



Reconstructing northern Cordilleran terranes along known Cretaceous and Cenozoic strike-slip faults: Implications for the Baja British Columbia hypothesis and other models

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Abstract

We present a new reconstruction of the mid-Cretaceous (100 Ma) paleogeography of the United States and Canadian Cordillera, based on (a) restoring displacements within the major Late Cretaceous to Cenozoic contractional and extensional belts, and (b) restoring displacements along the major Late Cretaceous to Cenozoic dextral strike-slip faults of the northern Cordillera. The reconstruction moves the southern end of Insular superterrane to the latitude of the southern Klamath Mountains, the southwest Intermontane superterrane to central Oregon, and the southern Coast orogen into the intervening region. Restored terranes partly fill in the region of the Columbia embayment. Total displacements range from ~450 to 900 km, and increase from east to west. These values are smaller than those determined by paleomagnetic studies (1100–3000 ± 500–900 km), but they indicate that discrepancies between geologic and paleomagnetic data sets are not as large as is often assumed. The reconstruction results in the juxtaposition of geologic features that have previously been correlated or that have a high probability of having evolved together. Collectively, these relations lend strong support to the reconstruction, which we call the minimum fault-offset model. The model has important

implications for the Baja British Columbia controversy and the tectonic evolution of the Cordillera. Most importantly, no interpretations of mid-Cretaceous and older geology of the Cordillera should be based on the current location and arrangement of terranes in the northern part of the system, because these terranes were all located farther south during the mid-Cretaceous.

Résumé

Nous présentons une nouvelle reconstruction de la paléogéographie de la Cordillère des États-Unis et du Canada durant le Crétacé moyen (100 Ma), fondée sur (a) le rétablissement des déplacements dans les principaux domaines de contraction et d'extension du Crétacé tardif au Cénozoïque, et (b) le rétablissement des déplacements le long des principales failles de décrochement dextre dans le nord de la Cordillère du Crétacé tardif au Cénozoïque. Cette reconstruction place la partie sud du superterrane insulaire à la latitude du sud des monts Klamath, la partie sud-ouest du superterrane intermontagneux au centre de l'Oregon, et le sud de l'orogène côtier dans la région intermédiaire. Les terranes rétablis remplissent en partie la région du rentrant de Columbia. Les déplacements totaux se situent entre ~450 et 900 km et augmentent de l'est vers l'ouest. Ces valeurs sont plus petites que celles déterminées à partir d'études paléomagnétiques (1100–3000 ? 500–900 km), mais elles indiquent que les différences entre les données géologiques et paléomagnétiques ne sont pas aussi importantes que ce qu'il est souvent présumé. Cette reconstruction juxtapose des éléments géologiques qui ont été corrélés dans le passé, ou qui ont une forte probabilité d'évolution conjointe. Collectivement, ces relations appuient fortement la reconstruction que nous appelons le modèle de déplacement par faille minimal. Ce modèle comporte des implications importantes pour la controverse Baja – Colombie-Britannique et l'évolution tectonique de la Cordillère. Plus important encore, aucune interprétation de la géologie des roches d'âge crétacé moyen ou plus anciennes dans la Cordillère ne devrait être basée sur l'emplacement et l'arrangement actuels des terranes situés dans la partie nord du système, puisque ces terranes étaient tous situés plus au sud durant le Crétacé moyen.

INTRODUCTION

One of the most distinctive characteristics of the North American Cordillera is the abundance of dextral strike-slip faults of Late Cretaceous to Cenozoic age that sliver the orogenic belt, particularly in Washington, Canada, and Alaska (Fig. 1; Gabrielse, 1985, 1991; Umhoefer and Schiarizza, 1996). Total displacement across individual faults, determined from offset geologic features, varies from tens to hundreds of kilometres, with much of this displacement having taken place during the Late Cretaceous to Eocene (e.g. Lanphere, 1978; Gabrielse, 1985, 1991; Monger, 1991; Umhoefer and Schiarizza, 1996). A likely explanation for the dextral strike-slip faulting involves coupling between the North American plate and the obliquely subducting Kula plate, which separated from the Farallon plate at ~85 Ma and moved rapidly northward relative to North America until its demise at ~43 Ma (Woods and Davies, 1982; Engebretson *et al.*, 1985).

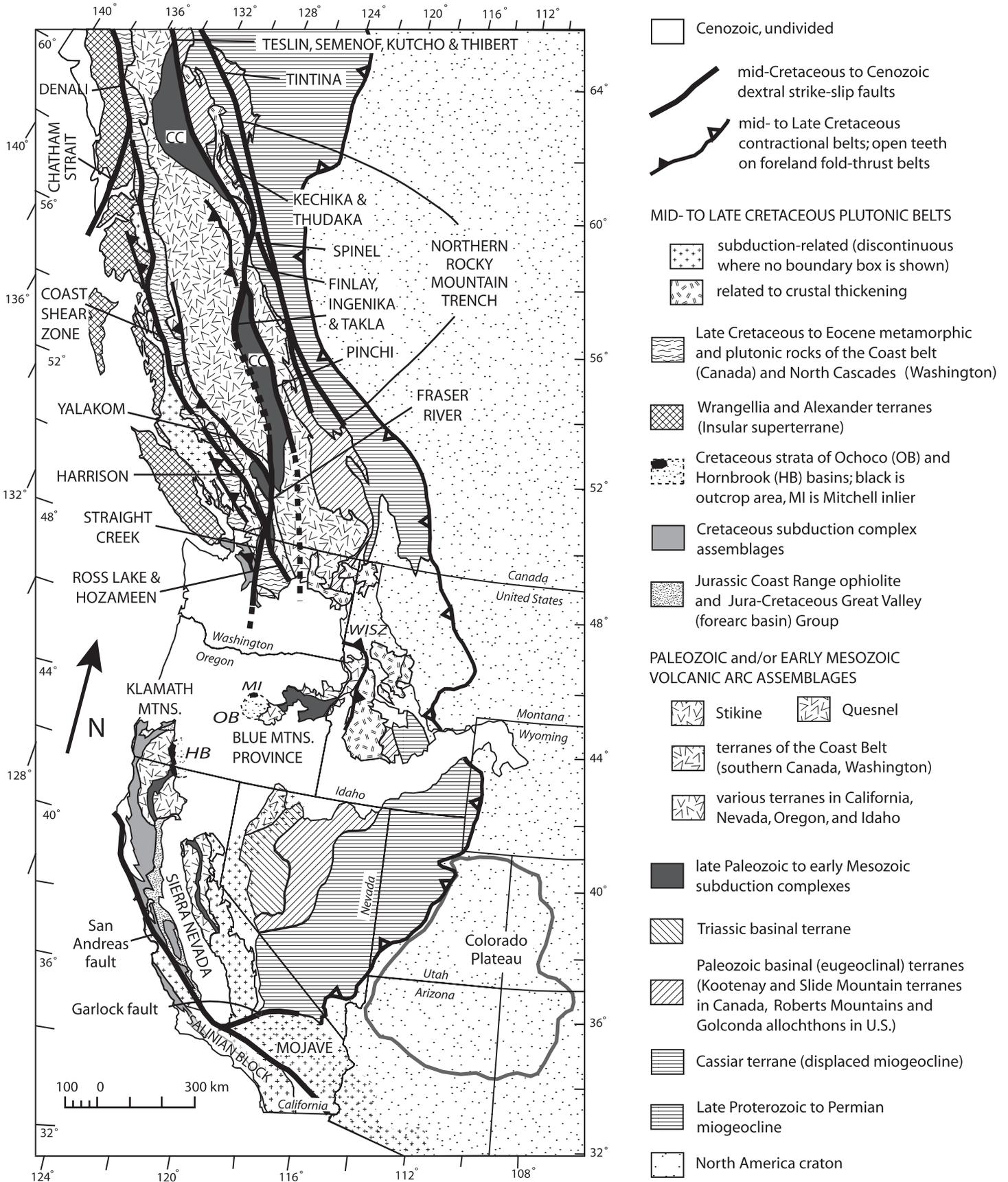
Paleomagnetic data from terranes of the northern Cordillera also support the concept of northward translations during the Late Cretaceous to early Paleogene, but generally indicate much larger amounts of displacement than can be accounted for by geologic relations. For terranes in Washington and British Columbia, the paleomagnetically determined displacements range from 1100 to 3000 km (± 500 –900 km) for the interval 100 Ma to 50 Ma (e.g. Beck *et al.*, 1981; Ague and Brandon, 1996; Wynne *et al.*, 1995, 1998; Irving *et al.*, 1996; Ward *et al.*, 1997; Stamatakos *et al.*, 2001; Enkin *et al.*, 2002, 2003; Haskin *et al.*, 2003; Housen *et al.*, 2003; Kim and Kodama, 2004). These data place the Insular super-

terranes and terranes of the Coast belt (Fig. 2) somewhere between Baja California and western Washington, with the southern option leading to the term “Baja British Columbia” to describe the block of displaced terranes (e.g. Cowan *et al.*, 1997).

As discussed by Cowan *et al.* (1997), conflicting translation values indicated by paleomagnetic data versus geologic data cannot both be correct, and they proposed a number of tests to determine which model is most likely. In their analysis, the debate over the displacement history of the Baja British Columbia block was framed as one between a paleomagnetically based reconstruction at *ca.* 90 Ma with ~3000 km translation (their “hypothesis B”) and an alternate *ca.* 90 Ma reconstruction with essentially no offset (their “hypothesis A”). Many studies since this publication have addressed the Baja British Columbia controversy in the context of these two hypotheses. A problem with this view, however, is the clear evidence from fault offset data that terranes in the northern Cordillera have moved hundreds of kilometres northward since the mid-Cretaceous; thus, a “no-offset” model for the Baja British Columbia block cannot be correct.

Figure 1. (facing page) Map of the Canadian and U.S. Cordillera, showing location of major faults and features discussed in text. Map was constructed primarily from Wheeler and McFeely (1991), Wheeler *et al.* (1991), and Burchfiel (1993), with supplemental more detailed data from various map sources. WISZ = western Idaho shear zone.

OFFSETS OF NORTHERN CORDILLERAN TERRANES ALONG KNOWN FAULTS



Surprisingly, although much is known about Cretaceous and Cenozoic strike-slip faulting in the northern Cordillera, few studies have attempted to restore any of the fault blocks back to their pre-faulting locations or to evaluate the geologic compatibility of such a restoration (*cf.* Davis *et al.*, 1978; Gabrielse, 1985, 1991; Saleeby and Busby-Spera, 1992; Bassett and Kleinspehn, 1996; Umhoefer and Schiarizza, 1996). Our goal in this paper is to provide a new comprehensive restoration of the major dextral strike-slip faults in the northern Cordillera, up to *ca.* latitude 60°N, using currently available data on fault offsets, and to evaluate the resulting

restoration in terms of its geologic compatibility with the stable geology to the east. The faults we focus on are shown in Figure 1. Our reconstruction restores displacement on these faults back to 100 Ma. Although some of the major northern Cordillera strike-slip faults were active largely during the Cenozoic, others were active during the mid- to Late Cretaceous, as far back as 100–85 Ma (see below); a reconstruction age of 100 Ma thus allows all of the major faults to be restored. For simplicity, we do not consider faults along the western edge of the Insular superterrane (*e.g.* Cowan, 1982). In order to generate a realistic 100 Ma paleogeographic map, we also restored displacements along the major Late Cretaceous and Cenozoic contractional and extensional belts of the Cordillera and strike-slip domains of western California (*e.g.* the San Andreas fault).

