Structural controls on mid-Cretaceous sedimentation in the Toney Butte area of the Mitchell Inlier, Ochoco Basin, Central Oregon

Rebecca J. Dorsey and Robert J. Lenegan
Department of Geological Sciences
1272 University of Oregon
Eugene, OR 97403-1272
rdorsey@darkwing.uoregon.edu

In Press: *GSA Special Paper, Convergent Margin Terranes and Associated Regions*
(edited by M. Cloos, C. Gilbert, J. G. Liou, B. Carlson, and S. Sorenson)

ABSTRACT

Cretaceous sedimentary rocks in the Mitchell inlier of central Oregon accumulated in a forearc basin within a poorly understood part of the North American Cordillera. Sedimentary units are broadly to tightly folded, and include the Albian Hudspeth Formation (marine mudstone and turbidites) and the Cenomanian Gable Creek Formation (submarine-fan conglomerate and sandstone). Previous and new mapping in the Toney Butte area reveals interference of the NE-trending Mitchell anticline and the NW-trending, basement-cored Toney Butte anticline. The entire ~ 1.2-1.4 km-thick Main Mudstone member of the Hudspeth Formation pinches out across the Toney Butte anticline, and the overlying Gable Creek Formation is laterally continuous and rests depositionally on basement rock in the core of the fold. Two leading hypotheses are considered to explain the map relationships: (1) pinch-out of the Main Mudstone member is due to pre-existing erosional paleotopography and all folds are Tertiary age; or (2) the Toney Butte anticline initially grew during deposition of the Main Mudstone member, was overlapped by the Gable Creek Formation, and was further folded and rotated after deposition of Cretaceous strata. Based on critical map and stratigraphic relationships, we favor the second hypothesis. Accounting for ~37 degrees of post-basinal clockwise rotation (Housen and Dorsey, 2005), the data are interpreted to record growth of a basement-cored anticline due to N-S crustal shortening during Albian sedimentation in a large forearc basin. We infer that this folding episode resulted from regional transpression associated with northward translation of accreted terranes in the Blue Mountains along the western U.S. Cordilleran margin.

1. Introduction

The western Cordillera of North America is a collage of accreted terranes with a complex history of deformation, magmatism, and sedimentation. The Cordilleran margin was the site of protracted Paleozoic and Mesozoic mountain building events that resulted from convergence and collision of various island arcs and exotic terranes with cratonal North America (e.g. Dickinson, 1979, 2004; Coney et al., 1980; Silberling et al., 1984; Manduca et al., 1993; Lund and Snee, 1988; Burchfiel et al., 1992; Vallier and Brooks, 1995). Orthogonal convergence, collision, and oblique convergence, acting in sequence and in combination, affected western North America from Late Paleozoic to early Tertiary time along the entire Cordilleran margin from the southern Sierra Nevada through western Nevada and western Idaho to British Columbia (Fig. 1A). The relative importance of horizontal shortening versus strike-slip displacement, and the timing and amount of translation of terranes, vary in time and space and are the subject of ongoing debate (e.g. Umhoefer, 1987; Wynne et al., 1995; Monger and Price, 1996; Cowan et al., 1997; Mahoney et al., 1999; Housen and Beck, 1999; Enkin et al., 2003; Umhoefer, 2003; Wyld et al., in press). This controversy remains unresolved and highlights the need for detailed modern studies of datable sedimentation and deformation in areas where rocks of appropriate age are exposed.

The Ochoco basin contains a thick succession of mid- to Late Cretaceous marine sedimentary rocks that rest unconformably on older rocks of the Baker and Izee terranes in central Oregon (Fig. 1B; Dickinson and Vigrass, 1965; Oles and Enlows, 1971; Dickinson and Thayer, 1978; Dickinson, 1979; Wilkinson and Oles, 1968; Kleinhans et al., 1984). Albian to Cenomanian strata of the Ochoco basin are well exposed in the Mitchell inlier of central Oregon and are the focus of this paper. The Ochoco basin is thought to be the northward continuation of the Cretaceous Great Valley forearc basin in California and the Hornbrook basin of southern Oregon (Fig. 1; Kleinhans et al., 1984; Nilsen, 1986). This large forearc basin system existed during Cretaceous intracontinental collision, transpression, and regional-scale mountain building in eastern Oregon and western Idaho (Lund and Snee, 1988; Selverstone et al., 1992; Manduca et al., 1993; McClelland et al., 2000). Thus information about the basin's stratigraphy, composition, and deformation history should provide useful insights into Cretaceous regional tectonics, plate interactions, and terrane translation in this region. This paper presents the results of a field-based study of Albian-Cenomanian sedimentary rocks and syn- to post-depositional structures exposed in the Toney Butte area, in the northeastern part of the Mitchell inlier (Fig. 2). Integrative analysis yields new insights into the development of two large folds, including a NW-trending basement-cored anticline that we conclude grew during deposition of Albian forearc-basin strata.

2. Geologic Setting

Cretaceous sedimentary rocks of the Ochoco basin depositionally overlap westernmost exposures of the Baker and Izee terranes, which belong to the composite Blue Mountains province of Mesozoic accreted terranes in central and eastern Oregon (Fig. 1B; Dickinson and Vigrass, 1965; Brooks and Vallier, 1978; Dickinson and Thayer, 1978; Dickinson, 1979; Silberling et al., 1984; Wernicke and Klepacki, 1988; White et al., 1992; Avé Lallemant, 1995; Vallier and Brooks, 1995; Dickinson, 2004). The Wallowa terrane consists of Permian to Lower Jurassic volcanic and related sedimentary rocks that formed in oceanic plateaus and volcanic island arcs outboard of the North American margin. The Baker terrane includes Devonian to Late Triassic igneous and sedimentary rocks that have been metamorphosed to greenschist and (locally) amphibolite and blueschist grades, and represent exhumed parts of a Triassic and/or Jurassic subduction zone complex that is probably related to formation of the Wallowa volcanic arc. The Izee terrane consists of Late Triassic to Middle Jurassic sedimentary rocks that accumulated in a complex system of marine basins prior to and during Jurassic arc-continent collision (e.g. Dickinson and Thayer, 1978; Dickinson, 1979).

The amalgamated terranes of the Blue Mountains were initially accreted to the North American margin during Late Jurassic or early Cretaceous arc-continent collision and related mountain building in the Salmon River suture zone of western Idaho (Fig. 1) (Brooks and Vallier, 1978; Coney et al., 1980; Oldow, 1984; Selverstone et al., 1992; Dilek and Moores, 1993; Vallier, 1995; Wyld and Wright, 2001; Gray and Oldow, 2005). The suture zone was later modified by Early Cretaceous (~130-120 Ma) collision, thrusting, and metamorphism, followed by mid-Cretaceous (~118-90 Ma) transpressive deformation, strike-slip displacement, continued metamorphism, and pluton emplacement in the western Idaho shear zone. The latter stage of transpressive deformation formed subvertical fabrics with dextral shear indicators and resulted in final truncation of the continental margin (Lund and Snee, 1988; Manduca et al., 1993; McClelland et al., 2000; Gillaspy et al., 2000). The boundary between outboard oceanic terranes and rocks of continental origin in western Idaho is represented by an abrupt change in the $^{87}Sr/^{86}Sr$ isotopic signature, with isotopic ratios less than .704 indicating rocks of oceanic origin and ratios greater than .706 representing rocks of continental affinity (Fig. 1) (Armstrong et al., 1977; Fleck and Criss, 1985; Criss and Fleck, 1987; Manduca et al., 1992). The abrupt, steep gradient in isotopic compositions is the result of protracted convergence, dextral transpression, and tectonic truncation of the North American margin. Mid-Cretaceous oblique collision and transpression in western Idaho was accompanied by rapid uplift, exhumation, mountain building, and erosion of amphibolite, schist, marble, and gneiss (Lund and Snee, 1988; Selverstone et al., 1992; McClelland et al., 2000).

The Mitchell inlier is the largest area (~180 km^2) of exposed Cretaceous sedimentary rocks in central Oregon, and it makes up an overall NE-trending belt of Albian to Campanian marine deposits that belong to the larger Ochoco basin (Fig. 2) (Wilkinson and Oles, 1968; Oles and Enlows, 1971; Kleinhans et al., 1984). Wilkinson and Oles (1968) divided the stratigraphy into two intertonguing formations, the Hudspeth and Gable Creek Formations. They defined the Hudspeth Formation as a "widespread and thick sequence of marine mudstone with subordinate siltstone and sandstone" (Wilkinson and Oles, 1968, p. 133), and described the Gable Creek Formation as conglomerate and sandstone of fluvial-deltaic origin. Wilkinson and Oles (1968) believed the sediments were derived from a rising landmass to the north and transported via a major river system to a shallow marine embayment. Later work by Kleinhans et al. (1984) reinterpreted the Gable Creek Formation as coarse-grained deposits of a submarine fan system. This interpretation was based on recognition of diagnostic turbidite facies and micropaleontologic data supporting an outer neritic to upper bathyal environment, and is supported by this study.

Several small exposures of Cretaceous strata are exposed east and southeast of the Mitchell inlier (Fig. 1B). Up to 730 meters of Cretaceous conglomerate, sandstone, and siltstone are exposed at Antone Ranch (Dobell, 1948; Dawson, 1951), where facies associations and the presence of thick-shelled Trigonia and leaf imprints suggest a continental and marginal-marine environment. At Goose Rock, interbedded conglomerate, sandstone and minor mudstone of uncertain depositional environment form a sequence over 90 meters thick (Kleinhans et al., 1984). At Bernard Ranch, up to 1,500 m of pebbly sandstone and conglomerate reveal cross-bedding, good sorting and rounding, marine fossils, and transgressive stratigraphic relationships that suggest a shallow marine depositional environment (Dickinson and Vigrass, 1965). At two locations near Bernard Ranch, shallow marine Cretaceous deposits depositionally overlie and overlap tectonized contacts between pre-Cretaceous rocks of the Baker terrane (accretionary subduction complex) and Izee terrane (arc-related sedimentary basin) (Fig. 1B; Dickinson and Vigrass, 1965). Cretaceous strata of the Ochoco basin are also known from limited subsurface studies, which revealed dominantly marine sandstone and siltstone with palynomorphs and foraminifera that indicate an Albian to Campanian age (Thompson et al., 1984).

3. Stratigraphy and Sedimentology

The geology of the Mitchell inlier is dominated by Cretaceous sedimentary rocks and pre-basinal metamorphic rocks that are deformed by a large NE-trending Tertiary fold known as the Mitchell anticline (Fig. 2A) (Wilkinson and Oles, 1968; Oles and Enlows, 1971; Kleinhans et al., 1984). A thick section of mudstone, sandstone, and conglomerate of the Hudspeth and Gable Creek formations rests unconformably on Paleozoic metasedimentary basement rocks in the Toney Butte area (Figs. 2B, 3). Basement rock includes metachert, phyllite, argillite, quartzite, chlorite schist, and marble of the Baker Terrane. Measured sections and mapping transects were used to construct a SW-NE facies panel that reveals key aspects of the stratigraphic architecture (Fig. 4). The facies panel shows that the lower part of the section depositionally overlies and onlaps basement rock along a low-angle nonconformity. Lateral facies changes are seen in the lower members of the Hudspeth Formation and unit Kg-2 of the Gable Creek Formation, and a small growth fault is present in the lower Gable Creek Formation. Ammonites collected from the Main Mudstone member of the Hudspeth Formation range from early to late Albian in age (112 to 99 Ma) and occur in correct stratigraphic order (Fig. 3) (McKnight, 1964; Kleinhans et al., 1984; P. Rodda, personal communication, 2000). No fossils have been found in the Gable Creek Formation, but it is inferred to be Cenomanian or younger based on its interbedded and conformable contact with the Hudspeth Formation (Wilkinson and Oles, 1968) and the presence of Albian to Campanian fossils in the subsurface of the Ochoco basin (Thompson et al., 1984).

3.1. Hudspeth Formation

The Hudspeth Formation was defined by Wilkinson and Oles (1968) as including the Basal member (Khb), Main Mudstone member (Kh1), and a series of stratigraphically higher mudstone units (Kh2 to Kh11) interbedded with units of the Gable Creek Formation. This study confirmed the basic organization of Wilkinson and Oles (1968) and made slight modifications to facilitate mapping and stratigraphic analysis (Fig. 3). We divide the Hudspeth Formation into: (1) Basal member (Khb), which is informally subdivided into four units (green sandstone, conglomerate, mudstone, and tan sandstone); (2) Main Mudstone member (Khmm); and (3) a higher unit of mudstone (Khm), stratigraphically between Kg-1 and Kg-3 of the Gable Creek Formation, that was mapped previously as Kh3 by Oles and Enlows (1971) (Figs. 2B, 3).

The Basal member of the Hudspeth Formation is subdivided into four units (from oldest to youngest): green sandstone, mudstone, conglomerate, and tan sandstone (Fig. 3). The contact with basement rock is well exposed in the southwest-plunging part of the Mitchell anticline axis, and locally elsewhere along mapped fold limbs. It is a transgressive nonconformity with a very thin basal zone containing rare outsized clasts of underlying basement lithologies that passes directly into the various units of the Basal member. Detailed mapping reveals that bedding in basal Hudspeth units in most places is parallel to both the lower contact with basement rock and upper contacts with younger units. Green sandstone is the oldest unit exposed in the Toney Butte area and consists of moderately to poorly sorted sandstone and pebbly sandstone. Sand grains and clasts are composed of low-grade metamorphic detritus including phyllite, meta-chert, quartzite, and chlorite schist that closely resemble lithologies in the underlying basement. Planar lamination, normal grading, linear sole marks, and abundant wood fragments are common in this unit. Paleocurrent indicators are rare and inconclusive, but suggest overall transport to the northwest or southeast (Lenegan, 2001). Green sandstone interfingers laterally with mudstone and conglomerate units of the Hudspeth Formation (Fig. 4).

