]. F_1 folds in the Chickaloon Formation near the "corners" of the bend are deformed by upright megakinks so that they are rotated in a clockwise sense as they "enter" the bend from the west and in a counterclockwise sense as the "exit" the bend region to the east (Figure 2). These megakinks appear to be fault-bend folds allowing relatively deformable rocks north of the TBF to be strike slipped around the bend in a manner analogous to fault-bend folding above ramps in dip-slip faults [*Little*, 1988].

Figure 9 illustrates the kinematic development of this part of the BRFS in Eocene time as inferred from the geometry of folding and faulting in this region. Figure 9a shows nucleation of wrench folds in the Chickaloon Formation at 45° along preexisting basin-margin fault (TBF) and beginning of dextral-slip and fault-bend folding of northern blocks around right-stepping bend. Because F_1 folds in the Chickaloon Formation in the study area have all apparently been fault-bend folded through the bend, this kinematic model implies a minimum dextral slip along the TBF of about 22 km. Figure 9b illustrates a possible configuration after the fault-bend folding and during initial phase of later pull-apart basin development. A localized transtensional strain in the fault-bend region results in superposition of late-stage folds across previously clockwise-rotated wrench folds [*Little*, 1988]. The last snap-shot (Figure 9c) is during a later period of regional oblique-normal faulting, at which time the late generation of wrench folds is nucleated at about 60° to the strike of adjacent throughgoing faults.

Mid-Eocene Normal Separation Along the Terrane-Bounding Fault

Sometime after lower Eocene deposition of the Chickaloon Formation and prior to intrusion of an undeformed ~48 Ma silicic dike into its trace, the TBF underwent its last major increment of displacement. As indicated above, some of this displacement was dextral strike slip. In detail the TBF, which dips 65–80° northward, is a net oblique-slip fault having a major component of normal slip. Displacement along this fault in mid-Eocene time resulted in yet another increment of Chugach terrane uplift, and thus perpetuated the "tradition" of normal-separation faulting which had been established by Paleocene time.

Uplift on the southern side of the TBF has downdropped lower Eocene sedimentary rocks of the Chickaloon Formation against metamorphosed Cretaceous rocks of the Valdez Group and locally has resulted in complete erosion of the McHugh Complex thrust plate (Figure 3, F-F′). The present juxtaposition of different structural levels across the TBF suggests an Eocene normal-slip component of at least 3 km prior to intrusion of the ~48 Ma dike. This conservative figure is estimated by adding the ~0.5-km minimum preserved stratigraphic thickness of the Chickaloon Formation where it is truncated against the Cretaceous subduction complex (e.g,. Figure 3, E-E′) to an estimate of the amount of structural omission required to obtain the observed discontinuity in late Paleocene/early Eocene metamorphic grade across the fault. A minimum estimate of the latter figure of 2.5 km was obtained by using 50°C/km as a maximum for the early Paleogene geothermal gradient in the accretionary prism [e.g., *Hudson and Plafker*, 1982] together with a maximum paleotemperature of ~170°C for the base of the Chickaloon and a minimum temperature of ~300°C for the Valdez Group. The former paleotemperature is estimated by the method of *Price* [1983] from the mean vitrinite reflectance of ~0.9 measured near the base of the Chickaloon Formation in the map area [*Little*, 1988]. Because of the assumption of time independence used for this organic maturation "geothermometer," and the likelihood that maximum burial of the Chickaloon Formation did not occur until Neogene time (see below), this is almost certainly a maximum estimate for the prefaulting temperature of the Chickaloon Formation. The ~300°C paleotemperature is an estimated minimum required to stablize M_2 greenschist facies metamorphic assemblages in the subduction complex [*Liou et al.*, 1985].

Further evidence for mid Eocene normal separation along the TBF is suggested by emplacement of a thick vein of silica-carbonate rock along most of that fault's trace in the map area. This laterally continuous, fault-filling vein is typically about 3–6 m wide and is commonly faulted against or intruded by late Eocene silicic dikes (Figure 10). Where the vein is now faulted, its original deposition from hydrothermal fluids is suggested by local inclusion of septa or xenolithic blocks of various country rock lithologies within the vein. Petrographic examination of the vein rock indicates a complicated history of multiple episodes of veining, brecciation, recementation, recrystallization (or grain growth), and locally mylonitization [*Little*, 1988]. Where it is developed, a mylonitic foliation in these rocks generally dips steeply north, subparallel to the vein margins, and is commonly tightly folded at a mesoscopic scale, suggesting a complicated or prolonged movement history [e.g., *Ghosh and Sengupta*, 1987]. Typically, there is a transition from microbreccia along the northern edge of the vein to foliated or mylonitic rocks along the southern edge (Figure 10). This relationship suggests that the component of normal slip along the TBF has brought up hotter and more ductile fault rocks to the south [e.g., *Sibson et al.*, 1981]. Deposition of the fault-filling vein may have been triggered by dilational earthquake ruptures that led to sudden drops in fluid pressure along