Because our reconstruction focuses on restoring known displacement along the major strike-slip faults of the northern Cordillera, but does not include any paleomagnetically based displacement values, we call it the minimum fault-offset model (or reconstruction). The reconstruction is what we consider the best paleogeographic map for the northern Cordillera during the mid-Cretaceous, based on currently available geologic data. In the Baja British Columbia controversy, we present it as the preferred minimum-translation model because it uses known strike-slip fault offsets instead of ignoring them as do models that show Canada and Washington terranes in their current positions.

In the sections below, we first summarize data on the displacement history of the faults shown in Figure 1 and explain the parameters we used to create the minimum fault-offset reconstruction. We then analyze the geologic compatibility of this model. Finally, we discuss the implications of the minimum fault-offset reconstruction for the Baja British Columbia hypothesis and other regional relations and tectonic interpretations of the North American Cordillera.

DISPLACEMENT ALONG NORTHERN CORDILLERA STRIKE-SLIP FAULTS

The Tintina fault and co-linear Northern Rocky Mountain Trench (NRMT) fault form a >2600-km-long, northwest-striking feature (Fig. 1) that has compelling evidence for major dextral motion. Permian to Late Cretaceous age features that are offset across the Tintina fault provide multiple lines of evidence for 430 km of displacement occurring after about 65 Ma (Gabrielse, 1985, 1991; Murphy and Mortensen, 2003; Gabrielse *et al.*, this volume). Larger values of offset (750–900 km) are indicated for the northern NRMT, although it is not clear exactly how much of this occurred before versus after the mid-Cretaceous (Gabrielse, 1985, 1991). Eocene or younger displacement of 125 km appears to have affected the NRMT at about latitude 57°N, near where it splays into the Spinel and other faults (Fig. 1), along which there is at least 85 km of additional Cenozoic

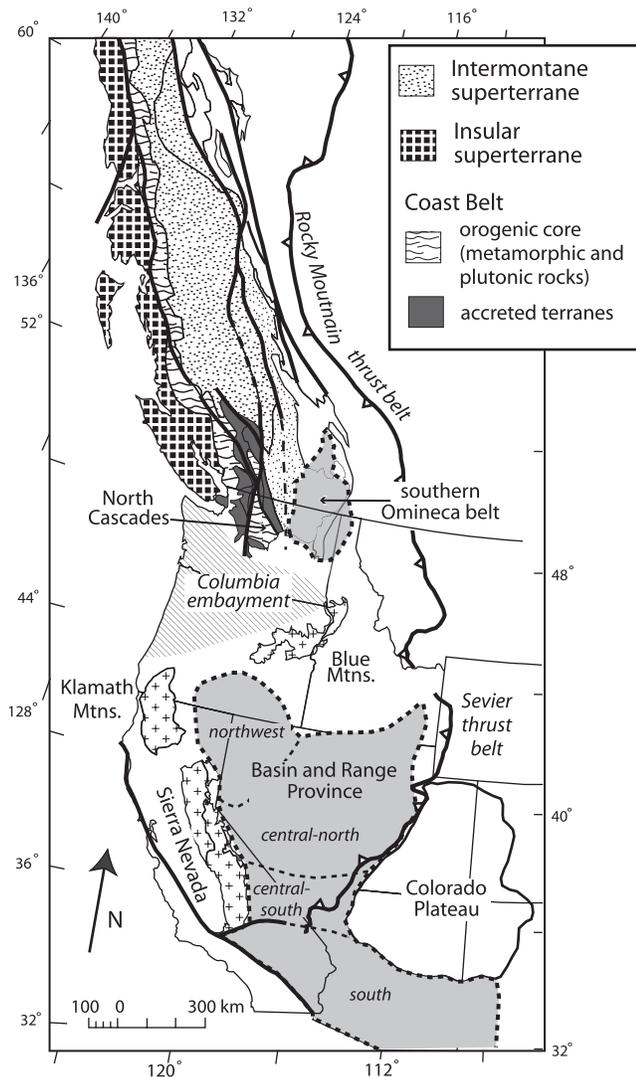


Figure 2. Map of the Canadian and U.S. Cordillera (same area as Fig. 1), emphasizing distribution of Insular and Intermontane superterranes, and metamorphic rocks and accreted terranes of the Coast belt, and showing location of the North Cascades Range, southern Omineca belt, Columbia embayment, and the four main parts of the Basin and Range province.

offset (Gabrielse, 1985, 1991). According to McMechan (2000, and references therein), Late Cretaceous or younger dextral displacement on the NRMT decreases from 325 km at $\sim 56^\circ\text{N}$ latitude to 80 km near 54°N to <5 km at $\sim 52^\circ\text{N}$. Declining displacement values from north to south along the Tintina-NRMT system are apparently taken up via a combination of motion along other strike-slip faults, Eocene extension in the southern Omineca belt and nearby areas, and Late Cretaceous to Paleocene shortening in the Rocky Mountain fold-thrust belt of southern Canada (Figs. 1 and 2; Price and Carmichael, 1986; Parrish *et al.*, 1988; Gabrielse and Yorath, 1991; van der Velden and Cook, 1996; McMechan, 2000; Price, 2003; Struik and Anderson, 2003). In our reconstruction, we use the Tintina value of offset (430 km) for the northern part of the NRMT, down to *ca.* 57°N latitude, and then use the declining values cited by McMechan (2000, and references therein) for more southerly portions of the NRMT.

West of the Tintina-NRMT is a more north-trending fault system that includes the Kechika and Thudaka faults in the north, and the Finlay, Ingenika, and Takla faults from about 57°N to 54°N (Fig. 1). Farther south, these faults project towards and are considered linked with the Fraser River and Straight Creek faults of southern British Columbia and northern Washington (Fig. 1) (Gabrielse, 1985, 1991). The Kechika-Thudaka-Finlay-Ingenika-Takla part of this fault system generally records 110–125 km of dextral offset, except for the northern Kechika fault, which has 170 km of dextral displacement (Gabrielse, 1985, 1991). This ~ 50 km excess on the Kechika is likely linked to displacement on the adjacent NRMT fault. Timing of displacement on the Kechika-Thudaka-Finlay-Ingenika-Takla system is Late Cretaceous to Eocene or Oligocene, but it is not known how much displacement occurred during the Paleogene versus the Cretaceous (Gabrielse, 1985, 1991). Some offset on the Thudaka and Kechika faults has been dated at ~ 100 Ma (H. Gabrielse, pers. comm., 2004), but it seems likely that most of the displacement is younger because the ~ 100 Ma Semenof-Teslin-Kutchok-Thibert-Pinchi fault system (see below) is offset by the Kechika-Thudaka-Finlay-Ingenika-Takla system (Fig. 1). Farther south, the Takla fault is inferred to connect into the Fraser River and Straight Creek faults (Fig. 1; Gabrielse, 1985, 1991). Most estimates of the amount of displacement on these faults range between 100–110 km, with offset occurring mainly during the Paleogene (Kleinspehn, 1985; Gabrielse, 1991; Umhoefer and Miller, 1996; Umhoefer and Schiarizza, 1996). Displacement on the combined Kechika to Straight Creek fault system is believed to feed northward into the Tintina-NRMT system (Gabrielse, 1985; Price and Carmichael, 1986). We use an average value of 110 km offset for this entire (Kechika-Straight Creek faults) system in our reconstruction.

Two older, more northwest-trending sets of faults are offset by the Kechika-Straight Creek fault system (Fig. 1). In the north, these include the Teslin, Semenof, Kutchok, Thibert, and Pinchi faults. In the south, they include the Yalakom and

Ross Lake-Hozameen faults. The Teslin, Semenof, Kutchok, Thibert, and Pinchi faults form a linked system that records ~ 200 km of dextral offset, mostly during the mid-Cretaceous (~ 100 Ma) but locally continuing into the Eocene (Gabrielse, 1985, 1991, pers. comm., 2004; Hansen, 1989). The Yalakom and Hozameen-Ross Lake faults also form a linked system but this one was active primarily during the Paleocene and Eocene with only minor offset during the Late Cretaceous (post-85 Ma), and involved dextral displacement of about 120 km (Kleinspehn, 1985; Umhoefer and Miller, 1996; Umhoefer and Schiarizza, 1996; Miller, 2002). Restoration of 110 km of dextral offset on the Kechika-Straight Creek fault system realigns the Teslin-Semenof-Kutchok-Thibert fault system with the Pinchi fault in the north, and the Yalakom fault with the Ross Lake-Hozameen faults in the south, consistent with all available data on fault linkages (Gabrielse, 1985, 1991; Umhoefer and Miller, 1996; Umhoefer and Schiarizza, 1996).

Farther west and north, the Denali fault system is a major dextral fault that runs for more than 2000 km through southern Alaska, southwestern Yukon, and into southeastern Alaska (Fig. 1). Various criteria suggest a displacement of 300–400 km along the Denali fault since the Early Cretaceous with about 40 km of this offset occurring after 38 Ma (Forbes *et al.*, 1973; Eisbacher, 1976; Lanphere, 1978; Nokleberg *et al.*, 1985; Plafker *et al.*, 1989; Gabrielse, 1991). Because of uncertainties about the total offset on the Denali, we use a conservative value of 325 km in our reconstruction.

In southeastern Alaska, the Denali fault appears to splay into the Chatham Strait fault and Coast shear zone (Fig. 1) (Lanphere, 1978; Gabrielse, 1991). Offset on the Chatham Strait fault occurred after the Early Cretaceous and has been estimated at 240 km (St. Armand, 1957), 190 km (Lathram, 1964), 200 km (Ovenshine and Brew, 1972), 100–180 km (Sonnevill, 1981), and ≥ 150 km (Hudson *et al.*, 1982). From these values, it appears that an offset of 200 km is reasonable to use in our reconstruction. Approximately 100 km of the displacement may be post-Oligocene (Hudson *et al.*, 1982), but the age of inception of faulting can only be constrained as mid-Cretaceous or younger (Gabrielse, 1991).

The remaining ~ 125 km of offset on the Denali fault presumably continues into the Coast shear zone (Fig. 1) (Lanphere, 1978; Gabrielse, 1991; McClelland *et al.*, 2000). The Coast shear zone is a complex structure that runs for at least 800 km from near the Denali-Chatham Strait fault intersection to at least 52°N latitude (Fig. 1). It is typically a 10–15 km wide, steeply dipping ductile shear zone in which the most prominent structures record reverse-sense shear, with minor dextral offset, from 65–55 Ma (Crawford *et al.*, 1987; Stowell and Hooper, 1990; Wood *et al.*, 1991; Gehrels *et al.*, 1991; Ingram and Hutton, 1994; Klepeis *et al.*, 1998; Andronicos *et al.*, 1999; Rusmore *et al.*, 2001). Older structures locally preserved within the shear zone, however, record dextral displacement between at least 85 Ma and 65 Ma (Hollister and Andronicos, 1997; Andronicos *et al.*,

1999; McClelland *et al.*, 2000). The amount of dextral offset during the Late Cretaceous is indeterminate but considered to be large, based on several factors: large ductile strains indicated by dextral structures; the great width of the dextral shear zone; and the fact that the Coast shear zone forms a fundamental, deep seated, near-vertical boundary that separates geologic provinces of completely contrasting histories (mid-Cretaceous metamorphic belt to the west versus mostly Paleogene Coast plutonic complex to the east). Other, likely significant displacement (up to 1 km-wide), ductile shear zones with Late Cretaceous dextral offset, have also been documented recently just east of the southern part of the Coast shear zone (Rusmore *et al.*, 2004). We therefore infer that the remaining offset from the Denali fault (~125 km) is taken up by dextral displacement along the (proto-)Coast shear zone and associated structures.