The conglomerate unit of the Basal member contains both matrix- and clast-supported pebble-cobble conglomerate with minor interbedded sandstone, and locally contains oversized subangular to angular clasts of metamorphic basement rock (Fig. 5A). Unlike the green sandstone, conglomerate clasts are composed primarily of volcanic, chert, and plutonic rock fragments with only a minor metamorphic component. Tan sandstone consists of fine-grained, planar laminated, medium- to thick-bedded turbiditic sandstone with locally interbedded mudstone and shale.

It is composed of quartz, feldspar, chert, and volcanic lithic fragments compositionally equivalent to the conglomerate unit, and is gradational with the overlying Main Mudstone member. The entire thickness of the tan sandstone (~100 m) passes laterally into Hudspeth mudstone south and west of Toney Butte (Figs. 2B, 4).

Mudstone units of the Hudspeth Formation are lithologically similar at different stratigraphic levels, and consist primarily of dark gray to black mudstone with minor shale. Calcite-cemented concretions in mudstone are aligned parallel to bedding and commonly contain ammonites and woody debris. The Main Mudstone member gradationally overlies tan sandstone of the Basal member and shows significant thickness variations in the study area (Figs. 2B, 4). The upper ~60 meters of the Main Mudstone member shows a slight coarsening-up trend revealed by increasing thickness and abundance of thin-bedded sandstone turbidites, but its contact with overlying conglomerate of the Gable Creek Formation is sharp and probably erosional.

3.2. Gable Creek Formation

The Gable Creek Formation consists of interbedded conglomerate and sandstone that are divided into three map units (Kg-1, Kg-2, Kg-3) based on their relation to interbedded units of Hudspeth mudstone. Within each map unit there are numerous mappable pairs of conglomerate and sandstone that are assigned a letter for their position in the section (Figs. 3, 4). Map relations show that conglomerate of Kg-1A rests unconformably on basement rock on the north and northeast flanks of Toney Butte (Fig. 2, 4). In all other areas, the basal Gable Creek conglomerate (Kg-1A) is in sharp, concordant contact with the underlying Main Mudstone member of the Hudspeth Formation. Conglomerate beds typically are medium- to thick-bedded, massive (structureless), and clast-supported (Fig. 5B), with minor matrix-supported pebbly sandstone in the upper parts of some beds. Clast size ranges from small pebble to cobble size and averages 1-4 cm in diameter. Sandstone units contain medium to thin-bedded sandstone and minor mudstone (Fig. 5C), with lesser amounts of coarse- to very coarse-grained sandstone and pebbly sandstone. Channeling, normal grading, inverse grading, planar laminations, vertical fluid escape structures, and tool and scour marks are common. Rare cross stratification, bioturbation, wood fragments, and transported pelecypods are found in some sandstone units. In most places sandstone units are gradational with underlying conglomerate over thicknesses of a few meters. Clasts in the Gable Creek Formation consist dominantly of chert, intermediate to silicic volcanic rocks, and minor granitic to intermediate plutonic rocks (Little, 1986; Lenegan, 2001).

Conglomerate of the Gable Creek Formation commonly reveals imbricated clast fabric with a-axes oriented parallel to flow, yielding reliable indications of paleocurrent direction (Fig. 5D, 6). Clast imbrications were measured at different locations on the NW limb of the Mitchell anticline and restored for local bedding dip by untilting beds about the strike of bedding. The additional effects of vertical-axis rotation are discussed below. Clast imbrication data from the Gable Creek Formation record overall transport to the southwest (in present coordinates; Fig. 6), consistent with the direction obtained by Little (1986) .

4. Geologic Map and Structural Data

The geologic map in Figure 2B reveals important aspects of superposed folding that were not identified in previous published studies. Two orthogonal anticlines, the northeast-trending Mitchell anticline and the northwest-trending Toney Butte anticline (named here), intersect to produce the quasi-domal structure seen at Toney Butte. The Toney Butte anticline is cored by phyllite, quartzite, and chlorite schist in basement rock of the Baker terrane, and it is recognized by opposing bedding dips in Cretaceous sedimentary rocks on the north and south limbs of the anticline (Fig. 2B). Although not mapped in this study, the core of the anticline also contains some Tertiary-age shallow intrusive bodies similar to those seen at Toney Butte and elsewhere in the Mitchell inlier (E. Taylor, personal comm. 2003). The southwest limb of the Toney Butte anticline reveals a complete section of Hudspeth and Gable Creek formations, but the Basal and Main Mudstone Hudspeth members are missing on the northeast limb of the fold where the lower Gable Creek Formation rests directly on basement rock (Fig. 2B) (Lenegan, 2001). There are no good exposures of the basal contact in this area, but the map pattern reveals a moderately dipping, locally irregular contact that is confidently interpreted as depositional (not a fault).

Four geologic cross sections illustrate the main structural features in the Toney Butte area. Cross sections A-A' and B-B' were constructed at 1:12,000 scale, and cross sections C-C' and D-D' were constructed at 1:6,000 scale (based on detailed mapping) to illustrate useful smaller-scale fold geometries. The Mitchell anticline, where it is not complicated by other structures, is a simple fold that reveals a simple correlation of the Gable Creek Formation across its axis (Fig. 7A). The depth to Basal Hudspeth Formation and underlying basement rocks is uncertain at this location. The Toney Butte anticline is shown in Figure 7B. The Basal and Main Mudstone members of the Hudspeth Formation are about 1500 m thick on the south limb of the anticline, but they are conspicuously absent on the north limb where basement rocks are directly overlain by the Gable Creek

Formation. We considered two initial interpretations of this cross section. The first involves wedging and pinch-out of Hudspeth mudstone in a complex zone of converging strata on the south limb and core of the anticline (solid lines, Fig. 7B). In the second interpretation, a thick interval of Gable Creek Formation passes to the south through a large lateral facies change into the Main Mudstone member of the Hudspeth Formation (dashed lines, Fig. 7B). Straight forward correlation of the base of the Gable Creek Formation around the study area (Fig. 2B, 7A) argues against a large north-south lateral facies change and supports the solid-line interpretation in Figure 7B (see also Interpretation section, below)

A tight, upright to overturned anticline-syncline pair on the southwest flank of Toney Butte is revealed in an oblique air photo (Fig. 8) and cross section C-C' (Fig. 9A). Here, conglomerate of the Basal Hudspeth thins and grades laterally to the west across the syncline into tan sandstone, and this sandstone makes up the lower part of a turbidite sandstone unit that passes laterally to the west across the anticline into mudstone. We considered an alternate interpretation in which the western contact between sandstone and mudstone may be a fault truncation, but we do not favor a fault interpretation for this contact because (1) dramatic lateral thinning of Basal Hudspeth conglomerate is clearly demonstrated in 1:6,000 scale mapping and the derived cross section (Figs. 8, 9A); (2) a coherent section of mudstone is exposed on the west limb of the anticline with no evidence for brittle fault-zone textures where a large fault would be required; and (3) a similar abrupt lateral transition from Basal Hudspeth sandstone into mudstone is seen on the south flank of Toney Butte where there are no local structural complications (Fig. 2B; south of C'). Thus we interpret the map pattern on the west flank of Toney Butte to reveal tight, asymmetric, west-vergent folds that deform stratigraphically complex deposits of the Basal Hudspeth Formation; these deposits pass laterally over a short distance through the folds into the Main Mudstone member. These folds involve at least 200 m of section, have a wavelength of ~300 m, and an amplitude of ~100 m (Figs. 8, 9A).

Cross section D-D' (Fig. 9B) reveals tight fold geometries and abrupt lateral facies changes similar to those described above. The conglomerate unit of the Basal Hudspeth is more than 50 meters thick on the north limb and passes laterally to the south into tan sandstone across the axis of the northern syncline. The tan sandstone unit grades laterally northward into conglomerate, and appears to maintain a constant thickness to the south. The cross section is under-constrained in the subsurface; the Basal tan sandstone may grade laterally into mudstone to the south as is seen nearby to the west of this cross section (Fig. 2B).

Stereonet plots and statistical analysis of bedding provide information about the orientation of fold axes in the Toney Butte area (Fig. 10). Four structural domains were defined on the basis of bedding orientations that permit identification of folds with different orientations. Three of the domains (A-C) are shown on the geologic map (Fig. 10), and the fourth domain (D) is a small area restricted to the immediate vicinity of the Mitchell anticline axis in the Basal member of the Hudspeth Formation. The domains contain folds with markedly different orientations (trend, plunge): 349, 16° in Domain A; 077, 12° in Domain B; 265, 12° in Domain C; and 216, 41° in Domain D (Fig. 10). The data for Domain D closely resemble a fold axis orientation (215, 31°) that was derived from a three-point construction along the contact between basement rock and Basal Hudspeth Formation in the axis of the anticline.

A small oblique-sinistral fault SW of Toney Butte offsets the Main Mudstone member of the Hudspeth Formation and Gable Creek Formation through sandstone Kg-1B, but younger conglomerate Kg-1C is not offset (Figs. 2B, 4). The fault strikes 036 and dips 85° to the SE, and the fault plane has brittle striae that rake 44° from the SW. A syndepositional origin for this fault is indicated by stratigraphic thickening of strata into the hanging wall, an abundance of matrix-supported conglomerate in hanging-wall deposits, and the fact that it is depositionally overlapped by younger units of the Gable Creek Formation.

5. Interpretation

5.1. Depositional Processes and Environments

Deposition of the Hudspeth Formation at Toney Butte was initiated in early Albian time by subsidence and submergence of previously eroded metamorphic rocks of the Baker terrane. The green sandstone unit of the Basal member was derived from nearby exposures of basement rock and deposited on a submarine slope by sandy turbidity currents and subaqueous debris flows. Conglomerate and tan sandstone of the Basal member also were deposited by sediment-gravity flows, but their composition reflects a change of provenance to a larger, integrated source area that included volcanic, chert, and plutonic rocks. Rare oversized basement clasts likely fell from channel walls or were dislodged from the substrate and incorporated into flows as they moved down slope. Mudstone units of the Hudspeth Formation record slow deposition by suspension settling in a sediment-starved marine basin. Micropaleontologic data indicate outer neritic to upper bathyal water depths (Kleinhans et al., 1984). Where mudstone and shale are interbedded with thin-bedded sandstone, deposition occurred by dilute low-density turbidity currents on a submarine basin plain. Lateral interfingering of mudstone unit Khm with Gable Creek conglomerate to the northeast (Figs. 2B, 4), combined with paleocurrent data from the Gable Creek conglomerate that show consistent transport toward the southwest (Fig. 6), suggest that this basin-plain setting occupied the distal fringing part of a large submarine-fan system that entered the basin from the northeast (present coordinates).

Conglomerate and sandstone of the Gable Creek Formation were deposited by sediment-gravity flows in a submarine fan system (Kleinhans et al., 1984; Little, 1986; Lenegan, 2001). Clast-supported conglomerate was deposited by non-cohesive debris flows (grain flows) that may have formed in the basal layer of coarse-grained turbidity currents (e.g. Lowe, 1982). Matrix-supported conglomerate was deposited from cohesive debris flows, and sandstones were deposited by turbidity currents and sandy debris flows (e.g. Walker, 1975; Lowe, 1982; Shanmugam, 1996). The up-section change from laterally continuous to more discontinuous stratal geometries seen in Gable Creek unit Kg-1 (Fig. 4) may record slight progradation of an upper-fan channel system over a supra-fan depositional lobe. The subsequent abrupt transition to overlying mudstone, which interfingers laterally with Gable Creek unit Kg-2 to the northeast, records a relatively rapid back-stepping of the submarine fan that could be due to (1) external factors such as a rise in eustatic sea level, increased subsidence rate, or decreased rate of sediment supply, or (2) intrabasinal processes such as channel switching in the upper part of the submarine fan.

5.2. Folding History

Truncation of the Basal and Main Mudstone members of the Hudspeth Formation against basement rock west of Toney Butte was previously interpreted by Oles and Enlows (1971) to be due to a large down-on-the-west fault. Our work shows that this interpretation is contradicted by several observations: (1) Gable Creek conglomerate depositionally overlies basement rock on the north limb of the Toney Butte anticline where it previously was mapped as Tertiary Clarno Formation (Oles and Enlows, 1971), and can be mapped east from there across the trace of the hypothesized fault (Fig. 2B); (2) the contact between various units of the Hudspeth Formation and older basement rocks west of Toney Butte shows no signs of fault gouge or pervasive fracture that would be expected for a large fault; and (3) stratigraphy is not offset ~3 km northeast of Toney Butte where the inferred fault was mapped by Oles and Enlows (1971). We therefore conclude that truncation of the lower Hudspeth units in this area is not due to fault offset, and instead reflects low-angle onlap of strata onto structural and/or erosional paleo-relief that existed in Albian time. The base of the Gable Creek Formation rests directly on pre-Cretaceous basement rock on the northeast limb of the Toney Butte anticline, and it correlates to the base of the Gable Creek Formation southwest of the anticline where it overlies a thick interval of Hudspeth mudstone. It is clear from the map pattern that a major stratigraphic omission occurs across a large anticline, which suggests a folding control on the stratigraphy.

