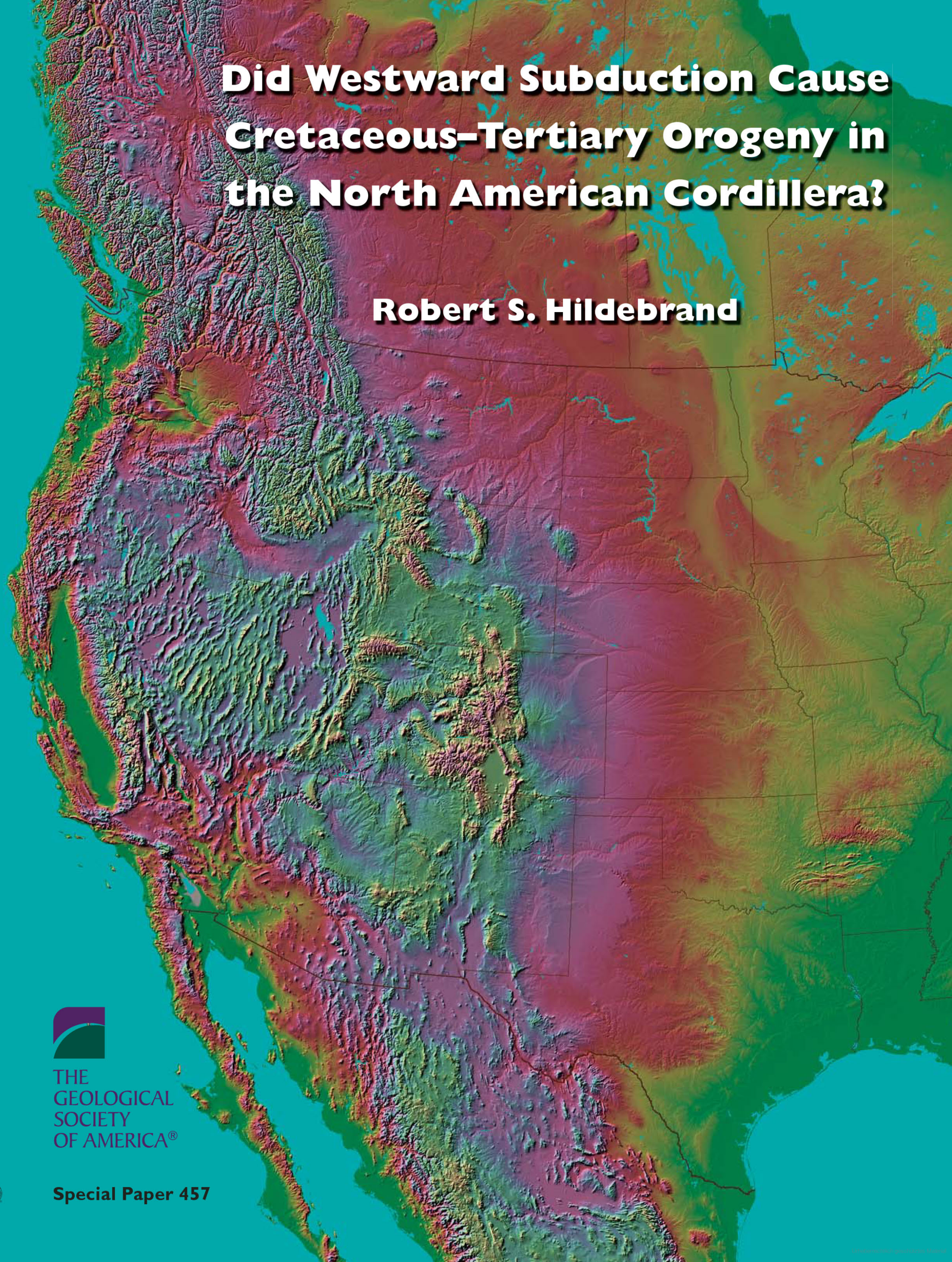
Did Westward Subduction Cause Cretaceous–Tertiary Orogeny in the North American Cordillera?

Robert S. Hildebrand



THE GEOLOGICAL SOCIETY OF AMERICA®

Special Paper 457

Hildebrand • Did Westward Subduction Cause Cretaceous–Tertiary Orogeny in the North American Cordillera? • Special Paper 457

Did Westward Subduction Cause Cretaceous–Tertiary Orogeny in the North American Cordillera?

Robert S. Hildebrand
Department of Geosciences
University of Arizona
1040 E. 4th St.
Tucson, Arizona 85721
USA

THE
GEOLOGICAL
SOCIETY
OF AMERICA®

Special Paper 457

3300 Penrose Place, P.O. Box 9140 ▪ Boulder, Colorado 80301-9140, USA

2009

Published by The Geological Society of America, Inc.
3300 Penrose Place, P.O. Box 9140, Boulder, Colorado 80301-9140, USA
www.geosociety.org

Printed in U.S.A.

GSA Books Science Editors: Marion E. Bickford and Donald I. Siegel

Library of Congress Cataloging-in-Publication Data

Hildebrand, R. S. (Robert S.)
Did westward subduction cause Cretaceous-Tertiary orogeny in the North American cordillera? / Robert S. Hildebrand.
p. cm. — (Special paper ; 457)
Includes bibliographical references.
ISBN 978-0-8137-2457-7 (pbk.)
1. Orogeny—North America. 2. Orogenic belts—North America. 3. Geology—North America. 4. Geology, Stratigraphic. I. Title.
QE621.5.N7H55 2009
551.8′2097—dc22

2009019247

Cover: Color, shaded relief map of the central parts of western North America. Careful study of this extraordinary map reveals many of the large-scale geological features discussed in the text because much of the topography directly reflects the development of the Cordilleran orogeny. The image was made and generously provided by Ray Sterner at The Johns Hopkins University Applied Physics Laboratory using digital elevation data obtained by the Shuttle Radar Topography Mission (SRTM), the 11-day STS-99 mission by the Space Shuttle Endeavour in February 2000. The data set used for this map was SRTM30 which is SRTM data enhanced with the earlier data set GTOPO30. This map is a direct descendent of the maps at http://fermi.jhuapl.edu/states/, one of the earliest shaded relief map sites on the web.

10 9 8 7 6 5 4 3 2 1

Contents

Contents

The Geological Society of America
Special Paper 457
2009

Did Westward Subduction Cause Cretaceous–Tertiary Orogeny in the North American Cordillera?

Robert S. Hildebrand
Department of Geosciences, University of Arizona, 1040 East Fourth Street, Tucson, Arizona 85721, USA

ABSTRACT

The North American portion of the Cordilleran orogen extends continuously from Alaska to southern Mexico, and from east to west over much of its length the orogen comprises an easterly vergent fold-thrust belt, a complexly deformed metamorphic hinterland that collapsed gravitationally, and an interlaced mosaic of exotic terranes. Although most models for the development of the Cordilleran orogen invoke Late Jurassic–Cretaceous intraplate, backarc shortening above an eastwardly dipping subduction zone, a simple collisional model in which the leading edge of North America was subducted to the west, beneath a segmented, arc-bearing microcontinent, better fits the data.

During the early Mesozoic, Panthalassic Ocean crust was subducted westward beneath a ribbon continent named Rubia, where it created a generally low-standing continental arc. At about 124 Ma, the widespread deposition of intraformational gravels and conglomerates atop the passive margin marked the passage of the North American shelf over the outer bulge of the trench and its entry into the subduction zone. Loading by the "bulldozed" and thickened accretionary wedge—as well as the overlying eastern edge of the Rubian ribbon continent—depressed the lithosphere to create the Cretaceous foredeep, which migrated eastward during progressive convergence. As the westernmost edge of North America was subducted, the dewatering of slope-rise and rift deposits abruptly created voluminous melts that rose to thicken and assimilate the overlying exotic crust, where they formed Cordilleran-type batholiths. Owing to the difficulty of subducting an old craton, convergence slowed to a halt by 80–75 Ma, causing the shutdown of Cordilleran-type magmatism, and finally, during the Maastrichtian, break-off of the North American plate. The first segment to fail was likely the Great Basin segment, located south of the Lewis and Clark lineament and north of the Sonoran segment. There, slab failure rates were apparently slow enough that there was considerable lithospheric necking, and so slab-failure magmas were prevented from rising into the overriding plate. The diachronous break-off caused a catastrophic stress inversion in both upper and lower plates. Released from its oceanic anchor, the partially subducted edge of the North American craton rose rapidly, causing its stress regime to change from extensional to compressional, which, along with continued convergence, generated the thick-skinned Laramide

*e-mail: bob@roberthildebrand.com.

Hildebrand, R.S., 2009, Did Westward Subduction Cause Cretaceous–Tertiary Orogeny in the North American Cordillera?: Geological Society of America Special Paper 457, 71 p., doi: 10.1130/2009.2457. For permission to copy, contact editing@geosociety.org.

deformation. Uplift and gravitational collapse of the overlying Rubian plate formed the linear belt of Paleocene-Eocene metamorphic core complexes within the orogenic hinterland. In the Canadian segment, located north of the Lewis and Clark line, the Coast plutonic complex was uplifted rapidly as asthenosphere rose through the torn lower-plate lithosphere to invade Rubia with a 1500-km linear belt of break-off–generated magmas. Within the Sonora segment to the south, break-off magmatism was also prevalent. Both the Canadian and Sonoran segments have abundant porphyry copper mineralization temporally and spatially associated with the break-off magmas, which suggests a genetic link between slab failure and porphyry copper mineralization. By 53 Ma, eastwardly dipping subduction of Pacific Ocean crust was generating arc magmatism on the amalgamated Cordilleran collision zone in both the Canadian and Sonoran segments. Oceanic schists, such as the Orocopia-Pelona-Rand, were formed in the ocean basin west of Rubia and accreted during initiation of the new easterly dipping subduction zone.

A major transform fault, called the Phoenix fault, connects the Sevier fold-thrust belt at the California-Nevada border with that in eastern Mexico and separates the Great Basin and Sonoran segments. It juxtaposes the Sierra-Mojave-Sonora block alongside the Transition Zone of the Colorado Plateau.

Cordilleran events affected the subsequent development of western North America. For example, the structural Basin and Range Province appears to coincide with the region where exotic allochthons sit atop North American crust in both the Great Basin and Sonoran segments. Also, within the triangular Columbia embayment, large segments of Rubia appear to have escaped laterally during the Cordilleran orogeny to create a lithospheric "hole" that was later filled by basalt of the Columbia River and Modoc plateaux.

The real voyage of discovery consists not in
seeking new landscapes but in having new eyes.
—Marcel Proust

INTRODUCTION

The Cordilleran orogenic belt (Fig. 1) is a diverse and interlaced ensemble of fault-bounded blocks with a complicated history. It extends at least from Alaska to southern Mexico, and is viewed by most North American geologists as reasonably understood (Dewey and Bird, 1970; Coney and Evenchick, 1994; Burchfiel et al., 1992). Since the landmark papers by Burchfiel and Davis (1972, 1975), nearly all workers who have created or utilized plate models for the main development of the Cordilleran orogenic belt postulate Neoproterozoic to Cambrian rifting of Laurentia to form a westerly facing passive margin, active until the late Devonian; then 110 m.y., from the Late Devonian to the early Triassic, punctuated by the successive accretion of exotic allochthons, which converted the passive margin to an active margin; and finally eastwardly directed subduction of Pacific oceanic crust beneath North America. Although there are numerous minor variants for the tectonic evolution from the middle Paleozoic to the Triassic (Gehrels et al., 2000b), there is general consensus that within this temporal scheme major crustal shortening during the Late Jurassic–Cretaceous Cordilleran (Sevier-Columbian) orogeny represents a period of backarc, intraplate thrusting behind a magmatic arc (Fig. 2) on the upper plate near or on its westernmost margin from the latest Devonian until the Cretaceous (Armstrong, 1968; Burchfiel and Davis, 1972, 1975; Gabrielse and Yorath, 1991; Monger and Price, 2002; Scholten, 1982; Saleeby and Busby-Spera, 1992; Miller et al., 1992; Oldow et al., 1989; DeCelles, 2004; DeCelles and Coogan, 2006; Gehrels et al., 2000a, 2000b; Smith et al., 1993; Thompson et al., 2006; Wyld et al., 2006; Dickinson, 2000, 2004, 2006; Colpron et al., 2007; Evenchick et al., 2007). The cause of this deformation is variably attributed to rapid convergence (Hyndman, 1972), flat subduction (Dickinson, 2004), subduction of an oceanic plateau (Murphy et al., 2003), or subduction of a spreading ridge (Bird, 1988).

A critical review of existing data, coupled with new field observations, suggests that the backarc model is probably incorrect. In this contribution, I develop an alternative model on the basis of these data and posit that the main event of the Cordilleran orogeny was a microcontinent-continent collision, which developed in the Cretaceous during the thwarted subduction of North America beneath a previously consolidated, composite superterrane to the west. I call this superterrane Rubia, and it includes most of the Cordilleran terranes and previously

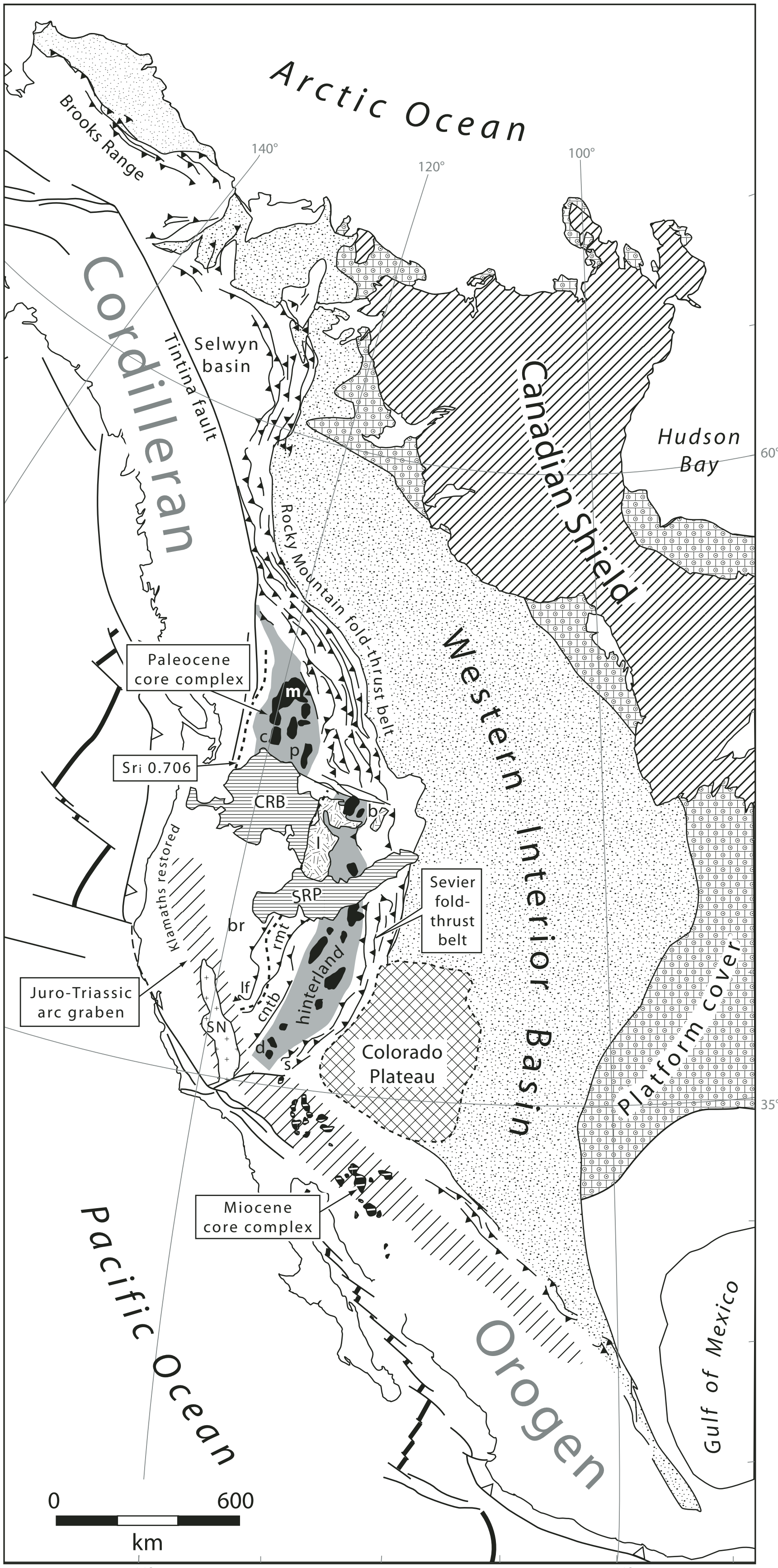


Figure 1. Geological sketch map showing distribution of Cordilleran orogenic belt in western North America and main tectonic elements used in the backarc model. Note that here the Klamath Mountains are restored to a position north of the Sierra Nevada. Diagonal-lined area is Mesozoic arc graben from Busby-Spera et al. (1990). Other authors draw the Mesozoic arc terrane curving northeasterly from the north end of the Sierra Nevada to the Idaho batholith. Abbreviations: b—Boulder batholith; c—Cascades; cntb—Central Nevada thrust belt; CRB—Columbia River basalts; d—Death Valley; I—Idaho batholith; lf—Luning-Fencemaker thrust belt; m—Monashee complex; p—Priest River complex; rmt—Roberts Mountain thrust; s—Spring Mountains; SN—Sierra Nevada batholith; SRP—Snake River Plain.

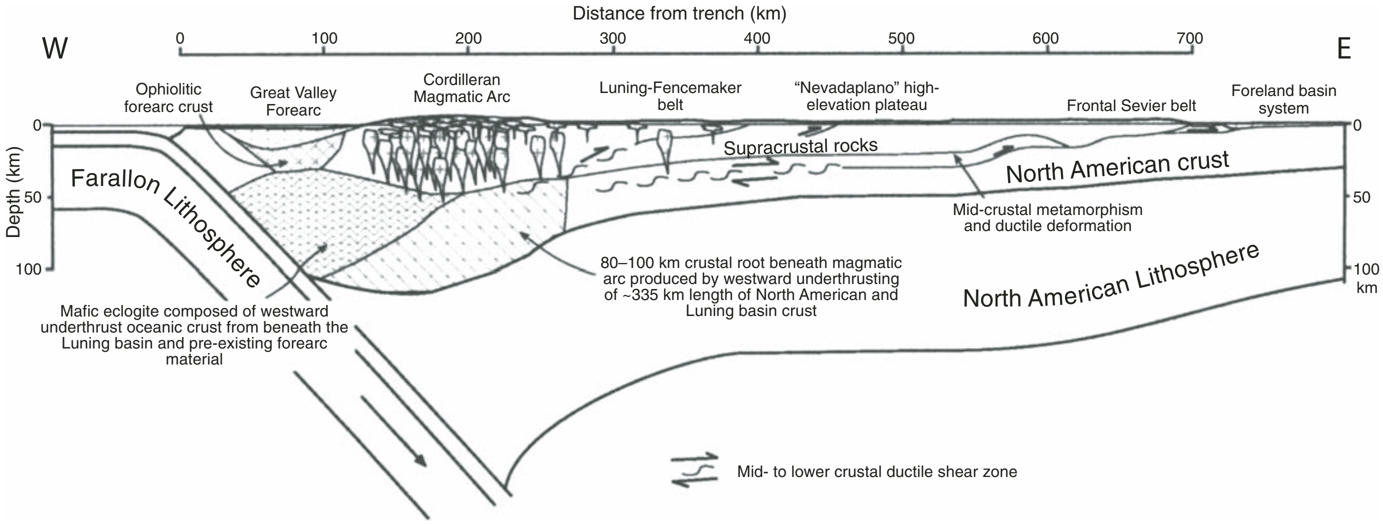


Figure 2. A more or less typical cross section, illustrating the main components of the generally accepted backarc, or intraplate, model for the development of the Cordilleran orogeny (from DeCelles and Coogan, 2006). Note that in order to have created the Sevier thrust belt, stresses must have traveled through the ductile regions of the crust and emerged at the platform edge of the North American passive margin. Also in this model, huge quantities of North American crust must have vanished beneath the Sierra Nevada in order to balance the thin-skinned shortening.

identified superterranes (Monger et al., 1982; Johnston, 2001, 2008), plus new additions, within the Canadian and American sectors of the orogen.

In this new model for the Cordillera, western North America was a passive continental margin from the latest Precambrian until about 124 Ma, when its outermost edge was subducted, and the passive margin platform rode over the outer trench swell, was eroded, and, until about 75–70 Ma, partially subducted beneath an arc-bearing microcontinent as the Panthalassic Ocean closed. Following ocean closure, collision, and slab break-off, a new easterly dipping subduction zone formed outboard of the amalgamated western North American margin. This hypothesis is similar to a few models for the Canadian and Alaskan sectors of the orogen (Gabrielse and Yorath, 1991; Moore et al., 1994; Johnston and Borel, 2007; Johnston, 2008).