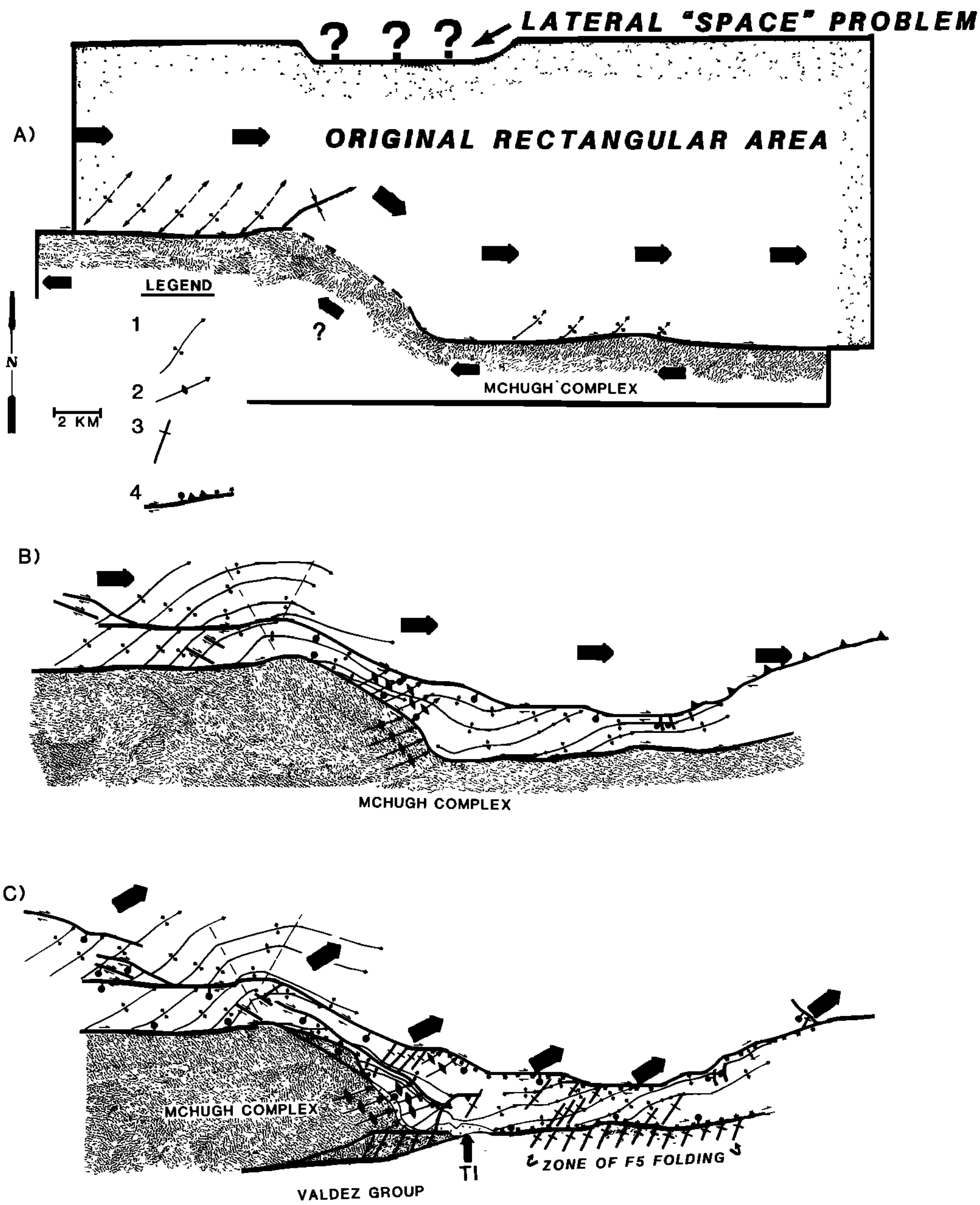

Fig. 9. Cartoon showing Eocene kinematic development of wrench structures in the map area prior to displacement along "transecting" fault. Blank areas are underlain by an over 1-km-thick section of the Chickaloon Formation, which has later been extensively eroded. Arrows show inferred relative displacement direction of fault blocks. Map symbols: 1, axial trace of first-phase wrench fold; 2, axial trace of late-stage folds in fault-bend region; 3, axial trace of late-stage folds outside of fault-bend region; 4, fault (dextral slip, thrust, normal separation, intruded by dikes [decorated pattern]). TI, late Eocene silicic dikes. See text for explanation.

the fault and to a resultant hydraulic pumping of fluids into the rupture zone [e.g., *Sibson*, 1987].

Late Eocene Intrusion of Silicic Dikes

Numerous silicic dikes and small stocks of late Eocene age intrude previously faulted and folded rocks in the study area. These subvolcanic intrusions have sharp chilled margins and a massive or flow-banded texture and are here called suite B. As mentioned above, they provide an important constraint on the timing of the last major phase of displacement along the BRFS. Where microcrystalline to fine grained, these light colored dacitic to rhyodacitic intrusions can be petrographically indistinguishable from suite A dikes, but unlike the latter contain no more than 10% phenocrysts of Ca-oligoclase, now in part replaced by laumontite ± albite. Suite B dikes are typically stained to an amber-orange color because of deuteric oxidation of pyrite and other opaque oxides to hematite and coating of fractures by hematite-carbonate-sericite veins. Identical iron staining of the TBF zone in general (Figure 10) suggests that it was altered by hydrothermal fluids emanating from suite B

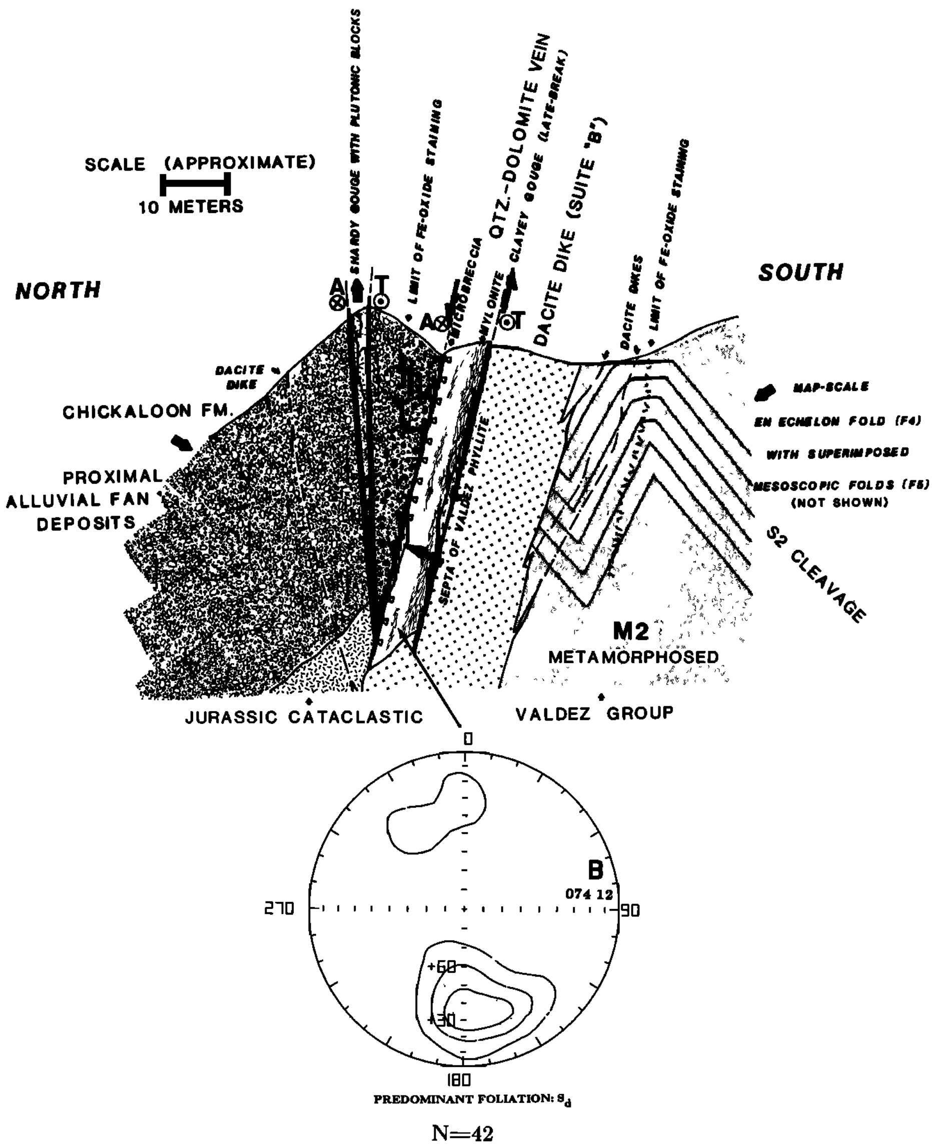

Fig. 10. Representitive schematic cross section across the terrane-bounding fault zone (TBF) as it appears today. Note (1) Eocene normal separation across the fault zone to bring up M2 metamorphic rocks on its footwall and (2) dilation of the fault by silica-carbonate veining and dike intrusion. Local reactivation of the fault has resulted in only minor displacement of fault-filling suite B dikes of middle to late Eocene age. Lower hemisphere equal-area stereogram shows poles to mylonitic foliation in fault-filling quartz-dolomite vein (contour intervals 1.8, 5.4, and 9.0 % data/1% area).

intrusions at depth. Dacite dikes that intrude the TBF have fission track ages on zircon (± 2σ errors) of 47.8 ± 7 Ma and 42.9 ± 5.5 Ma (samples 6 and 7, Figure 2 and Table 1). Other isotopic determinations include a K-Ar age on hornblende of 37.7 ± 2.2 Ma [*Little*, 1988] for the King's Mountain granodiorite stock intruding the Matanuska Formation (Figure 11) and a fission track annealing age on zircon of ~41 Ma for a dike intruding the Chickaloon Formation (sample 3).