The two most likely explanations for map and stratigraphic relationships seen in the Toney Butte anticline are: (1) northward pinch-out of the Hudspeth Formation across the fold axis is unrelated to folding and reflects onlap onto pre-existing erosional paleotopography, and the Toney Butte anticline is entirely Tertiary in age; or (2) the anticline initially grew during deposition of the Hudspeth Main Mudstone member, it was overlapped by the Gable Creek Formation, and was further folded and rotated clockwise after deposition of the Cretaceous section. To test these hypotheses we produced three reconstructions of cross-section B-B' (Fig. 7B) by restoring the base of the Gable Creek Formation to horizontal and evaluating different possible pre-Gable Creek stratal geometries (Fig. 12). Figure 12A illustrates the traditional, non-folding hypothesis in which the entire 1.2-1.4 km-thick Main Mudstone member pinches out against an erosional paleohigh along a large buttress unconformity south of Toney Butte. At first glance this model appears plausible and conceptually consistent with evidence for onlap seen elsewhere in the study area. However, spatial constraints from the cross section would require a vertical elevation drop of 1.2-1.4 km over a horizontal distance of ~1.7 km, equivalent to a surface gradient of 35°-40°. While this is possible for a deep terrestrial canyon that is suddenly flooded by marine water, most areas of subaerial erosion form much lower surface gradients so this interpretation would require preservation of a rare paleo-landscape. Moreover, the non-folding buttress model requires that bedding in the Basal Hudspeth Formation onlaps the basement rock at a high angle to its contact with underlying basement (Fig. 12A). This prediction is contradicted by field data, which shows that bedding in the Basal Hudspeth sandstone is consistently parallel to its lower and upper contacts (e.g. Figs. 8, 9; Lenegan, 2001). For these reasons, we conclude that pre-existing erosional paleotopography is not the sole explanation for pinch-out of the Main Mudstone member across the axis of the Toney Butte anticline.

We next consider two possible geometries for syn-basinal folding prior to deposition of the Gable Creek Formation. The first is a south-vergent, fault-related compressional fold produced by kink-band migration (Fig. 12C; e.g. Suppe and Medwedeff, 1990; Suppe et al., 1992, 1997; Narr and Suppe, 1994). This model predicts an angular unconformity between the Main Mudstone member and the Gable Creek Formation, an abrupt change in bedding dip across the syncline axis, and no progressive tilting or fanning dips in the growth strata (Khmm). Although an angular unconformity is not observed in the study area, it could have been removed by later erosion that left the concordant part of the contact preserved. However, the kink-fold model works best with a layer-cake stratigraphy, no onlap of sediment onto the fold limb, and no lateral facies change from basal Hudspeth sandstone and conglomerate (Khb) into basinal mudstone (Khmm). We therefore consider the first fold geometry to be unlikely.

The second geometry involves progressive tilting and limb rotation during fold growth with potentially complex stratal onlap, thinning, and fanning dips in growth strata on the southern limb of the anticline (Fig. 12C; e.g. Hardy and Poblet, 1994; Patton, 2004). This model produces several features that are consistent with our observations: (1) a coarse, locally-derived clastic unit (Khb) accumulates on the flank of the growing uplift and passes laterally into distal turbidites and mudstone (Khmm); (2) bedding in Khb is generally parallel to its contact with basement rock and displays very low-angle onlap with the basement; (3) a steep unusual paleo-cliff is not needed in the pre-depositional landscape; and (4) northward pinch-out of the Main Mudstone member is spatially and genetically associated with the Toney Butte anticline, which is well demonstrated in the map pattern (Fig. 2B). While this hypothesis predicts fanning dips in the Main Mudstone member that are not seen on the map, we observed strong brittle shearing and highly variable bedding dips in the transect south of Toney Butte that are related to small late-stage faults. Steep bedding dips in the Gable Creek Formation record strong post-Gable Creek deformation. Post-Cretaceous small-scale faults and lateral expansion of the anticline during later folding would be likely to overprint and obscure fanning-dip patterns produced in an earlier phase of folding; this is a common problem in complexly deformed terranes. For these reasons we favor the second geometry (Fig. 12C) for fold growth during deposition of the Hudspeth Main Mudstone member.

From the above analysis, we conclude that the Toney Butte anticline initially formed as a south-vergent basement-cored uplift, similar to folds associated with Laramide-style contractile deformation in Utah and Wyoming (Fig. 12C) (e.g. Evans, 1993; Narr and Suppe, 1994). In this interpretation, uplift of the anticline prevented deposition across its core during subsidence and sedimentation elsewhere in the basin. The presence of Hudspeth mudstone northeast of Toney Butte (Fig. 2A) indicates that the anticline was flanked on the north by another syncline. Later reactivation of this fold tilted the Gable Creek Formation on both limbs into its current orientation. We infer that the Toney Butte anticline and secondary folds originally formed with an E-W trend and sub-horizontal plunge, and later were re-folded by the Mitchell anticline and rotated into their present orientations (Fig. 11). Tertiary andesite and dacite at Toney Butte were intruded at the intersection of the two anticlines, similar to shallow intrusions that are spatially associated with Tertiary structures elsewhere in the Mitchell area (Oles and Enlows, 1971).

We considered the possibility that the Toney Butte anticline and associated smaller folds may have been created by forceful shallow intrusion of Tertiary magmas. However, observed map and stratigraphic relationships point to early, synbasinal growth of the fold during deposition of the Main Mudstone member. Although local shearing and contact metamorphism of the country rock is common around the margins of other shallow intrusions in the Mitchell inlier (Oles and Enlows, 1971), it is unlikely that intrusion of the magmas alone could have produced the systematic large scale and geometry of the Toney Butte and Mitchell anticlines. These folds clearly have a tectonic origin. Our interpretation of the age and mechanism of the Toney Butte anticline therefore rests on key map and stratigraphic relationships summarized above.

Unlike the Toney Butte anticline, the Mitchell anticline shows no evidence for growth during deposition of Cretaceous sedimentary units. Geologic mapping by Oles and Enlows (1971) showed that the Tertiary John Day Formation and Columbia River Group basalts are deformed by the Mitchell anticline and Sutton Mountain syncline, and these units display systematic thickness variations across the limbs of the folds. We therefore infer that the northeast-trending Mitchell anticline formed in Tertiary time and re-folded the mid-Cretaceous northwest-trending Albian Toney Butte anticline.

6. Discussion

The data presented above provide evidence for contractional deformation in the Ochoco basin during deposition of the Albian Main Mudstone member of the Hudspeth Formation. When structural features are restored for ~37° of post-depositional clockwise rotation (Housen and Dorsey, 2005), the Toney Butte anticline restores to an ~E-W trend and is interpreted to record approximately N-S shortening (Fig. 12C). Restoration of paleocurrent data from the Gable Creek Formation (Fig. 6) gives overall transport toward the south. The large area over which the Gable Creek Formation is exposed in the Mitchell inlier indicates that a large volume of gravel and sand was supplied to the Ochoco basin during Cenomanian time. The large influx of coarse detritus from the north immediately following an episode of south-vergent folding and shortening implies, though does not require, a genetic relationship between the two. We suggest that regional-scale crustal shortening responsible for the Toney Butte anticline also produced high topography in the Blue Mountains to the north, and that resulting erosion of older volcanic and chert-bearing rocks produced the large volume of clastic detritus preserved in the Gable Creek Formation (Fig. 13). Some of this detritus probably also was sourced east of the Mitchell area, but our data do not constrain how much of the sediment load was derived directly from the north versus that which entered from the east and was funneled south along the axis of the basin.

Previous workers have interpreted the Ochoco basin to be a northward continuation of the Cretaceous Hornbrook basin in southern Oregon and the Great Valley sequence in California (Fig. 1A), which formed in a large forearc basin during eastward subduction of the Farallon plate and coeval arc magmatism in the Sierra Nevada and Idaho batholiths (e.g. Kleinhans et al., 1984; Nilsen, 1986). Original continuity of these basins is supported by recent terrane reconstructions for the western Cordillera (Umhoefer, 2003; Wyld et al., in press; Umhoefer and Blakey, in press), and is corroborated by this study. Mid-Cretaceous forearc sedimentation took place during a protracted period of Cretaceous transpression, plutonism, and metamorphism in the western U.S. Cordilleran orogenic arc system (Fig. 1A; Gastil et al., 1981; Todd et al., 1988; Lahren et al., 1990; Schweickert and Lahren, 1990; Busby-Spera and Saleeby, 1990; Tikoff and de St. Blanquat, 1997; Greene and Schweickert, 1995; Johnson et al., 1999; Wyld and Wright, 2001). Although data in this study do not constrain the position of the Ochoco basin relative to north America, a recent paleomagnetic study by Housen and Dorsey (2005) provides evidence for 1760 ± 460 km (or 1200 ± 460 km assuming an *ad-hoc* 5° inclination error) northward translation of the Ochoco basin since ~93 Ma. We therefore suggest that the Ochoco basin formed at approximately the latitude of the southern Sierran arc during mid-Cretaceous time (Fig. 13).

McClelland et al. (2000) proposed a two-stage model in which: (1) oceanic terranes of the Blue Mts province were accreted to North America during Late Jurassic or Early Cretaceous orthogonal collision in the Salmon River suture zone (SRSZ; Selverstone et al., 1992; Getty et al., 1993; Gray and Oldow, 2005); and (2) subduction stepped outboard in mid-Cretaceous time to a position west of the Ochoco basin, and the Idaho batholith (magmatic arc) became the site of a large transpressive flower structure in the western Idaho shear zone (WISZ) that accommodated dextral transpression and rapid exhumation of deep crustal rocks during and after ~118-90 Ma. According to this model, mid-Cretaceous translation of outboard terranes was accommodated by the strike-slip component of transpression in the WISZ. We infer that mid-Cretaceous north-south shortening documented at Toney Butte (this study) is an expression of dextral transpressive strain that affected the forearc region during northward translation of the Ochoco basin along the Cordilleran margin. Post-Late Jurassic thrusts and folds in the Blue Mountains (Kays and Stimac, 2002) may have also resulted from margin-parallel shortening during the same time.

Conglomerate clast compositions in the Gable Creek Formation pose a unique problem for interpreting Cretaceous paleogeography and tectonic history of the Blue Mountains. Based on the similar timing of crustal exhumation (~118 to 90 Ma) and basin filling (~112 to 93 Ma), some workers have suggested that detritus eroded from the Salmon River suture zone accumulated in the Ochoco basin (Lund and Snee, 1988; Selverstone et al., 1992). However, this hypothesis fails to explain the pronounced compositional mismatch between high-grade metamorphic rocks in western Idaho (amphibolite, schist, quartzite, and gneiss) and conglomerate clasts in the Gable Creek Formation (primarily chert and low-grade metavolcanic and plutonic rocks) (Little, 1986; Lenegan, 2001). This mismatch could have resulted from topographic barriers that diverted regional streams and metamorphic detritus away from the basin. Alternatively, the Ochoco basin and Blue Mts. province may have been located south of their present position in mid-Cretaceous time, adjacent to the Sierra Nevada arc (Fig. 13), as indicated by the paleomagnetic study of Housen and Dorsey (2005). Middle Eocene deposits in northeastern Oregon contain a population of ~ 45-Ma detrital zircons and abundant detrital kyanite derived from metamorphic rocks in western Idaho (Cowan and Reiners, 2004), indicating that northward translation of the Blue Mountains had ended by middle Eocene time.

A recent reconstruction of Cordilleran terranes (Umhoefer and Blakey, in press) suggests that the Ochoco basin may have formed on accreted oceanic rocks adjacent to Salinian-Mojave or southern Sierra Nevada crust, and later was translated northward as a relatively small tectonic sliver along the transpressive Cordilleran margin (see also Wright and Wyld, this volume). According to this hypothesis, most of the terranes in the Blue Mountains were in their current position by early Cretaceous time (e.g. Wyld and Wright, 2001; Dickinson, 2004; Wyld et al., in pess), and Baker terrane rocks that underlie the Ochoco basin were juxtaposed against similar Baker terrane rocks in central and eastern Oregon by mid- to Late Cretaceous northward motion of the small hypothesized sliver (Umhoefer and Blakey, in press). While this idea has merit, we believe it is contradicted by several observations: (1) a kinematic study of deformation fabrics in the western Idaho shear zone shows that 118-

to 90-Ma plutons accommodated a large but unknown amount of syn- to post magmatic dextral transpressive shear between the Blue Mountains province and cratonal North America (McLelland et al., 2000); (2) the only time constraints on the end of shearing and translation are the ~ 45-Ma kyanite-bearing fluvial deposits in northeastern Oregon (Cowan and Reiners, 2004) and a paleomagnetic study of the Eocene Clarno volcanics indicating that they formed at their present-day latitude (Grommé et al., 1986); (3) stratigraphic studies in the Izee-Suplee area, southeast of Mitchell, show that Late Triassic slide breccias and olistostromes were emplaced by mass flows in fault-bounded marine sub-basins of the Izee terrane, and were progressively deformed during thrusting at the margin of the emergent Baker terrane (Dickinson and Thayer, 1978; Dickinson, 1979); and (4) mid-Cretaceous deposits that are demonstrably correlative to those of the Mitchell inlier depositionally overlie tectonized contacts between the Baker and Izee terranes near Bernard Ranch, southeast of Mitchell (Fig. 1B; Dickinson and Thayer, 1978), and these strata therefore comprise an overlap assemblage that accumulated on previously amalgamated terranes of the Blue Mountains. Thus a growing body of evidence indicates that the Baker and Izee terranes have been adjacent to each other since Late Triassic time, and the entire Blue Mountains province was translated northward approximately 1200-1700 km between about 93 and 45 Ma (Housen and Dorsey, 2005).

7. Conclusions

Cretaceous sedimentary rocks exposed in the Mitchell Inlier of central Oregon record sedimentation in the Ochoco forearc basin during co-eval subduction of the Farallon plate and dextral transpressive deformation in the Cordilleran magmatic arc system. Detailed mapping and structural analysis at Toney Butte reveal a pattern of superposed folds including the NW-trending Toney Butte anticline and the NE-trending Mitchell anticline. This study documents systematic stratigraphic pinch-out of the entire thickness (~1.2-1.4 km) of the Main Mudstone member of the Hudspeth Formation across the axis of the Toney Butte anticline. After evaluating different hypotheses for paleorelief and accounting for ~37° of post-basinal clockwise rotation (Housen and Dorsey, 2005), we conclude that the Toney Butte anticline initially grew during deposition of the Albian Main Mudstone member as an east-trending basement-cored uplift, and was later refolded in Tertiary time by the Mitchell anticline.