After, and possibly even during, the collision, part of the southwestern margin of North America was displaced to the southeast, and the Sierra Nevada–Mojave–Sonora block juxtaposed against the craton in its place. This idea is not new, for other workers—Hamilton and Myers (1966), Burchfiel and Davis (1975), Stevens et al. (1992, 1998), Dickinson (2006)—earlier suggested that the truncation occurred in the late Paleozoic or Permian–Triassic, but in the model presented here the movement is considered to be largely Late Cretaceous–Tertiary.

Although it is true that the collisional model presented here flies in the face of many "facts" as presently understood, it is powerful because it unites previously difficult-to-explain features of the Cordillera, such as high-grade metamorphism in the hinterland, Laramide basement uplifts, the distribution of metamorphic core complexes, the origin of Cordilleran-type batholiths, and regional-scale Tertiary extension, into a logical continuum. Despite its potential flaws, the model is far simpler, and explains more aspects of the geology, than the current backarc model. Nevertheless, it might be incorrect or even just partly so. Additional studies and tests—brought into focus by comparing and contrasting the existing backarc model with the collisional model presented here—should be profitable and might resolve some of the more enigmatic aspects of Cordilleran evolution.

GEOLOGICAL OVERVIEW OF THE CORDILLERA

The regional geology of western North America consists of long, linear geotectonic elements that parallel the Cambrian continental margin for much of its length (Fig. 1). The largest and most continuous elements in the Cordilleran orogen are the Cordilleran passive margin, the Cretaceous fold-thrust belt, the related foredeep, the Sevier hinterland belt, and the belt of accreted terranes. Except for a 500 km stretch along the southwestern margin of North America, these elements occur, with some variations, for nearly 10,000 km from southern Mexico to Siberia. The summary that follows is not meant to be exhaustive, but rather to provide a review of the geology and its framework to provide a common basis for the discussions that follow.

The Cordilleran continental margin, or miogeocline, may have developed during the Neoproterozoic, but this is doubtful, for the coarse clastics and volcanic rocks of the Neoproterozoic Windermere Supergroup, which are commonly considered to be rift-facies rocks of North America, are at least 150 m.y. older than the onset of passive margin subsidence (Bond and Kominz, 1984; Hoffman, 1988, 1989; Stewart, 1972). Even in the improbable case that the rifting did last 150 m.y., volcanic rift basins (Roots, 1983; Harper and Link, 1986) are nearly absent.

The eastern limit of rifting defined the western edge of North America and coincided with the western limit of younger shelf sediments on the passive margin (Bond and Kominz, 1984). The Sevier shelf domain consists of a lower, mature, siliciclastic blanket of Cambrian age overlain by shallow-water carbonate and interbedded shale (Poole et al., 1992). Westward, or outboard, of the platform are fine-grained siliciclastic and limy rocks deposited coevally with the platform but deposited on the ancient continental slope and rise (Cook, 1970; Peterson, 1977). Within the Utah-Idaho-Wyoming sector, the Sevier shelf edge is currently located within the eastern Sevier thrust belt, and in Canada the shelf edge crops out among thrust slices in the Main Ranges just west of Banff (Price and Mountjoy, 1972). Here I use the term Rocky Mountain platform or shelf to refer to the entire Cambrian-Jurassic west-facing platform formed along the western margin of North America. Understanding the position of the shelf edge is critical for unraveling the evolution of the orogen as allochthonous rocks outboard of this critical facies belt could be exotic, and so should be carefully scrutinized. It is important to note that in the United States the Rocky Mountain platform passes westward into basinal facies rocks and that it is not the same shelf as the Antler shelf, presently located west of the deeper water basinal facies. Likewise, the shelf within Canada ends abruptly and is entirely different than the carbonate bank of the more westerly Cassiar platform (Johnston, 2008). This topic will be discussed in more detail in a subsequent section.

During the Cretaceous and early Tertiary, sedimentary rocks of the passive margin were detached from their basement and translated eastward as stacked thrust sheets to form the present-day fold-thrust belt (Armstrong, 1968; Price and Mountjoy, 1970; Bally et al., 1966). The fold-thrust belt extends from Alaska to southern Mexico and represents one part of the major deformational event of the Cordilleran orogeny (Fig. 1). Balanced cross sections constructed by numerous workers (Dahlstrom, 1970; Price, 1981; Oldow et al., 1989; Allmendinger, 1992; DeCelles and Coogan, 2006) show eastwardly transport with a minimum of two hundred kilometers of shortening across the belt, except in northern Canada, where there is only a minimum of 50 km of shortening. Within the United States the fold-thrust belt developed during what Armstrong (1968) called the Sevier orogeny. In Canada the fold-thrust belt formed during what is termed the Columbian orogeny (Monger and Price, 2002). Because the Sevier and Columbian orogenies were contemporaneous and constitute a single continuous and linear belt of rocks and structures, I use the term Cordilleran orogeny to refer to the Cretaceous deformation that created the entire belt, whereas the term Laramide is used only to refer to a series of Late Cretaceous–Tertiary basement-involved uplifts, for the most part located in the Rocky Mountain foreland east of the fold-thrust belt and mainly south of the Lewis and Clark lineament (Fig. 1) in keeping with the original definition by Armstrong (1968).

Coincident with the development and transport within the fold-thrust belt, large volumes of rock were eroded from the rising tectonic welt and transported eastward to accumulate in the Cretaceous to Paleocene foredeep basin (Price, 1994; Beaumont, 1981). This basin, known overall as the Western Interior Basin, extended from Alaska to Mexico, and along with the Cordilleran miogeocline and the fold-thrust belt, it is now a major geotectonic element of the Cordillera (Fig. 1). The locus of the basin and its related foredeep bulge migrated eastward in front of the advancing thrust belt (Currie, 2002; White et al., 2002).

To the west of the fold-thrust belt is another major geotectonic element of the Cordillera known in Canada as the Omineca belt, and in the United States simply as the Sevier hinterland (Fig. 1). This belt lies along the western side of the fold-thrust belt from Canada to southern California and is characterized by Precambrian crystalline basement of North America, intensely metamorphosed and deformed supracrustal rocks, allochthonous Devonian to early Cretaceous plutons (Wright and Wooden, 1991; Parrish, 1995), metamorphic rocks (>9 kb and 800 °C) of Mesozoic age, large recumbently folded nappes (Raeside and Simony, 1983; Snoke and Miller, 1988), many exposed today in the cores of Paleocene-Eocene metamorphic core complexes (Armstrong, 1982; Hodges and Walker, 1992; Coney and Harms, 1984), which formed as shortening in the fold-thrust belt to the east ended. This belt is one of the keys to unraveling the evolution of the orogen and is characterized by rocks likely to have been exotic with respect to the North American craton, yet thrust onto it during the Cordilleran orogeny. This element probably formed the highest mountains in the entire orogenic belt (Mulch et al., 2004), but its significance went largely unnoticed, partly because it isn't very wide, but more probably because the mountains collapsed and eroded so rapidly that they no longer form a continuous mountain front.

West of the Sevier hinterland–southern Omineca corridor lies a tectonic collage (Helwig, 1974) of Paleozoic and Mesozoic microcontinents, subduction complexes with blueschists, broken-formation and ophiolitic mélange, sedimentary basins, carbonate platforms, seamounts, and arcs, many of which were bound together prior to their accretion along the western margin of North America. These terranes are interpreted to have developed offshore from North America and in large part were united during the late Paleozoic and early Mesozoic prior to colliding with North America. Some of these linkages will be discussed in more detail in a later section.

WHY CURRENT MODELS FAIL

Several lines of reasoning suggest that there are problems with the notion of an easterly dipping subduction zone beneath North America prior to the Cordilleran orogeny and the consequent development of the orogen in a backarc setting (Fig. 2). The following are some of the major weaknesses of the backarc model.

1. In general, there is no evidence for collision, in the form of deformation or exotically derived sedimentation, on the Rocky Mountain shelf from the Cambrian to the Cretaceous.

For example, extensive areas of western Nevada were supposedly incorporated as part of North America after the Mississippian, but the Rocky Mountain shelf had no deformation or sedimentation related to major 190–143 Ma deformation, including 7–14 km of crustal thickening and major thrusting in the Black Rock Desert and other nearby terranes (Wyld et al., 1996, 2003).

During the Jurassic, deformation doubled the crust and generated westerly vergent, recumbent thrust nappes and associated metamorphism, yet there were no deformational effects on the Rocky Mountain shelf, only 80–100 km away after restoration of Basin and Range normal faulting. Jurassic sedimentary rocks of the Morrison (U.S.) and Fernie Formations and the Kootenay Group (Canada) are the only units of the passive margin sequence known to contain westerly derived sediment, but they apparently contain no plutono-metamorphic debris and are some 25–40 Ma older than the initiation of foredeep sedimentation in the Western Interior Basin. Additionally, the Morrison Formation doesn't thicken westward but instead thins westward from depocenters some distance from the platform edge along the Utah-Colorado border (Heller et al., 1986; DeCelles, 2004).

2. As it is presently ~500 km from the Sevier shelf edge to the 0.706 isopleth, restoring the 220-plus kilometers of shortening (DeCelles and Coogan, 2006) and Basin and Range shortening of 250 km (Gans and Miller, 1983; Wernicke, 1992) across the Sevier fold-thrust belt in Utah and Nevada puts rocks outboard of the shelf edge and all of Nevada past the hypothesized western margin of North America as approximated by the 0.706 Sr isopleth (Elison et al., 1990). This is a difficulty for the current backarc model because in it most of these rocks are considered North American.
3. The Sevier fold-thrust belt is thin-skinned, and for the most part, did not involve crystalline basement, which means that compressive stress must have been transmitted in the cover from the continental margin several hundreds of kilometers inland (Fig. 2) (Dahlen and Suppe, 1988). It is difficult to imagine how this might have been accomplished, especially since the intervening cover wasn't deformed at that time and there is no evidence that it was stronger than the deformed rocks. In fact, judging by the preponderance of nearly flat-lying Paleozoic rocks on cratons, upper continental crust must have a yield strength greater than the differential stresses placed on continents at their margins on a somewhat regular basis by collisions and subduction.

   Furthermore, the exact method of moving a block of rock, such as the Belt-Purcell Supergroup contained on the Lewis-Eldorado-Hoadley thrust, which was at least 450 km by 100 km by 30 km, a hundred kilometers or more over the North American carbonate platform without subduction as required by the backarc model, is perplexing.
4. The four hundred kilometers or so of Triassic to Cretaceous shortening between the Sierra Nevada and the thin-skinned Sevier fold-thrust belt also creates problems in constructing balanced crustal-scale cross sections, which forced some authors to invoke westward underthrusting, or some sort of counterflow of North American crust beneath the Sierra Nevada (e.g., DeCelles and Coogan, 2006; Ducea, 2001; Fig. 2), something for which there is no evidence. Since the Sierra Nevada were topographically low standing during the Triassic–Jurassic, it is difficult to require thick continental crust beneath them (see no. 5 below).
5. Backarc thrust belts seem to form only where there is unusually thick arc crust and very flat subduction, such that there is exceptional shear coupling between the two plates—a feature possibly unique to the southern Andes. However, most continental arcs are generally low-standing features with crust of more or less average thickness (Hildebrand and Bowring, 1984), and the Jurassic-Triassic Sierra Nevada–Mojave–Sonoran arc appears to have been little different, for volcanic rocks were erupted and/or deposited mostly in shallow submarine environments (Busby-Spera, 1984, 1986; Busby-Spera et al., 1990; Busby et al., 2002; Fiske and Tobisch, 1978; Fisher, 1990; Riggs and Busby-Spera, 1990, 1991; Wadsworth et al., 1995; Haxel et al., 2005). The pulse of voluminous magmatism that likely led to crustal thickening in the Sierra Nevada, and other Cordilleran-type batholiths of the orogen, started at about 120 Ma (Bateman, 1992), ended abruptly at about 80 Ma, and simply isn't accounted for in the current backarc model.
6. The backarc model inadequately explains the intense shortening, high-grade metamorphism (>9 kb and ~800 °C), convergent temperature-time paths, and extensional collapse of the Sevier hinterland, where a minimum of 70 km of shortening and as much as 30 km of crustal thickening occurred, at least in part, contemporaneously with thrusting in the Sevier fold-thrust belt (Camilleri et al., 1997). This means that the crust was doubled to twice normal cratonic thickness. It is unclear how the compressive stresses required could be generated in a backarc environment and how the thin continental crust of a backarc basin could produce the observed pressures during deformation, given that the deformation was generally thin-skinned. It also fails to explain how older phases of the deformation, metamorphism, and crust thickening could have taken place adjacent to the North American passive margin without leaving any evidence.
7. The backarc model constrains all post-Mississippian magmatism to North American crust, yet Jurassic and Early Cretaceous plutons throughout Nevada and in the Sevier hinterland have isotopic compositions inconsistent with their derivation from North American continental crust (Wright and Wooden, 1991).
8. If the Roberts Mountain allochthon collided with North America and converted the passive margin to an active margin during the Late Devonian–Early Mississippian, then why was there so little arc magmatism in western North America until the Triassic (Wyld, 2000) about 100 million years

later? Similarly, the backarc model provides no satisfactory method or actualistic model to explain the sudden flare-up of magmatism within the various Cordilleran batholiths during the period 120–80 Ma (Ducea, 2001), despite hundreds of millions of years of assumed steady-state easterly directed subduction. What changed?

9. Another feature difficult to explain in the backarc model is the puzzling lack of rift deposits and rift basins on the North American margin. It is, of course, possible that the rifted margin was highly asymmetrical (Lister et al., 1991) such that rifted crust was predominantly on one margin like the present-day North Atlantic margin (Keen and Dehler, 1997); but since that rare occurrence reduces the width of the rifted margin on the North American side, it would be even more likely that palinspastically restored units west of the Cordilleran fold-thrust belt would not have been floored by North American crust. Nevertheless, the paucity of rift deposits is entirely unaccounted for in the backarc model.
10. While not strictly a flaw in the backarc model, the Mesozoic continental arc terrane of the Sierra Nevada is typically assumed to lie along the edge of the Paleozoic North American craton; but, in fact, the Sierra Nevada is oriented at a very high angle to the northeasterly trends of the miogeocline, the Sevier thrust belt, the Luning-Fencemaker thrust belt, the Roberts Mountain thrust, and the hypothesized edge of the craton as reflected by the 0.706 isopleth (Fig. 1). As the thrust faults of the Sevier fold-thrust belt appear to be truncated at a high angle, it is difficult to make the truncation entirely older than the Sevier orogeny, as suggested by some workers (Burchfiel and Davis, 1975; Hamilton, 1978; Saleeby and Busby-Spera, 1992; Dickinson, 2000). This suggests that the batholith was juxtaposed against those other elements sometime during or after the Cordilleran orogeny.

Overall, the problems with the backarc model (Fig. 2) for western North America indicate the need for a fresh look at the evolution of the Cordillera. I propose that a collisional model better explains the known geology and has interesting implications for the subsequent evolution of western North America. In the sections that follow I present data and explore the evidence from individual belts within the orogen and bring together various components to support an actualistic, and fully testable, collisional model for the evolution of the Cordilleran orogeny.

THE PASSIVE MARGIN AND WESTWARD CORRELATIONS

Rocks of the miogeocline are complex in detail, but collectively they form a westerly facing sedimentary platform and slope succession, sitting unconformably atop the North American craton. Rocks deposited during rifting are sparse to nonexistent, but possible candidates include rocks of the Gog Group and Mount Harper complex within Canada (Powell et al., 2006; Roots, 1983) and an amalgam of sedimentary rocks and basaltic lavas in the northern Utah–southern Idaho area (Harper and Link, 1986).

The oldest passive margin rocks deposited on the thermally subsiding margin (Bond and Kominz, 1984) are Cambrian sequences of quartzose siliciclastic rocks overlain by shelf-to-slope carbonate rocks that pass abruptly westward into sparse and thin, shaly basinal-facies rocks (Rigo, 1968; Stewart, 1970). The Paleozoic carbonate shelf-to-basin transitions are observable today in the eastern Sevier fold-thrust belt near the Utah-Wyoming border (Peterson, 1977; Rose, 1977; Doelling, 1980; Palmer and Hintze, 1992) and in the Main Ranges of the Canadian Rockies (Cook, 1970; Aitken, 1971). The basal Cambrian sandstone also grades westwardly into shale at the shelf edge (Oriel and Armstrong, 1971; Middleton, 2001). Overall, the platform-to-rise transition persisted in more or less the same position, except for occasional eastward transgressions and Pennsylvanian uplift and sags in east-central Utah, from the Cambrian at least through the Jurassic (Hansen, 1976; Koch, 1976; Rose, 1977; Blakey, 2008). The shelf-slope transition was termed by some the Wasatch hinge line (Hintze, 1988; Poole et al., 1992), which is not strictly correct, as the hinge line is the most landward point of lithospheric stretching and the shelf edge probably marks the most landward point of upper crustal extension (brittle faulting).

Some workers argued for thick off-shelf sediment accumulation of >13 km (DeCelles and Coogan, 2006), but there is no evidence that those allochthonous rocks were ever part of North America (Fig. 3). The concept of a thick offshore sequence stems directly from the pre-plate-tectonics eugeosynclinal concept, where off-shelf basinal sections were "supposed" to be much thicker than their platformal, miogeosynclinal counterparts (Schuchert, 1923). Whereas there are many factors, such as whether the margin was windward- or leeward-facing, that might influence how starved a given off-shelf sequence might be, during the Cambrian North America was rimmed by carbonate platforms and there is nowhere evidence for any topographically high-standing terrain that might have shed significant amounts of clastic detritus outboard of the carbonate platform. Thus, the Cambrian basinal facies of North America were especially starved. The overall scheme for western North America would have been an abrupt carbonate rim with a narrow slope-facies debris fan and a thin, sediment-poor, contourite-dominated rise facies (Fig. 4). Furthermore, because virtually all of western and central North America was covered by epeiric seas throughout most of the Paleozoic (Poole et al., 1977; Blake, 1995; James and Mountjoy, 1983), there were few places, if any, where there might have been extensive highlands capable of producing large volumes of sedimentary debris along the western North American margin.