Other ~38–45 Ma old silicic dikes and stocks similar to suite B are widely distributed in south-central Alaska. Such shallow-level intrusions occur throughout the Matanuska Valley region [e.g., Barnes, 1962] and also farther north in the Talkeetna Mountains segment of the early Tertiary calc-alkaline arc [*Csejtey et al.*, 1978]. Hornblende from two rhyodacitic dikes intruding a thick sequence of basaltic and andesitic lava flows and interbedded silicic tuff in the central Talkeetna Mountains [*Adams et al.*, 1985] yields K-Ar ages of 39.8 ± 2.5 and 43.6 ± 2.6 Ma [*Little*, 1988]. Late Eocene intrusions in the Matanuska Valley locally include basaltic phases that give the suite a bimodal aspect, and the silicic part of this suite is characterized by primitive initial $^{87}Sr/^{86}Sr$ ratios of ~0.704 indicative of a strong mantle component [*Silberman and Grantz*, 1984]. Perhaps a decrease in the rate of subduction and increase in the age of subducted oceanic crust in the Gulf of Alaska during a period of plate reorganization in late Eocene time [*Engebretson et al.*, 1986] led to a temporary steepening in the dip of the subducted slab and to a short-lived southward migration of arc magmatism from the Talkeetna Mountains region into the previously forearc area of the Matanuska Valley and northern Chugach Mountains.

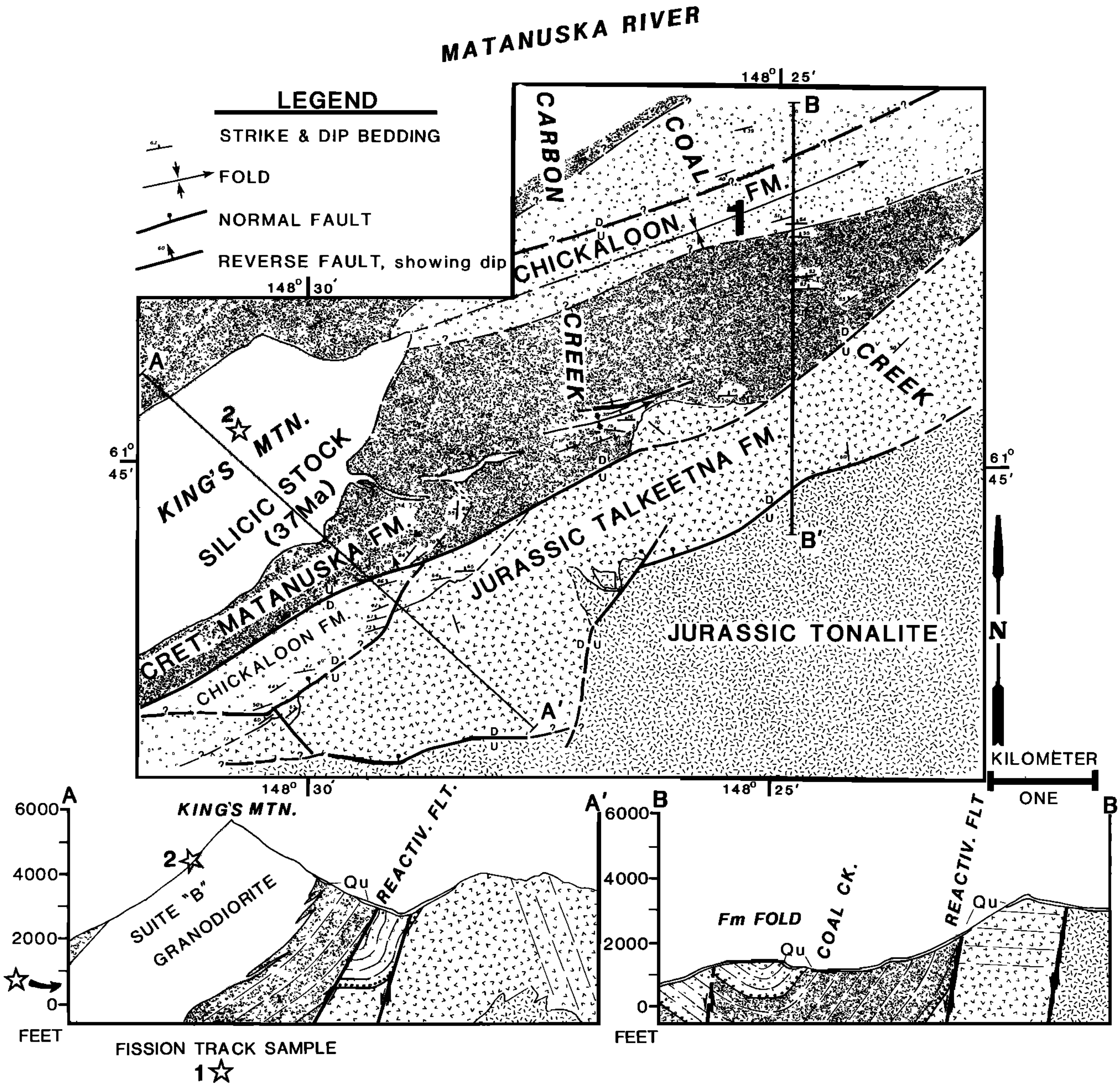

Fig. 11. Simplified geologic map and cross sections of Peninsular terrane rocks near King's Mountain on western limb of southern Alaska's orocline as modified from *Little et al.* [1986]. Location of this map shown in Figure 4. Bold 1 refers to location mentioned in text. Qu, Quaternary deposits, undifferentiated. Numbered stars, locations of fission track samples (Table 1 and Figure 13).

LATE EOCENE TO NEOGENE DEFORMATION: CONTRACTION OF THE FOREARC BASIN

Where middle to upper Tertiary strata are preserved in the forearc basin, their deformation reflects a shortening of the basin perpendicular to its trend during that time period. A widespread middle or upper Eocene to Oligocene unconformity in southern Alaska records an event of regional uplift and erosion affecting the forearc basin [*Fisher and Magoon*, 1978], Aleutian arc [*Marlow et al.*, 1973], and the accretionary prism [e.g., Byrne, 1986] as well as a nonmarine basin in the present central Alaska Range region [*Wahrhaftig et al.*, 1969]. During the time of this unconformity, the present Matanuska Valley area was folded into east-northeast trending upright folds and the Castle Mountain fault along its northern margin (Figure 1, A-A') suffered a component of reverse slip [*Barnes and Payne*, 1956; *Clardy*, 1974] Regional contraction of the forearc basin resumed in Mio-Pliocene time as indicated by upright folding and thrusting of Neogene sediments in Cook Inlet [*Boss et al.*, 1976; *Fisher and Magoon*, 1978], by conjugate fault systems in the Matanuska Valley [*Bruhn and Pavlis*, 1981], and by continued Neogene reverse slip along the Castle Mountain fault system (up to ~1 km [*Clardy*, 1974]). The latter fault also suffered minor dextral strike slip in Neogene time [*Grantz*, 1966; *Detterman et al.*, 1976; *Bruhn*, 1979]. Where the BRFS is overlapped by Neogene sediments in the Kenai Lowlands and Cook