We infer that Albian north-south shortening at Toney Butte resulted from the margin-parallel component of regional transpression in terranes of the Blue Mountains province as they were translated northward along the Cordilleran margin. In this interpretation, regional N-S shortening produced an orogenic highland in older volcanic and low-grade metamorphic rocks north of the Ochoco basin, creating a source for voluminous gravel and sand (Gable Creek Formation) that was transported south into the forearc basin. A new paleomagnetic study by Housen and Dorsey (2005) provides evidence for ca. 1200-1700 km of northward translation of the Mitchell Inlier since ~93 Ma. The paleomagnetic results are consistent with a pronounced compositional mismatch between detritus in the Ochoco basin and the expected source terrane in western Idaho. Taken together, both datasets suggest that the Ochoco basin may have been located at the approximate latitude of the Sierra Nevada arc in California during mid-Cretaceous time.

Acknowledgements

Expenses for this study were supported by a grant-in-aid from Texaco to R. Lenegan. Jack Roden, Audrey Jackson, and Joe and Evelyn Fitzgerald are thanked for granting us access to their properties for field work. Ben Andrews and Sheri Forst provided valuable assistance in the field, and Peter Rodda spent several days in the field with us and provided many expert ammonite identifications. Our understanding of Cretaceous geology in the Mitchell area and the western U.S. has benefited from discussions with John Dilles, Bernie Housen, Susanne Janecke, Alan Kays, Andrew Meigs, Marli Miller, Ed Taylor, Paul Umhoefer, Ray Weldon, and Sandra Wyld. We thank Darrel Cowan, Karen Kleinspehn, Brian Mahoney, Peter Mustard, Ed Taylor, and Paul Umhoefer for insightful reviews of this manuscript and its previous incarnations. We are especially grateful to Mark Cloos for encouraging us to contribute to this special volume.

REFERENCES CITED

Armstrong, R.L., Taubeneck, W.H., and Hales, P.O., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition: Oregon, Washington, and Idaho, *Geol. Soc. Am. Bull., 88*, 397-411.

Avé Lallemant, H. G., Pre-Cretaceous tectonic evolution of the Blue Mountains Province, northeastern Oregon, 1995, *USGS Prof. Paper* 1438, 271-304.

Brooks, H.C., and Vallier, T.L., 1978, Mesozoic rocks and tectonic evolution of eastern Oregon and western Idaho, in *Mesozoic paleogeography of the western United States, Pacific Coast Paleogeography Symposium,* vol. 2, edited by D.G. Howell and K.A. McDougall, pp. 133-145, SEPM Pacific Section.

Burchfiel, B.C., Cowan, D.S., and Davis, G.A., 1992, Tectonic overview of the Cordilleran orogen in the western U. S., in *The Cordilleran Orogen:*

conterminous U. S.: The Geology of North America, Decade of North American Geology, vol. G-3, edited by B.C. Burchfiel et al., pp. 407-480, Geol. Soc. America, Boulder.

Busby-Spera, C.J., and Saleeby, J.B., 1990, Intra-arc strike-slip fault exposed at batholithic levels in the southern Sierra Nevada, California: *Geology, 18*, 255-259.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes, *Nature, 288*, 329-33.

Cowan, D.S., Brandon, M.T., and Garver, J.I., 1997, Geologic tests of hypotheses for large coastwise displacements- A critique illustrated by the Baja British Columbia Controversy, *Am. J. Science, 297*, 117-178.

Cowan, D.S., and reiners, P.W., 2004, Age and provenance of lower Tertiary fluvial strata, Elkhorn Mountains, E. Oregon. *Geol. Soc. Am. Abstr. with Progr., 36 (4), 34.*

Criss, R.E., and Fleck, R.J., 1987, Petrogenesis, geochronology, and hydrothermal systems of the northern Idaho batholith and adjacent areas based on $^{18}O/^{16}O$, D/H/ $^{87}Sr/^{86}Sr$, A-Ar, and ^{40}Ar-^{39}Ar studies, in *Geology of the Blue Mountains Region of Oregon, Idaho, and Washington*, edited by T.L. Vallier and H.C. Brooks, pp. 171–196, U.S. Geol. Surv. Prof. Paper 1436.

Dawson, J.W., 1951, Geology of the Birch Creek area, Dayville quadrangle, M.S. thesis, 84 pp., Oregon State Univ., Corvallis.

Dickinson, W.R., 1979, Mesozoic forearc basin in central Oregon, *Geology, 7*, 166-170.

Dickinson, W.R., 2004, Evolution of the North American Cordillera *Ann. Rev. Earth Planet. Sci., 32*, 13-45.

Dickinson, W.R., and Thayer, T.P. (1978, Paleogeographic and paleotectonic implications of Mesozoic stratigraphy and structure in the John Day inlier of central Oregon, in *Mesozoic paleogeography of the western United States, Pacific Coast Paleogeography Symposium,* vol. 2, edited by D.G. Howell and K.A. McDougall, pp. 147-161, SEPM Pacific Section.

Dickinson, W.R., and Vigrass, L.W., 1965, Geology of the Suplee-Izee area, Crook, Grant, and Harney Counties, Oregon, *Oregon Dept. Geol. Min. Indust. Bulletin, 58*, 109 p.

Dilek, Y., and Moores, E., 1993, Across-strike anatomy of the Cordilleran Orogen at 40 degrees N latitude; implications for the Mesozoic paleogeography of the Western United States, in *Mesozoic paleogeography of the Western United States; II*, edited by G.C. Dunne and K.A. McDougall, pp. 333-346, Pacific Section SEPM, Book 71.

Dobell, J.P., 1948, Geology of the Antone District of Wheeler County, Oregon, M.S. thesis, 102 pp., Oregon State Univ., Corvallis.

Enkin, R.J., Mahoney, J.B., Baker, J., Riesterer, J., and Haskin, M.L., 2003, Deciphering shallow paleomagnetic inclinations: 2. Implications from Late Cretaceous strata overlapping the Insular/Intermontane Superterrane boundary in the southern Canadian Cordillera, *J. Geophys. Res., 108*, 2186, doi:10.1029/2002JB001983.

Evans, J.P., 1993, Deformation mechanisms and kinematics of a crystalline-cored thrust sheet: The EA thrust system, Wyoming, in *Laramide basement deformation in the Rocky Mountain foreland of the Western United States*, edited by C.J. Schmidt et al., pp. 147–161, *Geol. Soc. Am. Special Paper, 280*.

Fleck, R.J., and Criss, R.E., 1985, Strontium and oxygen isotopic variations in Mesozoic and Tertiary plutons of central Idaho, *Contributions to Mineralogy and Petrology, 90*, 291–308.

Gastil, G., Morgan, G.J., and Krummenacher, D., 1981, The tectonic history of peninsular California and adjacent Mexico, in *The geotectonic development of California; Rubey Volume I*, edited by W.G. Ernst, pp. 284-306, Prentice-Hall, Englewood Cliffs.

Gillaspy, J., Tikoff, B., Kolker, A., and Wojtal, S., 2000, Transpressional fabric in orthogneiss of the western Idaho shear zone, Idaho, *Geol. Soc. Am. Abstr. with Progr*., 32(7), 99.

Getty, S. R., Selverstone, J., Wernicke, B. P., Jacobsen, S. B., Aliberti, E., and Lux, D. R., 1993, Sm-Nd dating of multiple garnet growth events in an arc-continent collision zone, northwestern U.S. Cordillera, *Contrib. Miner. Petrol., 115*, 45-57.

Gray, K.D., and Oldow, J.S., 2005, Contrasting structural histories of the Salmon River belt and Wallowa terrane: Implications for terrane accretion in northeastern Oregon and west-central Idaho: *Geol. Soc. Am. Bull., 117,* p. 687-706.

Greene, D.C., and Schweickert, R.A., 1995, The Gem Lake shear zone; Cretaceous dextral transpression in the northern Ritter Range pendant, eastern Sierra Nevada, California, *Tectonics, 14*, 945-961.

Grommé, C. S., M. E. Beck Jr., and D. C. Engebretson (1986), Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific Northwest, *J. Geophys. Res., 91,* 14,089-14,103.

Hardy, S., and Poblet, J., Geometric and numerical model of progressive limb rotation in detachment folds, *Geology, 22*, 371-374, 1994.

Housen, B.A., and Beck, M.E., Jr., 1999, Testing terrane transport; an inclusive approach to the Baja B.C. controversy, *Geology, 27*, 1143-1146.

Housen, B. A. and Dorsey, R.J., 2005, Paleomagnetism and tectonic significance of Albian and Cenomanian turbidites, Ochoco basin, Mitchell Inlier, central Oregon, *J. Geophys. Res., 110,* B07102, doi:10.1029/2004JB003458.

Johnson, S.E., Tate, M.C., Fanning, C. M., 1999, New geologic mapping and SHRIMP U-Pb zircon data in the Peninsular Ranges Batholith, Baja California, Mexico; evidence for a suture? *Geology, 27*, 743-746.

Kays, M.A., and Stimac, J.P., 2002, Growth and destruction of the Wallowa terrane, *Geol. Soc. Am. Abstr. with Progr., 34(5)*, A-21.

Kleinhans, L.C., Barcells-Baldwin, E.A., and Jones, R.E., 1984, A paleogeographic reinterpretation of some middle Cretaceous units, north-central Oregon: Evidence for a submarine turbidite system, in *Geology of the upper Cretaceous Hornbrook Formation, Oregon and California*, edited by T.H. Nilsen, pp. 239-257, Pacific Section SEPM, 42.

Lahren, M.M., Schweickert, R.A., Mattinson, J.M., and Walker, J.D., 1990, Evidence of uppermost Proterozoic to Lower Cambrian miogeoclinal rocks and the Mojave-Snow Lake fault: Snow Lake pendant, central Sierra Nevada, California, *Tectonics, 9*, 1585-1608.

Lenegan, R.J., 2001, Middle Cretaceous sedimentation and tectonics of the Mitchell inlier, Wheeler County, central Oregon, M.S. thesis, 133 pp., Univ. Oregon, Eugene, 125 pp.

Little, S.W., Stratigraphy, petrology, and provenance of the Cretaceous Gable Creek Formation, Wheeler County, Oregon, M.S. thesis, 133 pp., Oregon State Univ., Corvallis.

Lowe, D.R., 1982, Sediment gravity flows II: depositional models with special reference to the deposits of high-density turbidity currents, *J. of Sedim. Petrol., 52*, 279-297.

Lund, K., and Snee, L.W., 1988, Metamorphism, structural development, and age of the continent-island arc juncture in west-central Idaho, in *Metamorphism and crustal evolution, western coterminous United States, Rubey Volume VII*, edited by W.G. Ernst, pp. 296-331 Englewood Cliffs, New Jersey, Prentice Hall,.

Mahoney, J.B., Mustard, P.S., Haggart, J.W., Friedman, R.M., Fanning, C.M., McNicoll, V.J., 1999, Archean zircons in Cretaceous strata of the western Canadian Cordillera; the "Baja B.C." hypothesis fails a "crucial test", *Geology, 27*, 195-198.

Manduca, C.A., Silver, L.T., and Taylor, H.P., 1992, $^{87}Sr/^{86}Sr$ and $^{18}O/^{16}O$ isotopic systematics and geochemistry of granitoid plutons across a steeply dipping boundary between contrasting lithospheric blocks in western Idaho, *Contrib. Miner. Petrol., 109*, 355-372.

Manduca, C.A., Kuntz, M.A., and Silver, L.T., 1993, Emplacement and deformation history of the western margin of the Idaho Batholith near McCall, Idaho: Influence of a major terrane boundary, *Geol. Soc. Am. Bull.*, 105, 749-765.

McClelland, W.C., Tikoff, B., and Manduca, C.A., 2000, Two-phase evolution of accretionary margins: examples from the North America Cordillera. *Tectonophysics, 326*, 37-55.

McKnight, B.K., 1964, A stratigraphic study of the marine Cretaceous rocks near Mitchell, Oregon, M.S. thesis, 89 pp., Oregon State Univ., Corvallis.

Monger, J.W.H., and Price, R.A., 1996, Comment on " Paleomagnetism of the Upper Cretaceous strata of Mount Tatlow: Evidence for 3000 km of northward displacement of the eastern Coast Belt, British Columbia" by P.J. Wynne, et al., and on "Paleomagnetism of the Spences Bridge Group and northward displacement of the Intermontane Belt, British Columbia: A second look" by E. Irving, et al., *J. Geophys. Res., 101*, 13793-13799.

Narr, W., and Suppe, J., 1994, Kinematics of basement-involved compressive structures, *Am. J. Science, 294*, 802-860.

Nilsen, T.H., 1986, Cretaceous Paleogeography of Western North America, in *Cretaceous Stratigraphy of Western North America*, edited by Abbott, P.L., Pacific Section, SEPM, 1-39.

Oldow, John S., 1984, Evolution of a late Mesozoic back-arc fold and thrust belt, northwestern Great Basin, U.S.A. *Tectonophysics 102*, 245-274.

Oles, K.F., and Enlows, H.E., 1971, Bedrock geology of the Mitchell quadrangle, Wheeler County, Oregon Dept. Geol. Min. Indust. Bulletin 72, 62 pp.

Patton, T.L., 2004, Numerical models of growth-sediment development above a monocline, *Basin Res., 16,* 25-39.

Payne, J.D., and McClelland, W.C., 2002, Kinematic and temporal constraints for truncation of the wetsren Idaho shear zone, *Geol. Soc. Am. Abstr. Progr.*, 34(5), 102.

Schweickert, R.A., and Lahren, M.M., 1990, Speculative reconstruction of the Mojave-Snow Lake fault: Implications for Paleozoic and Mesozoic orogenesis in the western United States, *Tectonics, 9, 1609-1629*.

Selverstone, J., Wernicke, B.P., and Aliberti, E.A., 1992, Intracontinental subduction and hinged unroofing along the Salmon River Suture Zone, West Central Idaho, *Tectonics, 11*, 124-144.

Shanmugam, G., 1996, High-density turbidity currents: are they sandy debris flows? *J. Sedim. Res., 66*, 2-10.