Locally along the U.S. Cordillera, where thrusts haven't overrun and buried the facies changes, there are, west of the shelf edge, sequences of dominantly fine-grained rocks, which are the remnants of off-shelf sediments on the North American margin. The rocks of these regions separate the rocks of the Rocky Mountain shelf from another Paleozoic shelf sequence, the Antler shelf,

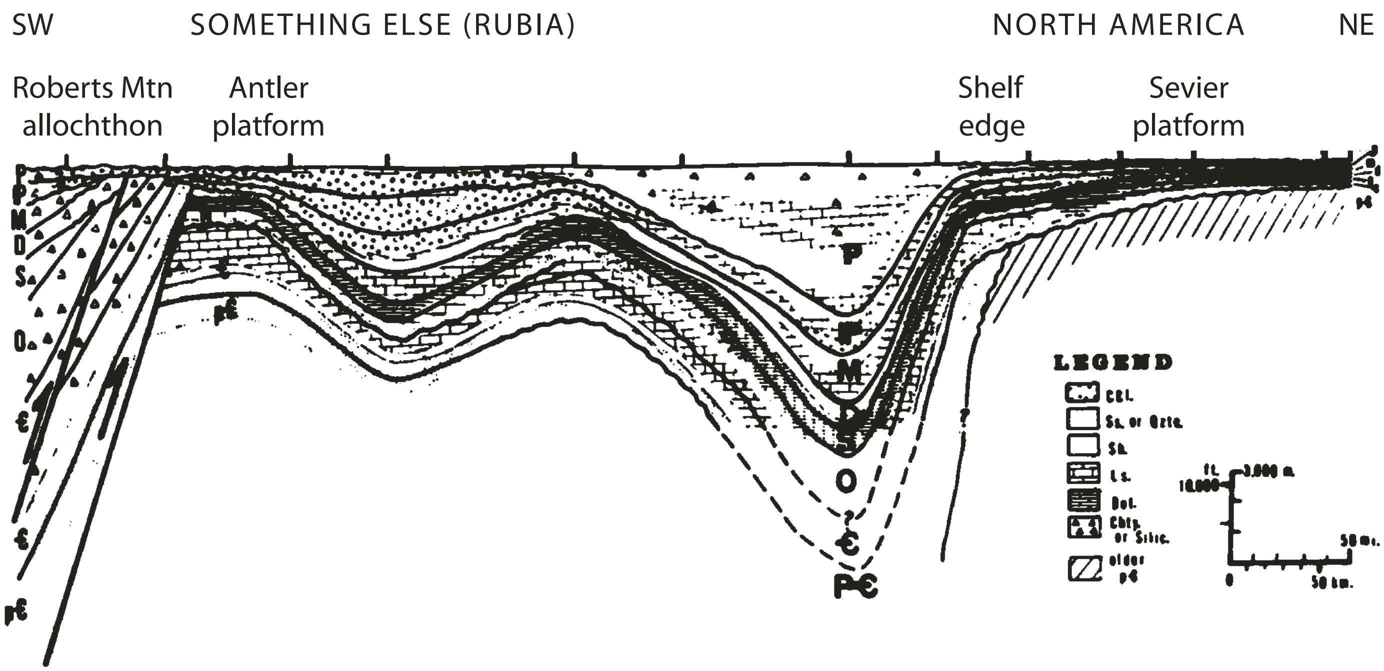


Figure 3. This palinspastic restoration through the North American passive margin from Wyoming to western Nevada (modified from Peterson, 1977) illustrates the widely held belief that the passive margin rocks extend westward from North America to lie beneath the allochthons emplaced during the Antler orogeny. It is important to recognize that there are two entirely different platforms: (1) the eastern Sevier platform, and (2) the Antler shelf, separated by a deep-water basin mostly without recognized basement: Only the Sevier platform sits on cratonic basement.

located to the west (Fig. 3) and now preserved in extensive allochthons within the Sevier fold-thrust belt. It was rocks of the Antler shelf—not the Sevier shelf—that were overthrust by rocks of the Roberts Mountain and Golconda allochthons, and partially buried by orogenic flysch from the collision zone. The west-facing Antler platform edge is well documented in Nevada and California from the Paleozoic to the Triassic, and there is no doubt that it is a different platform than the Sevier platform (Kepper, 1981; McCollum and McCollum, 1984; Heck and Speed, 1987; Montañez and Osleger, 1996; Morrow and Sandberg, 2008; Sheehan, 1986; Harris and Sheehan, 1998; Stevens et al., 1998; Stevens and Stone, 2007). Nevertheless, some workers (Stewart, 1970; Stewart and Poole, 1974; Poole and Sandberg, 1977; Poole et al., 1992) correlated rocks of the Antler shelf west of the hinterland in Nevada with rocks of the slope-rise and Sevier platform in the thrust belt, but it is hard to understand how the correlations could have been considered solid, given the intervening off-shelf slope-rise facies as well as the high-grade and complexly folded hinterland belt. The failure to recognize that there are two separate Paleozoic platforms in western North America was, in my opinion, the most critical error in the paleogeographical reconstruction of the margin, and which, more than any other factor, allowed the intraplate model to flourish; for if the North American margin wasn't overthrust and buried by the Roberts Mountain–Golconda allochthons and their orogenic debris during the Antler orogeny, then the North American margin would have remained passive and undisturbed until the Cordilleran orogeny, as suggested here.

In collisional belts, all rocks outboard of the shelf edge should be considered suspect, and extreme care must be accorded correlations across strike, for even though they might be similar in age to rocks of the shelf, the slope-rise sediments are typically strongly deformed and likely are tectonically interleaved with much younger, but similar appearing, trench deposits. This is an important point because ophiolitic debris and mélanges might not occur along a suture zone. One has only to imagine closing the Atlantic Ocean or to look at the sedimentary sequences on both sides of the Tethyan sutures to understand that similar rocks and sequences from opposite sides of an ocean can end up juxtaposed across a suture zone. A good example occurs in Iran, where nearly identical Baikalian platformal sequences with similar sedimentary gaps and regional disconformities occur on both sides of the Main Zagros ophiolitic suture (Stöcklin, 1974).

In the Canadian Cordillera the story is similar to that in the United States. A westwardly thickening wedge of mature and shallow marine clastic rocks sits unconformably on cratonic basement. The lower clastic rocks are overlain by two margin-parallel facies: an inner carbonate bank and an outer slope to basinal facies, which are separated by an algal reef complex known as the Kicking Horse Rim (Aitken, 1971). The shelf-slope facies transition occurs today in the Main Ranges close to the Alberta–British Columbia border, where the Middle Cambrian carbonate platform terminates into the shaly slope-to-basinal facies of which the best-known accumulation is the Burgess Shale (Cook, 1970; McIlreath, 1977; Price and Mountjoy, 1972). The facies change is

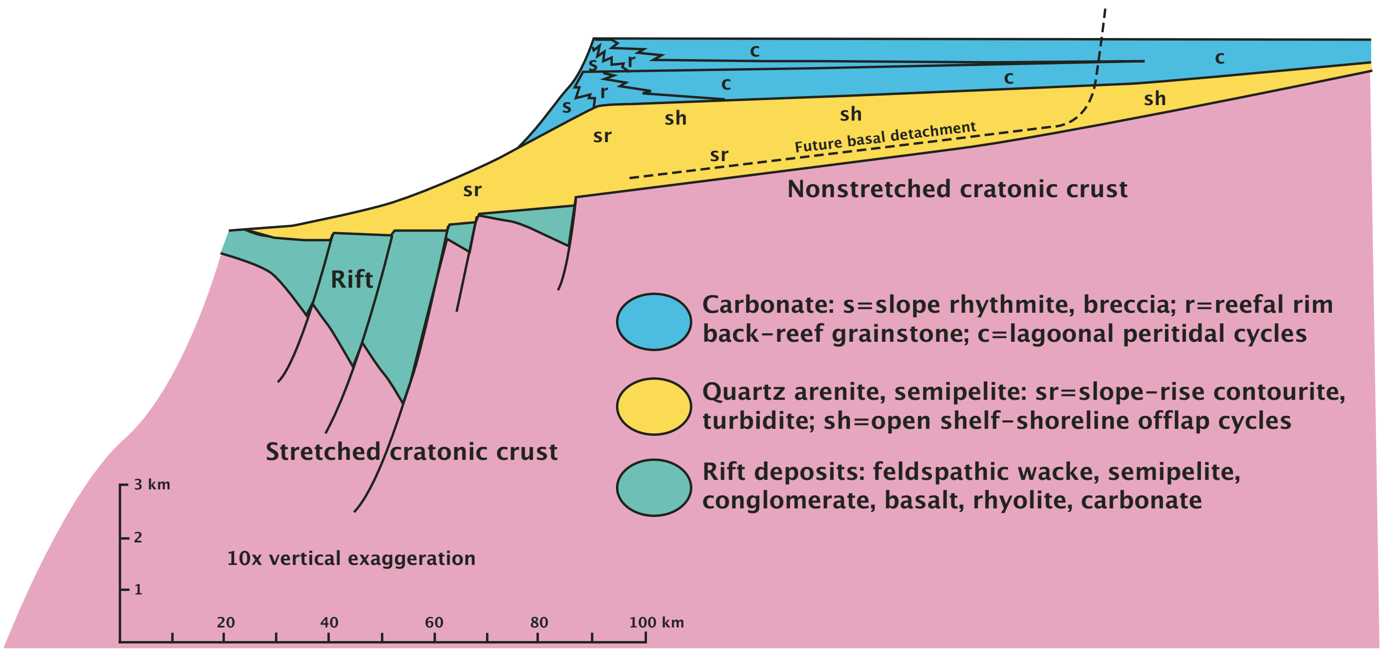


Figure 4. This figure shows an idealized passive margin (modified from Hoffman et al., 1988), illustrating the general coincidence of the platform edge and the extended upper crust.

the locus of faulting and huge gravity collapse scarps, and marks changes in penetrative strain and styles of folding (Dahlstrom, 1977; Stewart et al., 1993).

In Canada the equivalent of the Antler shelf is the Cassiar platform, which lies to the west of the off-shelf basinal sedimentary rocks (Johnston, 2008). Like their counterparts in the Great Basin region, rocks of the Cassiar platform constitute a shallow-water, mixed carbonate-siliciclastic platform ranging in age from Neoproterozoic to Jurassic. A number of lines of evidence, including faunal provinciality, basement ages, and contrasting Mesozoic structural evolution, led Johnston (2008) to suggest that rocks of the Cassiar platform were part of a much larger ribbon continent that was exotic with respect to North America prior to the Cretaceous.

When the effects of thrusting in the foreland fold-thrust belt are restored, it is likely that the platform-to-basin facies transition would approximate the boundary between non-stretched and stretched upper cratonic crust (Fig. 4). This follows directly from the well-documented idea that cooling is the primary cause of subsidence in passive margins (Watts et al., 1982; Bond and Kominz, 1984), confirmed by direct observations on existing passive margins (Ginsberg and James, 1974; Bott, 1980; Mougenot et al., 1983), direct observations in orogenic belts (Hoffman et al., 1988; Hildebrand and Bowring, 1999), and is suggested by the continuity of subsurface reflectors on seismic lines west of the thrust belt (Allmendinger et al., 1987; Cook et al., 1988, 1992). If this is correct, then basinal rocks to the west of the Rocky Mountain platform would have been deposited on extended or transitional crust and rocks of the Antler-Cassiar platform, which were situated even farther west, likely bear no affinity for North America.

The ongoing interactions between the Philippine Sea and Eurasian plates provide an enlightening example of how easily such correlations can be incorrect, despite similar age, rock type, and faunal assemblages. There, the Philippine oceanic to continental arc is obliquely colliding with Eurasia to form an arc-continent collisional orogen on the island of Taiwan (Suppe, 1984, 1987). Numerous carbonate platforms and basins occur over the length of the Philippine Islands, and, in large part, the ages of these platforms are synchronous with the ages of sedimentation on the Chinese Eurasian margin; yet it would be incorrect to correlate the carbonate rocks on the eastern side of the Philippines with those on the eastern side of the Chinese Eurasian margin, despite any superficial similarities they might have, because the Philippine arc lies between them.

Nevertheless, the correlation of the Sevier and Antler shelves (Fig. 3) led directly to models involving the Devonian collision of the Cambrian to Devonian Roberts Mountain allochthon and associated rocks with the western margin of North America during what is called the Antler orogeny (Burchfiel and Davis, 1972, 1975; Dickenson, 1977; Speed, 1977; Schweickert and Snyder, 1981; Miller et al., 1984). The spurious correlations across the collapsed shale basin and the high-grade hinterland are not the only lines of evidence to suggest that this collision did not involve North America.

1. There is no known deformation or sediment accumulation related to this orogeny on the Rocky Mountain shelf.
2. Thickening and burial to 7–14 km, simultaneous with abundant thrusting in the Luning-Fencemaker fold-thrust belt, significantly before 143 Ma and possibly as old as 190 Ma,

involved rocks of the Antler shelf; but there was no sign of this activity in rocks of the Rocky Mountain shelf, despite the observation that this deformation was widespread and affected all of the arc terranes of Nevada and eastern Oregon (Wyld et al., 2004).

3. Extensive Jurassic deformation and metamorphism, including the formation of recumbent nappe-like structures and intrusion of plutons, occurred within the hinterland belt, and involved rocks of the Antler shelf, yet there is no evidence of deformation or plutonic-metamorphic debris of this age anywhere on the Sevier platform. Both the Jurassic Morrison Formation of the Rocky Mountain shelf in the United States and the Kootenay Group in Canada have some westerly derived sediment, but they apparently lack orogenic debris, don't thicken westward, and, as the Morrison Formation is well dated to 155–148 Ma (Kowallis et al., 1998, 2007) and the Kootenay to 152–144 Ma, they are some 20–40 m.y. older than initiation of the Cordilleran foredeep at about 124–115 Ma (Ross et al., 2005; Greenhalgh and Britt, 2007).

It appears, then, that throughout the Paleozoic, and much of the Mesozoic, the North American margin remained passive as rocks of its shelf recorded no major tectonic events, except for some minor uplift of the Ancestral Rockies (Mallory, 1972) and simultaneous formation of small isolated basins such as the Paradox (Hite and Cater, 1972). These were likely related to far-field effects of the Ouachita orogeny (Kluth and Coney, 1981). A compelling feature of the shelf is the complete lack of sedimentary rocks that contain orogenic debris such as plutonic or metamorphic clasts, derived from the west until the Cretaceous. Late Devonian to Mississippian and Jurassic tectonic events, generally attributed to have occurred along the western margin of North America, involved rocks of the Antler-Cassiar platform, which was probably not amalgamated with North America until the Cretaceous–Tertiary Cordilleran orogeny.

FOLD-THRUST BELT AND EXOTIC SLICES

From northern Canada to Death Valley the fold-thrust belt (Fig. 1) is reasonably well studied and understood because it has been extensively explored for petroleum. The general findings are that during the Cretaceous, older rocks of the miogeocline were detached from their Precambrian basement along a décollement in Cambrian shale, then folded, and transported eastward toward the continental interior (Price and Mountjoy, 1970; Bally et al., 1966). Shortening across the fold-thrust belt varies from place to place, but except in northernmost Canada, it is generally >200 km (Oldow et al., 1989; Allmendinger, 1992; DeCelles and Coogan, 2006; Price, 1981; McMechan et al., 1992). As this shortening does not include penetrative strain, the total shortening is greater. What follows here are descriptions of thrust sheets carrying Precambrian strata and minor crystalline basement along the length of the orogen. These thrust sheets originated west of the continental slope, carry strata that have no North American correlatives, and hence are interpreted as lying on the hanging wall of a suture separating rocks of North America to the east from rocks of an accreted superterrane to the west.

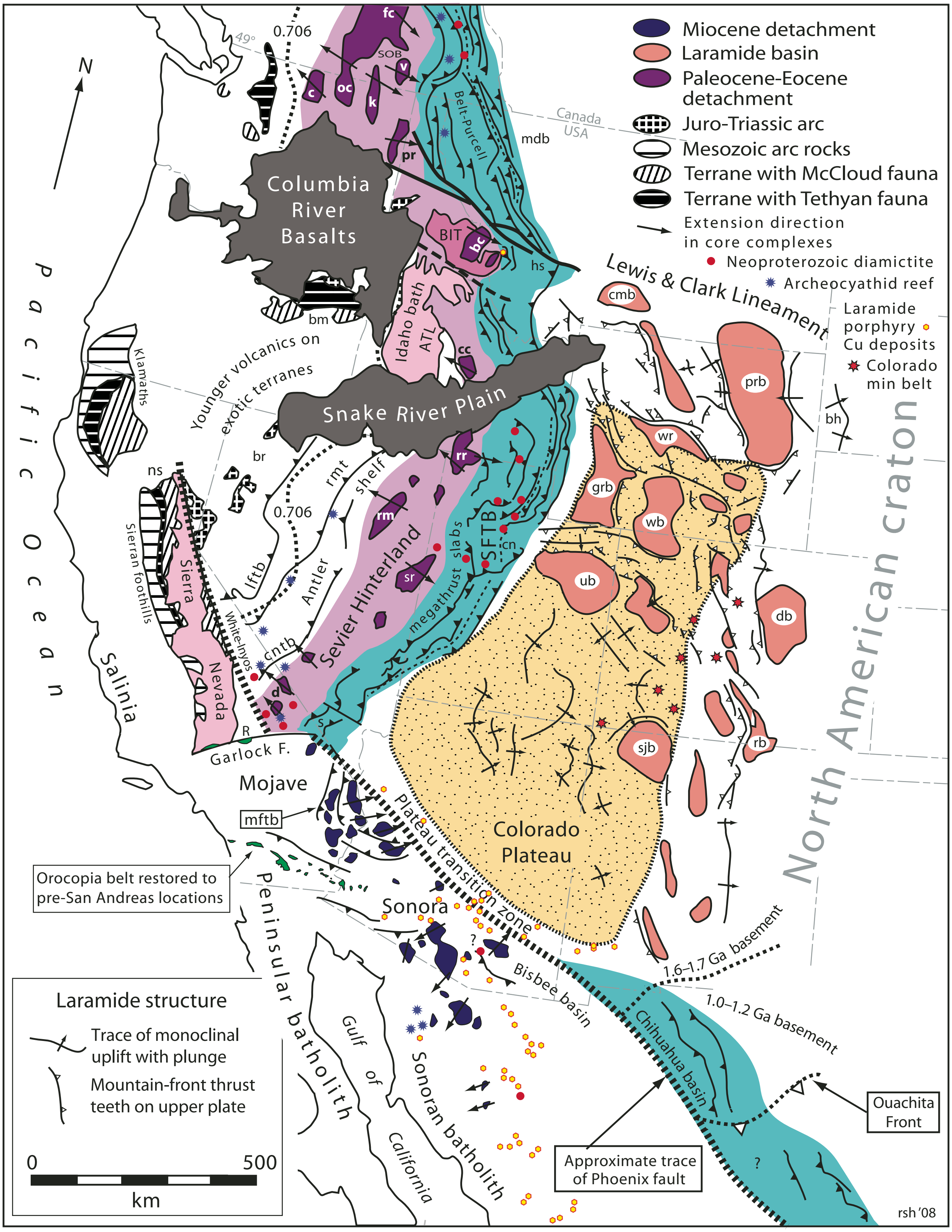
During thrusting the lower plate is pulled down beneath the overriding plate with its thickening allochthons so that the subjacent crust is depressed to form a foreland basin (Fig. 1) and an associated foredeep bulge (Stockmal et al., 1986; Yu and Chou, 2001). Both the basin and bulge migrate in front of the advancing thrust front (Currie, 2002; White et al., 2002; Goldstrand, 1994; Ross et al., 2005). The oldest foredeep sedimentation in both the U.S. and Canadian sectors is apparently Aptian, or about 124–115 Ma (Heller and Paola, 1989; Currie, 2002; Ross et al., 2005; Britt et al., 2007). I will expand on the timing of thrusting and initiation of the foredeep in a subsequent section.

In central British Columbia allochthons of Neoproterozoic clastic sedimentary rocks, collectively termed the Windermere Supergroup, emerge acutely southeastward from the Tintina fault zone and lie structurally upon platformal rocks of the North American passive margin. To the south, and for a strike length of ~175 km, several thrust systems such as the Purcell thrust, carry nearly 30 km of Mesoproterozoic Belt-Purcell Supergroup rocks and overlying Windermere rocks over off-shelf rocks of the North American margin (Wheeler and McFeely, 1991). Just north of the U.S. border, the thrusts override the platform-basin facies change, and the Belt-Purcell rocks sit entirely upon platformal rocks. The Lewis thrust carries Belt-Purcell rocks even farther eastward, where they sit structurally atop orogenic deposits of the foredeep (Fermor and Moffat, 1992).

These rocks continue southward into Montana where—in what is termed the Montana Disturbed Belt (Fig. 5)—a huge slab of Belt Supergroup rocks, 70–110 km wide, ~450 km long, and as much as 30 km thick, was transported onto the platform along the Lewis-Eldorado-Hoadley-Steinbach thrust system (Mudge

→

Figure 5. Geological sketch map of northwest Mexico, western United States, and southwesternmost Canada, illustrating the various tectonic elements discussed in the text. Approximate eastern limit of exotic allochthons marked by dashed line in thrust belt. Note that this is also the suture. Abbreviations: ATL—Atlanta lobe; bc—Bitterroot complex; bh—Black Hills; BIT—Bitterroot lobe; br—Black Rock Desert; c—cascades core; cc—Clearwater complex; cmb—Crazy Mountains Basin; cn—Charleston-Nebo salient; cntb—Central Nevada thrust belt; d—Death Valley; db—Denver Basin; fc—Frenchman Cap; grb—Green River Basin; hs—Helena salient; k—Kettle complex; lftb—Luning-Fencemaker thrust belt; mdb—Montana disturbed belt; mftb—Big Maria fold-thrust belt; ns—northern Sierra Nevada; oc—Okanagan complex; prb—powder river basin; pr—Priest River complex; rm—Ruby Mountains; rmt—Roberts Mountain thrust; R—Rand schist; rb—Raton basin; rr—Albion–Raft River–Grouse Creek Ranges; sjb—San Juan Basin; s—Spring Mountains; SFTB—Sevier fold-thrust belt; SOB—Shuswap–southern Omineca belt; sr—Snake Range; ub—Uinta Basin; v—Valhalla complex; wb—Washakie Basin; wr—Wind River Basin. Orocopia belt is restored to pre–San Andreas fault configuration after Nourse (2002), but the modern shoreline is left as is for reference. Note also that the extension within the younger Basin and Range Province is not restored. In this and subsequent figures, I use the geomorphological Colorado Plateau. Extension directions in Cordilleran core complexes after Wust (1986).