Farther south, the Coast shear zone projects towards and may link up with the co-linear Harrison Lake fault (Fig. 1) (Gabrielse, 1991; Monger, 1991). This structure is a wide (~1 km) ductile shear zone with high strain fabrics indicative of dextral shear occurring mostly between 95–90 Ma (Monger, 1986; Journeay, 1990; Monger and Journeay, 1994; Brown *et al.*, 2000). Total offset along this fault is unknown, but is potentially large based on the width of the shear zone and the large strains indicated by structures within it.

Linking Faults and Extending Displacement to the South

In many cases, the strike-slip faults described above end under the cover of younger rocks or into younger structures that cut or obliterate them, and therefore the original length of, or continuity between, the faults is uncertain. The most commonly accepted linkages have been described in the previous section. Here we review these and other potential linkages, and discuss how the faults may project to the south into Washington and Oregon. A guiding premise in this analysis is that large strike-slip displacements on faults in one area of the Cordillera must be accommodated structurally in some way along strike; the displacement cannot just end without explanation.

It is well established that the Tintina-NRMT fault system exhibits declining displacement values south of ~57°N, and that displacement on this system ends at ~52°N and does not continue farther south. It is also well established, however, that displacement on the Tintina-NRMT system is kinematically linked to displacement on the Kechika-Straight Creek fault system, extension in the southern Omineca belt, anomalously large magnitude shortening in the southern Canada portion of the Rocky Mountain fold-thrust belt, and to stepover transfer of strike-slip to the Yalakom and Ross Lake-Hozameen fault system (Parrish *et al.*, 1988; Gabrielse and Yorath, 1991; van der Velden and Cook, 1996; McMechan, 2000; Price, 2003; Struik and Anderson, 2003). It is therefore possible to accommodate the full displacement on the Tintina

fault in northern Canada by a spectrum of structures in central and southern British Columbia and northern Washington.

It is not known where the Pinchi fault continues to the south. Irving *et al.* (1996) suggested that it originally ran through the southern Intermontane terrane (their “intra-Quesnellia fault”), but was overprinted and obscured by the widespread effects of Eocene extension in the southern Omineca belt. Although the exact location of any projection of the Pinchi fault is unknown, the 200 km of displacement along it cannot just end. We therefore concur with Irving *et al.* (1996) that younger tectonism in southern British Columbia has likely obscured the continuation of this fault and we adopt the projection used by those authors (dashed line in Fig. 1) in our reconstruction.

As discussed above, displacement on the Denali fault can be partitioned into 200 km on the Chatham Strait fault and ~125 km on the (proto-)Coast shear zone. Farther south, the Coast shear zone projects into the Harrison Lake fault, which is in turn cut by the Straight Creek fault. Assuming that the Straight Creek fault offset of ~110 km continues into northern Washington, the Harrison Lake fault should reappear east of the Straight Creek fault somewhere in the vicinity of the southern North Cascades. Although no specific correlation has been proposed, there is considerable evidence for dextral ductile shear in the Cascades metamorphic core, starting at ~90 Ma and continuing until at least 70 Ma (Brown and Talbot, 1989; Haugerud *et al.*, 1991; Hurlow and Nelson, 1991; Walker and Brown, 1991; Journeay *et al.*, 1992; Miller *et al.*, 1993). This is consistent with the timing of dextral shear in the Harrison Lake fault. Alternatively, displacement on the Harrison Lake fault continues south on a structure now buried beneath the Cenozoic cover of central Washington, south of the North Cascades.

The Straight Creek, Ross Lake-Hozameen, and Pinchi faults all project southward into the Cenozoic cover of the Columbia embayment (Figs. 1 and 2). We believe that it is reasonable to assume that the faults continue south under the younger cover rocks, and we therefore project them along strike in our reconstruction.

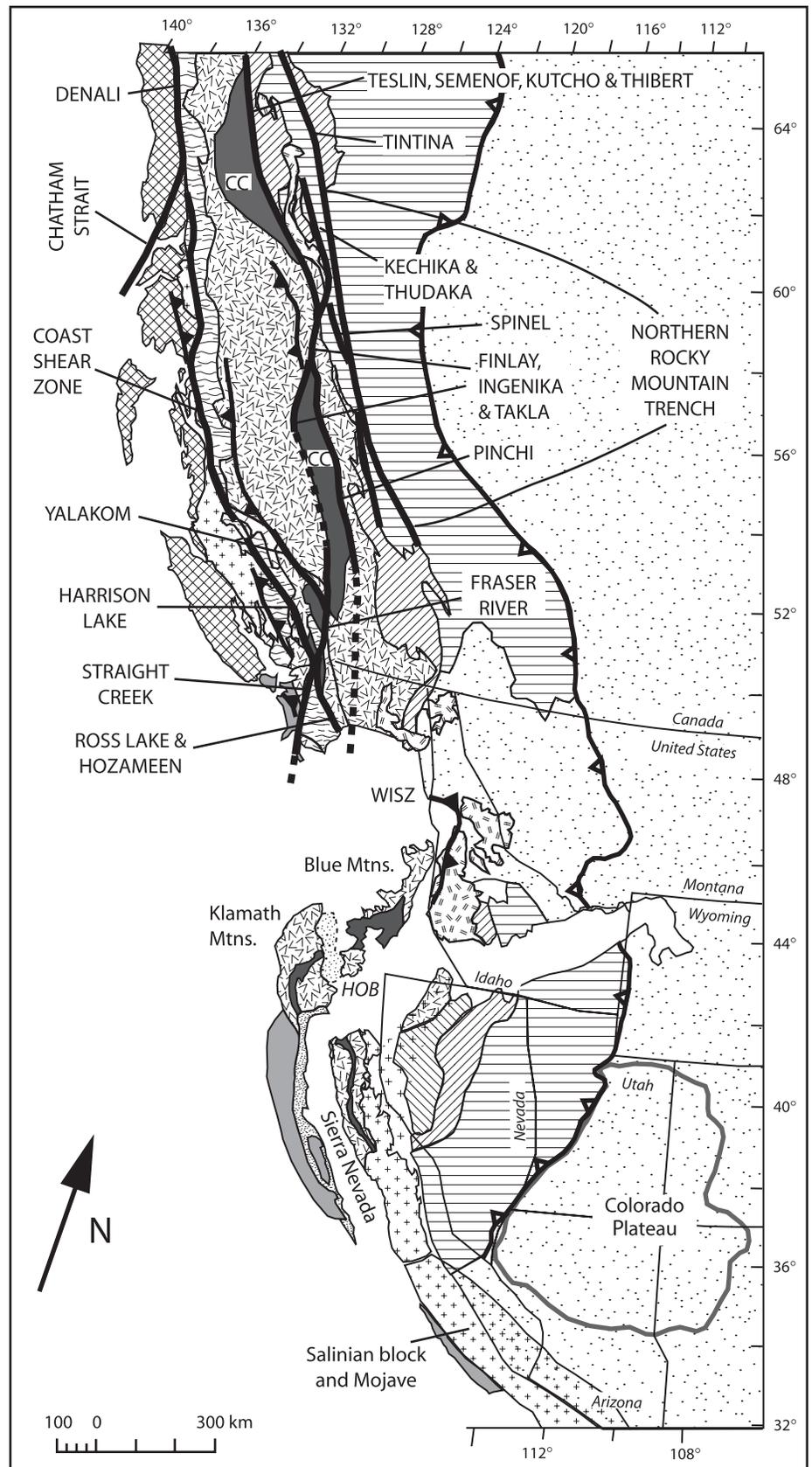
MINIMUM FAULT-OFFSET RECONSTRUCTION

A main goal in this paper is to restore dextral offset along the Late Cretaceous to Cenozoic strike-slip faults of the north-west Cordillera and to evaluate the resulting locations of the various displaced terranes. For this exercise to have validity, however, we must also restore other post-Early Cretaceous crustal motions (extension, contraction, strike-slip) that affected the spatial distribution of rocks in the Cordillera. These crustal motions include: (a) Cenozoic strike-slip displacement along the San Andreas and Garlock faults in California; (b) Cenozoic extension in the Basin and Range province of the western U.S. and southern Omineca belt of southern British Columbia and northeast Washington; (c)

Late Cretaceous to Cenozoic dextral faulting in western California and southwest Oregon; (d) mid-Cretaceous to Paleogene shortening in the Rocky Mountain fold-thrust belt of Canada, the Sevier fold-thrust belt of the U.S., and in the accreted terranes of the northwest Cordillera; and (e) Late Cretaceous to Cenozoic rotation of the Blue Mountains province and transpressional displacement along the adjacent western Idaho shear zone (WISZ in Fig. 1). Other more minor displacements (such as Laramide shortening in the U.S.) could be considered but would not significantly affect the outcome of our restoration and so are not included. Paleomagnetic evidence exists for some Late Cretaceous to Cenozoic clockwise rotation within terranes of the northern Cordillera, but these motions are interpreted to reflect distributed dextral shear (Irving *et al.*, 1996), and so are not included in our reconstruction.

Many of the displacements listed above can be restored independently of the northern Cordillera dextral strike-slip faults, and those restorations are shown in Figure 3. Extension in the southern Omineca belt and shortening in the Coast belt and accreted terranes of the northwest Cordillera, however, partially overlapped in space and time with the strike-slip faulting or was kinematically linked to it; these restorations

Figure 3. Same area as Figure 1 after restoration of Basin and Range extension, strike-slip displacement on the San Andreas and Garlock faults, strike-slip displacement within the Franciscan complex, rotation of the Blue Mountains province, transpressional deformation along the western Idaho shear zone (WISZ), and shortening within the Rocky Mountain and Sevier fold-thrust belts. All symbols and patterns same as in Figure 1. See text for explanation of restoration motions.



are most easily done simultaneously with restorations of the strike-slip faults (see Fig. 4). In this section, we explain the basis for the various restorations shown in Figures 3 and 4.

Saleeby and Busby-Spera (1992) went through a similar exercise in order to create a palinspastically restored base map for use in their tectonic analysis of the early Mesozoic U.S. Cordillera. Our methodology is similar to theirs, but we focus more attention on the Canadian Cordillera, restore motions only back to the mid-Cretaceous, and build on more recent data sets.