Silberling, N.J., Jones, D.L., Blake, M.C., Jr., and Howell, D.G., 1984, Lithotectonic terrane map of the western conterminous United States, Part C, in *Lithotectonic Terrane Maps of the North American Cordillera*, edited by Silberling, N.J., and Jones, D.L., U.S. Geol. Surv. Open-File Report 84-523, 43 pp.

Suppe, J., and Medwedeff, D.A., 1990, Geometry and kinematics of fault-propagation folding, *Eclogae Geol. Helv., 83*, 409-454.

Suppe, J., Chou, G.T., Hook, S.C., 1992, Rates of folding and faulting determined from growth strata, in *Thrust Tectonics*, edited by K.R. McClay, Chapman & Hall. London, pp. 105-121.

Suppe, J., Sabat, F., Munoz, J. A., Poblet, J., Roca, E., Verges, J., 1997, Bed-by-bed fold growth by kink-band migration; Sant Llorenc de Morunys, eastern Pyrenees. *J. Struct. Geol., 19*, 443-461.

Thompson, G.G., Yett, J.R., and Green, K.E., 1984, Subsurface stratigraphy of the Ochoco Basin, Oregon, Oregon Dept. Geol. Min. Indust., Oil and Gas Investigations, No. 8, 18 pp.

Tikoff, B., and de Saint Blanquat, M., 1997, Transpressional shearing and strike-slip partitioning in the Late Cretaceous Sierra Nevada magmatic arc, California, *Tectonics, 16*, 442-459.

Todd, V.R., Erskine, B.G., and Morton, D.M., 1988, Metamorphic and tectonic evolution of the northern Peninsular Ranges Batholith, Southern California, in *Metamorphism and crustal evolution of the Western United States, Rubey Volume 7*, edited by W.G. Ernst, pp. 894-937. Prentice-Hall, Englewood Cliffs.

Umhoefer, P.J., 1987, Northward translation of “Baja British Columbia” along the late Cretaceous to Paleocene margin of western North America, *Tectonics, 6*, 377-394.

Umhoefer, 2003, A model for the North America Cordillera in the Early Cretaceous; tectonic escape related to arc collision of the Guerrero Terrane and a change in North America plate motion, in *Tectonic evolution of northwestern Mexico and the Southwestern USA,* edited by S.E. Johnson, S.R. Paterson, J.M. Fletcher, G.H. Girty, D.L. Kimbrough, A. Martin-Barajas, p. 117– 134. *Geol. Soc. Am. Special Paper, 374.*

Umhoefer, P.J., and Blakey, R.C., in press, Moderate northward translation of Baja British Columbia from southern California and its relation to the Laramide orogenic belt, in *Paleogeography of Western North America: Evidence for and Against Large-Scale Displacements,* edited by J. W. Haggart, R. J. Enkin, and J. W. H. Monger, *Geol. Assoc. Canada Special Paper.*

Vallier, T.L., 1995, Petrology of pre-Tertiary igneous rocks in the Blue Mountains region of Oregon, Idaho, and Washington: Implications for the geologic evolution of a complex island arc. In *Geology of the Blue Mountains region of Oregon, Idaho and Washington: Petrology and tectonic evolution of pre-Tertiary rocks of the Blue Mountains Region*, edited by T.L. Vallier and H.C. Brooks, pp.125-209, USGS Prof. Paper 1438.

Vallier, T.L., and Brooks, H.C., 1995, Geology of the Blue Mountains region of Oregon, Idaho, and Washington: petrology and tectonic evolution of pre-Tertiary rocks of the Blue Mountains region, USGS Prof. Paper 1428, pp. 125-209.

Walker, R.G., 1975, Generalized facies models for resedimented conglomerates of turbidite association, *Geol. Soc. Am. Bull., 86*, 737-748.

Wernicke, B.P., and Klepacki, 1988, D.W., Escape hypothesis for the Stikine Block, *Geology, 16*, 461-464.

White, J.D.L., White, D.L., Vallier, T.L., Stanley, G.D., Jr., and Ash, S.R., 1992, Middle Jurassic strata link Wallowa, Olds Ferry, and Izee terranes in the accreted Blue Mountains island arc, northeastern Oregon, *Geology, 20*, 729-732.

Wilkinson, W.D., and Oles, K.F., 1968, Stratigraphy and paleoenvironments of Cretaceous rocks, Mitchell Quadrangle, Oregon, *Am. Assoc. Petrol. Geol. Bull., 52*, 129-161.

Wyld, S.J., and Wright, J.E., 2001, New evidence for Cretaceous strike-slip faulting in the United States cordillera and implications for terrane-displacement, deformation patterns, and plutonism, *Am. J. Science, 301*, 150-181.

Wyld, S. J., Umhoefer, P.J., and Wright, J. E., in press, Reconstructing northern Cordilleran terranes along known Cretaceous and Cenozoic strike-slip faults: Implications for the Baja B.C. hypothesis and other models. In: *Paleogeography of Western North America: Evidence for and Against Large-Scale Displacements,* edited by J. W. Haggart, R. J. Enkin, and J. W. H. Monger, *Geol. Assoc. Canada Special Paper*.

Wynn, P., Irving, E., Maxson, J., and Kleinsphen, K., 1995, Paleomagnetism of the Upper Cretaceous strata of Mount Tatlow: Evidence for 3000 km of northward displacement of the eastern Coast Belt, British Columbia, *J. Geophys. Res., 100*, 6073-6092.

FIGURE CAPTIONS

Figure 1. Regional tectonic setting of the Ochoco basin. (A) Simplified pre-Tertiary geology of the western United States, modified from Wyld and Wright (2001). Dashed line through Oregon and Washington defines Columbia embayment and follows approximate trend of fabrics in accreted terranes of the Blue Mountains and Klamath Mountains. Line for SRSZ coincides with $^{87}Sr/^{86}Sr$ isotope boundary of Armstrong et al. (1977; and Fig. 1B). (B) Distribution of accreted terranes in central and eastern Oregon, which together make up the Blue Mountains superterrane. Modified from Dickinson (1979). Black areas indicate Cretaceous strata of the Ochoco basin; circled dots show location of subsurface wells (Thompson et al., 1984). Approximate extent of Ochoco basin is indicated with dashed line. White areas are post-Cretaceous volcanic and sedimentary rocks. AR, Antone Ranch; BM, Blue Mountains; BR, Bernard Ranch; CLMSZ, Cuyamaca-Laguna Mountains shear zone; GR, Goose Rock; IB, Idaho Batholith; J, Jurassic; KM, Klamath Mountains; MSLF, Mojave-Snow Lake Fault; MZ, Mesozoic; OB, Ochoco Basin; Pc, Precambrian; Pz, Paleozoic; SCSZ, Sierra Crest Shear Zone System; SDM, Seven Devils Mountains; SFTB, Sevier Fold and Thrust Belt; SRSZ, Salmon River Suture; WM, Wallowa Mountains; WNS, Western Nevada Shear Zone.

Figure 2. (A) Simplified geologic map of the Mitchell inlier showing distribution of the Hudspeth and Gable Creek Formations, NE- trending Mitchell anticline, and other geologic features (modified from Kleinhans et al., 1984; original map from Oles and Enlows, 1971). (B) Geologic map of the Toney Butte area based on mapping by Lenegan (2001) with minor additions from Oles and Enlows (1971). TB, Toney Butte; TBA , Toney Butte anticline.

Figure 3. Composite stratigraphic section for the Toney Butte area. Patterns same as in Figure 2B.

Figure 4. SW-NE facies panel showing stratigraphic architecture of Cretaceous deposits west and southwest of Toney Butte. Base of unit Kg-1C serves as the datum. Lithic designators are explained in Figure 3. Letters (A-H) indicate order of conglomerate-sandstone units in Gable Creek Formation. Location of transects is shown in Fig. 2B; bold lines indicates measured sections, thin lines indicate mapping transects.

Figure 5. Outcrop photographs showing lithologies and features of Cretaceous strata in the Toney Butte area. (A) Clast-supported conglomerate of the Basal Hudspeth Formation with oversized clasts of basement rock (upper part of photo). The largest clast, visible above the notebook, is ~80 x 20 cm. Notebook is 19 cm long. (B) Clast-supported conglomerate of the Gable Creek Formation showing very thick, massive nature and interbedded sandstone (dashed lines). Bedding dips obliquely away from viewer. (C) Bedded sandstone of the Gable Creek Formation, showing high sandstone:shale ratio typical of sand-rich turbidites. Notebook is 19 cm long. (D) Imbricated clast fabric in Gable Creek conglomerate. Dashed line indicates bedding (interbedded sandstone unit). Clasts dip to the right side of the photo indicating transport to the left. Hammer is 33 cm long.

Figure 6. Rose diagrams of paleocurrent data from clast imbrications in the Gable Creek Formation, restored to horizontal using bedding strike and dip, present-day coordinates. After restoring for ~37° of post-Albian clockwise rotation (Housen and Dorsey, 2005), southwest-directed paleocurrents restore to southerly for mid-Cretaceous time.

Figure 7. Geologic cross sections of the Toney Butte area. (A) Cross section A-A' (NW to SE) across the Mitchell anticline. (B) Cross section B-B' (N-S) showing two possible interpretations for the northward pinch-out of Main Mudstone member (Khmm) across basement-cored anticline. Solid lines represent wedging beds and progressive unconformity produced by growth of E-trending monocline during deposition of Khmm; dashed lines represent large lateral facies change from Gable Creek conglomerate in the north to Khmm mudstone in the south, and involves no syn-depositional tilting. Solid line interpretation is preferred, as discussed in text. Patterns are same as in Figure 2B; see Fig. 2B for location of section lines.

Figure 8. Oblique aerial photograph with contact lines based on 1:6,000 scale mapping, showing tight folds in Basal member of Hudspeth Formation west of Toney Butte. Sub-units of Basal Hudspeth Formation are: Khbs-g, green sandstone; Khbm, mudstone; Khbc, conglomerate; Khbs, tan sandstone (Fig. 3). Khmm, Main Mudstone member of Hudspeth Formation; Pzb, Paleozoic basement rocks. Location of this area indicated by position of cross-section line C-C' in Fig. 2B. Line of section is ~700 m long.

Figure 9. Detailed geologic cross sections. (A) Cross section C-C', southwest flank of Toney Butte. (B) Cross section D-D', south flank of Toney Butte. Both cross sections show tight, asymmetric to overturned folds and rapid lateral facies changes from coarse-grained Basal Hudspeth units into mudstone. Patterns

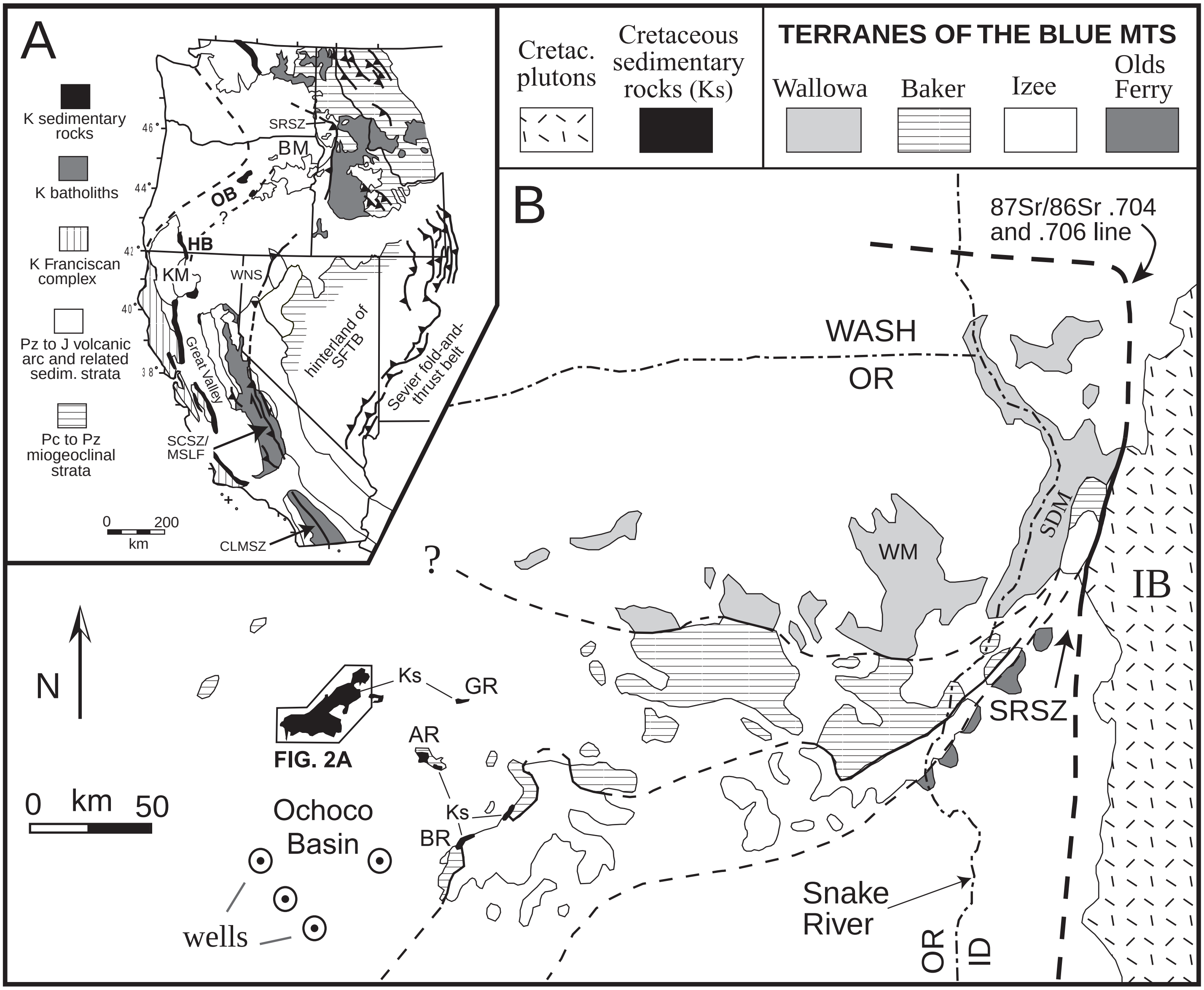
are same as in Figure 2B; see Figures 2B and 8 for location of cross sections.