Miocene detachment
Laramide basin
Paleocene-Eocene detachment
Juro-Triassic arc
Mesozoic arc rocks
Terrane with McCloud fauna
Terrane with Tethyan fauna
Extension direction in core complexes
Neoproterozoic diamictite
Archeocyathid reef
Laramide porphyry Cu deposits
Colorado min belt
Laramide structure
Trace of monoclinal uplift with plunge
Mountain-front thrust teeth on upper plate
0
500
km
N
Pacific Ocean
Columbia River Basalts
Snake River Plain
Colorado Plateau
North American craton
Lewis & Clark Lineament
Sevier Hinterland
Belt-Purcell
Canada
USA
49°
0.706
Idaho bath
ATL
BIT
Younger volcanics on exotic terranes
Klamaths
Sierran foothills
Sierra Nevada
White-Inyo
Salinia
Garlock F.
Mojave
mftb
Orocopia belt restored to pre-San Andreas locations
Sonora
Peninsular batholith
Gulf of California
Sonoran batholith
Plateau transition zone
Bisbee basin
Chihuahua basin
1.6–1.7 Ga basement
1.0–1.2 Ga basement
Ouachita Front
Approximate trace of Phoenix fault
SFTB
megathrust slabs
Antler
shelf
rmt
lftb
cntb
110°
rsh '08

and Earhart, 1980; Mudge, 1982; Sears, 1988, 2001; Cook and Velden, 1995). Near the southern boundary of Glacier National Park, rocks of the shelf emerge for ~150 km from beneath the Lewis-Eldorado system, where they form a tightly folded and imbricate thrust stack of platformal and interleaved foredeep rocks in the Sawtooth Range (Mudge, 1982). Rocks of the Belt-Purcell Supergroup are entirely allochthonous (Sears, 2007).

South of the northern Montana segment the thrust belt emerges from the Lewis and Clark shear zone, where it forms a westerly concave salient termed the Helena salient (Fig. 5). There, several thrust systems, such as the Sapphire, Lombar, and Indian Creek, carry thick sections of the Belt eastward over the platform (Sears, 2001; Lageson and Schmitt, 1994).

Moving southward to the area just north of the Snake River Plain, the thrust belt is broken up by mid- to late-Cenozoic normal faults, but like thrusts farther north, western thrusts carry thick successions of Proterozoic strata. Paleoproterozoic crystalline basement occurs within the Cabin–Medicine Lake system just east of the Idaho batholith (Skipp and Hait, 1977; Skipp, 1987) and in the Tendoy Range of southwestern Montana (DuBois, 1982).

On the southeastern side of the Snake River Plain the Sevier belt forms a broad salient that continues southward through Idaho, westernmost Wyoming, and northeastern Utah (Fig. 5). The sector contains at least eight major thrust systems and is the main area along the U.S. portion of the fold-thrust belt where the platform edge wasn't overridden by Proterozoic-laden thrust sheets (Peterson, 1977; Rose, 1977; Palmer and Hintze, 1992). The western Paris, Willard, and Meade thrusts all carry the typical thick sections of Proterozoic sedimentary rocks, whereas other, more easterly, thrusts root in a detachment within Cambrian shale (Armstrong and Cressman, 1963; Armstrong and Oriel, 1965; Royse et al., 1975; Lamerson, 1982; Royse, 1993a). One of the thrust systems, the Ogden, has an antiformal duplex of Paleoproterozoic crystalline basement that now constitutes the Farmington complex (Bryant, 1984; Yonkee, 1992; Yonkee et al., 1989, 2003).

Just south of Provo, Utah, is another eastward reentrant, named the Charleston-Nebo salient (Fig. 5), where thrusts of the Charleston-Nebo system carry a large, overturned, almost recumbent, anticline composed of thick sequences of Pennsylvanian-Permian rocks not present on the North American platform, and lesser amounts of Paleoproterozoic crystalline basement (Tucker, 1983). Thrusts farther west, such as the Sheeprock, carry thick sections of Precambrian clastic rocks (Christie-Blick, 1982, 1983, 1997; Rodgers, 1989). Large areas of the eastern part of the thrust belt are buried by synorogenic sedimentary rock, and the entire area west of the Wasatch Mountain front was severely disrupted by Cenozoic normal faults.

There are four major thrust systems in south-central Utah, and the westernmost, the Canyon Range–Wah Wah system, carries 4–10 km of dominantly siliciclastic rocks of Neoproterozoic age and as much as 12 km of Paleozoic strata, whereas the North American platform to the east is only ~1.5 km thick (Hintze, 1988). The Canyon Range thrust is the type "megathrust" of DeCelles (2004) and DeCelles and Coogan (2006). Like the Santaquin embayment to the north, 50 km of the frontal fold-thrust belt in south-central Utah is also dominantly buried by orogenic deposits (DeCelles, 2004) and broken by younger normal faults. The eastern faults in the area rise out of a décollement in Cambrian shale (Lawton et al., 1997; DeCelles et al., 1995).

In the Las Vegas area there are several major thrust systems. The structurally lowest Wilson Cliffs thrust places Cambrian carbonates and clastics atop eolian Aztec Sandstone of the North American platform (Burchfiel et al., 1974a, 1998). Just to the west, thick sequences of Neoproterozoic sedimentary rocks, collectively known as the Pahrump Group, along with their Paleozoic cover, sit unconformably on crystalline basement in a series of thrusts (Burchfiel et al., 1974a, 1974b; Brady et al., 2000; Snow, 1992; Wernicke et al., 1988).

The southernmost example of the "typical" Sevier fold-thrust belt occurs near Las Vegas (Burchfiel et al., 1974a) and then ends abruptly in the northeastern Mojave Desert near the state line with California (Figs. 5 and 6). An arcuate, convex-to-the-southwest thrust belt lies south of the Sevier belt. There is no evidence that north-northeasterly trending faults of the Sevier fold-thrust belt are deformed by the east-southeasterly trending folds and faults. As the rock types, age of thrusting, and deformational styles change abruptly (Hoisch et al., 1988; Walker et al., 1995), there is likely a structural break between the two (Fig. 6). Most of the thrusts to the west within California appear to be considerably older than those of the Sevier fold-thrust belt (Stevens et al., 1998; Walker et al., 1995).

To the southeast, the Sevier fold-thrust belt is absent for ~500 km. Instead, variably metamorphosed crystalline basement, Paleozoic sedimentary rocks, and Mesozoic clastic, volcanic, and plutonic rocks dominate and, depending on location, were transported on either northerly and southerly vergent systems of thrust faults (Hamilton, 1982; Haxel et al., 1984; Harding and Coney, 1985; Boettcher et al., 2002) that likely delineate different terranes. In places the Paleozoic supracrustal rocks were correlated with strata in the Grand Canyon (Hamilton, 1982; Reynolds, 2007), but there are major stratigraphic differences, and many of the units in Arizona are tectonically thinned to only 10% of their cratonic thicknesses.

Miogeoclinal rocks and the Sevier-type fold-thrust belt appear again in northern Mexico (Figs. 1 and 5), where they continue southward through the Sierra Madre Oriental of Mexico to at least the Tehuantepec narrows in southern Mexico (de Cserna, 1989; Campa U., 1985). In the best studied section within Mexico, ~200 km of shortening occurred along easterly directed Cretaceous thrust faults (Suter, 1987). Unfortunately, much of the western margin of the belt and the adjoining hinterland terrane are covered by thick Tertiary volcanic deposits.

Overall, the similarity of the large structures and rock types over the length of the U.S.-Canadian sector of the fold-thrust belt is remarkable. Huge, thick allochthons carrying tens of kilometers of Meso- to Neoproterozoic sedimentary rocks—and locally 1.7–1.5 Ga crystalline basement—were thrust onto rocks of the North American platform. The platform-to-basin facies transition

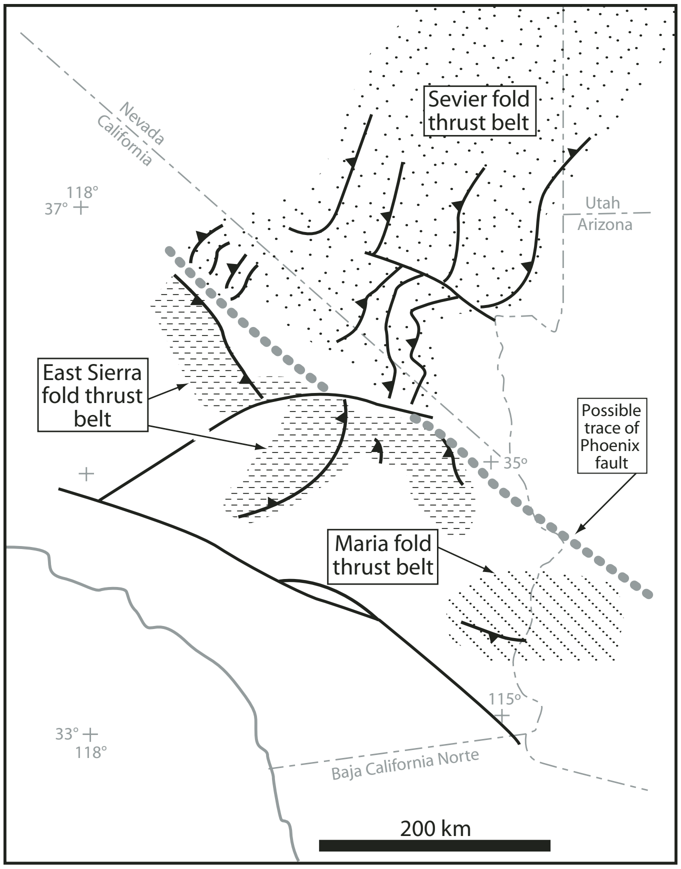


Figure 6. Sketch map from Walker et al. (1995), showing the apparent truncation of the Sevier thin-skinned thrust belt by rocks and structures of the Mesozoic magmatic arc.

is exposed for only a few hundred kilometers, as it is mostly overridden by the megathrust sheets, but its existence nevertheless demonstrates that the traditional idea (Stewart, 1970; Stewart and Poole, 1974; Stewart et al., 2002) of the megathrust sheets having been torn from the outer part of the North American continent is difficult to entertain, as there simply are no correlative units between the megathrusts and the platform. Similarly, just to the west of, and partly within, the megathrusts lies the hinterland belt (Figs. 1 and 7), where rocks were recumbently folded, and subjected to temperatures of ~800 °C and pressures >9 kb during the Jurassic. It is hard to comprehend how such metamorphism and deformation, which basically doubled the thickness of the crust, could have had no effect on the platform if it were only 80–100 km away, the typical width of the megathrust sheets.

THE HINTERLAND BELT

Lying directly west of the middle and late Precambrian megathrust sheets in the western Cordilleran thrust belt from southern Canada to Death Valley is the hinterland belt (Figs. 1 and 5; Table 1). Ever since Armstrong (1968) recognized the belt, its origin has proved elusive, as it contains low-grade sedimentary rocks, high-grade metamorphic rocks, several ages of crystalline basement, and both metaluminous and peraluminous intrusions—all cut by thrust and normal faults of significant displacement. Its eastern and western boundaries are somewhat obscure owing to at least two major periods of extensional faulting and variable exhumation; but in a general sense the hinterland is a northerly trending strip characterized by Paleocene-Eocene core complexes, both Jurassic and Cretaceous metamorphism, dominantly westerly vergent Jurassic folds, and generally sparse Jurassic-Cretaceous plutons.

Rocks of the hinterland are exposed in Paleocene-Eocene core complexes found in the Albion, Raft River, and Grouse Creek ranges in northeastern Nevada, northwestern Utah, and southern Idaho in what can best be termed the type area (Armstrong, 1968; Snoke, 1980; Howard, 1980; Todd, 1980; Snoke and Miller, 1988; Wells, 1992). Present-day structural relief within the hinterland is visible because of Paleocene–Eocene extensional collapse of the thickened and hot hinterland zone as well as even younger Basin and Range extension.

The rocks in the Albion–Raft River–Grouse Creek ranges (Fig. 5) are best divided into an autochthon comprising Archean crystalline basement unconformably overlain by a thin veneer of quartzite and pelitic schist (Compton, 1972), all structurally overlain by migmatitic crystalline basement draped in recumbently folded nappes of variably metamorphosed supracrustal allochthons (Fig. 7). Within the autochthon, the deformation—as evidenced by small-scale structures—decreases downward from the basal thrust, whereas metamorphism postdates, or was possibly synchronous with, thrusting (Compton, 1980; Miller, 1980; Snoke and Miller, 1988). Early Cretaceous and Jurassic granites, present in the overlying allochthons, have not been described within the autochthon. The crystalline basement of the autochthon is generally interpreted to represent cratonic North America of the Wyoming province (Miller, 1980; Snoke and Miller, 1988).

Allochthonous rocks of the area generally contain evidence for two pulses of deformation, the first during the Late Jurassic,

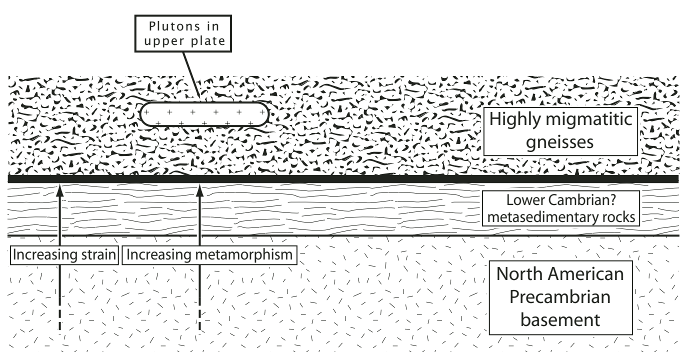


Figure 7. Schematic cross section illustrating the observed rock types and upward increasing strain and metamorphic gradients beneath the upper plate in the Utah-Nevada-Idaho sector of the hinterland. The fault between the upper and lower plates is here considered to be the suture zone that places exotic rocks atop rocks of North America.

TABLE 1. COMPARISON OF THE GEOLOGY OF VARIOUS CORE COMPLEXES IN THE HINTERLAND BELT, ILLUSTRATING THE OVERALL SIMILARITY IN PRESSURE-TEMPERATURE REGIMES, AGES OF METAMORPHISM, EXHUMATION, AND PLUTONISM

Location	**California**	**Nevada**	**Nevada**	**Utah-Idaho**	**Idaho**	**Idaho**
Name of complex	Funeral Mountains	Snake Range	East Humboldt–Ruby Range	Grouse Creek–Albion–Raft River	Pioneer	Clearwater
Autochthonous basement	–	–	None, but Archean core to nappe	Archean core overlain by quartzite	Archean core	–
Peak conditions of metamorphism	620–680 °C, 7–9 kb	610 °C, 8 kb	800 °C, 9 kb	600 °C, 6.5 kb	680 °C, 3.5 kb	600–650 °C, 9–10 kb
Age of metamorphism	Peak 91.5 Ma	79 Ma peak	85 Ma peak	84–69 Ma	70 Ma	Late Cretaceous
Age of exhumation	Late Cret.–early Tertiary	57–50 Ma	63–50 Ma	>Eocene	>50 Ma Challis	59–54 Ma
Age of plutonism	I: 91.5 ± 1.4 Ma; S: 62 Ma	100 ± 8 Ma, 78 ± 9 Ma	Jurassic granite	90–75 Ma	Synkinematic at 69 Ma; post at 49 Ma	–
Notes	Exhumation poorly dated	Early subhorizontal fabric indicates top to NE thrusting	Syntectonic leucogranite 85 ± 3 Ma	Metamorphism & deformation before 90 Ma in allochthons; also Jurassic metamorphism	84 Ma syntectonic; shallow levels exposed	1.787 & 1.587 Ga basement beneath Belt Supergroup
Location	**Idaho-Montana**	**Montana**	**Idaho-Washington**	**Wahington–British Columbia**	**Washington**	**British Columbia**
Name of complex	Bitterroot	Anaconda	Priest River	Okanagan/Kettle	North Cascades	Frenchman Cap, Thor-Odin, Valhalla
Autochthonous basement	–	–	Archean core overlain by quartzite	–	–	Paleoproterozoic overlain by metasediments
Peak conditions of metamorphism	700–725 °C, 7–8 kb	590–665 °C, 3.3–5.3 kb	770–930 °C, 7–11 kb	750–825 °C, 10 kb	640–740 °C, 9–12 kb	600–700 °C, 10 kb; 830 °C in Valhalla
Age of metamorphism	Peak 60 Ma	79 Ma peak	72 Ma	85–70 Ma	96–60	115–58 Ma
Age of exhumation	56 Ma start	>53–39 Ma	53–43 Ma	61–49 Ma	55–50 Ma	60–50 Ma
Age of plutonism	I: 100–79 Ma S: 66–49 Ma	–	–	Post-collapse plutonism 53–45 Ma	96–65 Ma; post-metamorphism at 48 Ma	Various ages in allochthon
Notes	–	Shallower level exposed than other core complexes	Allochthonous 1.57 Ga gneiss overlies autochthon	–	Previously not considered to be part of the hinterland belt	Core overthrust by Selkirk allochthon; inverted isograds beneath allochthon

Note: Data from sources cited in text; Cret.—Cretaceous; I—metaluminous plutons; S—peraluminous plutons.

and the second during the Late Cretaceous (Camilleri et al., 1997; McGrew et al., 2000). Plutons of Jurassic age occur within the allochthons. The Jurassic magmatism overlapped in time with minor folding, thrusting, and development of local metamorphic aureoles adjacent to the intrusions (Camilleri et al., 1997).

The second deformational and metamorphic event is more intense and pervasive. Thrust faulting during this contractional pulse caused at least 70 km of shortening and as much as 30 km of crustal thickening (Camilleri et al., 1997). Metamorphic assemblages within the area indicate deep burial and metamorphism, perhaps as early as Late Jurassic, followed by higher temperature Late Cretaceous peak metamorphism at 85 Ma with temperatures of 800 °C and pressures of >9 kb followed by a steep uplift path (McGrew et al., 2000). Exhumation was largely complete by the Eocene, when magmatic rocks intruded and overstepped extensional detachments (Miller et al., 1987; Camilleri, 1992).

The Ruby Range–East Humboldt Mountains (Fig. 5) just to the southwest in Nevada also contain rocks that record a complicated history of two Mesozoic orogenic events: (1) 153 Ma plutonic emplacement, polyphase folding, and upper amphibolite facies metamorphism; and (2) Late Cretaceous migmatization, metamorphism, and deformation (Snoke and Miller, 1988; Hudec, 1992; McGrew et al., 2000). Cretaceous migmatitic upper amphibolite facies rocks are tectonically stacked and include a local recumbent isoclinal fold cored by Archean basement and a structurally overlying section of Neoproterozoic to Mississippian sedimentary rocks possibly sitting on Proterozoic gneiss (Howard et al., 1979; Lush et al., 1988; McGrew et al., 2000). Migmatization was synkinematic with nappe emplacement at 84.8 ± 2.8 Ma, with peak metamorphic conditions of 9–10 kb pressure and 750–800 °C (Hodges et al., 1992; McGrew et al., 2000). The initiation of exhumation and uplift is not precisely dated, but exhumation spans the range 63–50 Ma (Snoke and Miller, 1988).

South of the Ruby Range lies the massive Snake Range (Fig. 5), which appears to be structurally simpler but still contains evidence for two periods of plutonism and metamorphism, one at about 160 Ma and the other starting at about 100 Ma with pre-metamorphic plutons, peak metamorphism at 79 Ma, and initial exhumation between 57 and 50 Ma (Snoke and Miller, 1988; McGrew et al., 2000). Allochthonous Neoproterozoic and Paleozoic sequences in both the Snake Range and the East Humboldt–Ruby ranges are similar to those in the megathrust sheets of the thrust belt.

The hinterland belt continues southward into the Death Valley area (Fig. 5), where rocks of the hinterland were metamorphosed during the Cretaceous with peak metamorphic conditions of ~620–680 °C and 7–9 kbar at 91.5 ± 1.4 Ma, followed by Late Cretaceous or early Tertiary extension, typical of other areas within the hinterland (Hodges and Walker, 1990, 1992; Applegate and Hodges, 1995; Mattinson et al., 2007).

Just like the Sevier fold-thrust belt, the hinterland belt does not appear to continue south of the Death Valley area. Thrust faults and high-grade metamorphic rocks occur in the northeastern Mojave Desert region and were deformed and metamorphosed to upper amphibolite facies at depths of 9–12 km beneath a large nappe (Hoisch et al., 1988). However, these thrusts involve crystalline basement and Mesozoic plutons, a characteristic of the Mojave-Sonora thrust belts and not the Sevier thrust belt. While deserving of more detailed study, the relations suggest that both the Sevier fold-thrust belt and the hinterland belt are truncated near the Nevada-California border and are not present in the Mojave region of California (Walker et al., 1995). Similarly, north of the Garlock fault and extending northward to southern Owens Valley, the East Sierran thrust belt comprises mostly northwest-striking, southwest-dipping thrust faults that are largely Triassic-Jurassic (Stevens et al., 1998).