Restorations Exclusive of Northern Cordillera Strike-Slip Faults

We first restored strike-slip displacement in western California. Stewart and Crowell (1992) summarize evidence for 330 km of dextral displacement along the San Andreas fault system. Restoring this motion moves the Salinian block down to the south end of the Sierra Nevada (Fig. 3). Blake *et al.* (1988), McLaughlin *et al.* (1988), and Jayko and Blake (1993) have documented that significant dextral displacement occurred during the Late Cretaceous to Paleogene in the Franciscan complex and nearby provinces of California and southern Oregon (Fig. 1). This displacement resulted in the northward dispersal of fragments of the Coast Range ophiolite and Great Valley Group, and parts of the southwestern Klamath Mountains (Fig. 1), into the Franciscan complex along strike-slip faults. Based on a variety of lines of evidence (Blake *et al.*, 1988; McLaughlin *et al.*, 1988; Jayko and Blake, 1993), these outliers originated anywhere from ~200 km to 500 km south of their current location. The implication of these data is that the Franciscan complex was operating as a transpressional accretionary complex during the Late Cretaceous to Paleogene, with material moving northward as well as mixing internally to form the more familiar melange of the complex. We restored this northward material transfer by moving outliers west of the Klamath Mountains down to their inferred sites of origin south of the province (a displacement of at least 300 km), and by moving adjacent Franciscan material south along with the outliers (Fig. 3). The moved material was then reincorporated graphically into the Franciscan complex and Coast Range ophiolite/Great Valley Group south of the Klamath Mountains.

Basin and Range extension affected the area shown in Figure 2, and began, depending on area, during the latest Eocene, Oligocene, or Miocene. The amount of extension varies significantly across the province. Following Wernicke (1992) and more recent data of J. Colgan (2000, and pers. comm., 2003), we divided the province into four different parts (Fig. 2) with different overall amounts of extension. In the sector from the southern Sierra Nevada to the Colorado Plateau, 230% extension is well documented (Wernicke, 1992). The area across central Nevada and Utah has extended by ~80% overall, and this also appears to be a reasonable value to use for the region encompassing northeast Nevada, northwest Utah, and southern Idaho (Gans, 1987; Levy and

Christie-Blick, 1989; Smith *et al.*, 1991; Wernicke, 1992). The northwest part of the Basin and Range province has been extended overall by no more than about 15% (Duffield and McKee, 1986; J. Colgan, 2000, and pers. comm., 2003). These values are consistent with the arguments by Levy and Christie-Blick (1989) and Wernicke (1992) that the entire Basin and Range province has been lengthened in an east-west direction by ~250 km. Applying this reasoning to the southern part of the province (south of the Garlock fault and Colorado Plateau) yields an overall value of ~50% extension for this area. Geologic provinces and state boundaries in Figure 3 were restored using these various values of extension. Displacement along the Garlock fault is restored simultaneously with Basin and Range extension as this is essentially a tear fault associated with differing extension values to the north and south (Wernicke, 1992). All regions west of the Basin and Range province were shifted eastward accordingly as we restored extension across the province.

Shortening across the Foreland fold-thrust belt of Canada and the U.S. also varies with area. Within the U.S., some shortening may have begun by Late Jurassic time, but most occurred after the Albian (post-99.6 Ma by the time scale of Gradstein *et al.*, 2005), so estimates for total shortening across this part of the system can be used as reasonable values in a 100 Ma reconstruction. These values include ~100 km for the central and southern U.S. parts of the system, increasing to ~150 km at the Canadian border (Armstrong, 1968; Price and Mountjoy, 1970; Lawton, 1985; Heller *et al.*, 1986; Levy and Christie-Blick, 1989; DeCelles, 2004). In the Canadian part of the thrust belt, shortening occurred from the Late Jurassic to the Paleocene and varied in magnitude from 200 km in the south to 50 km in the north (Price and Carmichael, 1986; Gabrielse and Yorath, 1991), but studies in the southern part of the belt indicate that up to half (100 km) of the shortening occurred prior to the early Campanian (83.5 Ma by the time scale of Gradstein *et al.*, 2005) (Price, 1981). This means that some significant proportion of the total shortening in the Canadian fold-thrust belt occurred prior to 100 Ma and should not be included in our reconstruction. As a reasonable estimate, we assume that post-100 Ma values of shortening in the Canadian fold-thrust belt vary from ~40 km in the north to ~150 km in the south (which is consistent with data for the adjacent northern U.S.). Throughout the entire system, most of the fold-thrust belt shortening occurred in the miogeocline, so we stretched the different parts of the miogeocline in an east-west direction in our base map restoration (Fig. 3), using the values cited above and holding the eastern margin of the miogeocline fixed along the frontal edge of the thrust belt. All geology (and state lines) to the west of the miogeocline moved westward accordingly.

Finally, we restored Late Cretaceous to Cenozoic motions involving the Blue Mountains province. Paleomagnetic studies of multiple areas in the Blue Mountains province consistently show clockwise rotation during the Cretaceous and Cenozoic (Mankinen and Irwin, 1990), and Housen and

Dorsey (2002) indicate that $37.5 \pm 9.6^\circ$ of this rotation took place after the Albian. The eastern margin of the province is pinned to non-rotated North America, however, by 110 ± 5 Ma to 90 ± 5 Ma intrusions along the western Idaho shear zone (WISZ in Fig. 3; Manduca *et al.*, 1993; Snee *et al.*, 1995). We therefore held the eastern edge of the Blue Mountains province in a fixed position, while rotating the rest of the province by 38° in a counterclockwise direction (Fig. 3).

The western Idaho shear zone is a complex structure, similar to the Coast shear zone of Canada, with a younger history of reverse-sense shear and dextral transpression whose structures largely overprint and obliterate an older boundary that likely accommodated significant strike-slip motion (Lund and Snee, 1988; Strayer *et al.*, 1989; Selverstone *et al.*, 1992; Manduca *et al.*, 1993; Snee *et al.*, 1995; McClelland *et al.*, 2000; Wyld and Wright, 2001). The younger reverse-slip dominated displacement occurred at *ca.* 90 Ma, whereas the major strike-slip displacement apparently occurred sometime during the Early Cretaceous. For the purposes of our restoration, we need only to account for the *ca.* 90 Ma displacements across the shear zone. Exact values are unknown, but the width of the shear zone (>5 km), the high strain structures found within it, and detailed kinematic studies suggest shortening of 10s of kilometres and dextral translation of comparable amounts (Lund and Snee, 1988; Strayer *et al.*, 1989; Manduca *et al.*, 1993; Giorgis and Tikoff, 2002; Giorgis *et al.*, 2003). For our restoration, we assume conservative values of 50 km shortening and 40 km dextral offset, and we moved the Blue Mountains province west and south accordingly (Fig. 3).

The Idaho batholith is removed in our restoration (Fig. 3) because most of the plutonic rocks in or associated with the batholith are younger than 100 Ma, and, in fact, most are younger than 85 Ma (Hyndman, 1983; Criss and Fleck, 1987; Lewis *et al.*, 1987; Toth, 1987; Snee *et al.*, 1995). Only along the western Idaho shear zone are older (118–110 Ma) plutonic rocks found (Manduca *et al.*, 1993) and these are too narrow to show at the scale of our figures. Some of the Cretaceous plutons in the Sierra Nevada are younger than 100 Ma also, but many are older (*e.g.* Chen and Moore, 1982; Stern *et al.*, 1981), and it is therefore convenient to leave the batholith in its current configuration in our restoration.

No post-100 Ma rotation is recorded by paleomagnetic data from the Klamath Mountains or Sierra Nevada (Mankinen and Irwin, 1990), so these remain in their current orientation in our base map (Fig. 3). An important point to stress about the position of the Klamath Mountains in Figure 3 is that it does not restore eastward toward the Sierra Nevada for the time frame we are considering: the westward motion of the Klamaths relative to the Sierra Nevada occurred earlier in the Cretaceous Period (Jones and Irwin, 1971; Constenius *et al.*, 2000). Significantly, however, restoration of Basin and Range extension and Blue Mountains province displacements results in juxtaposition of the mid- to Upper Cretaceous strata of the Hornbrook and Ochoco basins (compare

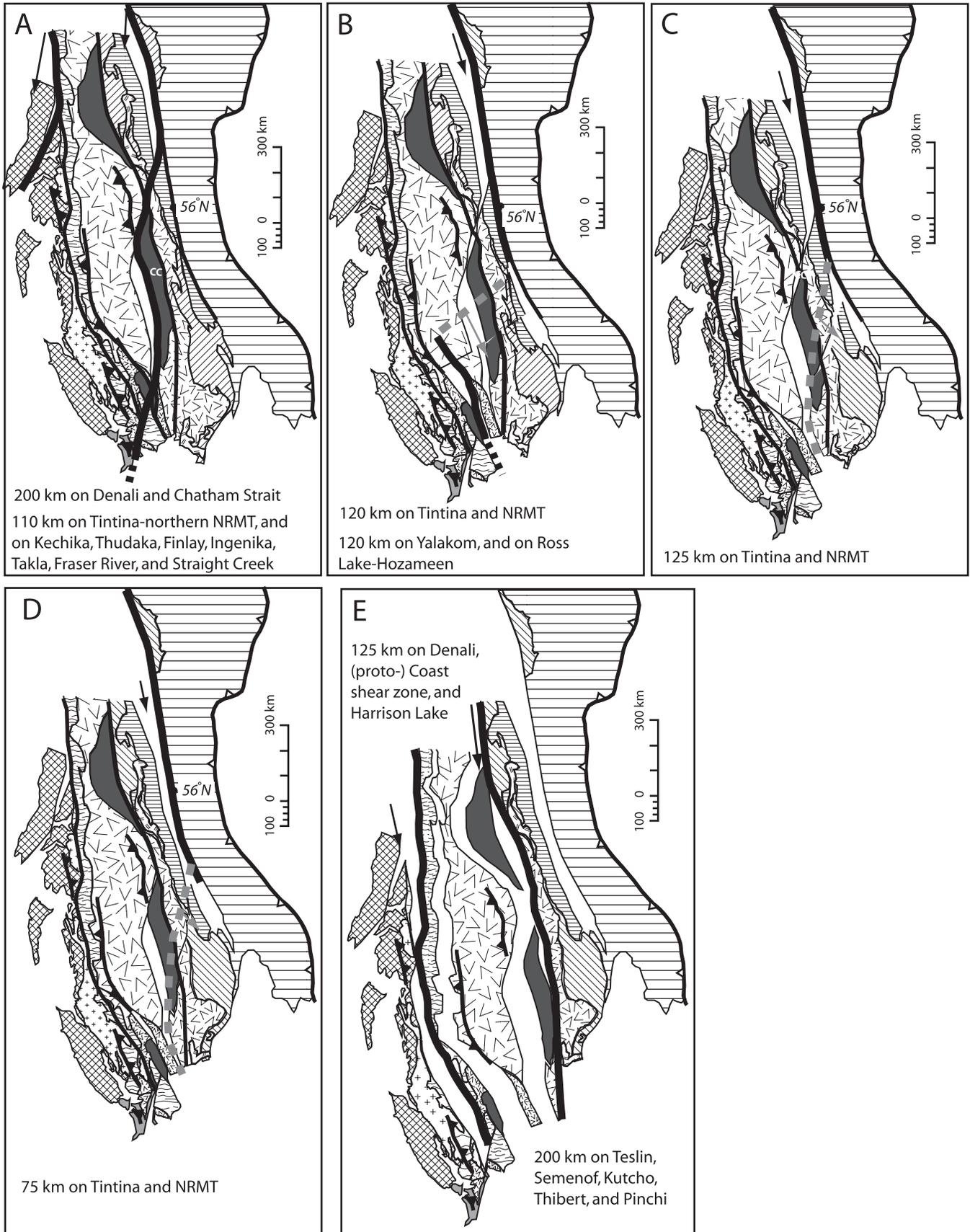
Figs. 1 and 3). These two basins, in which substantial thicknesses (up to 4300 m) of clastic sediments accumulated during the Albian to Maastrichtian, have long been considered to be related parts of a single sedimentary basin (Nilsen, 1984; Miller *et al.*, 1992), and their close juxtaposition in our reconstruction is consistent with this view. It is also important to emphasize that most of the strata in the Ochoco basin and about half of that in the Hornbrook accumulated during the Albian to Turonian (Kleinhans *et al.*, 1984; Nilsen, 1984; Miller *et al.*, 1992; Lindsley-Griffin *et al.*, 1993; Lenegan, 2001). The end of the Albian is 99.6 Ma according to the time scale of Gradstein *et al.* (2005). Thus, the Hornbrook and Ochoco basins were present and well-developed at the time of our reconstruction.