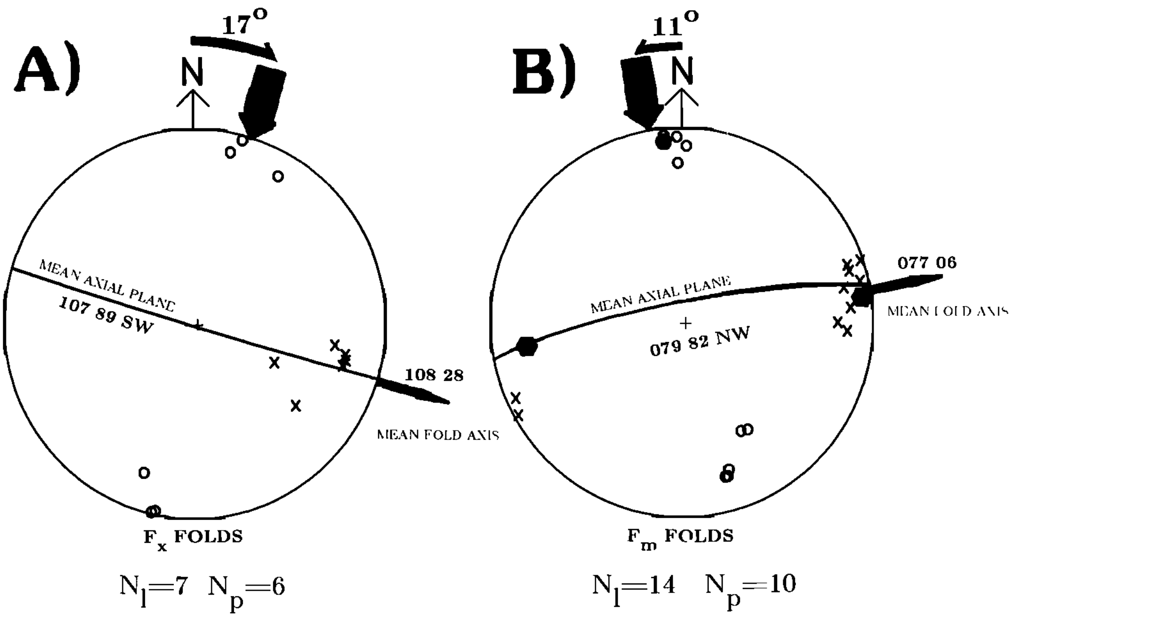

Fig. 12. Lower hemisphere equal-area stereograms showing orientation data for folds of the Chickaloon and Matanuska formations in the northern part of the study area along the southern edge of the Matanuska Valley. Symbols and methods same as in Figure 8. (*a*) upright folds (F_x) adjacent to the "reactivated" fault (Figure 2, location 1). (*b*) upright folds along the Chugach range front (F_m). Solid hexagons denote mean fold axes of map-scale F_m folds on the western limb of the orocline (Figure 11, location 1), and solid dots their axial planes. Open symbols represent map-scale folds on the eastern limb of the orocline just west of the Matanuska Glacier (Figure 2, location 3). Note similar orientation of F_m folds in both areas.

Inlet/Shelikof Strait shelf region (Figure 1), however, seismic reflection data indicates that Pliocene and younger displacement along the BRFS in that region is slight [*Fisher and von Huene*, 1984].

Although post-Eocene rocks are not exposed in the study area, one can locally infer for that region a late, possibly in part Neogene, history of minor reverse faulting and north-south shortening. A steeply north dipping block fault has over a kilometer of pre- to syn-Chickaloon normal separation but was last reactivated with an increment of reverse separation ("reactivated fault," Figure 1, A-A′; Figure 3, B-B′; and Figure 11, A-A′). Steeply north or south dipping faults which are marked by up to 1 m of clayey gouge locally cut or bound the middle to late Eocene dikes intruding the TBF (Figure 10) but do not significantly offset their contacts (e.g., Figure 3, E-E′), and are probably dip-slip faults.

Two post-early Eocene sets of parallel-style folds that accommodate an approximate north-south direction of maximum shortening deform Upper Cretaceous and Paleogene rocks of the forearc basin in the northern part of the map area. These folds may be the same age as well-dated folds of similar orientation and style in adjacent parts of the Matanuska Valley that formed during the Eocene-Oligocene unconformity prior to deposition of mildly deformed upper Oligocene rocks [*Barnes*, 1962; *Clardy*, 1974]. The first group of folds (F_x) have a curved, angular, or multihinged shape, and have west-northwest trending, subhorizontal axes that lie within a subvertical axial plane (Figure 12*a*). These folds are restricted to a narrow belt along the "reactivated" fault (Figure 2, location 1; Figure 3, B-B′), an observation which suggests that they may be related to the late increment of reverse slip along this fault. The second and more northern group of folds (F_m) are part of the southern limb of the Matanuska Valley synclinorium (Figure 2, locations 2 and 3; Figure 11, location 1). These open to close upright folds have a sinusoidal or concentric shape (Figure 11, B-B′), occur in wavelengths of up to 3 km, and are characterized by east-northeast trending, subhorizontal axes (Figure 12*b*). In the Matanuska Valley, folds of demonstrable Eocene/late Oligocene age are similar in style and orientation to F_m folds deforming the Chickaloon and Matanuska formations in the map area (Figures 2, 11). The similarity in orientation of inferred pre-late Oligocene age folds on both sides of the oroclinal bend (Figure 12*b*) suggests that the deflection may also be pre-late Oligocene in age.

POST-EARLY EOCENE DEVELOPMENT OF THE OROCLINAL BEND

Although southern Alaska's orocline [*Carey*, 1955] may have been inherited in part from an original reentrant in the continental margin, geologic evidence in the study area indicates that most of the deflection is related to post-early Eocene folding and rotation. Individual high-angle faults in the BRFS that involve the Chickaloon Formation can be traced continuously around the deflection (Figure 4). Both east and west of the bend, subvertical faults are characterized by dextral strike separations, associated Reidel shears, and horizontal slickenlines. Thus the deflection seems to be the result of oroclinal bending that either postdated or accompanied the Eocene strike-slip faulting event. In a similar way, L_2 lineations and F_4 axes in the Valdez Group rotate anticlockwise about a vertical axis as they approach the oroclinal axial trace from the east (Figure 2). Metamorphic foliations in the Valdez Group and McHugh Complex in the Kenai-Chugach Mountains to the west of the bend strike northeast to north-northeast [e.g., *Pavlis*, 1982; and *Budnick*, 1974], instead of east-northeast, as in the

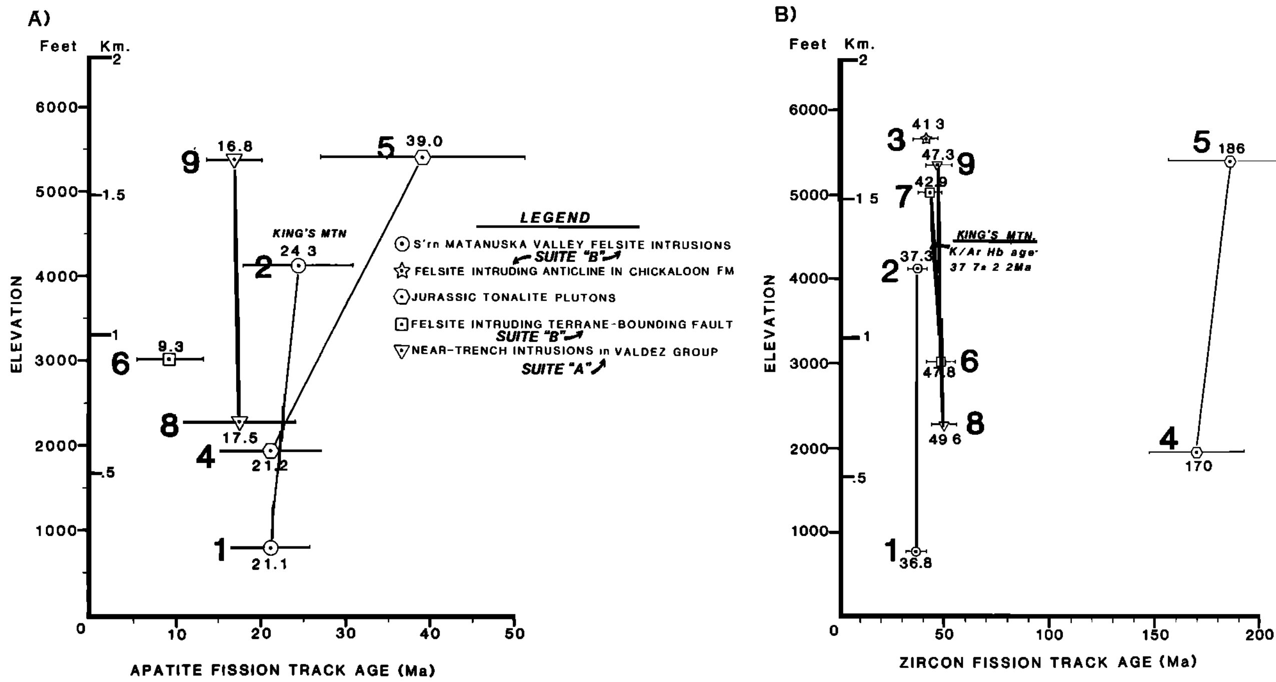

Fig. 13. Age versus elevation plot for fission track cooling ages of (*a*) apatite and (*b*) zircon as determined in this study. Solid lines join adjacent samples of the same lithology collected at different elevations. Numbers refer to sample locations in Figures 2 and 11 and in Table 1.