The Sevier hinterland continues north of the Snake River Plain (Figs. 1 and 5) in the vicinity of the Idaho batholith (Hyndman and Sears, 1988). The Pioneer metamorphic core complex contains an Archean core structurally overlain by Mesoproterozoic gneisses and intruded by a variety of plutons at 54–48 Ma (Silverberg, 1990; Link et al., 2007; Wust and Link, 1988). Slightly to the north and adjacent to the Bitterroot lobe of the Idaho batholith in the Bitterroot complex, metasedimentary rocks of uncertain affinity were intruded by mid-Cretaceous quartz diorite and tonalite plutons between 100 and 79 Ma and then by peraluminous granites between 66 and 49 Ma (Chase et al., 1978; Bickford et al., 1981). The metasedimentary rocks preserve a metamorphic peak of ~700–725 °C and 7–8 kb, which was attained by about 60 Ma and followed by gravitational collapse and rapid exhumation starting at about 56 Ma and continuing to at least 48 Ma (House et al., 1997, 2002; Hodges and Applegate, 1993).

Large numbers of gneissic to foliated Cretaceous plutons occur within the hinterland belt of Idaho (Lewis et al., 2005). Some of the plutons contain primary epidote and so are inferred to record crystallization at pressures >6 kb (Zen and Hammarstrom, 1984). Within the hinterland of Idaho and Montana there is some confusion as to how to divide the high-grade supracrustal rocks, because metamorphosed Belt Supergroup rocks strike into the area. Also present are numerous small Eocene granitoids and andesite dikes.

Nevertheless, recent work on the Clearwater core complex, which lies just to the northwest of the Idaho batholith (Fig. 5), and comprises a core of Paleoproterozoic 1.787 Ga anorthosite and gneiss interleaved with 1.587 Ga amphibolite mantled by polymetamorphic rocks of the Belt-Purcell Supergroup, reveals peak Late Cretaceous metamorphic pressures as high as 9–10 kb with temperatures of 600–650 °C prior to exhumation, which began at about 59–54 Ma (Doughty et al., 2007; Doughty and Chamberlain, 2007).

The Coolwater culmination of western Idaho, although not recognized to be a core complex, should be considered part of the hinterland belt owing to its Cretaceous upper amphibolite-grade metamorphism, plutonism, and deformation. There, Cretaceous paragneisses, deposited between 98 and 86 Ma, were overthrust by 1.425–1.370 augen gneiss along an easterly vergent thrust fault containing slivered ultramafic pods and bodies: Thickening and melting within the culmination stopped at about 61 Ma (Lund et al., 2008; Lund and Snee, 1988).

Along the Idaho-Montana border, additional core complexes were discovered recently within the hinterland belt. They include the Anaconda and Chief Joseph (O'Neill et al., 2004, 2005). The Anaconda complex exposes a more upper-crustal segment than do many of the other core complexes in the hinterland belt. Peak metamorphism, which occurred around 79 Ma, was ~3.3–5.3 kb and 600–665 °C (Haney, 2008). Exhumation occurred between about 63 and 45 Ma. At present there are no detailed studies on the metamorphism of the Chief Joseph complex, but the normal faulting is no younger than Eocene (O'Neill et al., 2004).

Several west-northwesterly trending sinistral strike-slip faults displace the hinterland and fold-thrust belt (Figs. 1 and 5). The Great Divide megashear has up to 500 km of left-lateral slip (O'Neill et al., 2007). That fault and others of the Lewis and Clark lineament ("Montana transform" of Sears, 2006) translated rocks of the hinterland belt westward into Washington, where they trend northward and cross the international border into Canada.

The southeasternmost core complex north of the Lewis and Clark lineament occurs in the Priest River complex of northern Idaho (Fig. 5), where 2.65 Ga Archean quartzofeldspathic gneiss is overlain by quartzite and migmatitic pelitic paragneiss, which in turn are structurally overlain by 1577–1511 Ma augen gneiss (Doughty et al., 1998; Doughty and Price, 1999; Doughty and Chamberlain, 2008). These authors report metamorphic monazite and xenotime ages of about 72 Ma, which date peak metamorphic conditions: Exhumation ages were determined by K-Ar methods to be 50–43 Ma, but they could be a bit older. The 1577 Ma age for the gneisses above the décollement is unknown on the North America craton (Hoffman, 1989), and therefore it likely represents exotic crystalline basement now sitting atop the North American craton and its thin veneer of autochthonous cover.

The rocks farther west, in the Cascades of Washington (Fig. 5), are not generally considered to be part of the hinterland belt, but they are fault bounded, and their metamorphic and structural evolution (Table 1)—as well as their proximity with the southern Ominica belt in Canada—suggest that they could be interpreted as part of the hinterland. Alternatively, they may simply be a southern extension of the Coast Plutonic Complex, which also underwent similar events at about the same time. The rocks include an upper plate of gneisses and possible metasedimentary and volcanic rocks, now preserved as amphibolites and layered gneisses of the Napeequa complex (Valley et al., 2003). The earliest structures within the Napeequa suggest westerly to southwesterly vergent thrusting and folding similar to many upper plate rocks elsewhere in the hinterland belt. A large fault, the Dinkleman décollement, has top-side to the northeast transport, separates rocks of the lower plate from the gneisses and their metamorphosed cover, and is associated with decreasing temperatures through time (Paterson et al., 2004). Although the evolution of this belt is not worked out in detail, it appears that epidote-bearing metaluminous plutons within the upper plate were emplaced between 96 and 91 Ma at 7–10 kb pressure into host rocks with peak metamorphic conditions of 9–11 kb and 640–740 °C, whereas later peraluminous granite sheets were intruded at 68 Ma (Matzel et al., 2004). One paragneiss contains detrital zircons dated at 73 Ma, which were buried, intruded by the peraluminous granites at 68 Ma, and exhumed during gravitational collapse of the hinterland by 55 Ma (Miller and Bowring, 1990; Matzel et al., 2004). In a general sense the geology of the area indicates northeast-southwest contraction and thickening from at least 96 to 73 Ma, which overlapped with significant plutonism at 96–65 Ma (Matzel et al., 2008), followed by extension and rapid exhumation by about 55–50 Ma (Paterson et al., 2004). Post-collapse plutonism started at about 48 Ma (Matzel et al., 2008).

In southern Canada the Omineca belt (Fig. 5) lies west of the Purcell allochthons and is generally better studied and understood than its counterpart in the Sevier hinterland. It comprises moderate to high-grade core complexes of metamorphosed and shortened North American cratonic basement (Armstrong et al., 1991; Johnston et al., 2000) structurally overlain by highly-deformed exotic basement and cover rocks of the Selkirk allochthon. In the Valhalla complex, peak temperatures were ~830 °C, and in the Monashee complex (Fig. 5) temperatures reached 600–700 °C at about 60–55 Ma with an estimated crustal shortening of 75% and thickening of >20 km during Mesozoic to early Tertiary time (Brown and Journeay, 1987; Parrish, 1995). Elsewhere in the region, gneissic rocks are isoclinally folded with amplitudes of 4–5 km, then refolded by another set of recumbent structures with amplitudes up to 8 km, and refolded again (Gabrielse, 1992).

The cover is variable, ranging from probable exotic rocks of the Kootenay terrane to exotic strata of uncertain affinity. Polyphase deformation typically includes several generations of folding within recumbent nappes (Fig. 8), which are often spectacularly exposed on steep to vertical mountainsides and in gently plunging cross sections (Raeside and Simony, 1983; Simony, 1992). The structures are remarkably similar to nappes found in the Alpine collisional belt (Bailey, 1968).

In other areas just to the south of the Scrip nappe, such as the Illecillewaet synclinorium, lower Paleozoic rocks were involved in southwest-verging folds and thrusts, intruded by 181–165 Ma plutons, and metamorphosed at pressures of 6–7 kb during the Jurassic, but they were exhumed such that 10 km of rock was removed from the area between 173 and 168 Ma (Colpron et al., 1996). These rocks were intruded by Cretaceous plutons between about 110 and 90 Ma and are situated today only ~130 km west of the North American shelf edge, which exhibits no evidence of the deformation, exhumation, and plutonism.

Metamorphism in the southern Omineca belt is highly variable, but in some well-studied areas, such as the Monashee complex, there were two compressional and metamorphic pulses, just as elsewhere in the Sevier hinterland. However, the main metamorphism within the North American plate occurred exponentially between 115 Ma and 58 Ma (Fig. 9), when the hot Selkirk allochthon was placed on top of the North American plate and progressively metamorphosed it (Parrish, 1995; Brown et al., 1992; Carr, 1986, 1995), leading to inverted isograds in the autochthon (Journeay, 1986). More than 15 km of rapid exhumation occurred on the core-complex normal faults between about

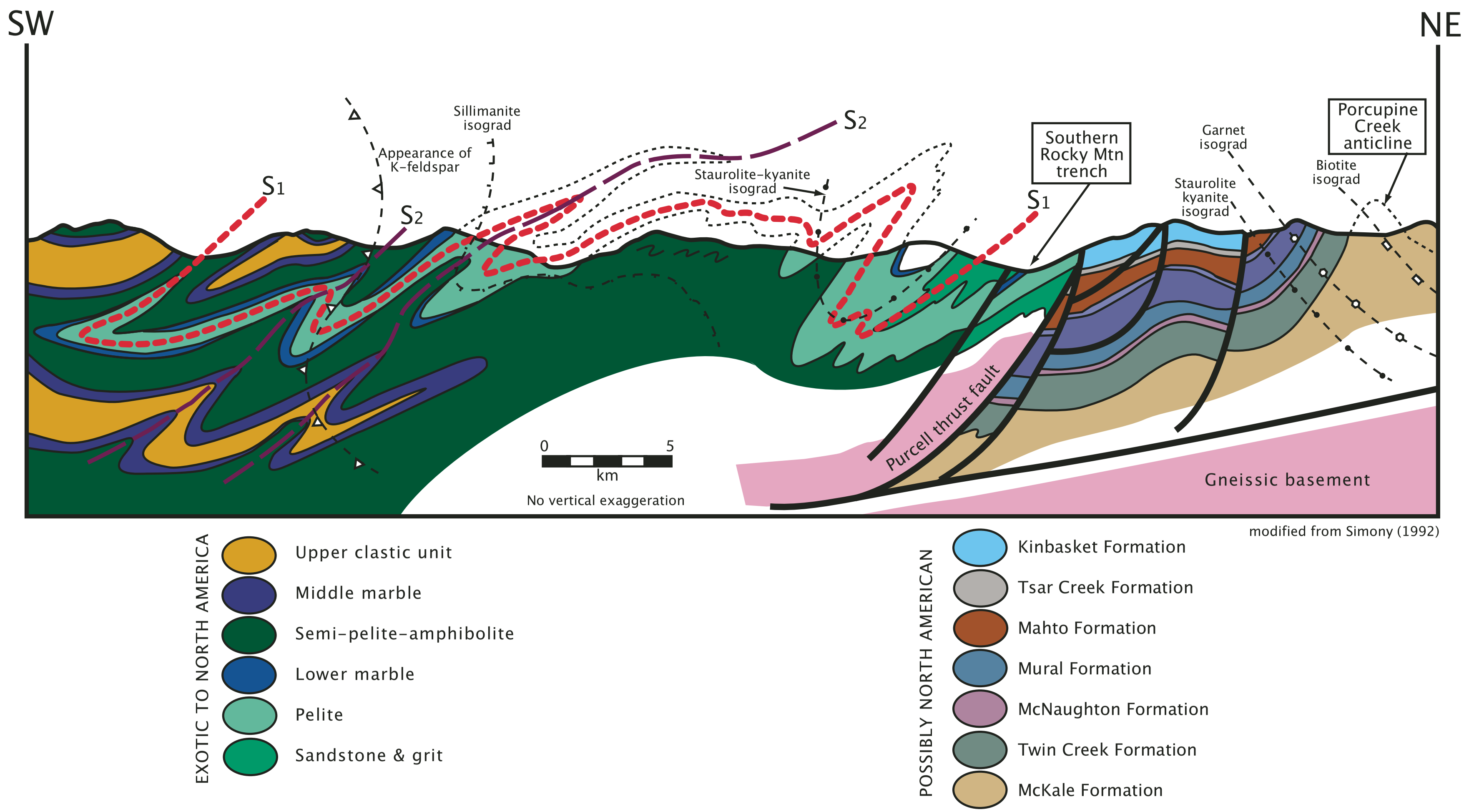


Figure 8. A southwest to northeast structural cross section from Simony (1992) shows the geology through the Selkirk Range to the western Rocky Mountains. Note the westerly vergent Scrip nappe refolded and carried by the Purcell thrust fault over much simpler structures. The earlier structures formed during the Jurassic, whereas the latest folding and thrusting was Cretaceous.

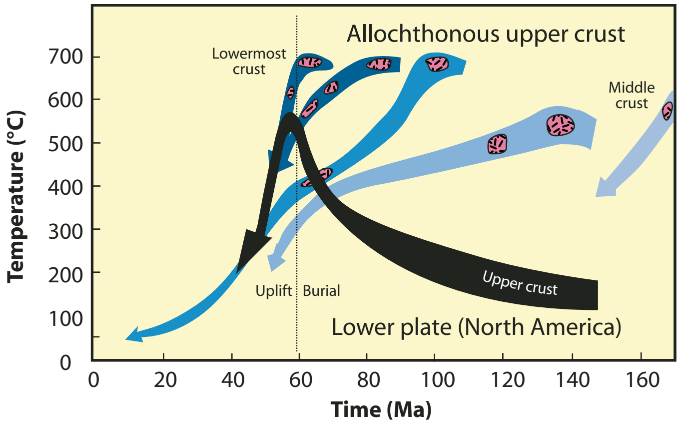


Figure 9. Diagram adapted from Parrish (1995), illustrating the thermal evolution of the Selkirk allochthon and the North American Monashee Complex. This evolution is probably typical of rocks throughout the Sevier hinterland–Omineca belt areas. The upper allochthonous plate cools slowly, while the lower plate progressively warms as it is buried, but once the allochthonous slab is placed on top it warms at a faster rate. Both plates cooled rapidly between 60 and 50 Ma as the orogen collapsed gravitationally. The figure also demonstrates that unless equivalent crustal levels are sampled for P-T-t (pressure-temperature-time) work there will be wide variations in the results, even though the overall P-T-t values might be more or less the same from locale to locale.

58 and 50 Ma (Parrish et al., 1988). The detailed work done by Parrish (1995) and summarized in Figure 9 illustrates the metamorphic paths for various crustal levels in the hinterland belt. This illustration makes it clear that a hot plate was emplaced upon a much cooler plate, and that both cooled together between 58 and 50 Ma. It also explains part of the variation in metamorphic ages obtained from rocks up and down the hinterland belt (Table 1), simply because the samples collected in the upper plate by various workers were not necessarily sampled from equivalent structural levels. LITHOPROBE seismic refraction data suggest the possibility that the basal décollement in the Canadian foreland belt passes westward beneath the allochthons and joins the Monashee detachment before climbing down beneath allochthons even farther west, perhaps to the Fraser River fault (Brown et al., 1992; Cook et al., 1988, 1992).

Recently, some workers (Kruse and Williams, 2007) challenged the idea that the Monashee and its overlying allochthons were separate entities and described the boundary between the two as a gradational boundary, but this idea runs counter to the preponderance of evidence, and, as we know that the crust was substantially thickened, then it merely serves to move the zone of thrusting to a different fault zone. Another point of contention is whether or not the hinterland belt contained substantial regions of migrating partially molten crust (Teyssier et al., 2005) or not (Carr and Simony, 2006). Both problems can be resolved if the lowermost part of the upper plate was partially molten and formed a zone where rocks above it spread laterally to create a broad zone of shear that overprinted the original suture.

In the northern and central British Columbia and Yukon sectors of the Cordillera, the rocks and structure are quite different, but they are still classified as part of the Omineca belt. Although a few core complexes occur there, the main area of Late Cretaceous extension is farther west within the Coast Plutonic Complex. There, arc magmatism ended in the mid-Cretaceous, and a narrow area, extending from Washington State to Alaska, was uplifted and rapidly exhumed by 60 Ma (Armstrong, 1988; van der Hayden, 1992; Andronicos et al., 2003). Within the complex, older plutons, now orthogneiss, show top over bottom to the southwest thrust displacements, but starting at about 67 Ma, plutons were emplaced in an extensional environment (Crawford et al., 1999). This Late Cretaceous–Paleocene suite of plutons continued to be emplaced after orogenic collapse and was attributed to asthenospheric upwelling (Mahoney et al., 2006).

The geology in Alaska is broadly similar to that described in southern Canada and the continental United States. In the Brooks Range of northernmost Alaska a Jurassic collisional belt was thrust on top of North American rocks, starting in the Late Cretaceous, and they collapsed at about 60 Ma (O'Sullivan et al., 2006; Vogl et al., 2002). Thrusts associated with this event deformed the earlier Jurassic (about 136 Ma) structures, as well as previously nondeformed passive-margin strata of North America on the North Slope (Moore et al., 2004; Potter and Moore, 2006). The Jurassic event in Alaska (Miller and Hudson, 1991) might be the same event recorded within the allochthons of the Great Basin and Canada.

Johnston (2001) presented an intriguing hypothesis in which most of central Alaska is made of an 8000-km-long ribbon continent containing segments of the North American craton and its collisional belt, which were sliced off and transported northward to interior Alaska and Yukon Territory, where they were wrecked in an oroclinal orogeny or large-scale buckling event. There is abundant paleomagnetic evidence for large-scale strike-slip movement along the western margin of North America (Irving et al., 1980; Irving and Wynne, 1992), but there is no evidence that parts of North America lie within the terrane wreck, as the oldest rocks in it appear to be Devonian.

The descriptions of the fold-thrust and hinterland belts presented above demonstrate that rocks and relationships along the western margin of North America are remarkably similar and extend from Death Valley to Alaska. The passive-margin sedimentary rocks were detached from their basement and moved farther onto the craton during an intense mountain building episode, which doubled the crustal thickness in the hinterland. The mountain building episode involved medium- to high-grade metamorphism associated with overthrusting of hot allochthons, and, at about 70–60 Ma, belt-orthogonal extension (Fig. 5) led to exhumation and denudation on regional detachment-type normal faults, as originally envisioned by Armstrong (1982) and Coney and Harms (1984).

FAILED SUBDUCTION OF NORTH AMERICA

Taken together, the consistent relations over most of the orogen, involving hundreds of kilometers of thrust transport eastward over the craton, simultaneous with high-grade metamorphism when a hot slab was placed atop autochthonous North America, lead me to conclude that the main collisional event of the Cordilleran orogeny was failed subduction of the North American continent beneath an exotic arc-bearing superterrane, which I call Rubia, and whose leading edge occurs at the easternmost edge and base of the megathrust slabs.

Rubia is named for superb exposures in the Ruby Mountains of Nevada, where many of the features characteristic of the superterrane are well exposed. Rubia is defined to include all the terranes amalgamated prior to collision with North America in the Cretaceous. As such it includes SAYBIA, the ribbon continent of Johnston (2001, 2008), which was defined to include rocks in Siberia, Alaska, Yukon, and British Columbia.

Farther west the suture is difficult to locate, as it is buried beneath exotic allochthons or highly modified along with strongly deformed basement of the upper-plate, high-grade metamorphic rocks, and younger normal faults. Nevertheless, it crops out in many spots along the belt. The best known and best exposed part of the suture occurs within the Monashee complex (Fig. 1) of southern British Columbia (Parrish, 1995), but it is also exposed in the Priest River and Pioneer complexes and in the Nevada-Utah-Idaho sector. In the model presented here, rocks above the suture belong to Rubia and are exotic with respect to North America.

Within the southern British Columbia sector of the collisional belt there is strong evidence that a hot upper plate was emplaced upon North America and that heat was conducted downward to metamorphose the uppermost parts of the craton (Journeay, 1986; Parrish, 1995). Elsewhere, the upper-plate rocks are typically strongly migmatitic, whereas beneath the thrust the rocks generally are not. The downward flux of heat into rocks of the North American plate likely resulted when the leading edge of the North American passive margin was pulled beneath the eastern edge of Rubia.