Figure 10. Simplified geologic map of the Toney Butte field area showing structural domains A to C, and stereonets with results generated by fold analysis. Domain D (not shown on map) is a small area in the immediate vicinity of the Mitchell anticline axis. See text for explanation.

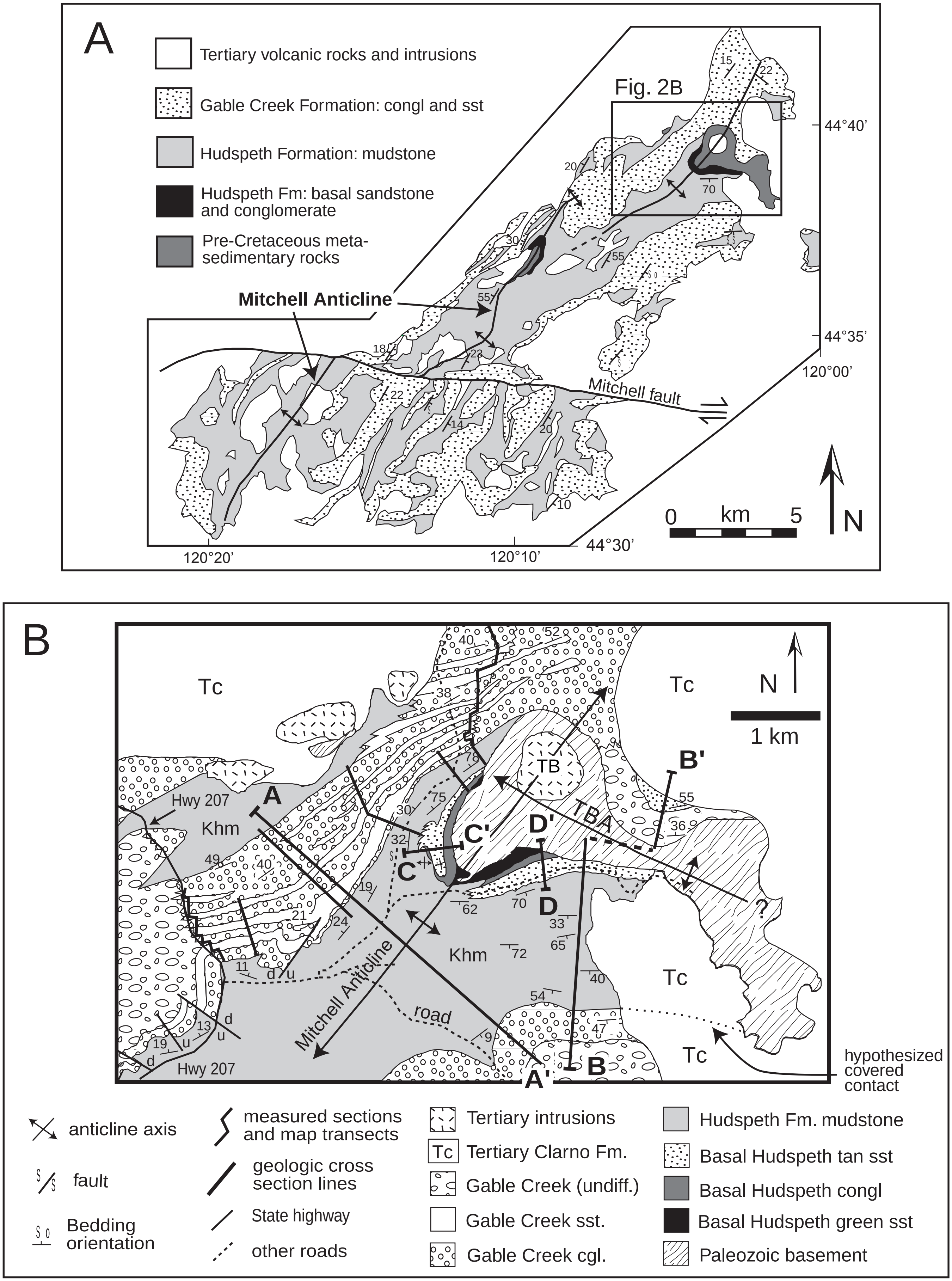
Figure 11. Schematic model for superposed folds at Toney Butte. Early folds (1) formed with ~NW trend (present coordinates) during deposition of the Main Mudstone member; this sketch illustrates a minor fold parasitic to the Toney Butte anticline. These were later folded about the Mitchell anticline axis (2) and rotated into their present orientations during Tertiary deformation.

Figure 12. Three hypothetical models for the Toney Butte anticline based on restoration of cross section B-B' (Fig. 7B) to its pre-Gable Creek orientation. This also restores ~37° of post- Gable Creek clockwise rotation (Housen and Dorsey, 2005). (A) Traditional hypothesis for pinch-out of the Hudspeth Main Mudstone member by stratigraphic onlap onto pre-existing erosional topography, with no syn-Hudspeth folding. (B) Growth-fold hypothesis assuming fold geometry 1 (e.g. Suppe and Medwedeff, 1990; Suppe et al., 1992). (C) Growth-fold hypothesis assuming fold geometry 2 (e.g. Hardy and Poblet, 1994; Patton, 2004). We conclude that the growth-fold hypothesis in C is most consistent with the field data and observations. See text for discussion.

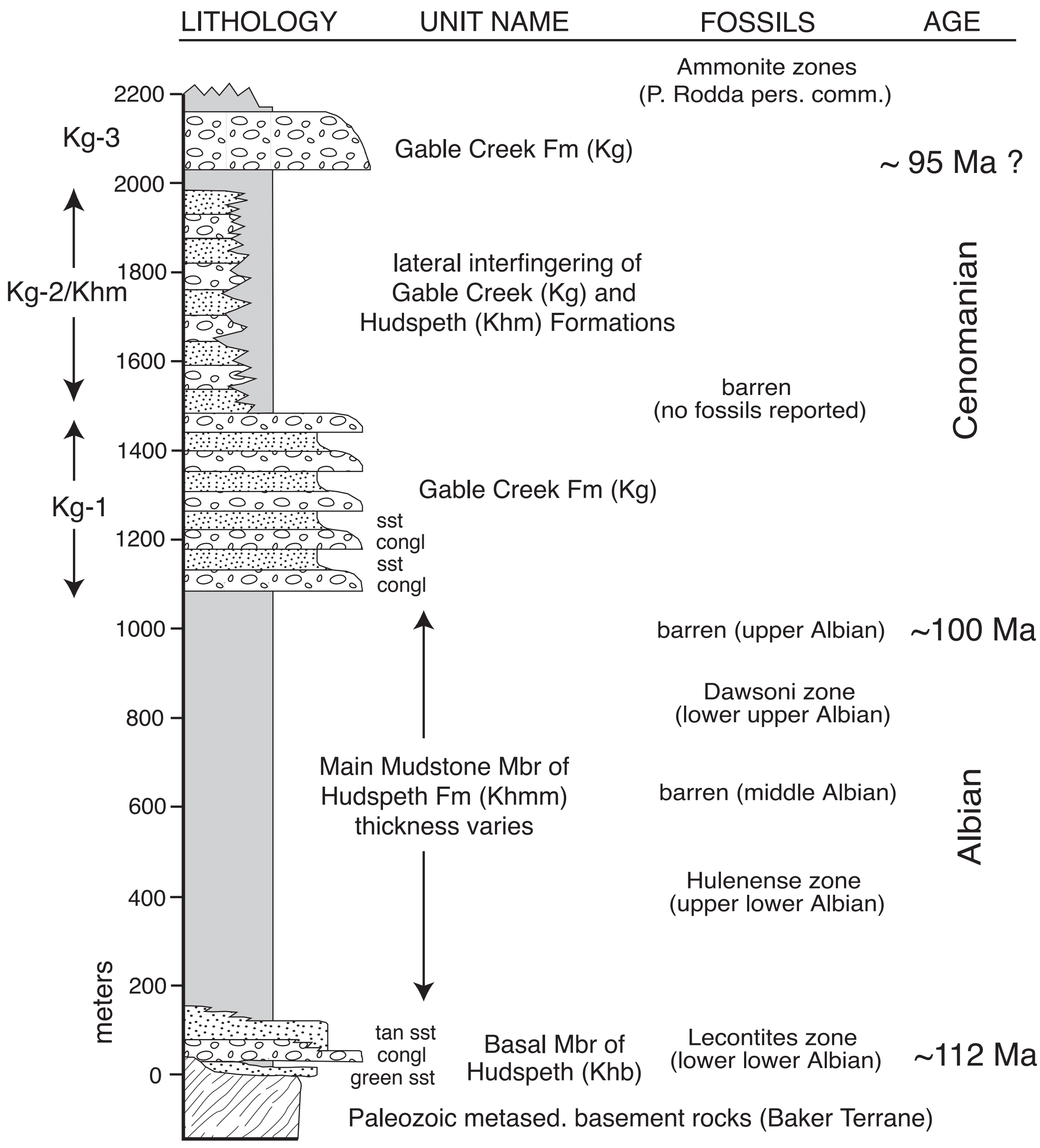
Figure 13. Interpretive sketch of regional tectonic setting for the mid-Cretaceous Ochoco forearc basin between a subduction zone to the west and magmatic arc to the east. N-S shortening, which formed the E-W trending anticline at Toney Butte, is interpreted to reflect the margin-parallel component of regional transpressive strain. Paleomagnetic data (Housen and Dorsey, 2005), and compositional mismatch between Ochoco basin detritus and metamorphic rocks exposed in western Idaho, suggest that the basin may have formed adjacent to the Sierra Nevada Batholith (SNB). Faults in the arc are schematic and inferred from previous studies that document Cretaceous intra-arc transpressive deformation. See text for discussion.