Restorations of Northern Cordillera Strike-Slip Faults

We used Figure 3 as a base map for the next steps in our restoration, which involves removing the dextral displacement along the northwest Cordillera strike-slip faults (Fig. 4). We used offset values and fault linkages discussed in prior sections. When restoring offset, all terranes and fault blocks west of the fault(s) in question were moved by the same amount in a direction broadly parallel to the fault(s). Some of the dextral motion was accompanied by extension in the southern Intermontane superterrane and southern Omineca belt (see Fig. 2), and by shortening in a broad region of deep-seated ductile strain in the metamorphic core of the Coast belt and North Cascades and in a series of thrust belts developed on either side of the core (see thrust symbols and metamorphic pattern on Figs. 1–4). These other motions are incorporated in the steps shown in Figure 4, as explained below and in the caption for Figure 4.

In the first step (Fig. 4A), we restored 200 km of displacement on the Chatham Strait and Denali faults. This leaves ~125 km remaining displacement on the Denali. We also restored 110 km on the Straight Creek, Fraser River, Finlay, Ingenika, Takla, Thudaka, Kechika fault system, with that same displacement feeding into the northern part of the NRMT and the Tintina fault. This leaves 315 km remaining displacement on the Tintina fault, which is close to the 325 km of offset cited by McMechan (2000, and references therein) for the NRMT at $\sim 56^\circ\text{N}$ latitude (located on Fig. 4A).

In the second and third steps (Figs. 4B and 4C), we restored 245 km on the Tintina-NRMT fault system north of $\sim 55^\circ\text{N}$ latitude, and accommodated this displacement to the south by a combination of stepping over to the Yalakom and Ross Lake-Hozameen faults, plus restoring extension in the region east of those faults. The extended area includes the southern Omineca belt (see Fig. 2), which was affected by about 30% extension during the Eocene (Parrish *et al.*, 1988), as well other parts of the southern Intermontane superterrane that experienced less pervasive but still significant extension during the early Cenozoic (Struik and Anderson, 2003). Extension was restored by shrinking the affected



region from the northwest, while holding the southeast boundary in a fixed position. For simplicity, the 120 km offset value on the Yalakom fault was used for the entire Yalakom-Ross Lake-Hozameen system.

In the fourth step (Fig. 4D), we restored the remaining 75 km displacement on the Tintina-NRMT system, while accommodating this motion to the south by internal strain and counterclockwise rotation of the southern parts of Cache Creek, Quesnel, Slide Mountain, Kootenay, and Cassiar terranes. This internal strain and rotation is intended to relate to some of the anomalous northeast-directed shortening in the southern Rocky Mountain thrust-belt that is believed to have been kinematically linked to part of the strike-slip motion on the Tintina-NRMT fault system (Price and Carmichael, 1986; van der Velden and Cook, 1996).

In the final step (Fig. 4E), we removed 200 km of dextral motion on the Teslin, Semenof, Kutcho, Thibert, and Pinchi fault system, and its presumed extension to the south. We also restored the remaining ~125 km on the Denali fault, feeding that value into the Coast shear zone and Harrison faults. We infer that this displacement is then accommodated to the south by some combination of dextral shear in the North Cascades core and/or other structures now buried underneath the Cenozoic cover of western Washington, but we do not attempt to display any image of how this displacement might be accommodated in detail. Instead, we simply move the rocks west of the Denali fault, Coast shear zone, and Harrison Lake fault (Insular superterrane) south along the boundary by 125 km.

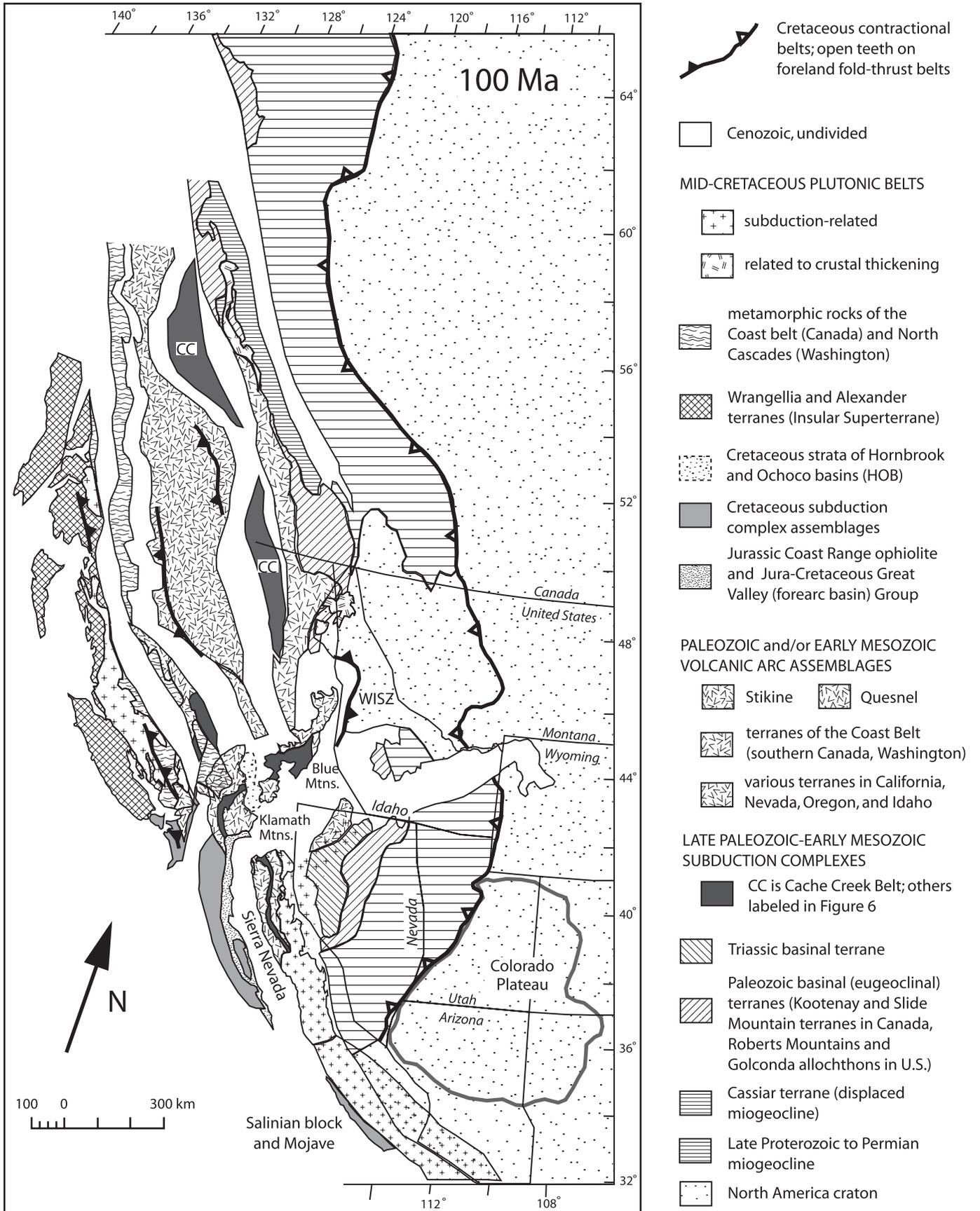
Simultaneously, in step 4E, we also moved the Insular and Intermontane superterranes west as a proxy for restoring the shortening across the metamorphic core of the Coast belt and North Cascades and in the adjacent fold-thrust belts of the northern Cordillera (see Fig. 1 for locations). Much of this shortening deformation occurred between 100–85 Ma,

although some (primarily in the metamorphic core of the Coast belt) continued into the Eocene and some (along the east side of the Stikine terrane) began earlier (Crawford *et al.*, 1987; Brandon *et al.*, 1988; Rubin *et al.*, 1990; Stowell and Hooper, 1990; Evenchick, 1991; McGroder, 1991; Journeay and Friedman, 1993; Rusmore and Woodsworth, 1994; Umhoefer and Miller, 1996; Andronicos *et al.*, 1999). Total amounts of shortening are known with certainty from only a few places, primarily in the fold-thrust belts east of the Coast shear zone, where shortening values of >40 km, >>50 km, and <160 km apply to mid-Cretaceous and younger structures (Evenchick, 1991; Journeay and Friedman, 1993; Rusmore and Woodsworth, 1994). Elsewhere, within the Coast belt and west of the Coast shear zone, structural relations (multiple thrusts and folds, high-strain fabrics, polyphase deformation) suggest major shortening over a broad region, possibly well over 100 km of shortening in the south (*e.g.* McGroder, 1991; Umhoefer and Miller, 1996). In our reconstruction, we chose to restore conservative but reasonable values of shortening, given the available data. Thus, we moved the Stikine block and associated terranes 50 km to the west, and we moved the Insular superterrane (mostly Wrangellia) and Coast belt to the west by an additional 100 km (in the north) increasing to 150 km (in the south).