study area, a discordance that suggests an orocline interlimb angle of 45–70°. Similarly, in Prince William Sound, oroclinal folding deflects early Tertiary structural fabrics in lower to lower middle(?) Eocene rocks of Orca Group [*Bol and Coe*, 1987; *Plafker et al.*, 1986]. Paleomagnetic data from various parts of southwestern Alaska including preliminary data for the Chickaloon Formation in the Matanuska Valley [*Stamatakos and Pavlis*, 1986] indicate that volcanic and sedimentary rocks of pre-late Eocene age have been rotated anticlockwise ~45–55° but that younger samples have not been so rotated [*Coe et al.*, 1985; *Thrupp and Coe*, 1986; *Harbert*, 1987; *Coe and Thrupp*, 1987]. The paleomagnetic data are thus consistent with geologic evidence in the study area that indicates a post-early Eocene and possibly pre-late Oligocene age for oroclinal bending of southern Alaska. This timing overlaps with that of proposed dextral strike slip along several major faults of Alaska [e.g., *Lanphere*, 1978; *Fuchs*, 1980] and supports the idea that oroclinal bending was accommodated at least in part by dextral strike-slip faulting on the western limb of the bend [*Grantz*, 1966; *Freeland and Dietz*, 1973]. Early Tertiary compression and oroclinal bending of Alaska south of the Tintina-Kaltag faults have been attributed to opening of the Atlantic Ocean [*Patton and Tailleur*, 1977]. This idea is strengthened by plate motion circuits that indicate a component of east-west convergence between Eurasia and North America in the Bering Sea region prior to ~48–50 Ma [*Harbert et al.*, 1987].

TERTIARY THERMAL HISTORY FROM FISSION TRACK DATA

Conclusions about the cooling history of rocks along the BRFS can be derived from a fission track study of zircon and apatite grains. These results have important implications for the early to late Tertiary faulting and uplift history in this part of the forearc. Fission track ages record the time at which a mineral passes through its 50% retention temperature for annealing of fission tracks and can be a powerful tool for precisely determining cooling and uplift rates [*Wagner and Reimer*, 1972; *Naeser*, 1979]. For geologically reasonable cooling rates, zircon and apatite fission track ages record cooling below temperatures of 200 ± 25°C and 105 ± 10°C, respectively [*Naeser and Faul*, 1969; *Naeser and Forbes*, 1976]. Four pairs and one isolated sample of Jurassic to Eocene intrusive rocks were collected for fission track dating in the detailed study area (Figure 2) and also near King's Mountain (Figure 11). These samples comprise a composite transect from the Matanuska Valley and southward across the BRFS into high glaciated peaks of the Valdez Group. The same type of intrusion was generally collected both at a mountain top and in an adjacent valley. Age data were obtained for nine zircon and seven apatite separates (Table 1 and appendix).

Suite A and B intrusions have similar Eocene fission track ages on zircon (Figure 13*a*) but different K-Ar ages and apparently cooled at different rates related to differing thermal and uplift histories. A Jurassic tonalite pluton in the Peninsular terrane has K-Ar ages on biotite and hornblende (L. R. Flynn, unpublished data, 1984) and fission track ages on zircon (samples 4 and 5) that are similarly from 170–187 Ma. These results indicate that the pluton cooled rapidly in Middle Jurassic time and that the basement of the forearc basin was never again heated above ~200°C. A sill from a swarm of suite A (early Eocene) sills that intrude M_2 metamorphic rocks in the Valdez Group has a K-Ar age on hornblende of 57.2 ± 3.4 Ma [*Little*, 1988]. Two other sills in the same swarm (samples 8 and 9) have zircon fission track ages of 47.3 ± 5.3 and 49.6 ± 6.8 Ma and apatite fission track ages of ~17 Ma. These data suggest cooling of the sills after their intrusion in early Eocene time from 500 ± 40°C (the Ar blocking temperature of hornblende) to 200 ± 25°C (annealing temperature of zircon fission tracks) in middle Eocene time at an average rate of ~30°C/Ma. For a geotherm as hot as 50°C/km, this implies an uplift and erosion rate of ~0.6 mm/yr. By Miocene time, the sills cooled further to a temperature of 105 ± 10°C (apatite fission tracks) at a slower average rate of ~3°C/Ma. Note that the earlier rapid cooling agrees with mid-Eocene constraints for block uplift of the subduction complex and juxtaposition of its M_2 fabric against the Chickaloon Formation. In contrast to the above slowly cooled sills, middle to late Eocene intrusions of suite B cooled quickly at high levels of the crust. For example, the 37.7 ± 2.2 Ma K-Ar age for hornblende in the King's Mountain granodiorite stock, which intrudes the Matanuska Formation of the forearc basin, is indistinguishable from the 37.3 ± 4.7 Ma zircon fission track age of the same sample (sample 2, Figures 11, 13) indicating that this kilometer-wide pluton cooled much more rapidly than the above-described 1- to 2-m-thick sills in the Valdez Group.

Apatite fission track ages appear to be independent of elevation and location and are distinctly younger than the zircon ages (Figure 13*b*). This indicates that most of the sampled levels of structural exposure (over 975 vertical meters) cooled rapidly in Miocene time between ~17 and 24 Ma. Two samples have anomalous ages with respect to the other apatite grains. The topographically highest sample (sample 5, Figure 2 and Table 1), from Jurassic tonalite of the Peninsular terrane, has the oldest apatite fission track age (~39 Ma) and may reflect Eocene differential uplift and erosion on the northern side of fault block B (Figure 4). Alternatively, this "old" age could be partially reset between an older primary age and younger heating event. A sample of a suite B dacite intruding the TBF that was collected within a few meters of a minor displacement fault cutting that dike has an apatite fission track age of 9.3 ± 3.9 Ma (sample 7). This young age with respect to surrounding samples is interpreted to have been reset by hydrothermal alteration along that brittle fault.