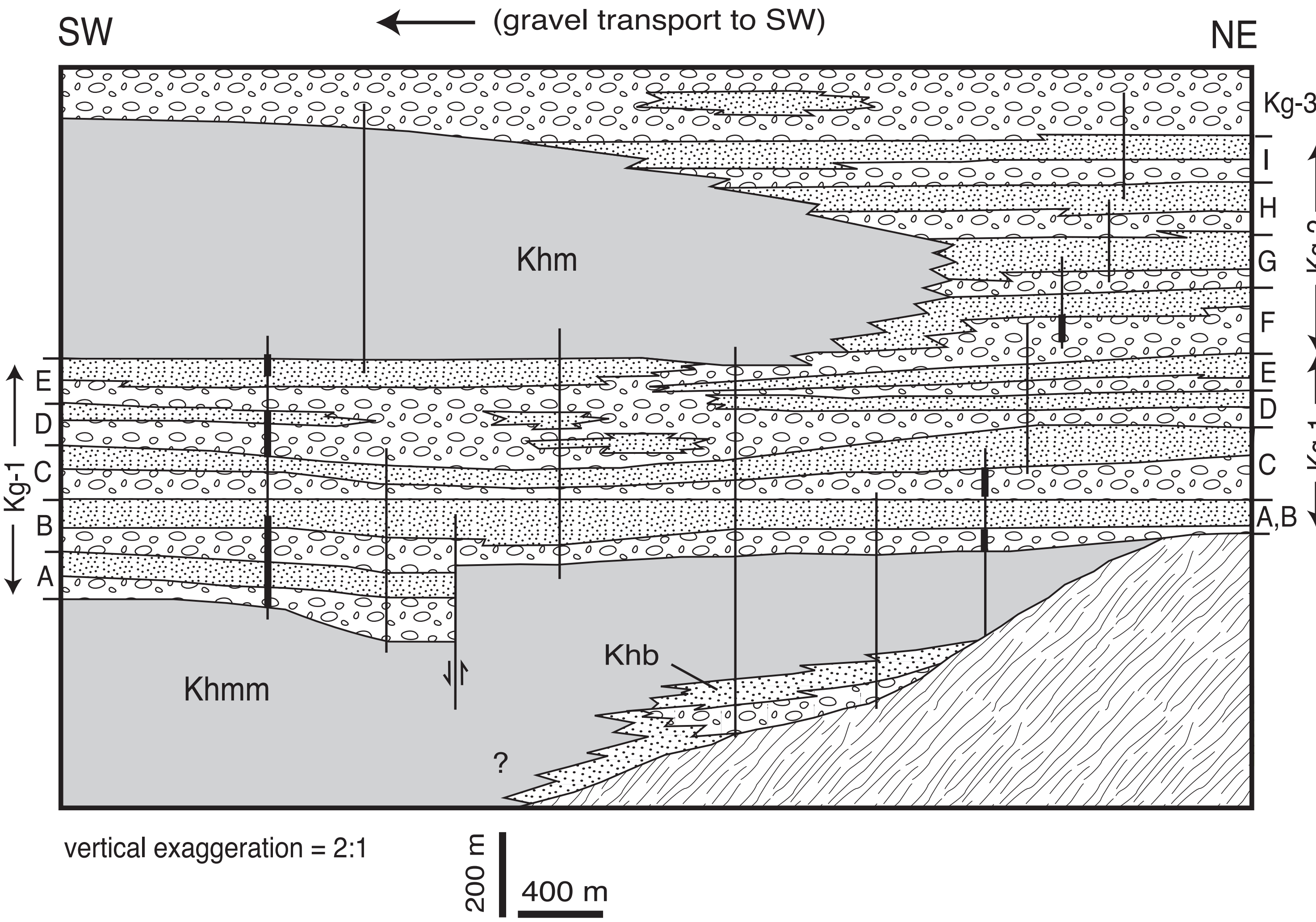
Dorsey and Lenegan, Figure 1



Dorsey and Lenegan, Figure 2

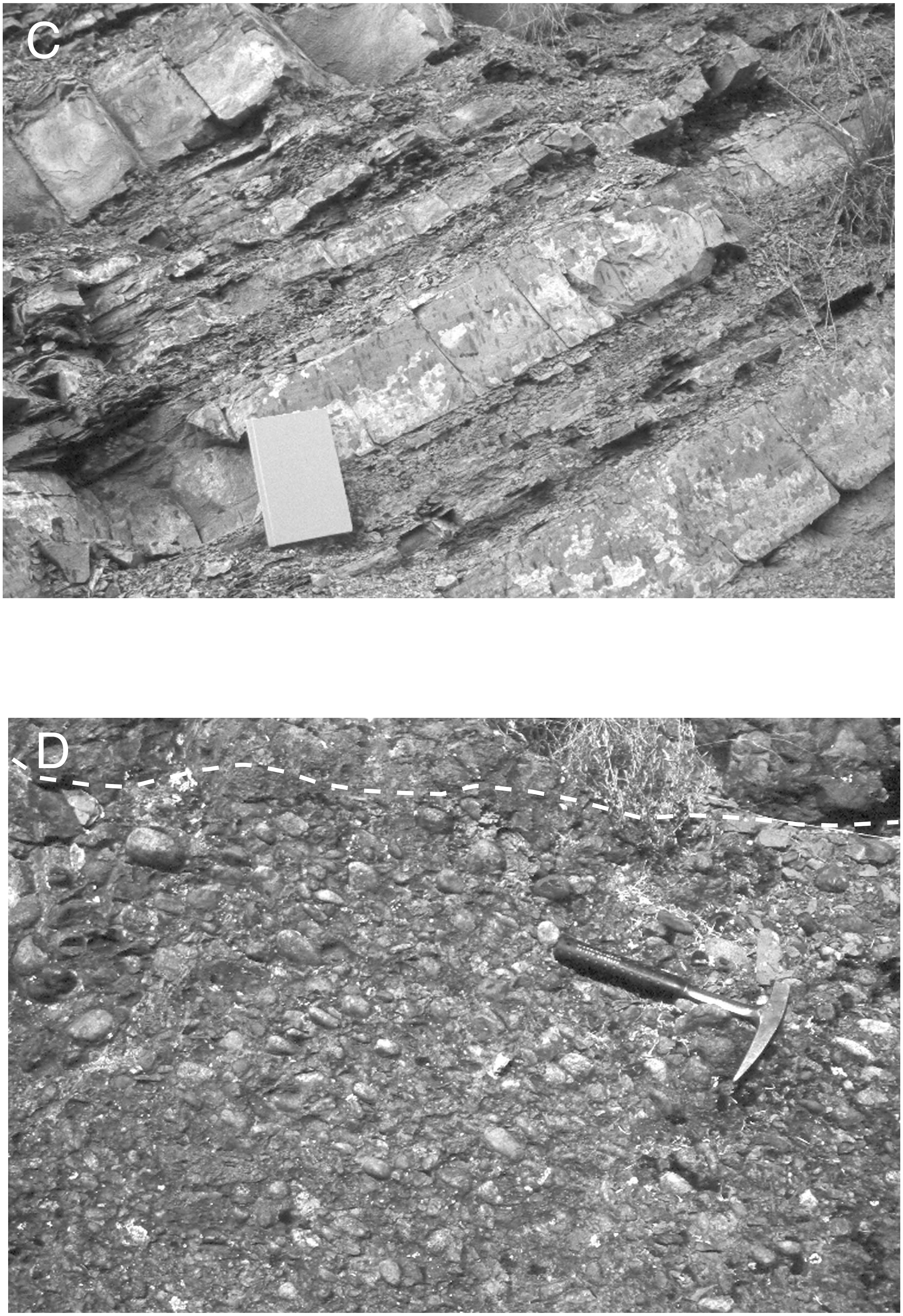


Dorsey and Lenegan, Figure 3

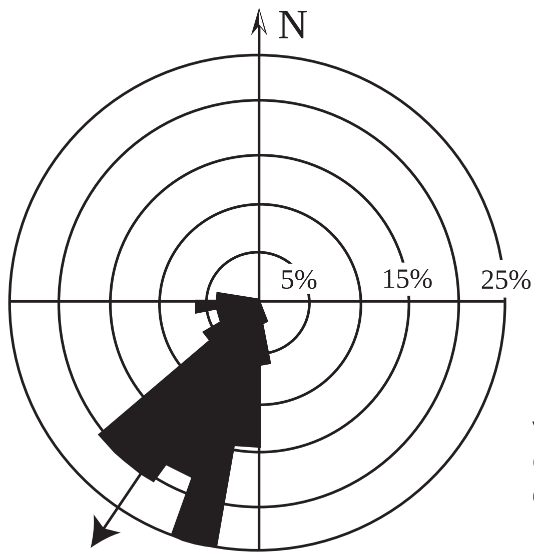


Dorsey and Lenegan, Figure 4

Dorsey and Lenegan, Figure 5A, 5B

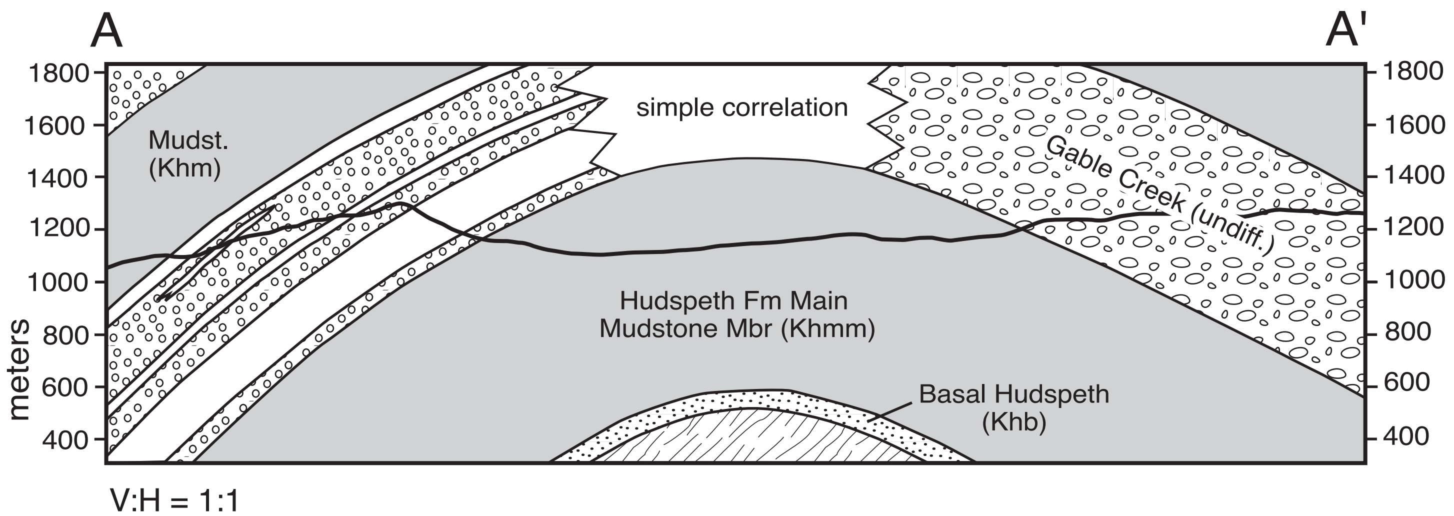


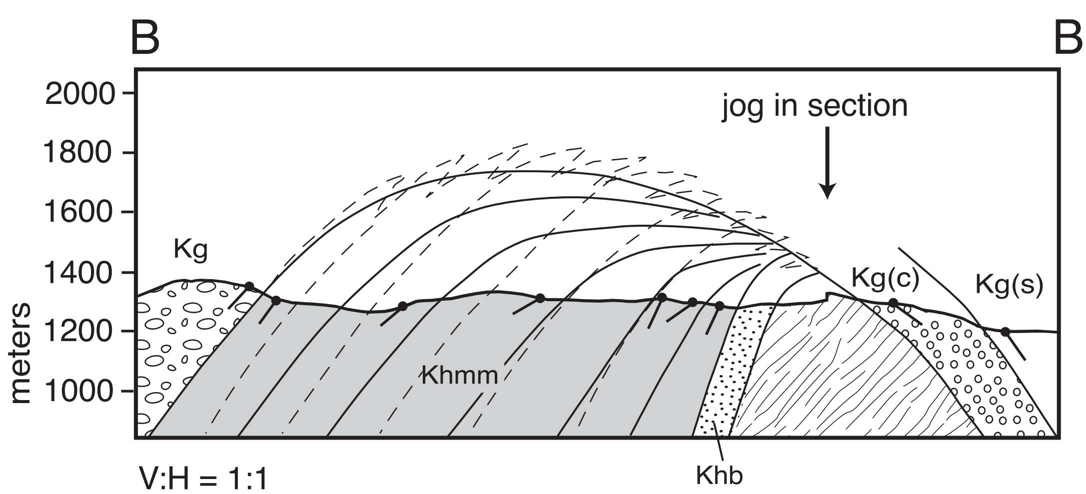
Dorsey and Lenegan, Figure 5C, 5D



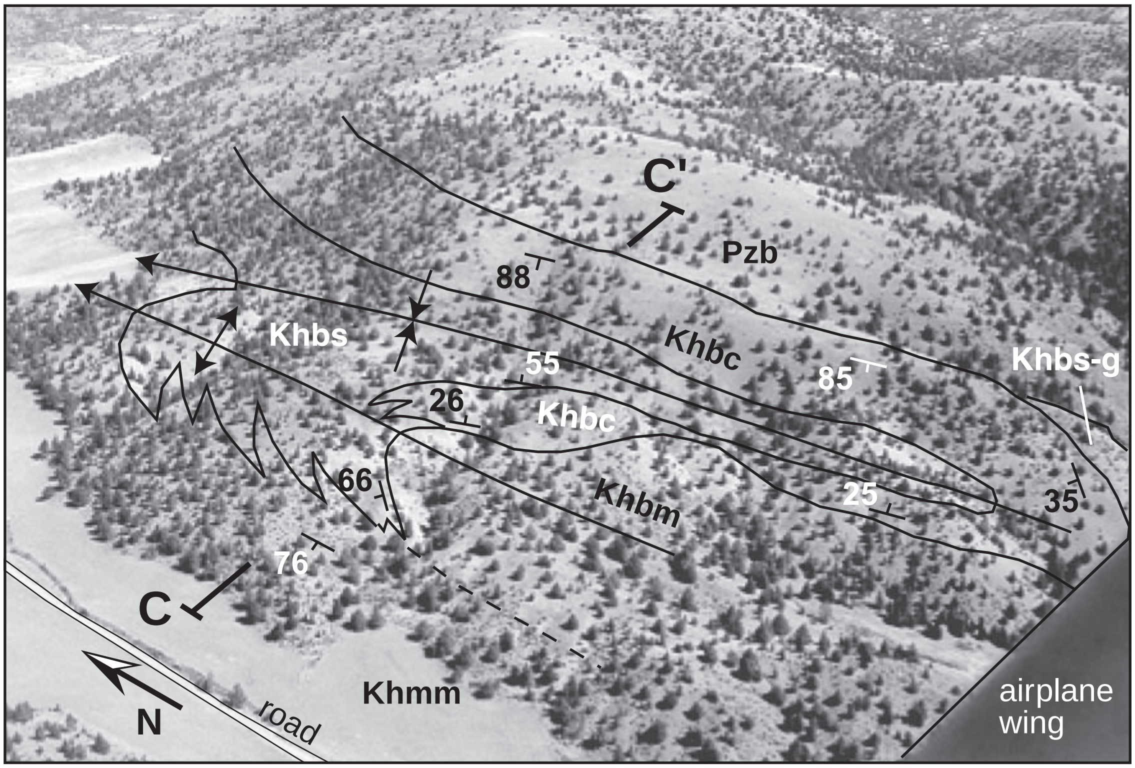
N = 65;
Vector Mean = 214;
Circular standard
deviation = 30