ANALYSIS OF THE MINIMUM FAULT-OFFSET MODEL

The final restoration, showing the entire Cordillera, is presented in Figure 5. The model restores the Insular superterrane ~900 km to the south, with its southern end located west of the southern Klamath Mountains. Quesnel terrane and the Cache Creek belt in the southeastern Intermontane superterrane restore ~450 km to the south, with southernmost Quesnel straddling what is now the Washington-Oregon

Figure 4. (facing page) Maps showing restoration of northern Cordillera strike-slip faulting, separated into different steps (see text for discussion). Faults moving in each step are emphasized with heavier lines. Once a fault has finished moving, it is no longer shown in subsequent steps. Location of 56°N latitude shown for reference. NRMT is Northern Rocky Mountain Trench fault. All symbols and patterns same as in Figure 1. (A) 200 km of displacement restored on Chatham Strait and Denali faults (see arrow). 110 km of displacement restored on fault system linking Straight Creek, Fraser River, Takla, Ingenika, Finlay, Thudaka, and Kechika faults to northern NRMT and Tintina fault (see arrow by Tintina fault). For simplicity in moving fault blocks, Kechika and Thudaka faults are shown merging into NRMT. (B) 120 km of displacement restored on Yalakom-Ross Lake-Hozameen fault system, and on NRMT and Tintina fault (see arrow by Tintina fault). Region that was southeast of heavy grey line is shrunk accordingly (see grey arrow), while holding its southeastern boundary fixed; this is equivalent to restoring extension in the transfer zone. (C) 125 km of displacement restored on Tintina fault and NRMT (see arrow). Region that was southeast of heavy grey line is shrunk accordingly (see grey arrow), while holding its southeastern boundary fixed; this is equivalent to restoring extension, mostly in southern Omineca belt. (D) Final 75 km of displacement restored on Tintina-NRMT faults. Block composing southern part of Cache Creek, Quesnel, Slide Mountain, Kootenay, and Cassiar terranes is rotated and internally strained in this step to accommodate this motion. (E) 200 km of displacement restored on Teslin, Semenof, Kutcho, Thibert, and Pinchi faults, and presumed extension of Pinchi fault to south, and 125 km displacement restored on Denali fault, proto-Coast shear zone, and Harrison Lake fault (see arrows). Stikine block moved 50 km west, and Insular superterrane and Coast belt blocks moved 100 km west as proxy for restoring major contraction across Coast belt orogen and adjacent Cretaceous thrust belts.



border. Stikine terrane and terranes of the Coast belt restore by variable amounts (~450–850 km) into the intervening region north and west of the Klamath Mountains. These results place the Insular superterrane in about the same position as the reconstruction of Saleeby and Busby-Spera (1992), but locate the other terranes farther south. The model does not generate any significant geologic overlaps and it produces a consistently northwest-trending margin for the Cordillera (Fig. 5; note that the Cordillera margin would continue to the northwest if Yukon and Alaska were included in the restoration). The displaced fault blocks also partly fill in the Columbia embayment west of Idaho (compare Figs. 2 and 5), thus offering a possible explanation for what geology originally resided in this region. These general relations indicate that the reconstruction is plausible and reasonable.

In the following sections, we evaluate more specific geologic relations produced by the minimum fault-offset model. If the model is valid, there should be a good match between the geology of the displaced fault blocks and the geology of the adjacent *in situ* parts of the Cordillera. This is particularly true for geologic features whose age does not greatly precede the 100 Ma time of our reconstruction. Older geologic features may not necessarily match well, depending on the complexity of tectonic processes that affected them at older times. The most crucial sector to analyze is the region between the Sierra Nevada and southern Canada because this is where the geology is most altered (compare Figs. 1 and 5). A more detailed view of the restored geology of this region is shown in Figure 6.

Jurassic Ophiolites and Cretaceous Melanges and Blueschists

One of the most striking matches created by the minimum fault-offset model relates to the position of Jurassic ophiolites and Cretaceous melanges and blueschists. These rocks form a distinctive feature in the Cordillera because (exclusive of Mexico and Alaska) they are found only in northwest Washington and southernmost British Columbia, and in southern Oregon and California (Fig. 6). None are known farther north in the Canadian Cordillera, or in the region between the Klamath Mountains and northern Washington.

Blueschist facies rocks and tectonic melanges that formed during the Early to mid-Cretaceous are found in the eastern and central belts of the Franciscan complex of California, in the western melange belt and San Juan Islands of northwest Washington, and in the Easton metamorphic suite of northwest Washington (Fig. 6; Blake *et al.*, 1985, 1988; Jayko *et al.*

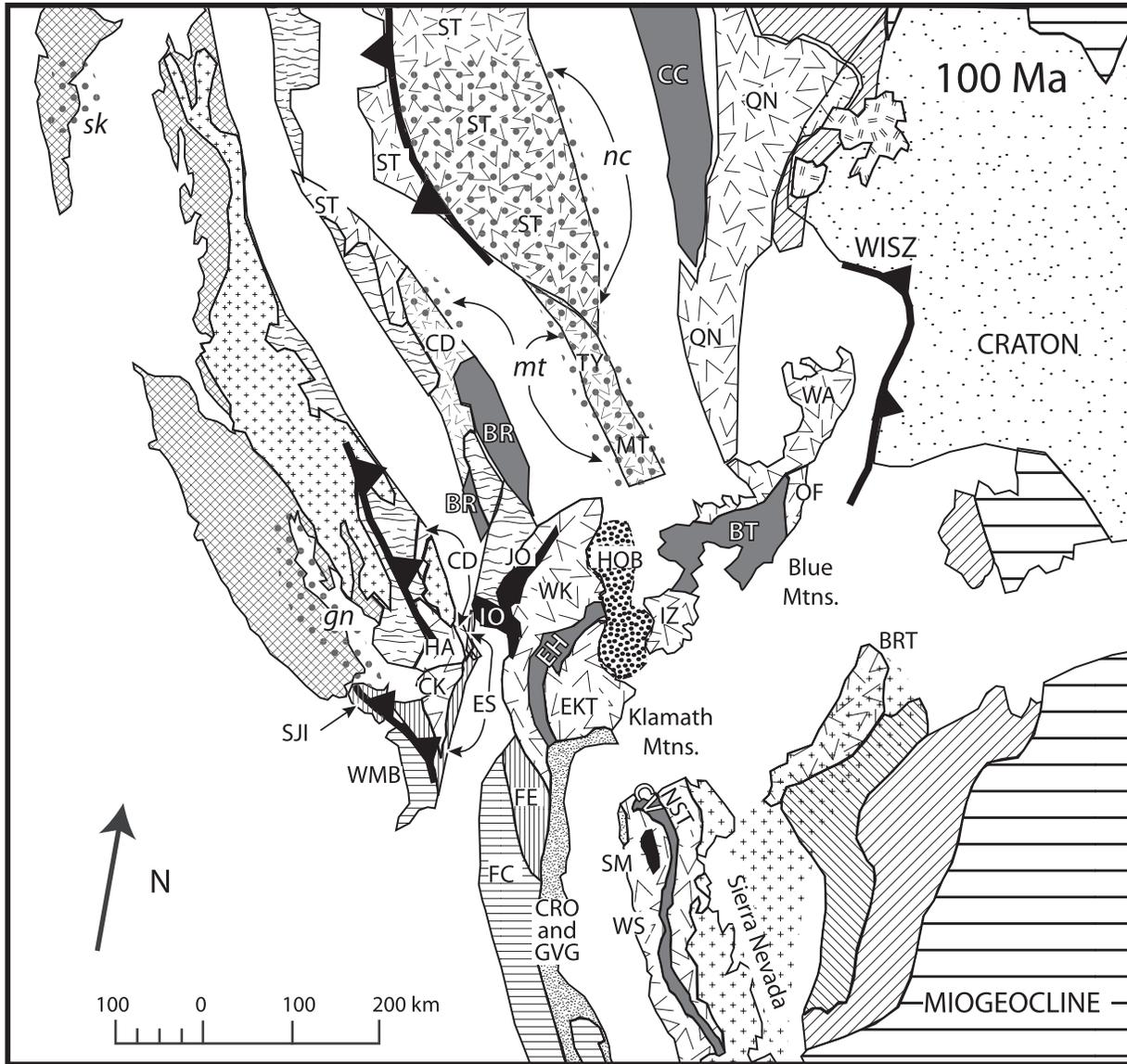
et al., 1986; Brandon *et al.*, 1988; Tabor *et al.*, 1989; Tabor, 1994). Jurassic ophiolites, formed in the narrow time interval of 165–160 Ma in supra-subduction zone rift basins, include the Coast Range ophiolite of western California, the Josephine ophiolite of the western Klamath Mountains, the Ingalls ophiolite of the Washington Cascades, and the Fidalgo ophiolite of the San Juan Islands, as well as the ophiolitic Smartville complex of the northwest Sierra Nevada (Fig. 6; Hopson *et al.*, 1981; Harper, 1984; Miller, 1985; Shervais and Kimbrough, 1985; Beard and Day, 1987; Brandon *et al.*, 1988; Wyld and Wright, 1988; Metzger *et al.*, 2002; Miller *et al.*, 2003).

Arguments that the northern group of ophiolites, melanges, and blueschists likely represent displaced fragments of the southern group have been made by many authors (Brown and Blake, 1987; Brandon *et al.*, 1988; Garver, 1988; Tabor *et al.*, 1989; Burchfiel *et al.*, 1992; Jayko and Blake, 1993; McLaughlin *et al.*, 1988; Metzger *et al.*, 2002; Miller *et al.*, 2003). In the minimum fault-offset model, these two groups are united in close proximity (Fig. 6), making a compelling argument in favour of the model. Particularly striking is that the Ingalls ophiolite restores to the southern end of its counterpart, the Josephine ophiolite (Metzger *et al.*, 2002; Miller *et al.*, 1993; Miller *et al.*, 2003) in the Klamath Mountains, and that the Washington blueschists and melanges restore to the northern end of their counterparts in the Franciscan belt of California (Brown and Blake, 1987; Tabor *et al.*, 1989; Miller *et al.*, 1993).

Mid-Cretaceous Contractional Belts

There are two broad categories of Cretaceous contractional belts in the U.S. and Canadian Cordillera (Figs. 1, 5, 6). One is the Rocky Mountain and Sevier fold-thrust belt, extending from Alaska to southern California. This is a classic retro-arc foreland system developed along the western edge of the craton. The other includes a variety of contractional belts in the accreted terranes and/or Cretaceous batholiths of western Canada, Washington, Idaho, Nevada, and California. This second group developed in an intra-arc or intra-orogen setting, rather than as a foreland system. In Canada and northern Washington, the intra-orogen contractional belts are represented by the metamorphic core of the North Cascades and Coast belt orogen and by associated thrust systems on either side of the core, which collectively record substantial shortening and exhumation between ~100–85 Ma. Farther south, in western Idaho, the western Idaho shear zone (WISZ in Fig. 6) records major ductile strain and dip-slip shearing at *ca.* 90 Ma, accompanied and followed shortly thereafter by >15 km exhumation and exposure of mid-crustal levels (Lund and Snee, 1988; Selverstone *et al.*, 1992; Manduca *et al.*, 1993; Snee *et al.*, 1995). Elsewhere in the U.S. Cordillera, such as in western Nevada and California, there is some localized intra-arc contractional deformation during the mid-Cretaceous (*e.g.* Saleeby *et al.*, 1990; Greene and Schweickert, 1995; McNulty, 1995; Wyld and Wright, 2001),

Figure 5. (facing page) Final reconstruction of Figure 4E superimposed on the base geology of Figure 3. This figure represents the minimum fault-offset reconstruction for 100 Ma.