Neogene cooling and erosion of rocks along the BRFS probably resulted from regional uplift and erosion of both southern edge of the forearc basin and adjacent parts of the Cretaceous subduction complex. If the present-day Cook Inlet geotherm of 20–25°C/km [*Magoon*, 1986a] has remained constant since late Eocene time, the difference between zircon (~48–43 Ma) and apatite (~17–22 Ma) ages for the two suites of Eocene felsic intrusions suggests that erosion in mid Eocene to early Miocene time proceeded at a mean rate of over 0.13–0.19 mm/yr. For a given sample pair, the difference in their elevation divided by the difference in their apatite ages defines an apparent uplift rate (AUR). The AUR is equal to the true uplift rate only when horizontal isotherms have remained at a constant depth beneath the surface while the rate of uplift has been exactly balanced by the rate of erosion [*Parrish*, 1983]. Given these assumptions, AUR values for adjacent apatite samples can be used to constrain the syn-Miocene uplift rate. North of the TBF the King's Mountain pluton (samples 1 and 2) has an AUR of ~0.32 mm/yr., using mean ages, or a minimum of ~0.07 mm/yr, using extreme 2σ values. South of the TBF, apatite pairs in suite A sills in the Valdez Group (samples 8 and 9) have a minimum AUR of ~0.1 mm/yr. Post-Miocene erosion has exhumed rocks that were heated to over ~100°C in the Miocene. Using the present geothermal gradient of ~25°C/km and a mean surface temperature near the study area of ~1°C [*National Climactic Center*, 1983], this temperature difference suggests ~4 km of erosion. Thus ~22 Ma apatite ages north of the TBF suggest a mean Miocene-Recent erosion rate of ~0.17 mm/yr, whereas apatite ages of ~17 Ma south of that fault suggest a more rapid mean erosion rate of ~0.26 mm/yr. The slightly faster apparent erosion rates for rocks south of the TBF may indicate more rapid Neogene uplift of the high crest of Chugach Range, possibly the result of northward block rotation or south-side-up block faulting [e.g., *Pavlis and Bruhn*, 1983]; however the minor magnitude of the apparent lateral gradient in apatite ages along the transect indicates that the present 2–3 km of topographic relief along the northern edge of the Chugach Mountains is largely glacial-erosional in origin and not the result of Neogene faulting.

CORRELATION OF UPLIFT AND STRIKE-SLIP FAULTING TO OUTBOARD EVENTS

A complex Paleocene/late Neogene history of deformation is recorded within the Border Ranges fault system in the north-central Chugach Mountains (Table 2). During this time span, North America moved westward in a mantle frame of reference, and the Kula plate was subducted at a nearly orthogonal to strongly right-oblique angle to the continental margin (Figure 14*e*) [*Engebretson et al.*, 1986]. Discrete pulses of regional uplift or faulting along the inboard edge of the accretionary prism overlapped in time or closely followed events of accretion and underplating along the Gulf of Alaska margin, and a period of forearc strike-slip faulting coincided with an event of rapid and oblique subduction.

The first phase of uplift and deformation along the BRFS (Figure 14*a*) closely followed emplacement and early metamorphism of an over 12-km structural thickness of the Valdez Group, probably by underplating to the base of the accretionary prism within a duplex system of imbricate thrusts [*Moore and Sample*, 1987; *Fisher et al.*, this issue]. Regional uplift of the forearc basin during or soon after this event is marked by a regression from upper bathyl to nonmarine conditions during deposition of the upper Matanuska Formation and its equivalents in Cook Inlet [*Magoon*, 1986b] and by deep erosion during the subsequent Cretaceous-Tertiary unconformity. At that time, normal separation along steeply north dipping block faults along the southern margin of the forearc basin in the study area resulted in localized deep erosion of Cretaceous and older rocks on upthrown fault blocks. Similar faulting and uplift along the southeastern margin of Cook Inlet resulted in a gentle northward tilting of the basin (Figure 1, C-C'). Near the Nelchina Glacier, Valdez Group phyllite was rapidly uplifted and exposed during this event before deposition of the upper Paleocene/lower Eocene Chickaloon Formation. A conservative uplift rate for the Valdez Group of over 0.55 mm/yr. is obtained if one assumes that its low-grade phyllites were underplated immediately after deposition in earliest Maastrichtian time (~74.5 Ma) at a minimum depth of 7.5 km (150°C for a 20°C geothermal gradient) and that they were exhumed by late Paleocene time (~61 Ma).

Uplift of the subduction complex continued in late Paleocene/early Eocene time during deposition of Chickaloon Formation alluvial fans. This uplift occurred within a few million years of accretion and also probably underplating [e.g., *Byrne*, 1982, 1986; G. S. Fuis et al., manuscript submitted to *Journal of Geophysical Research*, 1988; hereafter refered to F88) of seaward verging trench-fill turbidite sequences that

Table 2. Outline of Major Latest Cretaceous Through Neogene Tectonic Events in the North-Central Chugach Mountains and in the Accretionary Prism

Ma	*Time*	*Forearc Events*	*Igneous, Thermal Events*	*Trench Events*
~16 to ~22	Middle Miocene Early Miocene	Regional Uplift & Erosion of Forearc During Miocene-Recent	Widespread & Rapid Cooling Below ~100°C	Collision of Yakutat Block
	Late Oligocene	Nonmarine Deposition (Tsadaka Formation)		Orthogonal Subduction
~30 to ~44	Early Oligocene	Regional Unconformity	(~37-44 Ma) Intrusion of Silicic Dikes (Suite B)	Oroclinal Bending Completed
	Late Eocene	N-S Compression & Folding of Forearc Basin		
~44 to ~52	Mid-Eocene	Nonmarine Deposition (Wishbone Formation)	Intrude ~48 Ma Suite B Dike Into TBF	Accretion & Underplating of Outer Prince William Terrane (Montegue Belt Of Orca Group)
		Dextral Wrench Faulting	Cooling and Uplift of Suite A Sills	
	Mid-Eocene	Normal Separation On TBF to Uplift M2 Metamorphic Rocks		
~52 to ~61	Early Eocene	Tch Alluvial Fan System Fed by Up-Faulted Subduction Complex	(~52-57 Ma) Near-Trench Intrusion of Post-Kinematic Dacitic Sills Into Kv (Suite A)	Accretion & Underplating Of Inner Prince William Terrane
	Paleocene	Normal Separation Along North-Dipping Block Faults of BRFS	(~57 Ma) M2 Regional Metamorphism of Subduction Complex	F2 Folding About Subhorizontal S2
~61 to ~68	Paleocene	Regional Uplift & Erosion of Forearc Basin		
		Rapid Uplift and Erosional Beveling Of S1-Deformed Kv Phyllites	Low-Grade M1 Metamorphism	Accretion & Underplating of Kv
	Late Maastrichtian	Normal Separation Along North-Dipping Block Faults of BRFS		

Kv, Valdez Group; Tch, Chickaloon Formation

compose inner parts of the Prince William terrane (Figure 14*b*). These lower Tertiary accreted belts include the Ghost Rocks Formation on Kodiak Island (emplaced before intrusion of ~60 Ma plutons) and possibly the two most inboard structural belts of the Orca Group in Prince William Sound (emplaced by ~53 Ma) [*Helwig and Emmet*, 1981; *Byrne*, 1982; *Plafker et al.*, 1986]. At about the same time, deeper structural levels of the accretionary prism were metamorphosed in the greenschist