AGE OF THRUSTING AND COLLISION

The age of thrusting, and hence collision, is reasonably well constrained by a number of detailed sedimentological and paleontological studies. The earliest record of sedimentation that can be tied to disturbances along the entire western margin of North America occurs in the Aptian at about 124–115 Ma, when gravels and conglomerates, comprising a wide variety of sedimentary clasts such as chert, quartzite, limestone, and siltstone, were eroded from the Rocky Mountain platform and dispersed eastward to form a thin veneer over a regional unconformity and a calcrete-silcrete paleosol complex on the Morrison Formation and its equivalents (Leckie and Smith, 1992; Heller and Paola, 1989; Yingling and Heller, 1992; Currie, 2002; Ross et al., 2005; Zaleha and Wiesemann, 2005; Zaleha, 2006; Roca and Nadon, 2007; Greenhalgh and Britt, 2007). These gravels are known by various local names, such as Cadomin, Kootenai, Lakota, Cloverly, Ephraim, Buckhorn, Pryor, and so on, and they are extensive (Heller et al., 2003), occurring up and down the continent, eastward to the Black Hills of South Dakota (Fig. 5), and as far south as Silver City, New Mexico, where the gravels appear above a basal mudstone in the lower part of the Beartooth quartzite (Hildebrand et al., 2008). The gravels are overlain by marine mudstones and siltstones of Albian and Cenomanian age, which mark the first sedimentary rocks of the Western Interior Basin (Kauffman, 1977).

An older, linear basin of Jurassic age formed at about 176 Ma in the Canadian foreland region, where it is known as the Fernie-Kootenay basin (Gibson, 1985; Poulton et al., 1994). The earliest sedimentary rocks in the basin are shales derived from the east: Westerly derived sedimentary rocks were not transported into the basin and distributed axially until the Late Jurassic (Fermor and Moffat, 1992; Stockmal et al., 1992). Farther north some westerly derived sedimentary rocks dated as Middle to Late Jurassic crop out, but sedimentation had stopped by the Hauterivian (Evenchick et al., 2007). Whatever the significance of the basins—and they may have represented local transpressional interactions along the western margin of North America (Price, 2000)—for the most part, westerly derived plutono-metamorphic detritus did not arrive in the region until after deposition of the Cadomin Formation and its basinwide equivalents (Stockmal et al., 1992; Ross et al., 2005). A regional unconformity in the Foothills belt separates rocks of the Fernie-Kootenay basin from those of the Cadomin Formation.

Similarly, shallow marine–lacustrine rocks of the Jurassic Morrison Formation within the United States were deposited between 155 and 148 Ma (Kowallis et al., 1998, 2007) and locally formed sub-basins where the rocks coarsen westward. Just as with the Fernie-Kootenay, there is apparently no westerly derived plutono-metamorphic detritus. Others suggested that both the Morrison and the Fernie-Kootenay represent back-bulge deposits to a "phantom" foredeep, now eroded but once located to the west, or else they possibly reflect regional dynamic subsidence (Royse, 1993b; DeCelles and Currie, 1996; DeCelles, 2004). However, there is no evidence for a foredeep of Morrison age farther west, and the Morrison itself doesn't thicken continuously westward (Heller et al., 1986). In fact, there is evidence that instead of continual subsidence characteristic of a foredeep, the Morrison Formation was uplifted prior to deposition of the Buckhorn conglomerate of central Utah, as the conglomerate fills paleovalleys in the Morrison (Yingling and Heller, 1992; Currie, 1998; Heller et al., 1986) and has a thick paleosol at its top that is truncated by the Buckhorn Conglomerate (Currie, 1997); the Yellow Cat Member, the basal member of the overlying Cedar Mountain Formation, consists primarily of reworked Morrison Formation (Eberth et al., 2006).

A possible explanation for the localized surges in siliciclastic debris shed over the platform found in both the Fernie and Morrison basins is the presence of islands to the west. In the collision model presented here, sediment couldn't cross the trench region from the forearc region of the upper plate to the platform located on the lower plate. Thus, the westerly derived debris must have been caused by erosion of islands that emerged on westernmost North America, reasonably in the area of rift basins and tilted fault blocks. Emergent islands could have created the point sources for the westerly derived siliciclastics, as shown in Figure 10. Islands caused debris to be shed over the North Australia shelf several million years prior to subduction of the leading edge of the shelf beneath the New Guinean arc (Quarles van Ufford and Cloos, 2005) and to the west, where islands, such as the Aru, lie between the trench and present-day Australia (Verstappen, 1959).

Another plausible model for the origin of the Jurassic foredeep-like basins involves small areas of retreating subduction boundaries (Royden, 1993a, 1993b) that could have arrived at the North American margin well in advance of the main collision, and then escaped laterally during the main collision. This is considered unlikely, as there are no apparent Jurassic deformational structures that affect the Rocky Mountain shelf, but it might explain Jurassic detrital zircons in Morrison equivalents of Montana (Fuentes et al., 2009). Whatever the origin of the localized Jurassic sedimentation on the shelf, the first event seen over the entire margin was the sub-Cadomin unconformity upon which sediments were deposited during the Aptian between 124 and 115 Ma.

Heller and Paola (1989) labeled the 124–115 Ma gravels and conglomerates paradoxical, but the unconformity and the overlying conglomerates could have been generated by the passage of the North American craton over the outer forebulge of the trench (Currie, 1998). As the continent passed over the bulge (Stockmal et al., 1986; Yu and Chou, 2001) it was uplifted and eroded, and it shed abundant clasts of its Paleozoic and Mesozoic sedimentary cover both westward and eastward. Once any given strip passed over the bulge, it was pulled down into the trench and buried by fine-grained siliciclastic sediments. It is worthwhile to note that once over the bulge, the North American margin was extending as it was pulled downward into the mantle (Conrad and Lithgow-Bertelloni, 2002). In large part, only the upper plate and the off-scraped sediments of the fold-thrust belt, which were progressively transferred to the upper plate, are in a compressive regime. A prediction of this model is that initial sedimentary rocks within the foredeep might show evidence of down-to-the-west synsedimentary extension.

Dating the end of thrusting is more difficult, but on the basis of relations between thrusting and the Axhandle wedge-top basin, thrusting on the major in-sequence faults of the thrust-belt in Utah appears to have been mostly over at about 70–65 Ma (Lawton and Trexler, 1991; DeCelles and Coogan, 2006). On a more regional basis, the transition from the dominantly marine foredeep, generated by the thin-skinned thrusting, to localized and sedimentologically isolated nonmarine basins typical of the thick-skinned Laramide deformation, occurred during the Maastrichtian (71–66 Ma) (Dickinson et al., 1988; Raynolds and Johnson, 2003; Cather, 2004). In the Canadian foreland basin the minimum age for the end of thrusting appears to be marked by the youngest deformed rocks of the foredeep, which are mid-Paleocene (about 60 Ma), and by significant exhumation of the thrust wedge at about 58 Ma (Price and Mountjoy, 1970; Ross et al., 2005). The megathrust slab of Belt Supergroup rocks, which has a strike length of nearly 500 km in Montana and southern Canada, had minimal or steady-state denudation until 59 Ma, when it was cut

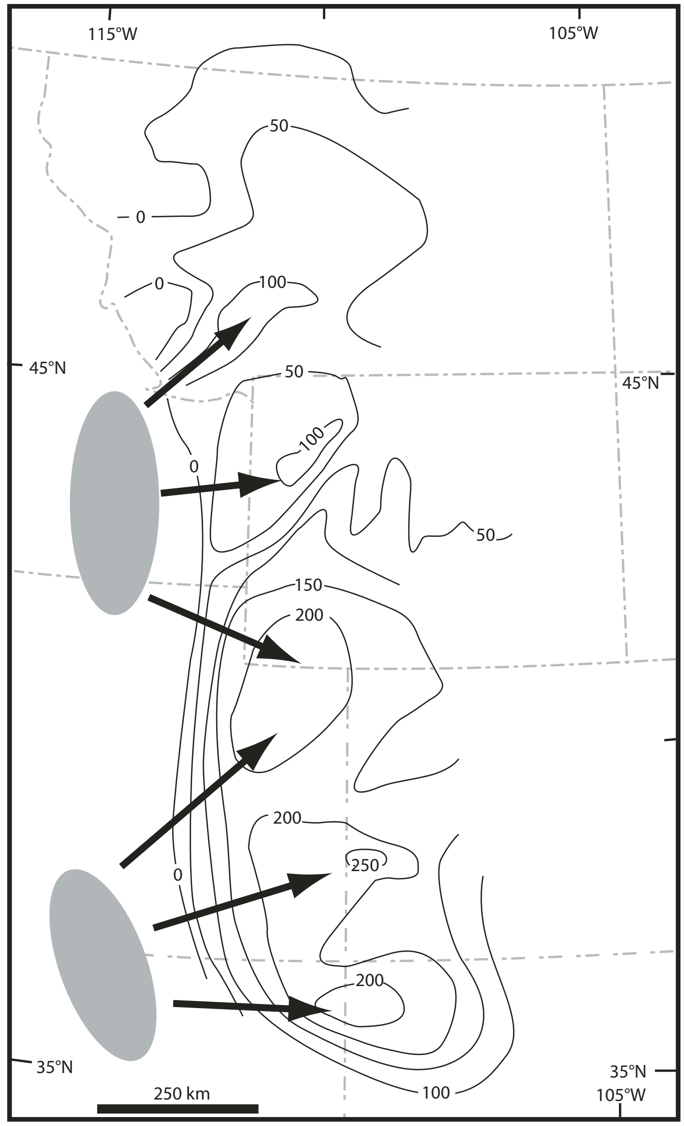


Figure 10. Sketch map modified from DeCelles (2004), showing the palinspastically restored isopachs for the Jurassic Morrison Formation. In this paper it is suggested that a set of islands, perhaps in the rifted margin, shed debris onto the Rocky Mountain platform.

by porphyritic intrusions and underwent rapid isostatic rebound (Sears, 2001). Thus the main compressional phase of the Cordilleran orogeny lasted approximately 50–60 m.y., from about 124 to around 70–60 Ma, and its demise might have been diachronous. Slightly younger ages in Canada suggest that thrusting might have shut down progressively from south to north.

EXOTIC ROCKS GENERALLY CONSIDERED PART OF NORTH AMERICA

In this section I examine many allochthonous sequences of rocks—the White-Inyos, the Pahrump Group and overlying Paleozoic rocks, the Belt Supergroup, and several successions in

Canada and in the U.S. Great Basin—generally considered to be part of ancestral North America, but here regarded to be exotic and which in some cases sat on or near the leading edge of the Rubian supercontinent.

Within the Utah-Nevada segment (Fig. 5) of the orogen the most easterly suspect rocks are huge megathrust slabs, containing thick late Precambrian-Cambrian clastic and carbonate successions and local crystalline basement, which occur mainly to the east of the hinterland belt, yet west of the Rocky Mountain shelf edge, and were thrust upon rocks of the Rocky Mountain platform (DeCelles and Coogan, 2006). Basin and Range extension moved many of these rocks well west of their postcollisional position within the thrust belt, and they now crop out in ranges of western Utah such as the House, Deep Creek, and Cricket ranges. The rocks contained within these more or less intact slabs, which are at least 80–100 km across, were locally intruded by Jurassic plutons; locally they exhibit intense Jurassic deformation and are considered here to be exotic with respect to North America because they originated west of the platform edge, have abundant 1.1 Ga detrital zircon profiles (Stewart et al., 2001), and have no definitive stratigraphic ties to North America. A well-studied example (DeCelles and Coogan, 2006; Currie, 2002) occurs above the Canyon Range thrust, which occurs in central and western Utah; was active from at least 145 to about 110 Ma, mostly before thrusting on the Rocky Mountain platform; and transported nearly 4 km of Neoproterozoic and Cambrian strata not found on the platform; and locally intruded by Jurassic plutons, at least 117 km eastward.

West of the megathrust slabs and the hinterland belt, and within the tectonic collage of exotic allochthons, the most easterly assemblage of rocks are platformal Cambrian to Permian limestones and siliciclastic rocks of the Antler shelf. These rocks, overlain to the west by rocks of the Roberts Mountain allochthon and its foredeep clastics of the Diamond Range sequence (Silberling et al., 1997), were cut by Jurassic–Early Cretaceous plutons and were transported eastward on thrusts during the mid-Jurassic to the mid-Cretaceous (Taylor et al., 2000; Finney et al., 2000). They are considered exotic with respect to North America because they lie so far west of the shelf edge that once Cretaceous shortening is restored they would be well off North American crust and would constitute an entirely different platform than that formed on North America, as discussed previously.

The Roberts Mountain allochthon (Fig. 5) consists of a stack of thrust nappes containing Cambrian to Devonian graptolitic shales, radiolarian chert, immature sandstones, barite beds, sedimentary exhalative deposits, minor pillow lavas, tuffs, and volcanogenic debris flows. There is considerable controversy as to whether rocks of the Roberts Mountain allochthon are exotic with respect to the Antler shelf, and hence in the old model, North America. Several workers (Finney and Perry, 1991; Finney et al., 2000; Poole et al., 1992) argued for a North American connection based on continuity of a section of Paleozoic rocks in north-central Nevada or detrital zircon peaks (Gehrels et al., 2000a); whereas others (Coney et al., 1980; Silberling et al., 1997; Wright and Wyld, 2006) suggest it to be exotic.

The presence of pillowed basalts and other alkaline volcanic rocks throughout most of the history of sedimentation within the Roberts Mountain allochthon (Poole et al., 1992) suggests that they were not part of North America, or even the Antler shelf, from the Middle Cambrian to the Middle Devonian because for most of that time both the Antler and Sevier shelves were quiescent with no evidence of magmatism. Also, as passive margins are cold and notoriously amagmatic after initial rifting, it is hard to understand how such magmatism would even originate and remain intermittently active for some 150 million years on a passive margin. Based on these arguments the Roberts Mountain allochthon is considered exotic with respect to both the Antler shelf and North America.

Rocks in other allochthons (Luning-Fencemaker thrust belt) of western Nevada (Fig. 5) lie even farther outboard and are dominantly sedimentary with minor basalt and range in age from Late Devonian to Triassic (Wyld et al., 2004; Whiteford, 1990; Murchey, 1990). Deformed rocks within the allochthons are unconformably overlain by Triassic volcanic rocks, which bracket the thrusting (Wyld, 1990). Other allochthons carry Jurassic arc rocks with shelf-basinal sequences (Dilek and Moores, 1995). Jurassic plutons of Nevada east to the hinterland cluster in the age range 165–155 Ma (Miller and Hoisch, 1995).

Another important line of evidence as to the accretion age of Nevadan rocks was presented by Wright and Wooden (1991), who showed that Jurassic and Early Cretaceous plutons, which cut all of the sedimentary successions from the quartzite-carbonate megathrusts westward, were exotic with respect to North America; that is, they had been decoupled and transported from their continental source region and now lie structurally upon North American crust. If the plutons are exotic with respect to North American basement, then their wall rocks must be as well. Thus, the transport age of the exotic allochthons must be younger than Early Cretaceous.

Seven and a half kilometers of Neoproterozoic and lower Paleozoic sedimentary rocks crop out west of the Sevier hinterland in the White-Inyo Mountains of eastern California (Fig. 5), where they are deformed into a series of large folds (Morgan and Law, 1998). The basement of the sequence is not exposed, but the section includes the classic group of Neoproterozoic–Lower Cambrian rocks such as the Wyman, Reed, Deep Spring, Campito, Poleta, and Harkless formations (Nelson, 1962, 1978; Mount and Bergk, 1998). The Ediacaran-Cambrian boundary appears to occur within the middle member of the Reed Dolomite, as indicated by a strong negative $\delta^{13}C$ excursion and occurrence of *Treptichnus pedum* (Corsetti and Hagadorn, 2003). Rocks of this age are not generally known to occur in the U.S. Cordillera, except for a much thinner and very different group of rocks of the same age in the Death Valley area.

The sedimentary succession in the White-Inyos is cut by Jurassic plutons in the age range 180–165 Ma (Coleman et al., 2003; Bateman, 1992). Because at least the youngest of these plutons postdate folding, the deformation that created the folds must be older (Coleman et al., 2003), and it therefore predates the

Cordilleran orogeny. Much of the deformation is, in fact, Permian (Stevens et al., 1998). Recent isotopic analyses (Ernst et al., 2003) of the Barcroft plutonic series (165 ± 1 Ma) show it to be metaluminous with isotopic signatures more typical of the Jurassic–Early Cretaceous of the Great Basin, whereas the 100 Ma peraluminous McAfee Creek Granite has isotopic signatures transitional between the Early Jurassic and Late Cretaceous peraluminous plutons (Wright and Wooden, 1991). Thus stratigraphy, time of deformation, age of plutonism, and the isotopic characteristics of the plutons all combine to suggest that this package of rocks more properly belongs with exotic rocks of central and western Nevada than with North America. Additionally, as the main bulk of the Sierran batholith is Cretaceous and the plutons in the White-Inyos are dominantly Jurassic in age, it may be that the two were not part of a contiguous batholith, as generally considered (Bateman, 1992; Saleeby and Busby-Spera, 1992).

In the Death Valley–southern Nevada sector (Fig. 5), rocks of the Pahrump Group and their crystalline basement are allochthonous (Burchfiel et al., 1974a, 1974b; Brady et al., 2000; Snow, 1992). Overlying Ediacaran-Cambrian sedimentary rocks of the Wood Canyon Formation contain detrital zircon peaks at about 1.1 Ga, and the slightly younger Zabriskie Quartzite contains abundant 3.0–3.4 Ga grains (Stewart et al., 2001): source ages markedly absent in western Laurentia. Higher in the stratigraphic succession is the distinctive Middle to Late Cambrian Bonanza King Formation, which farther north is part of the Antler shelf of central Nevada and westernmost Utah (Kepper, 1981; McCollum and McCollum, 1984; Montañez and Osleger, 1996; Morrow and Sandberg, 2008). This is well west of the Rocky Mountain shelf edge, and rocks of the Bonanza King Formation match poorly with those of the time-correlative Muav Formation of the Colorado Plateau. These rocks and those of the White-Inyos were folded and transported on thrust faults dated to be Permian at about 294–284 Ma (Snow, 1992; Stevens et al., 1998; Stevens and Stone, 2007). In the Spring Mountains near Las Vegas, carbonate rocks of the Bonanza King Formation sit structurally atop rocks of the Aztec Sandstone, a Jurassic eolianite of the North American platform (Burchfiel et al., 1998).

Stratigraphically higher in the sequence and crudely approximating the platform edge of the Bonanza King Formation is the Late Ordovician–Silurian carbonate shelf edge (Sheehan, 1986; Harris and Sheehan, 1998). This westerly facing shelf-edge facies transition also crops out in east-central Nevada and northwesternmost Utah, where it occurs west of the hinterland belt as part of the Antler shelf. Similarly, the Pennsylvanian–Early Permian Bird Spring carbonate shelf edge lies in eastern California and faces west (Stevens and Stone, 2007). Overall, the locations of the shelf edges, the non–North American detrital zircons, and the Permian thrust faults indicate that crystalline basement in the Death Valley area, the Pahrump Group, and overlying Paleozoic strata are most likely exotic with respect to North America.

Allochthonous crystalline basement of Paleoproterozoic age also occurs mostly within the Wasatch Range north and southwest of Salt Lake City, where outcrop areas are known as the Farmington Canyon and Santequin complexes (Yonkee, 1992; Bruhn et al., 1983; Schirmer, 1985). The basement rocks occur to the west of the shelf edge in extreme northeastern Utah (Rose, 1977) and structurally beneath the Jurassic Paris thrust. The band likely continues northward into Idaho, where Paleoproterozoic crystalline basement occurs within the Cabin–Medicine Lake system just east of the Idaho batholith (Skipp and Hait, 1977; Skipp, 1987) and in the Tendoy Range of southwestern Montana (DuBois, 1982). The basement is far traveled and appears to sit structurally upon Archean rocks of the Wyoming province. This northerly trending band of Proterozoic rocks may continue even farther northward, where it could have provided xenocrystic zircons to postcollisional plutons (Foster et al., 2006). Restoration of the shortening within the thrust belt restores the hypothesized crystalline basement well to the west of North American crust, as indicated by Sr isotopes (Armstrong et al., 1977; Fleck and Criss, 1985) and xenoliths (Evans et al., 2002) and that, coupled with isotopic and geological evidence that Archean basement likely continues to the edge of the craton (Hanan et al., 2008), indicate that the Farmington Canyon complex is exotic with respect to North America.

Rocks of the classic Belt-Purcell Supergroups within the United States and southern Canada (Fig. 11) were discussed in the section on the thrust belt, and because they are entirely allochthonous, nowhere sit on North American crust, lie outboard of the Cambrian shelf edge, occur in a megathrust slab like rocks farther south in Utah, and were transported hundreds of kilometers (Sears, 1988, 2007; Price and Sears, 2000), they are also likely to be exotic. The tremendous thickness—nearly 30 km—of the Belt succession suggests that it was deposited on oceanic crust, much as the present-day Bengal Fan in the Indian Ocean (Curray et al., 2002), in a trapped Caspian Sea–like basin (Hoffman, 1989), or possibly in a series of rift grabens (Sears, 2007). Price and Sears (2000) argued that movement of the Belt Supergroup was dominantly rotational, but this is contentious (Elston et al., 2000) and makes little sense in terms of the overall thrust belt, because shortening both north and south of the proposed rotational anchor near the Little Belt Mountains is at least 200 km.