MID- TO LATE CRETACEOUS INTRA-OROGEN CLASTIC BASINS

- Hornbrook and Ochoco basins (HOB)
- Canada-Washington basins: Georgia/Nanaimo (gn), Methow-Tyaughton (mt), Nechako (nc), Skidegate (sk)

CRETACEOUS SUBDUCTION COMPLEX ASSEMBLAGES

- melanges: western melange belt (WMB), central Franciscan (FC)
- coherent blueschists: Easton schist (ES), eastern Franciscan (FE), terranes of San Juan islands (SJI)

JURASSIC OPHIOLITES AND RELATED ROCKS

- Ingalls ophiolite (IO), Josephine ophiolite (JO), Smartville Complex (SM)
- Coast Range ophiolite (CRO) and Jura-Cretaceous Great Valley Group (GVG)

- TRIASSIC BASINAL TERRANE

- PALEOZOIC EUGEOCLINAL ASSEMBLAGES

LATE PALEOZOIC-EARLY MESOZOIC SUBDUCTION COMPLEX ASSEMBLAGES

- Cache Creek (CC), Bridge River-Hozameen (BR), and Baker (BT) terranes, eastern Hayfork and related terranes (EH), Calaveras complex (CV)

PALEOZOIC-EARLY MESOZOIC VOLCANIC ARC ASSEMBLAGES

- Cadwallader (CD), Harrison Lake (HA), Izee (IZ), Methow (MT), Olds Ferry (OF), and Tyaughton (TY) terranes, and terranes of the western Klamaths (WK) and Sierra (WS)
- Stikine (ST), Quesnel (QN), Chilliwack (CK), Eastern Klamath (EKT), Wallowa (WA), Black Rock (BRT), and Northern Sierra (NST) terranes

but no evidence for the major Late Cretaceous shortening and crustal unroofing seen farther north.

In the minimum fault-offset model, the intra-orogen contractional belts of western Washington and British Columbia restore to a position west of the Idaho contractional zone, and north of the area of little intra-orogen mid-Cretaceous shortening (Figs. 5 and 6). This appears to be a strong geologic match supporting the minimum fault-offset model because it unites the otherwise isolated Idaho system with the similar contractional belts of Canada and Washington, without impinging significantly on the area of little intra-orogen mid-Cretaceous shortening to the south.

Late Mesozoic Sedimentary Basins

Thick accumulations of mid- to Upper Cretaceous clastic strata are present in the accreted terranes of the western Cordillera and record important episodes of basin formation and sedimentation. In the U.S. Cordillera, these include the Great Valley Group of central California, and strata of the Hornbrook and Ochoco basins in Oregon and northernmost California (Figs. 1, 5, 6). Farther north, in Washington and British Columbia, a number of thick Cretaceous clastic sequences are recognized (Skeena, Virginian Ridge, Nanaimo, and Honna assemblages) and were deposited in various basins on Stikine (Skeena-Sustut and Nechako basins), terranes of the southern Coast belt (Methow-Tyauhton basin), and parts of the Insular superterrane (Georgia basin, which includes the Nanaimo basin, and Skidegate basin) (*e.g.* Yorath, 1991; Wheeler *et al.*, 1991). To avoid confusing terminology, we will refer to these collectively as the Canada-Washington basins. Their locations are shown in Figure 6 (except the Skeena-Sustut basin which is located north of the Nechako basin on Stikine).

Although the evolution of each of these various basins is distinct in detail, there are a number of important similarities between the Canada-Washington basins and the combined Hornbrook-Ochoco basin, and differences with the Great Valley basin, that are significant in terms of our minimum fault-offset reconstruction. Specifically, the Canada-Washington and Hornbrook-Ochoco basins share the following similarities (Dickinson and Vigrass, 1965; Nilsen, 1984; Kleinspehn, 1985; Yorath, 1991; Miller *et al.*, 1992; Garver, 1992; Lindsley-Griffin *et al.*, 1993; Garver and Brandon, 1994).

Figure 6. (*facing page*) Detail of the 100 Ma minimum fault-offset reconstruction for the region from the Sierra Nevada to southern British Columbia, emphasizing features discussed in text. Location of Canada-Washington Cretaceous basins from Yorath (1991) and Wheeler *et al.* (1991). Symbols and patterns not defined in legend for this figure are defined in legend for Figure 1.

- (1) Deposition began during the late Early Cretaceous (variably from the Hauterivian to the Albian) and continued into the Late Cretaceous.
- (2) Strata were deposited as overlap assemblages on older accreted terranes, and basal strata are typically unconformable on the older basement.
- (3) Depositional environments varied from non-marine to marine, with shallowing upwards successions in some areas and deepening upwards successions present in others.
- (4) Total thickness of basin strata is typically 1–6 km, with a maximum of 8 km in the Methow-Tyauhton basin.
- (5) Sediments in most basins were derived variably over time from both eastern and western sources, reflecting deposition in a complex and evolving paleotectonic setting.
- (6) Basin development and sedimentation is either known or suspected to be related to tectonism and uplift in nearby mid- to Late Cretaceous contractional belts (see previous section). This relationship is particularly well established for the Canada-Washington basins (Brandon *et al.*, 1988; McGroder, 1991; Yorath, 1991; Garver, 1992; Garver and Brandon, 1994; Schiarizza *et al.*, 1997), but has also long been suspected for the Ochoco basin based on its proximity to the coeval western Idaho shear zone (WISZ; Fig. 6) and evidence for an eastern sediment source (Dickinson and Vigrass, 1965; Kleinhans *et al.*, 1984; Miller *et al.*, 1992; Selverstone *et al.*, 1992; Lenegan, 2001). Likewise, sediments in the Hornbrook Formation were apparently derived largely from the uplifted Klamath Mountains block (Nilsen, 1984; Miller *et al.*, 1992). The term “intra-orogen” will be used for these basins and their clastic strata (Fig. 6), to emphasize their location and relation to nearby tectonism within the evolving Cordilleran orogen.

In contrast, the Great Valley basin records a very different history (*e.g.* Dickinson, 1976, 1981; Dickinson and Seely, 1979; Ingersoll, 1978, 1979, 1983; Blake and Jones, 1981; Cowan and Bruhn, 1992). In most places, the Great Valley Group was deposited conformably on oceanic crust of the Middle Jurassic Coast Range ophiolite and is not an overlap assemblage on older accreted terranes. Great Valley Group deposition spanned the Late Jurassic (Oxfordian) through the Late Cretaceous, and thus began tens of m.y. prior to deposition in the other basins. The principal depositional environment represented by Great Valley Group strata is deep-marine, and total thickness of accumulated strata is vastly greater (up to 15 km) than in the other basins. Finally, the Great Valley basin did not evidently owe its origin or development to nearby contractional tectonism and associated uplift; instead, it developed rather passively, as a subsiding oceanic basin between a coeval arc (inferred to be the Sierra

Nevada), from which the sediments were derived, and a coeval subduction complex assemblage (Franciscan complex) (Figs. 5 and 6).

In terms of our reconstruction, the important point about these various similarities and difference is that the Hornbrook-Ochoco basin shares much more in common with the Canada-Washington basins, from which it is currently far removed (Fig. 1), than with the Great Valley basin. In the minimum fault-offset model, however, the southern Canada-Washington basins restore to a position near the Hornbrook-Ochoco basin (Figs. 5 and 6). This appears to be another strong link in favour of the model because it unites the Hornbrook-Ochoco intra-orogen overlap strata with similar sedimentary accumulations farther north in the Cordillera. It also places the southern Methow-Tyaughton basin just north of the Hornbrook-Ochoco basin. This is intriguing in light of the long-standing recognition that the Hornbrook-Ochoco basin appears to be truncated on its northern side (Nilsen, 1984; Miller *et al.*, 1992); the Methow-Tyaughton basin may thus be a good candidate for the missing northern part of this basin. Finally, the model does not result in any overlap between the intra-orogen clastic basins and the subduction complex-fore-arc basin duo of the Franciscan complex and Great Valley Group (Fig. 6), a relationship that would be difficult to explain.

REGIONAL IMPLICATIONS

The reconstructions shown in Figures 5 and 6 should be viewed only as an approximation of the geology of the Cordillera at 100 Ma because too many assumptions are involved in the reconstruction for a precise outcome. Nonetheless, the general latitudinal location of terranes and provinces should be broadly correct for the fault offsets that we have considered. There are a number of important and interesting regional implications of this reconstruction.

Cretaceous Paleogeography and Paleotectonics

The fault-offset reconstruction provides a minimum option for the location of Canada and Washington terranes during the mid-Cretaceous, at 100 Ma. Other proposed models argue for more southerly locations (Beck *et al.*, 1981; Irving *et al.*, 1985; Wynne *et al.*, 1995; Ward *et al.*, 1997; Housen *et al.*, 2003; Umhoefer and Blakey, this volume). Regardless of which model is correct, it is clear that no interpretations of the paleogeography or paleotectonics of the mid-Cretaceous Cordillera should be based on the current arrangement and location of Canada and Washington terranes, because those terranes were not in their current location during the mid-Cretaceous. It is therefore important to re-evaluate paleotectonic and paleogeographic interpretations of Cretaceous Cordilleran geology in terms of a reconstruction such as we present in this paper. Several noteworthy relations are evident in this regard when comparing Figure 1 with Figures 5 and 6.

First, there is more complexity in the pattern of mid- to Late Cretaceous magmatism in the Cordillera than is commonly assumed. The Idaho batholith, which appears to form the link between northern and southern Cordillera batholiths in maps of present-day geology (Fig. 1) is almost entirely younger (mostly 85–53 Ma) than the Cretaceous batholithic belts of the Sierra Nevada and Insular superterrane (mostly 120–85 Ma) (Stern *et al.*, 1981; Chen and Moore, 1982; Hyndman, 1983; Criss and Fleck, 1987; Lewis *et al.*, 1987; Toth, 1987; Woodsworth *et al.*, 1991; Manduca *et al.*, 1993; Snee *et al.*, 1995; Foster *et al.*, 2001). Upper Cretaceous (85–60 Ma) magmatic arc rocks coeval with the main Idaho batholith are found in the Coast belt of Canada (Woodsworth *et al.*, 1991; Gehrels *et al.*, 1991), but there is no comparable Late Cretaceous arc magmatism in the Sierra Nevada batholith. The Idaho batholith is also dominated by peraluminous granitoids that reflect melting of Precambrian basement, most likely related to crustal thickening, and is therefore fundamentally different from the arc-related batholiths of the Sierra Nevada and Insular superterrane (Hyndman, 1983; Criss and Fleck, 1987; Lewis *et al.*, 1987; Toth, 1987; Woodsworth *et al.*, 1991; Manduca *et al.*, 1993; Snee *et al.*, 1995; Driver *et al.*, 2000; Foster *et al.*, 2001). Thus, there is a distinct gap in the mid-Cretaceous arc batholith belts of the Cordillera at the latitude of the Klamath Mountains (Figs. 5 and 6), and a marked difference from north to south of this latitude in the presence or absence of a Late Cretaceous magmatic arc.

There are also other notable differences north and south of the batholithic gap. First, as discussed in a prior section, there are major intra-orogen contractional belts and related clastic basins of mid- to Late Cretaceous age to the north (Figs. 5 and 6), whereas to the south, intra-orogen shortening during this time frame was much more limited, and the only major Cretaceous sedimentary basin (Great Valley Group) formed in a relatively quiescent oceanic fore-arc setting with no implication that basin development was related to contractional tectonism. Second, numerous major dextral strike-slip faults of mid-Cretaceous to Eocene age sliced through the northern Cordillera all the way to the miogeocline, translating large crustal blocks 100s of kilometres northward (Figs. 1, 4, and 5). To the south, there was distributed dextral faulting in the Franciscan (subduction) complex and limited dextral transpression along the arc axis during this time frame, but nothing comparable to what affected the northern region. These same differences were stressed by Davis *et al.* (1978) and Burchfiel *et al.* (1992), but they are even more obvious in the minimum fault-offset reconstruction.