Dorsey and Lenegan, Figure 6

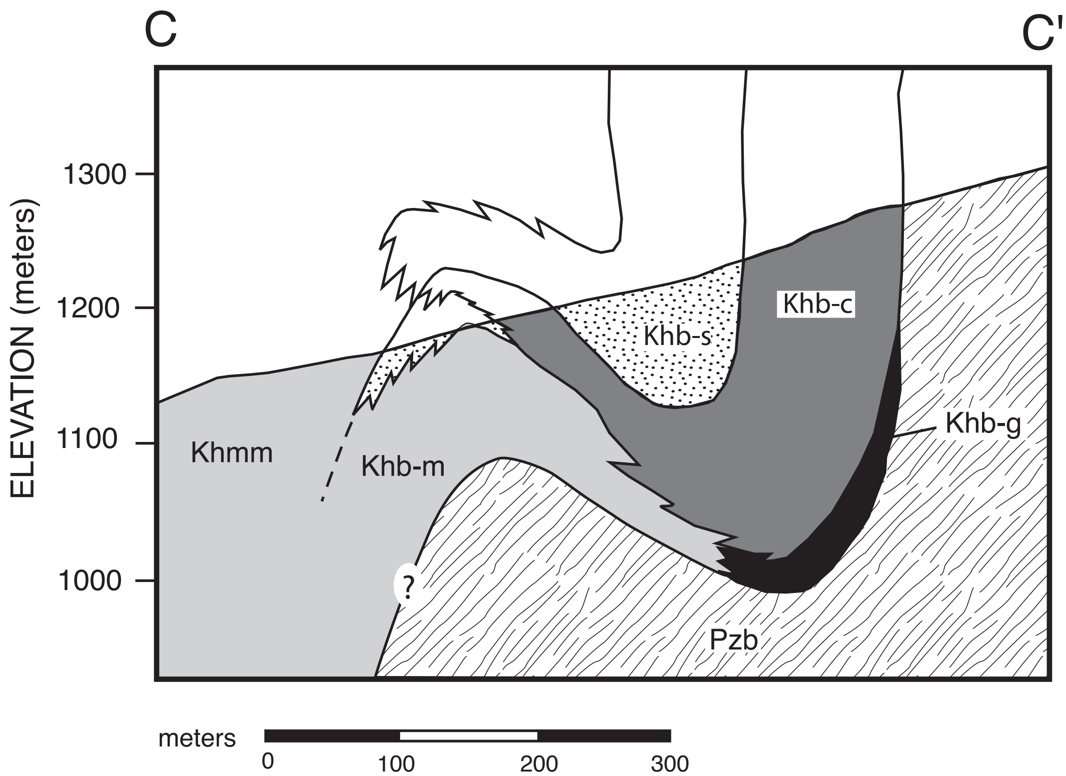


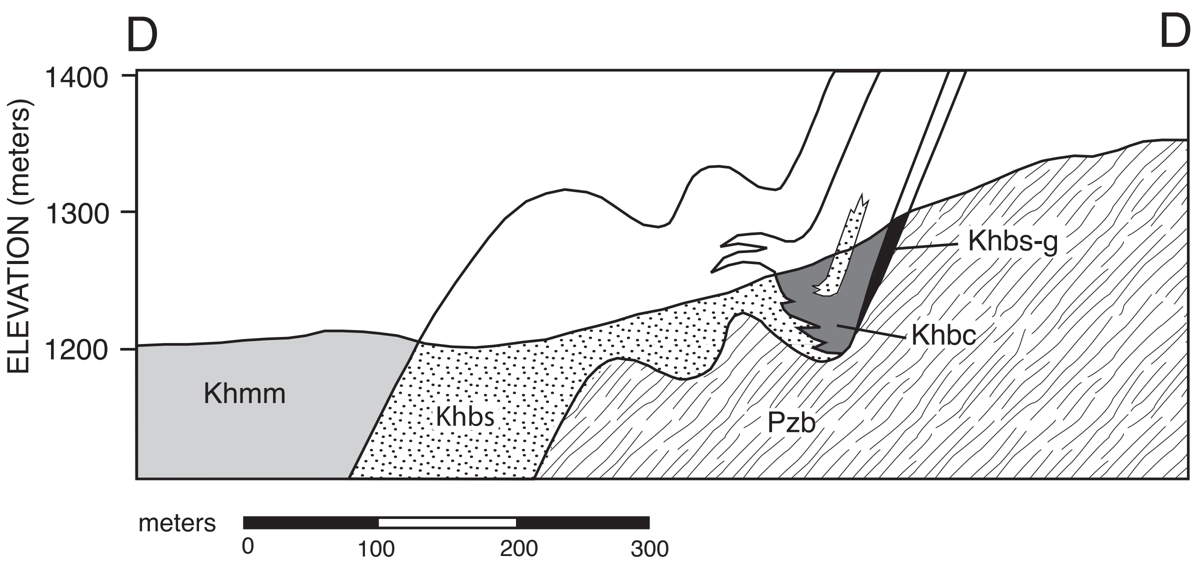


Dorsey and Lenegan, Figure 7

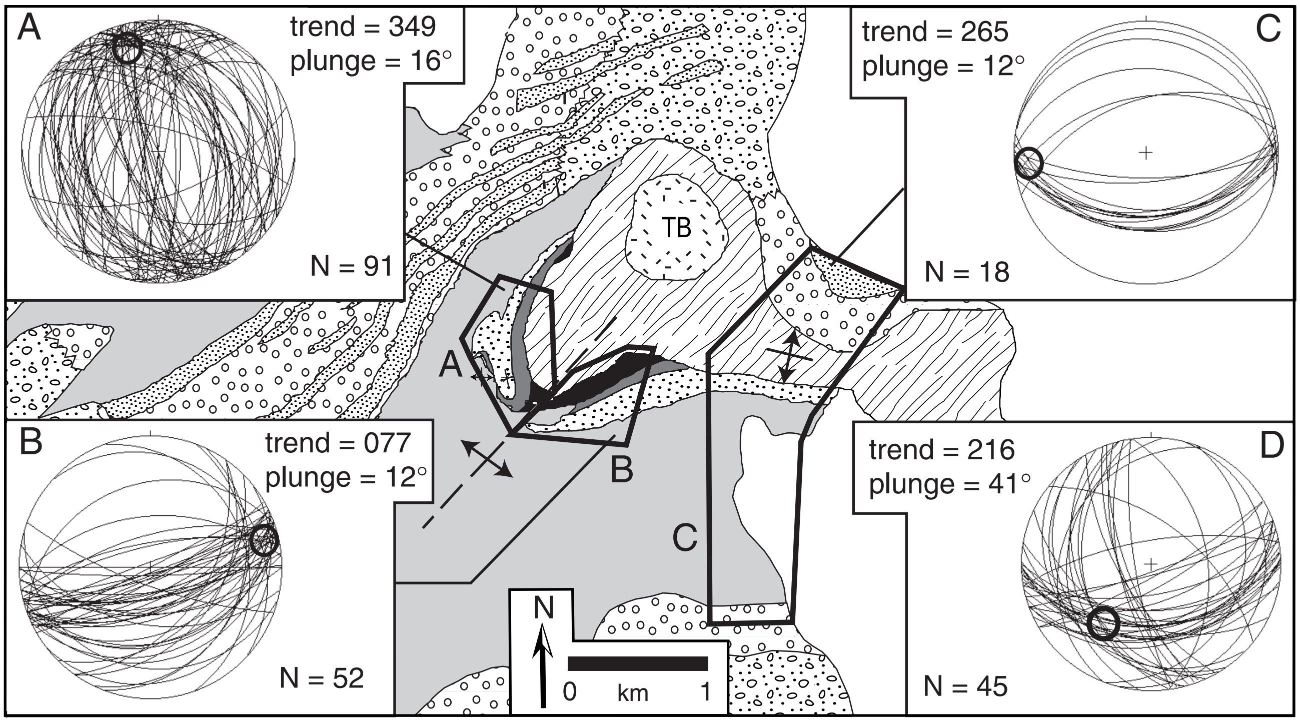


Dorsey and Lenegan, Figure 8

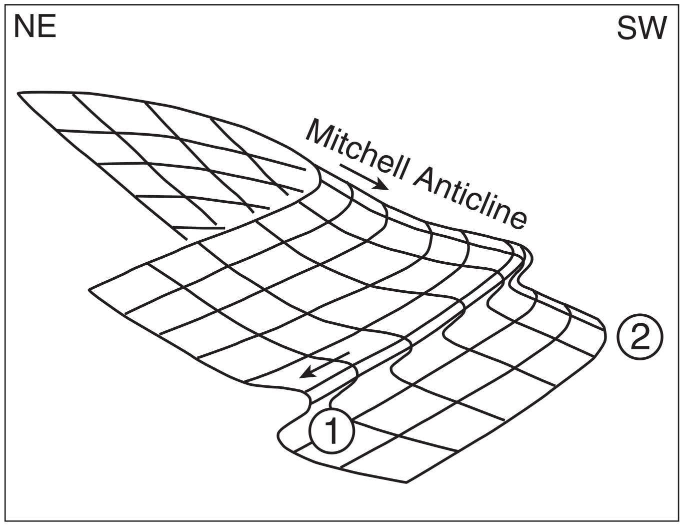




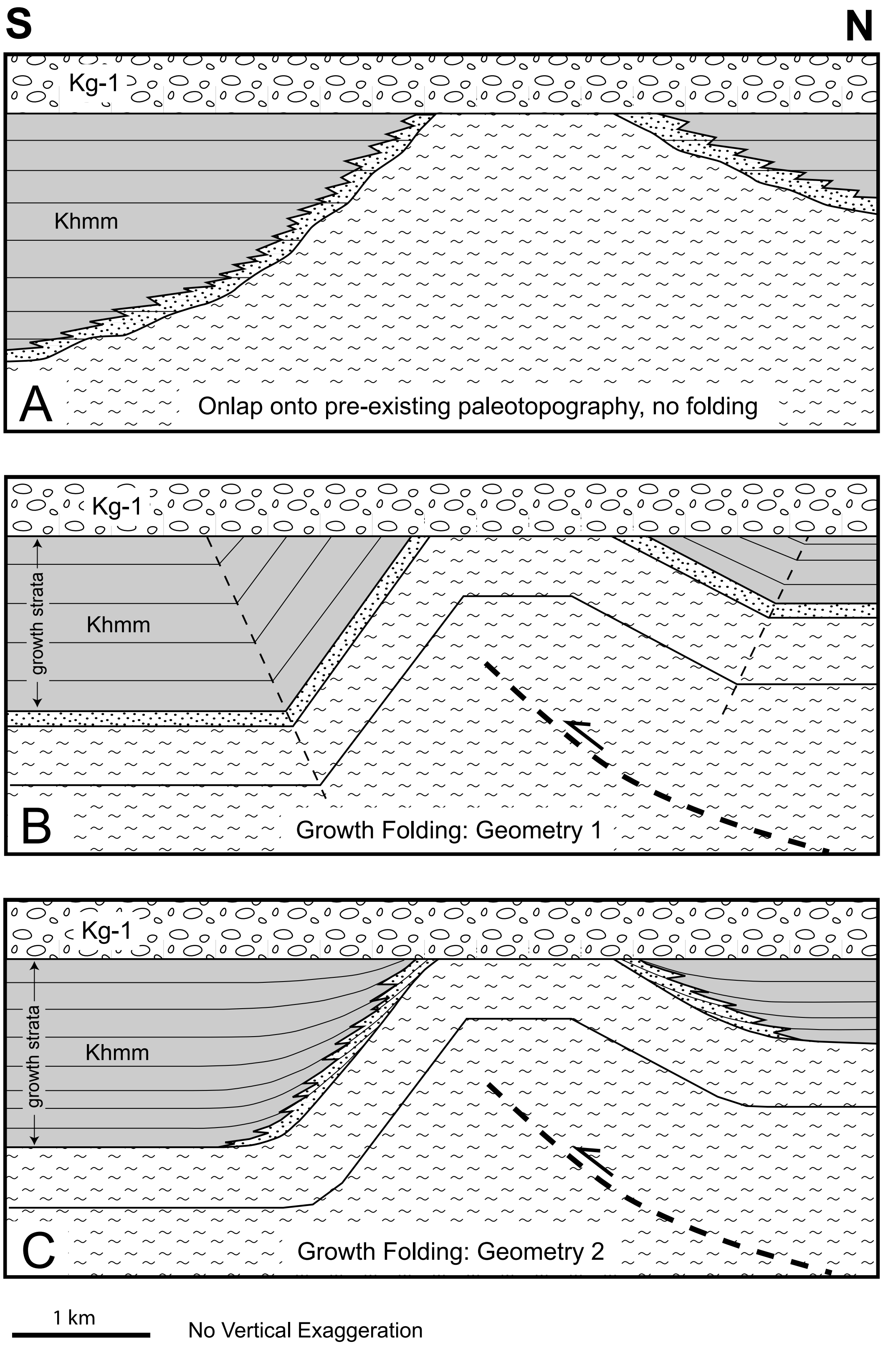
Dorsey and Lenegan, Figure 9



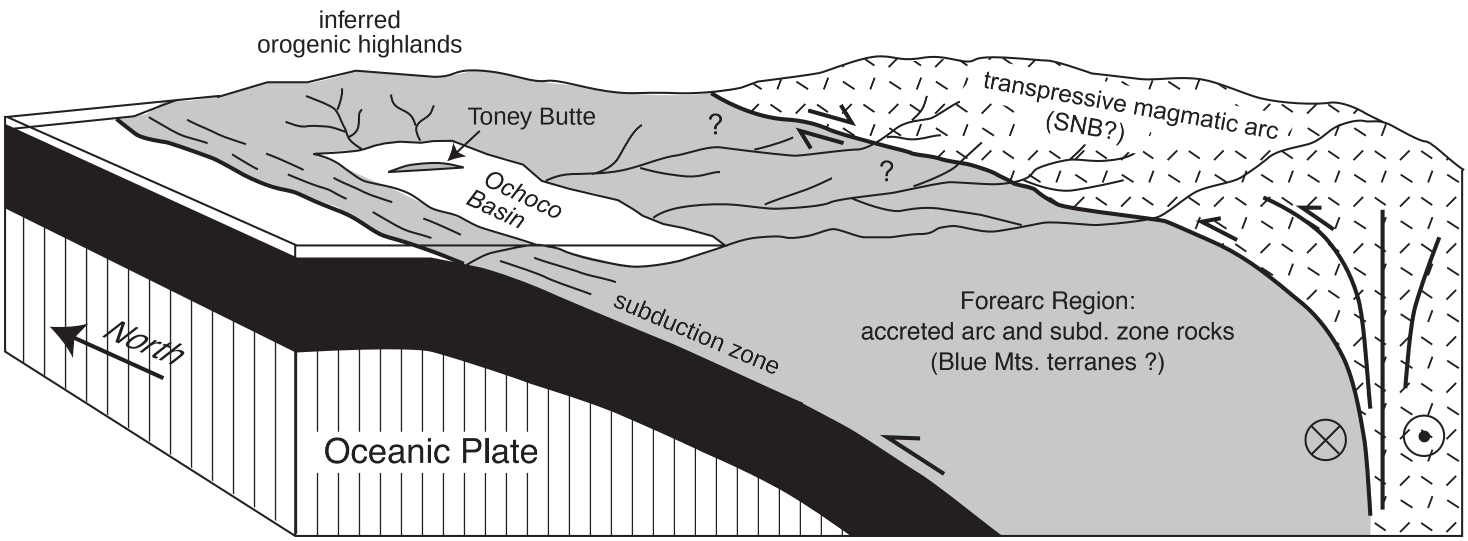
Dorsey and Lenegan, Figure 10



Dorsey and Lenegan, Figure 11



Dorsey and Lenegan, Figure 12



Dorsey and Lenegan, Figure 13