In western Idaho, rocks of the Blue Mountain–Wallowa terranes, assembled by 145–137 Ma, were thrust over Cretaceous gneisses–Belt Supergroup rocks and include a variable assemblage of 1.37 Ga gneisses, a spectrum of deformed and metamorphosed intrusions, with deformation having ended at 61 Ma (Lund et al., 2008). These authors considered detrital zircons in the 1.37 Ga gneisses to be Laurentian, but it is important to note that they are not necessarily North American because they could have been derived from the other rifted portion of Laurentia. This is a general problem over the length of the orogen, as detrital zircon studies simply cannot discriminate from which part of rifted Laurentia they were derived.

Within the southern Canadian Rocky Mountains, the Cambrian shelf edge occurs today within the Main Ranges. West of this facies change (Cook, 1970), which, as discussed earlier, likely marked the eastern edge of brittle-extended North American crust, are a few thrust panels that contain shaly basinal-facies rocks of the Chancellor Formation; but these rocks are overridden along the Purcell thrust by Mesoproterozoic rocks of the Purcell Supergroup (Price and Fermor, 1985). Within this thrust sheet and others to the west there are no rocks that can be convincingly related to North America. Packages of rocks within the Kootenay terrane, such as the Neoproterozoic Horsethief Creek Group, the Eocambrian Hamill Group, the *Archeocyathid*-bearing Badshot Formation, the overlying nonfossiliferous Lardeau Group, and the Mississippian basalt-bearing Milford Group, all lie west of the Purcell fault, are not known to sit on North American basement, contain older deformations including westerly vergent recumbent folds (Brown and Lane, 1988; Simony, 1992; Smith and Gehrels, 1992a, 1992b), do not occur in rocks east of the Purcell fault, were transported a minimum of 200 km eastward (Price and Mountjoy, 1970), and were variously intruded by plutons ranging in age from late Paleozoic to Cretaceous (Okulitch et al., 1975; Parrish, 1992; Crowley and Brown, 1994; Colpron et al., 1998). Overall, it is difficult to understand how these packages of rocks might relate to the North American continent, and I suggest they are better considered exotic.

Similarly, on the basis of faunal provinciality, contrasting Mesozoic development, basement types, arc magmatism, paleobotany, and paleomagnetic data, Johnston (2008) argued that the Cassiar platform of Canada—which, like the Antler platform of the Great Basin, is separated from the North American platform by a shaly basin—evolved separately from North America. This implies that all rocks to the west, such as the so-called pericratonic terranes (Colpron and Price, 1995; Colpron et al., 2006), are also exotic.

THE SUPERTERRANE

A major question is, what was the extent of Rubia, the arc-bearing terrane or microcontinent, postulated here to have collided with North America during the Cordilleran orogeny? As thrusting on the platform, and initiation of foredeep sedimentation was more or less coeval over the entire length of North America, Rubia must have been large enough to impact most of the margin almost simultaneously, perhaps within just a few million years.

Within Nevada, all of the terranes from the hinterland westward to the Jurassic-Triassic Black Rock arc terrane—and including the Roberts Mountain allochthon (Fig. 5)—accreted to Rubia during the Mississippian, were probably assembled prior to docking with North America, most likely by the Early Jurassic (Wyld et al., 1996, 2004). These terranes stretch into Idaho and eastern Oregon, where they include the massed Wallowa–Blue Mountain terranes (Fig. 5); however, younger cover and potential transcurrent faulting complicate the story, and there could be internal dislocations and translations yet to be discovered (Wyld and Wright, 2005, 2007; Lund et al., 2008).

One group of terranes, the Northern Sierra, Cache Creek, and part of the Klamath (Fig. 5), all have similar characteristics. The Klamath and Northern Sierra lie within California west of the Sierra Nevada, whereas the Cache Creek occurs extensively within the Canadian Cordillera. They all contain accretionary complexes of mélange, mafic to ultramafic volcano-plutonic rocks, and upper Paleozoic seamounts-plateaux with carbonate patch reefs and distinctive Tethyan fauna (Monger and Ross, 1971). Within Canada the Cache Creek terrane is juxtaposed against two other terranes: Stikinia and Quesnellia (Fig. 11). Both are large quasi-continental terranes with Devonian-Permian carbonates, arc magmatism, and another distinctive fauna called McCloud, which is known from northwestern Nevada and the Sonoma terrane of the western Sierran foothills (Carter et al., 1992). The Stikine, Quesnel, and Cache Creek terranes were amalgamated at least by the Early Triassic, but subduction beneath the microcontinent continued on into the Early Jurassic (Johnston and Borel, 2007).

Another group of terranes in Canada includes the so-called pericratonic terranes of the Yukon-Tanana and Kootenay, which were overthrust from the west by the already assembled Stikinia–Quesnellia–Cache Creek terrane before the intrusion of 186 Ma stitching plutons (Johnston and Erdmer, 1995). The pericratonic terranes are characterized by Late Devonian to Permian magmatic rocks and carbonates (Mortensen, 1992; Roots et al., 2006) and associated Carboniferous to Triassic blueschist-eclogite belts (Erdmer et al., 1998). East of the pericratonic terranes are dismembered basinal facies rocks along with Upper Devonian to Permian ophiolites, collectively termed the Slide Mountain terrane (Nelson, 1993). Interestingly, rocks of the Slide Mountain terrane contain giant fusulinids that are known only from a few locales: Kettle Falls, Washington; the eastern Klamaths; Sonora, Mexico; and an autochthonous locale from the miogeocline in West Texas, all of which indicate that Slide Mountain rocks in the Pacific Northwest and Canada are now far from their warmer-water zones of origin (Carter et al., 1992). The fossil data are supported by paleomagnetics, which indicate at least 2000 km of northward movement (Richards et al., 1993).

East of, and beneath, the belt of Slide Mountain rocks lie rocks of the Selwyn basin and the Cassiar platform. Rocks of the Cassiar platform were overthrust by Permian pericratonic rocks prior to deposition of Triassic conglomerates containing clasts of blueschist and eclogite, which cover the suture zone (Murphy et al., 2006; Johnston and Borel, 2007).

A huge allochthon, some 700 km long and up to 200 km across, of Neoproterozoic to Paleozoic rocks of the Selwyn basin (Figs. 1 and 5) was thrust over the miogeocline along the Dawson fault, and there are no direct stratigraphic links between footwall and hanging wall; thus they are strongly suspect. The fine-grained sedimentary rocks, chert, limy turbidites, and graptolitic shale with alkaline basalts, barite beds, and sedimentary exhalative Ag-Pb-Zn ore deposits (Goodfellow et al., 1995; Mair et al., 2006) are reminiscent of rocks within the Roberts Mountain allochthon and were likely deposited in a restricted oceanic basin. Rocks of the Selwyn basin are linked to those of the Cassiar platform, to the west, by a suite of 110–90 Ma plutons (Johnston, 2008).

Another collection of rocks, the Farewell terrane of Alaska (Fig. 11), also contains similar successions as those of the Selwyn basin and Roberts Mountain allochthon: Cambrian to Devonian deeper water sedimentary rocks and Devonian to Pennsylvanian carbonates, Devonian and Triassic phosphatic black shale, barite, and sandstone, with a variety of gabbroic sills and pillowed basalts (Bradley et al., 2006). These rocks are also similar in lithology, age, and metallogeny to rocks fairly widespread within the Yukon-Tanana Uplands terrane (Fig. 11) of the Alaska-Yukon border region (Dusel-Bacon et al., 2006) as well as rocks of the Kootenay terrane (Smith and Gehrels, 1992a, 1992b; Colpron and Price, 1995). The broad temporal and lithological similarities are suggestive that rocks in all five areas could have originated in the same basin (Turner et al., 1989) and were dispersed along Rubia prior to, or during, collision with North America.

An interesting assemblage of exotic rocks occurs just south of the Tintina fault in Alaska, where metamorphosed Devonian-Jurassic oceanic and metaclastic rocks of the Tozitza terrane were invaded by epizonal plutons and buried by bimodal volcanics prior to exhumation at 60 Ma (Till et al., 2007). They document that the eruption of the bimodal volcanics, deposition of lacustrine and fluvial sediments, and plutonism were contemporaneous with the cooling of the metamorphic rocks.

Within Alaska the Brookian collisional orogen involved an arc-microcontinent collision in the Jurassic (Miller and Hudson, 1991). The microcontinent contains Devonian sedimentary rocks cut by sparse Devonian orthogneiss with klippen of ophiolites sitting atop the imbricate thrust belt (Moore et al., 1997a, 1997b; Box, 1985). Overall, the rocks were likely part of the Yukon-Tanana package and formed part of a much larger assemblage that was amalgamated during the Jurassic.

Resolving the development of the Mexican terranes is hampered by extensive Cenozoic volcanic cover; yet the details that have emerged are similar to those farther north. Most terranes of central and western Mexico are interpreted to represent arc and accretionary terranes that were joined during the Late Jurassic–Early Cretaceous prior to extensive shallow submarine arc magmatism (Centeno-Garcia et al., 1993; Tardy et al., 1994; Centeno-Garcia and Silva-Romo, 1997; Centeno-Garcia, 2008).

The linkages discussed in the preceding discussion—and the near isochronous initiation of foredeep sedimentation along the entire belt—demonstrate that most terranes within the Canadian and U.S. sectors of the Cordillera were probably amalgamated prior to their Cretaceous encounter with North America. Furthermore, in the Canadian sector, part of the amalgamated terrane possibly sits atop North American crust, as imaged by LITHOPROBE (Cook et al., 1988, 1992). Within the Great Basin a set of COCORP (Consortium for Continental Reflection Profiling) deep seismic lines from western Utah to eastern California showed strong horizontal reflectors in the deep crust westward from central Nevada to eastern California (Allmendinger et al., 1987) that may represent the suture zone and possibly a thin veneer of Paleozoic siliciclastic metasedimentary rocks of the autochthon beneath Rubia. This suggests that cratonic North America continues beneath the allochthonous terranes well west of the 0.706 isopleth. Isotopic data from Idaho (Leeman et al., 1992) and Oregon (Evans et al., 2002) support this conclusion. Thus, the 0.706 isopleth, as well as Nd and Pb isotopic tracers, may not reflect North American crust but may instead represent crust within the overlying Rubian superterrane.

It appears that most of the exotic terranes now present along the western margin of North America were amalgamated into the Rubian superterrane prior to the Cordilleran orogeny, which is contrary to the commonly accepted hypothesis of progressive accretion along western North America during the Mesozoic (Burchfiel et al., 1992; Oldow et al., 1989; Umhoefer, 2003). Therefore, I propose that the Cordilleran orogeny represents one main collisional event in which the leading edge of North America was partially subducted beneath Rubia, the arc-bearing superterrane. This conclusion is similar to that reached in recent analyses of Canadian terranes (Johnston and Borel, 2007; Johnston, 2008).

THE SUTURE

In any collision model there must be a suture between the two plates. Although a suture is simply a fault zone that may or may not contain ophiolitic remnants, blueschist mélanges, or trench deposits, its main characteristic is that it separates rock packages that evolved separately over a significant time period and were separated by oceanic lithosphere. If there are no vestiges of an oceanic realm on the fault zone, then the suture is generally considered to be cryptic (Dewey and Burke, 1973; Gibb et al., 1983). In the context of the collisional model presented here, the main suture is a fault that places the megathrust blocks, and locally other exotic rocks, over the North American platform. Traced westward, the suture appears at deep levels within some Paleocene core complexes of the hinterland, such as the Raft River–Grouse Creek–Albion, the Pioneer, the Priest River, and the Monashee, where the suture is identified as the thrust that places deeper level exotic rocks, such as 1.5–1.6 Ga crystalline basement, above metasedimentary rocks sitting unconformably upon North American basement (Journeay, 1992; Parrish, 1995; Doughty et al., 1998; Snoke and Miller, 1988; Link et al., 2007). Even farther west, strong midcrustal reflectors seen on COCORP and LITHOPROBE lines (Cook et al., 1992; Allmendinger et al., 1987) likely represent the contact between exotic rocks of the upper plate and autochthonous rocks of the North American plate.

Other west-dipping thrust faults that occur east of the main suture likely merge with the suture at depth, but because they don't involve exotic rocks they are not considered here to represent the suture (for the opposing view, see Lallemand et al., 2001), even though the rocks were detached from North America and incorporated in the accretionary prism of the overriding plate. That is because there was never an ocean between them.

In the collisional model presented here, rocks of North America were ultimately pulled down beneath the accretionary prism and the exotic allochthons. Given that there seems to be little control over the dip of the descending slab by age of lithosphere (Cruciani et al., 2005), it is difficult to evaluate how steep it was in this case. However, as virtually all subducting plates dip at ~15° for the first 25 km or so, and because the flexure of the lithosphere is simple isostatic flexure, it follows that the density of the overriding plate plays a dominant role in how deep the top of the descending slab will be (Cloos, 1993). In the case of the Cordillera, it appears that little sediment was scraped off the descending plate prior to the arrival of the rigid and relatively-high-standing Rocky Mountain platform. The lack of offscraping might simply be because there wasn't much sedimentary rock to "bulldoze" off, or possibly because the bulk of the sedimentary rocks was subducted during subduction retreat (Royden, 1993a). Consider that the oceanic lithosphere adjacent to the continent was about 400 m.y. old, and therefore was cold, dense, and topographically very low standing. These factors, along with the overall low grade of metamorphism and general lack of basement involvement, suggest that the North American–Rubian plate boundary was actively retreating, and thus there would have been little possibility of incorporating slope-rise sediments into the accretionary wedge.

Another factor that might influence how much rise-slope material is bulldozed off the subducting plate is the age of the lithosphere. Owing to the increased flexural rigidity of old versus young lithosphere, old continental margins have bulge uplifts on the platform, whereas young margins have their bulge on the rise, much closer to the trench (Stockmal et al., 1986). Thus, in old margins like the Cordillera, rise-slope sediments could be subducted, whereas in young margins those sediments might be added to the accretionary prism. Thus, two lines of reasoning suggest that most slope-rise sediments of North America were subducted and not incorporated into the accretionary prism.

Once the high-standing platform entered the trench region it was detached from its basement, folded, and transported on thrusts toward the craton. The end result is that there need not be any sign of an ocean because all the evidence was already subducted. In that case, rocks of the North American platform were tucked beneath rocks of the upper plate.

One of the distinctive features of the main suture zone between rocks indigenous to North America, and those I suggest are exotic, is the juxtaposition of two distinctive assemblages. To the east lies a largely Phanerozoic shelf and westerly facing platform edge capped by thick Jurassic-Triassic sedimentary rocks, whereas to the west of the suture is a complex amalgam of crystalline basement, typically overlain by thick Neoproterozoic and Paleozoic clastic-carbonate successions with scarce to absent Jurassic-Triassic rocks. This is not a new finding, for it has long been recognized that 2.5 km of Jurassic-Triassic formations are abruptly truncated at the Wasatch line (Stokes, 1976), which closely approximates the location of the suture proposed here. The assemblages to the west exhibit older deformational episodes, including recumbent, westerly vergent folds, and have detrital zircon populations uncharacteristic of North American source terranes. Although not exposed everywhere, these relations are consistent from Canada to the southern Great Basin (see, e.g., Coogan, 1992; Price and Fermor, 1985) and aid in locating the frontal portion of the suture, which occurs at the front and base of the megathrust sheets over the entire length of the Cordillera.

Many of these thrust sheets are typical of what John Rodgers (1997) called exotic nappes—thrust plates with entirely different facies juxtaposed against platformal rocks. These include the megathrust sheets, which are composed of rocks not found on the North Amerian platform. Some of the more internal thrust sheets contain westerly vergent nappes formed during the Jurassic, which were deformed again during the Cordilleran orogeny.

Detailed paleomagnetic studies over 500 km of strike length within the foreland belt of the Canadian Cordillera indicate that Paleozoic carbonates within the Front Ranges have a steep Late Cretaceous remagnetization, whose poles are compatible with those from the North American craton (Enkin et al., 2000). If shallow inclinations measured in remagnetized carbonate rocks of the Main Ranges also formed during the Late Cretaceous, then the differing inclinations between the two belts suggest that the suture between Rubia and North America is at or near the Kicking Horse Rim in the Main Ranges and that previous correlations across the carbonate-shale facies change are in error (Enkin, 2006), as suggested here.

Cryptic sutures are well known from other orogenic belts. In northern Canada's Wopmay orogen, the suture is a simple mylonitic fault that carries a huge klippe of 2.1–1.9 Ga exotic rocks on top of the 3.0–3.5 Ga western Slave craton and its Paleoproterozoic continental margin (Hildebrand et al., 1991). The Iapetus suture in parts of the British Isles is cryptic and is simply a series of connected faults (Todd et al., 1991). In the Guayana shield of northeastern South America, mafic volcanic piles and related intrusions sit atop a quartzite-covered craton and are separated from it by several meters of mylonite, best interpreted to represent a suture (Hildebrand, 2005). Even the ongoing Eurasian-Philippine collision at Taiwan seems to have no oceanic material along the suture in the narrow Longitudinal Valley (Huang et al., 2006), although some ophiolitic olistostromes there originated on scarps formed by backthrusting (Suppe, 1987). In some orogens, paleontological or stratigraphic methods might serve to document the differences; but it is easy to envision the closure of the Atlantic Ocean, which is rimmed by the same age-passive margins—all with more or less the same unconformities (Vail et al., 1980)—sitting on formerly continuous basements.

Before this study it was generally accepted that Paleoproterozoic Selway terranes were accreted to the western margin of the Wyoming craton prior to the development of the Cordilleran margin (Foster et al., 2006). However, the presence of Archean basement beneath allochthons in several widely separated locations, such as the Grouse Creek–Albion–Raft River, the Pioneer, and the Priest River complexes (Fig. 5), suggests that the Selway terranes, as well as other areas of Precambrian crystalline basement in the thrust belt, such as the Farmington and Santequin complexes, are Rubian basement and are sitting structurally upon the western margin of the Archean Wyoming craton. This is in keeping with the abundant Paleoproterozoic xenocrystic zircons in plutons of the Idaho batholith (Bickford et al., 1981; Toth and Stacey, 1992; Foster and Fanning, 1997).

SLAB BREAK-OFF AND DEVELOPMENT OF METAMORPHIC CORE COMPLEXES

The end of major thrusting within the Sevier fold-thrust belt and consequent uplift of the belt, the uplift and gravitational collapse of the hinterland belt, cessation of deformation in many exotic terranes, and the initiation of Laramide thick-skinned thrusting and basin formation occurred more or less simultaneously during the Maastrichtian–Paleocene at about 70–60 Ma (Fig. 11). This suggests that these events might somehow be related, as originally suggested by Armstrong (1974). I offer that slab break-off (Price and Audley-Charles, 1987; Sacks and Secor, 1990; Davies and von Blanckenburg, 1995; Hildebrand and Bowring, 1999; Davies, 2002; Levin et al., 2002; Haschke et al., 2002) most logically explains the events.

Slab break-off is a simple process that must happen sooner or later in every collisional orogen. Despite its simplicity it has the potential to create complex geological phenomena because stress regimes change rapidly, and asthenosphere flows upward to melt and invade the collision zone. During collision, when the leading edge of a continent is partially subducted, subduction stops when the slab fails, because the strength of the descending, continent-oceanic slab is exceeded by the competing forces between buoyancy of the attached continent and downward pull of the attached oceanic lithosphere. This is because the buoyancy forces resisting the subduction of continental lithosphere are as large as those pulling oceanic lithosphere downward (Cloos, 1993). Eventually, this causes the subducting, dominantly oceanic plate to tear off at its weakest point and sink into the mantle because of its greater density. The zone of failure is likely at or near the synrifting limit of upper crustal extension on the passive margin, because to one side of this region is a craton with a thick root and to the other side is old, thick and strong oceanic lithosphere (Hildebrand and Bowring, 1999). The zone of thin, transitional, previously rifted crust on a continental margin is welded to the underlying mantle, just as the oceanic crust, whereas the upper part of normal continental crust is separated from the mantle by a plastic and viscously behaving lower crust, so it can easily be decoupled from the underlying mantle (Cloos et al., 2005). Thus, accurate reconstructions of the original platform edge on the passive margin should approximate the zone of failure, because, as discussed earlier, it typically lies at the cratonward limit of extended upper crust. This implies that during slab failure most of the transitional crust and its rift deposits will be subducted (Hildebrand and Bowring, 1999).