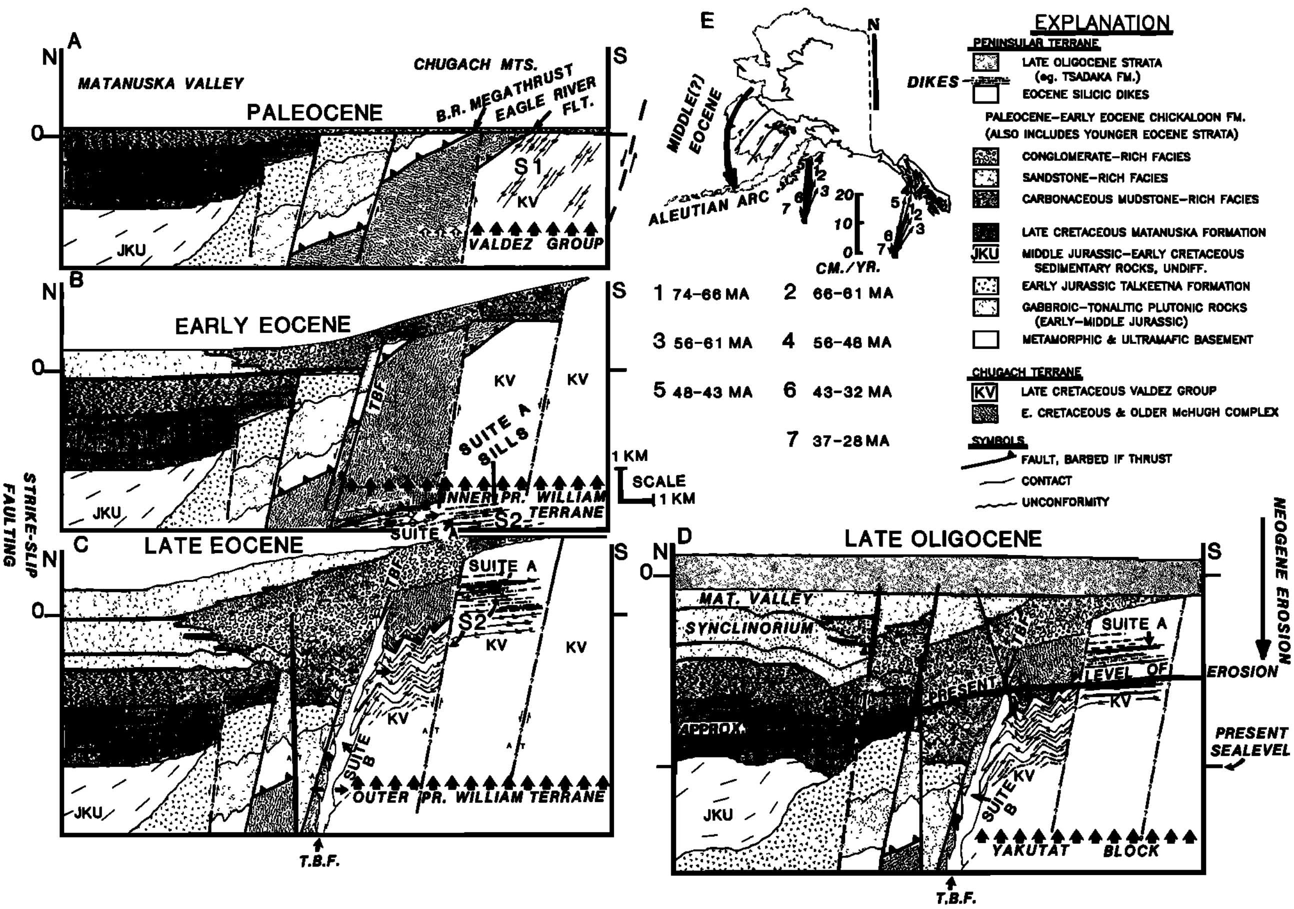

Fig. 14. Summary of Tertiary tectonic development of the BRFS. (*a*–*d*) Schematic cross sections across the north-central Chugach Mountains. Vertical arrows indicate underplating of subduction assemblages. (*e*) Velocities of Kula plate (pre 43 Ma) and Pacific plate (post 43 Ma) with respect to fixed North America are shown for present-day locations on the Kenai Peninsula and in southeastern Alaska [from *Wallace and Engebretson*, 1984]. Mid-Eocene time interval between Figures 14*b* and 14*c* is period of dextral wrench faulting out of plane of section. This strike-slip event coincides with a period of rapid oblique subduction (periods 4 and 5 in Figure 14*e*) and overlaps with geologic and paleomagnetic time constraints for oroclinal bending of southern Alaska.

facies (M_2) and ductilely flattened about a gently dipping foliation S_2. An inferred north-south direction of maximum finite extension within this foliation was sympathetic with the normal sense of dip slip along supracrustal parts of the BRFS, but the foliation could have developed either by pure shear extension of the accretionary prism or by simple shear related to its continued shortening by thrust faulting.

The third major period of uplift and normal-separation faulting along the BRFS (Figure 14*c*) overlapped with mid-Eocene accretion and underplating of landward verging outer parts of the Prince William terrane. These include the Paleocene/lower middle Eocene Montegue belt of the Orca Group in Prince William Sound and the possibly correlative Sitkalidak Formation on Kodiak Island [*Helwig and Emmet*, 1981; *Plafker et al.*, 1985; *Byrne*, 1986; F88]. Several additional kilometers of normal slip accumulated along the TBF between lower Eocene deposition of the Chickaloon Formation and ~43–48 Ma (zircon fission track age of dikes intruding that fault). This displacement resulted in the present juxtaposition of ~57 Ma M_2-metamorphosed rocks of the Valdez Group against the Chickaloon Formation, a throw that suggests a dip-slip rate of at least ~0.2 mm/yr along the TBF in early/late Eocene time. The thermal history of suite A sills in the Valdez Group for the same time period suggests uplift rates of over 0.6 mm/yr. Notably, both the Montegue belt of the subduction complex and Chickaloon Formation of the forearc basin contain lower Eocene fossils and were deformed at approximately the same time prior to intrusion of middle to late Eocene dikes [*Helwig and Emmet*, 1981; *Plafker et al.*, 1985].

Previous papers [e.g., *Moore et al.*, 1983] entertain the possibility of thousands of kilometers of relative displacement between the Peninsular and Chugach terranes in Paleocene-Oligocene time. Paleomagnetic inclinations of Paleocene-Eocene strata north of the BRFS are consistent with or only slightly displaced with respect to cratonic North American paleopoles [e.g., *Hillhouse et al.*, 1984; *Thrupp and Coe*, 1986]. In the central Chugach Mountains, the upper Paleocene/lower Eocene Chickaloon Formation sedimentologically links together the history of the Chugach and Peninsular terranes, and a dike having a minimum age of ~48 Ma intrudes their fault boundary. In a similar way, ~60 Ma silicic dikes intrude both terranes on Kodiak Island [*Davies and Moore*, 1984]. These observations together with fault mapping in the study area and to the west by *Pavlis et al.* [1987] suggest that the total amount of Paleogene dextral strike slip along the BRFS is probably no more than a few tens of kilometers and was completed by early late Eocene time. Thus it seems unlikely that major Tertiary displacements along the BRFS can explain low paleomagnetic inclinations in Paleocene rocks of the Ghost Rocks Formation indicative of their origin at ~25 ± 7° N latitude [*Plumley et al.*, 1983]. One concludes that any Tertiary "suture" or plate boundary must have been located somewhere in the accretionary prism to the south of the BRFS.

The post-early Eocene and pre-early late Eocene timing of dextral slip along the BRFS in the study region overlaps with constraints based on magnetic isochrons in the Gulf of Alaska for a mid-early Eocene to middle Eocene (~55–44 Ma) period of strongly right-oblique motion of the Kula plate relative to the continental margin of southern Alaska and western Canada [*Lonsdale*, 1988; *Engebretson et al.*, 1986]. This period of right-oblique convergence (Figure 14*e*, 4 and 5) also coincides with the timing of dextral strike slip along the Castle Mountain fault system in the Matanuska Valley (~15 km [*Fuchs*, 1980]) and overlaps with Late Cretaceous to middle Tertiary age constraints for proposed major displacements along the Denali and Rocky Mountain/Tintina systems in British Columbia and east-central Alaska (possibly as much as 400 km for the former [*Lanphere*, 1978] and over 750–900 km, for the latter [*Gabrielse*] 1985). Eocene strike-slip faulting in southern Alaska is also suggested by an apparent ~56–43 Ma "lull" [*Moore et al.*, 1983; *Wallace and Engebretson*, 1984] in the magmatic arc of southern Alaska (Figure 1). This apparent gap, however, may be in part an artifact of sampling, as indicated by 50–54 Ma K-Ar ages of basaltic and andesitic volcanic rocks in the Talkeetna Mountains [*Csejtey et al.*, 1978; *Hillhouse et al.*, 1984].