One obvious potential explanation of these features is that the North American Cordillera was interacting with a different tectonic plate north of the Klamath Mountains during the mid- to Late Cretaceous than it was south of the Klamaths, with the northern plate (Kula) converging more rapidly and more obliquely with the margin than the southern plate (Farallon). Relative motions of these two plates with North

America during the mid- to Late Cretaceous are consistent with this interpretation (Engebretson *et al.*, 1985). Essentially this exact model has been proposed and discussed previously by several authors, including Davis *et al.* (1978), McLaughlin *et al.* (1988), Burchfiel *et al.* (1992), and Jayko and Blake (1993), but it is given striking new support by the minimum fault-offset reconstruction, and therefore warrants renewed examination. The most important implication concerns the location of the initial Kula-Farallon ridge, a feature whose position is not constrained by ocean floor data and which could have originated anywhere between northern California and Central America (Engebretson *et al.*, 1985). The problem with this degree of uncertainty is that the Cretaceous evolution of a long segment of the Cordillera cannot be confidently linked to specific plate interactions. Geologic relations in the minimum fault-offset reconstruction provide strong support for a northern position of the initial Kula-Farallon ridge, and thus provide new impetus to revisit models linking geologic events with Kula-Farallon plate interactions.

Baja British Columbia Controversy

Our reconstruction provides an important alternative to the traditional fixist versus mobilist views regarding the mid-Cretaceous locations of northwest Cordillera terranes, as exemplified by Hypotheses A and B of Cowan *et al.* (1997) and cited by many subsequent studies. In their Hypothesis A, based on geologic relations, the accreted terranes of western Canada and northwest Washington were located approximately in their current position relative to the craton during the mid-Cretaceous. In their Hypothesis B, based on paleomagnetic data, the southern end of the Insular superterrane and Coast orogen (Baja British Columbia) was located west of present-day Puerto Vallarta along western Mexico during the mid-Cretaceous, and the southwestern end of the Intermontane superterrane was located at the latitude of the San Francisco Bay. Hypothesis A, however, does not incorporate known displacement on the northern Cordillera strike-slip faults. As is clear from Figures 5 and 6, restoration of these displacements has a major impact on the location of terranes at 100 Ma (compare with Fig. 3).

Cowan *et al.* (1997) discussed a number of predictions or tests made by their Hypotheses A and B that could be used to distinguish between them. Some of these predictions need to be modified in light of the minimum fault-offset reconstruction. We focus on those that are most strongly impacted by the new reconstruction.

Prediction 1 deals with the origin of terranes and rock units in the Coast orogen, and with the location along the continental margin where this orogenesis occurred. The essence of this prediction concerns whether the terranes of the Coast orogen, and the orogenic belt itself, are more compatible with an origin north or south of California. The minimum fault-offset reconstruction does not change the basic question, but it indicates that arguments in favour of

the northern option should be based on comparison with the geology of northern California, Nevada, and southern Oregon and Idaho, not on comparisons with Canadian terranes.

Prediction 2 concerns Cretaceous magmatic arc rocks of the North American Cordillera and whether they represent one continuous arc system running from southern California through northern British Columbia (Hypothesis A) or two separate arcs formed above two different subducting plates (Hypothesis B). As noted above, however, it is important to distinguish between mid- versus Late Cretaceous magmatism and between subduction-related versus crustal thickening-related magmatism when considering this question. Thus, the fault-offset reconstruction indicates that there was not a continuous magmatic arc during the mid-Cretaceous (Figs. 5 and 6). This prediction should probably be recast to evaluate more discrete time intervals during the Cretaceous and to include more specific consideration of the tectonic setting of magmatism in different areas (*cf.* Driver *et al.*, 2000).

Predictions 3 and 6 concern the provenance of intra-orogen Cretaceous sedimentary successions in the accreted terranes, specifically whether they contain detritus derived from the northern Cordillera (Hypothesis A) or the southwest Cordillera (Hypothesis B). The minimum fault-offset reconstruction, however, indicates that this whole topic needs to be re-evaluated by including sedimentary basins and sediment source regions of Idaho, Oregon, and California, as well as those in the northern Cordillera (Figs. 5 and 6). For example, the contractional belt of the western Idaho shear zone could be a source for sediments in the Methow-Tyaughton basin, the North Cascades block a source for sediments in the Hornbrook-Ochoco basin, and the Klamath Mountains a source for clastics of the Nanaimo assemblage (Fig. 6). Likewise, proximity of the Hornbrook-Ochoco basin to the Methow-Tyaughton basin and Nanaimo assemblage in the faults-only reconstruction invites comparison of these various coeval clastic successions to determine whether they are related.

Finally, the minimum fault-offset reconstruction suggests a new test for the Baja British Columbia problem, which is to evaluate and compare the overall geologic compatibility of different reconstructions. If a reconstruction is valid, then the geology of the displaced terranes should match well with the adjacent *in situ* geology of the Cordillera, at least for time frames close to the time of the reconstruction. We have shown here that the minimum fault-offset reconstruction fulfills this requirement surprisingly well. If alternative reconstructions are valid, it seems reasonable to argue that they should offer at least a similar level, if not a greater level, of geologic compatibility. Conversely, if the geologic compatibility of an alternative reconstruction is significantly less than that of the fault-offset model, then the alternative is a less plausible option. Umhoefer (2004) and Umhoefer and Blakey (this volume) have discussed the geologic compatibility of an intermediate displacement (1600 km for Baja British Columbia) model, but nothing equivalent has been

done for the large displacement paleomagnetic models. We suggest that doing so would provide a useful new way of looking at the Baja British Columbia controversy.

Implications for Early Mesozoic and Older Cordilleran Geology

Evaluation of the minimum fault-offset model by looking at older (pre-Jurassic) rocks and terranes is complicated because of increasing uncertainties about the older paleogeography of the Cordillera and the extent or nature of older terrane dispersal episodes. On the other hand, the reconstruction facilitates interpretations of the older geology because it strips off younger displacements that obfuscate older relations. For example, the reconstruction brings the Stikine and Quesnel arc assemblages of Canada into close proximity with coeval arc assemblages of the Blue Mountains province, Klamath Mountains, Sierra Nevada, and Black Rock terrane (Fig. 6), thus providing new insights into how the northern arc terranes may relate, in terms of correlations and paleotectonic reconstructions, to those farther south (*cf.* Saleeby and Busby-Spera, 1992). The reconstruction also highlights the complexity of the distribution of Paleozoic to early Mesozoic volcanic arc and subduction complex assemblages in the region between the northern Sierra Nevada and southern Stikine (Fig. 6). This complexity suggests terrane dispersal and shuffling during pre-100 Ma episodes of strike-slip faulting, a conclusion that has also been reached by other workers based on different criteria (Lund and Snee, 1988; Garver, 1988; Schweickert and Lahren, 1990; Jayko, 1990; Snee *et al.*, 1995; Wyld and Wright, 2001; Gabrielse and Murphy, 2003; Monger *et al.*, 1994; Christe and Wyld, 2004; Umhoefer, 2004; Wright, 2004). The pattern of terrane distributions in the reconstruction should help to clarify where older fault boundaries are most likely located and help to define the sense and amount of older offsets. Perhaps most importantly, the reconstruction emphasizes the need to more directly link British Columbia and Washington geology with that of Oregon, Idaho, California, and Nevada, as was done by Saleeby and Busby-Spera (1992), when interpreting the early Mesozoic and older evolution of the Cordillera.

Implications for Columbia Embayment

The minimum fault-offset reconstruction also has interesting potential implications for the origin of the Columbia embayment (Fig. 2), an enigmatic region of the Cordillera whose origin is obfuscated by the lack of pre-Cenozoic basement exposure. Specifically, the model suggests that the Columbia embayment may have formed as a “hole” left behind when the great dextral faults of the northern Cordillera moved the Insular superterrane, Coast belt, and Intermontane superterrane progressively northward away from the more stationary geology to the south (*e.g.* view panels in Figure 4 from panel ‘E’ backwards through panel ‘A’). In this context, the Columbia embayment may owe its origin to interactions during the Late Cretaceous and early Cenozoic between the North

American plate and the emerging and evolving Kula-Farallon spreading ridge (*e.g.* Engebretson *et al.*, 1985). This interpretation is very similar to that proposed by Davis *et al.* (1978), Burchfiel *et al.* (1992), and Miller *et al.* (1992), and offers new impetus for re-examining the origin of the Columbia embayment.

CONCLUSIONS

Large dextral offset on mid-Cretaceous to Cenozoic strike-slip faults of the northern Cordillera is well known, but no modern paleogeographic reconstruction has been made that explicitly shows where all the displaced terranes restore to prior to strike-slip offset. This paper is a first attempt at creating and analyzing a detailed fault-offset reconstruction using currently available offset data, and it builds on the earlier analyses of this topic by Davis *et al.* (1978) and Saleeby and Busby-Spera (1992). Refinements of the model are expected as new data become available, but the reconstruction is what we consider the best, current, geologic-based paleogeography for the northern Cordillera during the mid-Cretaceous.

The reconstruction restores terranes to their inferred positions at 100 Ma. We focused on the region south of *ca.* latitude 60°N, and we used accepted values of fault offset where these are known, conservative values where the amount of offset is less clear. The Insular superterrane restores ~900 km to the south, with its southern end located at the latitude of northern California. Terranes of the Intermontane superterrane restore ~450–650 km to the south, leaving southern Stikine, Quesnel, and Cache Creek belt straddling what is now the Washington-Oregon border. The southern end of the Coast orogen, the metamorphic core of the North Cascades, restores about 600–700 km to the California-Oregon border, while adjacent terranes of the southern Coast belt are dispersed across a broad swath north and west of the Klamath Mountains. These values are not sufficient to explain paleomagnetic data from the displaced terranes, but they do indicate that discrepancies between geologic and paleomagnetic data sets are not as large as is often assumed.

The reconstruction produces some striking geologic matches, including the juxtaposition of many geologic features that have previously been correlated or that have a high probability of having evolved together. These include Cretaceous intra-orogen contractional belts and synorogenic sedimentary basins, Cretaceous melanges and blueschists, and Jurassic supra-subduction zone ophiolites. The reconstruction creates a plausible paleogeographic arrangement of terranes, structural provinces, and sedimentary basins, and the restored terranes also, in part, fill in the region of the Columbia embayment. Collectively, these relations provide a compelling argument in favour of the minimum fault-offset model. An important next step will be to determine whether the larger-displacement, paleomagnetically based reconstructions of the mid-Cretaceous Cordillera offer an equivalent degree of geologic compatibility.

The minimum fault-offset reconstruction has important implications for the Baja British Columbia controversy, and for other models of Cordilleran evolution. Most importantly, no interpretations of mid-Cretaceous and older geology of the Cordillera should be based on the current location and arrangement of terranes in the northern part of the system, because these terranes were all located farther south during the mid-Cretaceous.

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