A Miocene–Recent period of uplift and deep erosion along the BRFS is recorded by early Miocene apatite fission track ages (Figure 14*d*). This regional uplift of the central Chugach Mountains probably overlapped in time with collision and underthrusting of the over 10-km-thick Yakutat block in the eastern Gulf of Alaska and with rapid Miocene and younger uplift of the eastern Chugach/St. Elias mountains [*Plafker*, 1983; *Bruns*, 1983; *Davis and Plafker*, 1986]. Uplift and erosion of the Cretaceous subduction complex are also recorded by the provenance of upper Miocene rocks in Cook Inlet [e.g., *Kirschner and Lyon*, 1973], but regional uplift of the forearc basin apparently died out to the west as indicated by the continuous Neogene subsidence history of the Cook Inlet basin.

By late Eocene time, the oroclinal bend had formed, the Aleutian arc was clearly in existence [*Marlow and Cooper*, 1983], and plate motions were reorganized into a pattern similar to that of the present day with the Pacific plate moving slowly (~5 cm/yr) northwestward along the Fairweather transform fault system (Figure 14*e*, 6 and 7) [*Engebretson et al.*, 1986]. Continuous, nearly orthogonal subduction along the Aleutian Trench in middle to late Tertiary time has resulted in accretion and growth of outer, submerged parts of the accretionary prism [e.g., *McCarthy and Scholl*, 1985] and has at times been associated with shortening of the forearc basin and components or reverse slip along its bounding fault systems. This period of forearc compression thus contrasts with the extensional character of dip slip along the BRFS in early Tertiary time and suggests a fundamental change in forearc dynamics.

DISCUSSION

The Cook Inlet basin is considered a type example of a mature type of ridged forearc [*Dickinson and Seely*, 1979], wherein a steep backstop fault bounds an uplifted platform of accretionary rocks along the seaward margin of a forearc basin (Figure 1, B-B'). Episodic uplift and erosion of the platform were probably related to more outboard accretion and underplating events along the southern Alaska margin. New seismic refraction and reflection data in southern Alaska have revealed that the accretionary prism contains several 10- to 15-km-thick panels of underplated oceanic rocks that overlie the present Benioff zone and are continuous with surface exposures of accreted belts in the Chugach and Prince William terranes [*Byrne*, 1986; F88; Fisher et al., this issue]. Discrete accretion events occurred in the early Paleocene (Valdez Group), late Paleocene-early Eocene (Ghost Rocks Formation) middle Eocene (Orca Group), and late Neogene (Yakutat block) and in each case coincide with or were closely followed by either localized uplift of the subduction complex by faulting along the backstop fault system or with a more regional uplift that also affected the adjacent forearc basin. Isostatic uplift in response to underplating of low-density metasediments to the base of the accretionary prism [*Moore et al.*, 1982; *Platt et al.*, 1985] together with vertical accommodation along the inner edge of that prism is probably the simplest explanation for the observed temporal coincidence between accretion events and uplift and deformation along the BRFS (Figure 1, B-B'; Figure 14). Other models that have been proposed for uplift of the forearc ridge include viscous upwelling within deeply buried parts of mature accretionary prisms [*Cloos, 1982; Pavlis and Bruhn*, 1983] or thermal expansion related to subduction of an oceanic spreading ridge [*Marshak and Karig*, 1977; *Moore et al.*, 1983].

Recent models of critical-taper accretionary wedge dynamics may help explain the normal sense of Paleogene dip slip along the BRFS and the subhorizontal disposition of the Paleogene S_2 fabric in the Valdez Group. If one assumes that the accretionary prism behaves as a single, mechanically continuous unit that is able to transmit longitudinal stress, these mechanical models predict that underplating and thickening of the prism should in fact lead to horizontal stretching and extension of the prism [e.g., *Davis et al.*, 1983; *Platt*, 1986]. On the other hand, by mid Tertiary time, the forearc region seems to have switched to a regime of horizontal compression. According to the critical-taper model, such a transition in stress states could have resulted from processes such as frontal accretion, prism erosion, or increased basal shear stress along the subduction zone decollement fault or possibly by a seaward shift in the location of the effective mechanical backstop of the accretionary prism [e.g., *Davis et al.*, 1983; *Platt*, 1986].

The post-early Eocene to pre-late Eocene timing of strike-slip faulting along the BRFS is consistent with a model of partially "trench-linked" transcurrent faulting, because mid-early through middle Eocene time was a period of strongly right-oblique subduction of young oceanic crust along the Gulf of Alaska margin [*Lonsdale*, 1988; *Engebretson et al.*, 1986]. According to this model, a portion of the trench-parallel component of oblique relative plate convergence is partitioned along wrench faults in the overriding plate between the trench and volcanic arc [e.g., *Karig*, 1978; *Karig et al.*, 1986; *Kimura*, 1986; *Lamb and Vella*, 1987]. Partial uncoupling of accretionary wedges from arc terranes along wrench faults is mechanically favored over oblique subduction by the following factors: (1) strongly oblique convergence between the overriding and underriding plates (at least 20^{o} from orthogonal; (2) strong coupling (i.e., high shear resistance) between the overriding and underriding plates, a situation favored by low fluid pressures or rapid subduction rates, especially in arcs that move compressionally (in an "absolute" frame of reference) toward their own subduction hinge; (3) a low dip angle of the subducted slab, a condition that would be favored by rapid subduction of young oceanic crust; and (4) a low magnitude of shear resistance (either frictional or viscous) along upper plate wrench faults relative to that in the subduction zone [*Fitch*, 1972; *Dewey*, 1980; *Beck*, 1983; *Jarrard*, 1986; *Mount and Suppe*, 1987]. Ductile deformation at low stress levels along wrench faults in the overriding plate would also be favored by a preexisting weakness or fault zone and by high heat flow to thermally weaken the crust, as near a volcanic arc [*Dewey*, 1980; *Woodcock*, 1986].

Conditions that should favor trench-linked strike-slip faulting along the present BRFS include the gentle dip of the Pacific plate (Figure 1, B-B′) [*Karig et al.*, 1976], the long-lived nature of the backstop fault system (BRFS), and the large magnitude of interplate shear resistance to be expected along the deeper reaches of gently dipping subduction zones [*Fukao*, 1979; *Karig*, 1982]. Yet geologic evidence suggests that during the Eocene period of rapid right-oblique subduction, only minor (tens of kilometers) of dextral slip accumulated along the BRFS. A possible explanation for the lack of major early Tertiary strike slip along that forearc fault system is that the amount of shear resistance along the base of what was in Paleogene time a thinner, narrower, and less lithified accretionary prism was possibly quite low [e.g., *Davis and von Huene*, 1987]. For this reason the total shear traction at the base of the overriding plate in Paleogene time may only have reached sufficient magnitudes to drive trench-linked faulting along more inboard strike-slip fault systems, such as the Denali fault (Figure 1), which may also have been thermally weakened by its proximity to the early Tertiary volcanic arc. That the overriding plate along the Paleogene Border Ranges backstop fault system was under horizontal extension and thus probably not strongly coupled to the underriding plate is indicated by repeated events of normal-separation faulting there and by its dilation by fault-filling dikes and veins.

APPENDIX: FISSION TRACK ANALYTICAL TECHNIQUES

The fission track ages of apatite were determined with the population technique; the external detector method was used to date the zircons [*Naeser*, 1976, 1979]. Apatite separates mounted in epoxy, polished, then etched in 7% HNO_3 at 23°C for 40 s. The zircons were mounted in teflon and etched in a eutectic melt of KOH-NaOH [*Gleadow et al.*, 1976] at 215°C for 30–50 hours. The teflon mounts were covered with a muscovite detector and irradiated along with neutron dose monitors (U-doped glasses SRM 962 also covered with muscovite detectors) in the U.S. Geological Survey reactor at Denver, Colorado. The neutron dose was determined using the track density in the muscovite detectors and the Cu calibration for SRM 962 [*Carpenter and Reimer*, 1974].

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