The marked lack of initial rift volcanics and associated rift valley clastic rocks in the Cordillera suggests that the slab and extended continental crust with its rift deposits were torn from North America and subducted exactly as predicted by the theory. The rapid exhumation and collapse of the Sevier hinterland, as well as the rapid erosion of foreland basin sediments, were likely caused by slab failure, because rapid uplift is highly improbable as long as the leading edge of the craton is attached to its oceanic anchor. Once the slab failed, the subducted continent was free to rise and likely did so rapidly, which in turn immediately shut down thin-skinned thrusting. In the Cordillera, this idea is supported by the observation that the huge Lewis-Eldorado-Hoadley thrust sheet and its load of Belt rocks were transported eastward in a steady-state configuration with minimal denudation until the cessation of thrusting at 59 Ma, when major isostatic uplift and erosion began immediately (Sears, 2001).

Shortly after slab failure the collision zone will rise rapidly as it tries to isostatically equilibrate. During uplift any especially hot parts of the upper-plate arc might collapse gravitationally. In the model presented here the Paleocene-Eocene extensional core complexes from Canada to Death Valley developed when the oceanic slab failed and broke off, generating uplift and exhumation of the hot hinterland. Farther south, within the Mojave-Sonoran segment, the core complexes are Miocene and may have had an entirely different cause.

The presence of a hot arc, or a belt of plutons, within the hinterland belt would explain why the hinterland directly adjacent to the thrust belt has more intense metamorphism and appreciably more exhumation, and contains an intense concentration of metamorphic core complexes. Another possibility is that the area had earlier been thickened and heated during Jurassic deformation and metamorphism.

An additional factor is that the process of break-off replaces relatively cool and dense lithospheric mantle with hot asthenosphere. For example, Cloos et al. (2005) calculated that, with a 30-km-thick crust, an initial mean surface elevation of 700 m, and removal of 50% of the lithospheric mantle, surface elevation would increase by ~2500 m. Additional study is needed to elucidate precisely why the hinterland belt failed and collapsed, but whatever the cause, the simplest method to shut down thin-skinned thrusting and produce rapid uplift of the hinterland, thrust belt, and foredeep is slab failure.

North of the Lewis and Clark line, the main belt of uplift appears farther west in the Coast Plutonic Complex, and possibly southward into the North Cascades, where 15 km of uplift occurred rapidly, starting in the Late Cretaceous. Overall, the belt is more or less one giant core complex some 1500 km long by only 75–100 km wide, so it is here attributed to uplift generated by slab failure.

Within the Great Basin, Paleocene-Eocene core complexes are not known west of the hinterland belt, but whether that area was simply cooler, did not have the same initial uplift, or relates to major longitudinal movement with Rubia is unknown. Nevertheless, the differences are likely significant. Based on the areas with and without metamorphic core complexes I theorize that a combination of the intense heat, either from within an active arc or from below during slab break-off, a thick crust basically doubled by overthrusting, and rapid uplift caused by slab break-off, were the critical components for creating the metamorphic core complexes of the hinterland belt.

The effects of strong uplift related to slab failure within the orogen might be visible in foredeep sedimentation. For example, the intense influx of volcano-feldspathic detritus into the Western Canada basin during the Maastrichtian (Leckie and Smith, 1992; Ross et al., 2005) might reflect sudden, strong uplift within the orogenic hinterland. In the next couple of sections I examine some additional implications of slab failure on the tectonic and magmatic development of the orogen.

LARAMIDE UPLIFTS AND THICK-SKINNED DEFORMATION

Some of the more enigmatic geologic features of the Cordilleran orogen are the Late Cretaceous to Eocene basement-involved Laramide uplifts and associated basins of the Rocky Mountain region (Figs. 5 and 13 [see below]). The uplifts generally have the form of asymmetrical anticlines with cores of Precambrian basement bounded by thrust faults, or steep to overturned monoclines that faced, and in many cases overrode, deep basins that subsided and received sediment during rise of the uplifts themselves. Many of these features have lengths of tens to hundreds of kilometers, have structural relief between basin-uplift pairs of 5–12 km, and involve the entire crust (Grose, 1974; Smithson et al., 1979; Brewer et al., 1982; Rodgers, 1987; Hamilton, 1988).

The Laramide features reflect fundamental changes in structural style and sedimentation within the U.S. segment of the Cordillera in that deformation changed from thin-skinned to thick-skinned, and the dominantly marine foreland basin sedimentation changed to localized, isolated nonmarine basins (Dickinson et al., 1988; Beck et al., 1988). Although there is some spatial and temporal overlap between the two styles of deformation (Kulik and Schmidt, 1988), the overall pattern of laterally continuous foreland basin sedimentation was generally followed by the development of localized depocenters and associated thick-skinned deformation such that in a general sense there are two deformational episodes with only minor temporal overlap between the two (Armstrong, 1968). In this contribution I use the term Laramide to refer to the thick-skinned deformation formed within the Rocky Mountain foreland during the Cordilleran orogeny. I maintain the traditional time connotation (Grose, 1974) for the deformation in that it generally postdates the thin-skinned thrusting and is Late Cretaceous to Eocene; but here I do not label rocks or deformation south of the Colorado Plateau as Laramide, even though ages overlap to some degree. This is because the area doesn't appear to have the diagnostic thick-skinned deformation. In the model presented here the Laramide is a localized event included as part of the Cordilleran orogeny, because it was caused by the same collisional event.

Most of the data indicate that the Laramide thick-skinned event started about the same time that the thin-skinned thrusting in the foreland stopped, as the more continuous finer-grained sedimentary strata of the foredeep are typically unconformably overlain by coarse debris shed from strongly emergent basement-cored uplifts (Raynolds and Johnson, 2003; Cather, 2004; Dickinson et al., 1988; Beck et al., 1988). Although there are minor variations in timing owing to sample inconsistencies, outcrop, etc., the best studied areas of the thrust and foreland belts all show evidence for rapid exhumation at about 70–60 Ma (Sears, 2001; DeCelles and Coogan, 2006; Ross et al., 2005), and the Laramide basins all started to form in the Maastrichtian between 71–66 Ma

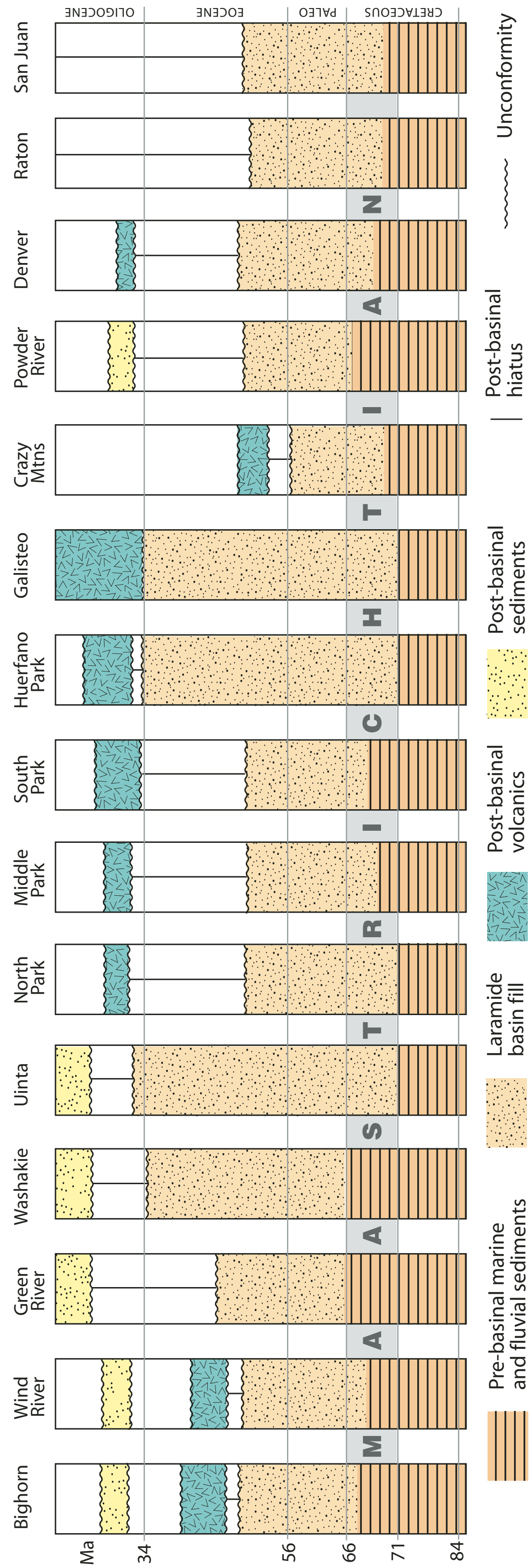


Figure 11. Chronostratigraphic diagrams for Laramide basins, showing age of inception, continuation, and termination of individual basins. Note that all basins formed during the Maastrichtian. Adapted from Dickinson et al., 1988.

(Fig. 11), deepened through the Eocene, and were basically dead by the Oligocene (Robinson, 1972; McDonald, 1972; Otteman and Snoke, 2004; Crowley et al., 2002; Dickinson et al., 1988). Perry and Flores (1997) suggested that Laramide deformation in Wyoming migrated northeastward to arrive at the Black Hills between 60 and 50 Ma.

The origin of this thick-skinned deformation has been especially problematic, because the mountains related to the Cordilleran hinterland and fold-thrust belt along western North America were shedding sediment eastward into the foreland when the Laramide event occurred. This led some workers to suggest that one simply couldn't separate the two events in terms of kinematics (Oldow et al., 1989). Other workers suggested that variations in flat-slab subduction, such as convergence velocity and dip beneath North America, generated the Laramide structures by increasing shear traction (Hamilton, 1988; Dickinson, 1981; Dickinson and Snyder, 1978; Bird, 1984). However, there was no arc magmatism of this age anywhere in the region, so a subduction model is generally nonviable. In the collisional model a solution is readily available because the two events are quite different in terms of kinematics in that the Cordilleran thrust belt involved rocks transferred to the upper, overriding plate and developed prior to slab failure, whereas the Laramide event involved rocks of lower plate North America and occurred during and/or just after slab failure.

Consider that prior to slab failure, rocks of the North American margin were scraped off their basement along a basal detachment, separated from North America, and transferred to the front of the overriding plate. These rocks were then transported eastward in a compressional environment because new material was constantly being added to the front of the thrust wedge (Cloos and Shreve, 1988a, 1988b). Down below, the North American plate was actively being pulled down by the descending oceanic slab (Spence, 1987; Royden, 1993a, 1993b; Conrad and Lithgow-Bertelloni, 2002) and so was extended. Overall, the upper and lower plates were weakly coupled. Once the slab failed, there was what I term catastrophic stress reversal, for almost immediately the lower plate began to rise, lifting the upper plate along with it. The rapid and significant uplift created by the isostatic rebound of doubly thick crust is here considered to have caused extension and gravitational failure in the upper plate, as was discussed in the previous section. On the other hand, as the lower plate rose, and a greater area of it contacted the base of the upper plate such that continued movement—most likely because the failure was diachronous (Fig. 13 [see below]) just as in the New Guinean example (Cloos et al., 2005)—produced much stronger coupling between the plates. This generated consistently increasing frictional drag and shear traction forces between the plates, which caused the entire crust of the lower plate to enter a progressively heightened compressive state, at least until horizontal convergence between the two plates ceased. Because the lower plate was old, cold, and rigid, the compressive stresses were most likely partitioned over a significant thickness, and so basement was involved in the resultant shortening. I believe that it was these stresses in the North American craton that created the Laramide thick-skinned structures (Fig. 13 [see below]). Similar basement-involved thrusts, such as the Mapenduma anticline, formed in the foreland of the Central Range arc-continent collision in Papua New Guinea during slab failure at about 6 Ma (Cloos et al., 2005).

Although in some cases slab failure will produce magmas as the asthenosphere wells up through the tear zone and melts adiabatically, other areas might not have any magmatism at all. Cloos et al. (2005) point out that greater ductile necking during slab separation leaves more lithospheric mantle under the orogen. This makes it much harder for magmas to penetrate and transit the residual lithosphere and so are much more likely to solidify at depth.

An important corollary is that different segments of the subducting plate can fail at different times and rates, which can lead to different results in each segment. For example, one segment, which had rapid and complete failure, might produce voluminous magmatism, whereas another segment with a slower rate of plate separation and considerable lithospheric necking might have no magmas rising into the upper plate crust at all. An amagmatic segment would have stronger coupling between the upper and lower plates and therefore would have more thick-skinned deformation in comparison with a segment with abundant magmatism, because the rising magmas heat and weaken the lower crust, which leads to weaker coupling.

SLAB BREAK-OFF MAGMAS AND THE SEGMENTED NORTH AMERICAN PLATE

As stated earlier, magmas are created during and just after slab failure as the asthenosphere wells up through the gap created in the torn slab (Hildebrand and Bowring, 1999; Cloos et al., 2005). Both arc magmatism and slab failure magmatism are expected to produce linear belts of magmas whose compositions might be rather similar and range anywhere from high-K basalt to rhyolite, depending on the composition of the crust they are transiting. Slab break-off magmatism can be expected to be strongly diverse, first because the lithospheric mantle source region is highly variable (Menzies et al., 1987; Foley, 1992), and second, because the rising magmas can assimilate between 10% and 75% crustally derived materials during their rise through the crust (Housh and McMahon, 2000).

The best candidate for a belt of magmatic bodies related to slab break-off during the Cordilleran orogeny occurs within the Coast Mountains of western Canada (Fig. 12). There, Jurassic to Late Cretaceous tonalitic-granodioritic plutons, deformed and metamorphosed to gneiss under amphibolite-granulite conditions, and generally considered to constitute the lower and middle crust of a Cordilleran-type magmatic arc, were rapidly exhumed just after arc magmatism ceased between about 65 and 60 Ma (Armstrong, 1988; Hollister, 1982; van der Haydan, 1992; Crawford et al., 1999). Extension, which took place at least between about 60 and 50 Ma, and involved at least 15 km of tectonic exhumation, was accompanied by a voluminous Late Cretaceous–

early Tertiary intrusive bloom of multiple sources (Hollister and Andronicos, 2000, 2006; Hollister et al., 2008; Mahoney et al., 2006; Andronicos et al., 2003). The strongly linear locus of uplift and plutonism coincides with the western buried edge of cratonic North America (Fig. 12) as inferred from two LITHOPROBE deep reflection seismic lines (Cook et al., 1992, 2004). The shutdown of arc magmatism just before the Late Cretaceous, the rapid exhumation of the central gneiss complex between 60 and 50 Ma, the voluminous Late Cretaceous–early Tertiary magmatism, and the colocation of the apparent western edge of cratonic North America in the subsurface combine to identify one region of slab failure during the Cordilleran orogeny. Furthermore, the isotopic character of magmas and xenocrystic zircons suggests that they are mixtures of asthenosphere and Paleoproterozoic crust (Samson et al., 1991), conditions that could have been met if magmas derived from upwelling asthenosphere interacted with the torn edge of western North America beneath the region (Ross et al., 1991). Magmas streaming through the narrow tear as it formed might explain the highly focused nature of the elongate Late Cretaceous tonalitic magmas along the western margin of the belt (e.g., Barker and Arth, 1990). Overall, the linear belt, some 1500 km long, of Late Cretaceous–early Tertiary plutons within the Coast Range Complex may be the best-exposed example of slab failure magmatism anywhere on Earth.

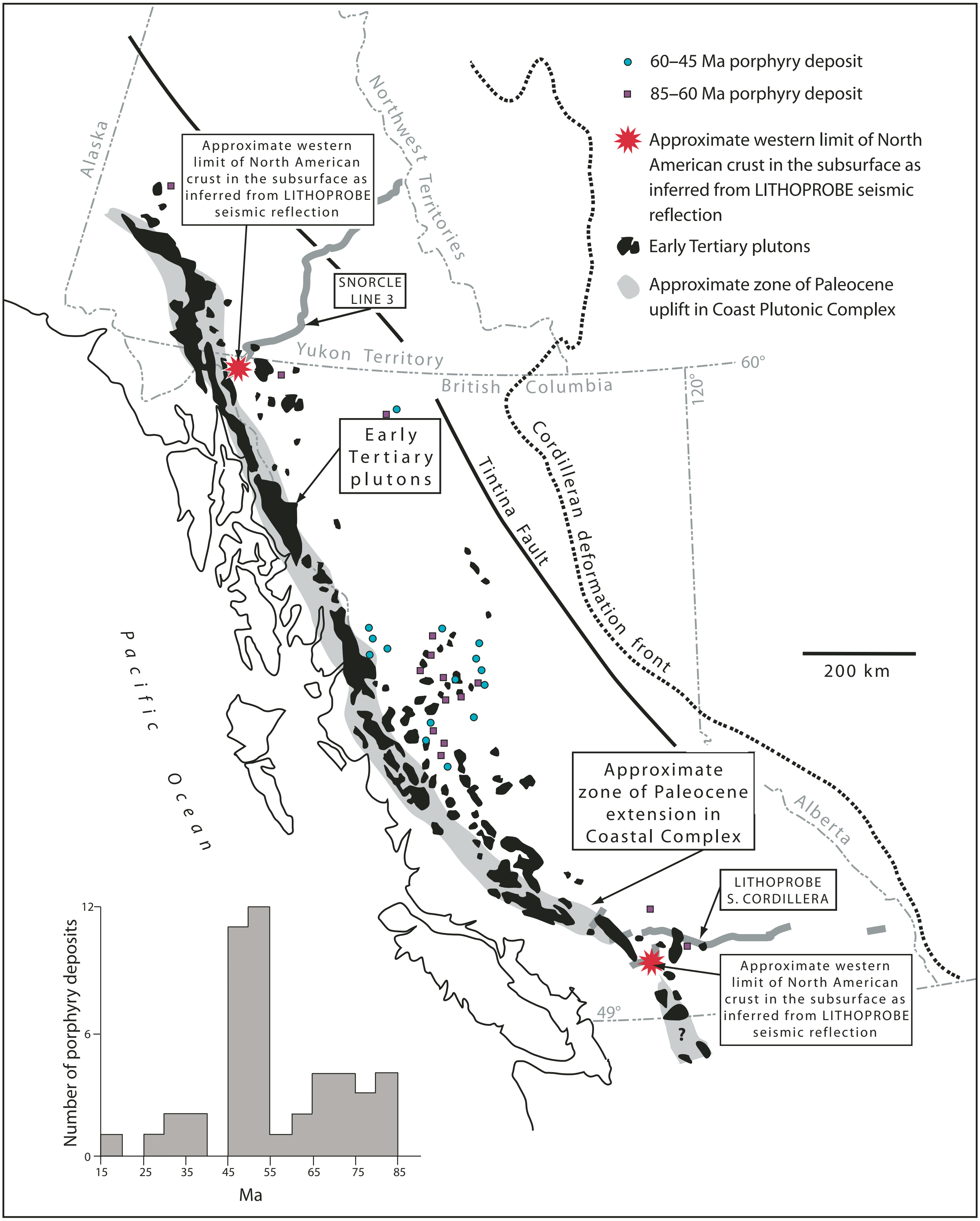
The Coast Range orthogneisses and batholith are similar to those along strike to the south in the North Cascades (Matzel et al., 2004), but despite the similarities the North Cascade block is fault bounded and may have younger deformation (S.A. Bowring, 2008, personal commun.). Thus its relationship to the Coastal belt is somewhat uncertain.

Even a cursory glance at the geological map of western North America (Figs. 13 and 16 [see below]) leads one to notice that for the most part the Laramide thick-skin belt doesn't extend north of the Lewis and Clark lineament—or, as it is sometimes called, the Montana transform (Sears, 2006; Foster et al., 2007)—whereas the contemporaneous postcollisional, slab failure magmatic rocks of Canada generally don't occur much south of it. This, and their temporal overlap, suggest a causal relationship. Perhaps the subducting oceanic slab was segmented, and the transform transected the edge of the craton at the site of the Montana transform. When the slab failed, it would then have been possible to have different thicknesses of lithospheric mantle on either side of the transform. Such differences could be the direct result of how much lithospheric stretching had occurred during break-off. Complete removal of lithospheric mantle leads to a greater rise in asthenosphere, which, in turn, would generate more magma. Increased magma pooling at the break-off zone would lead not only to more magmatism but would reduce the frictional coupling between the upper and lower plates, because it heats and thus weakens the lower crust. As pointed out by Cloos et al., (2005), where upwelling amounts are lower, break-off speed becomes more important, such that with 50% lithospheric thinning and slow break-off, no melts would be created at all. Thus, if the area south of the Lewis and Clark lineament had thicker remaining lithosphere after break-off, there would be no, or very little, magmatism, and, hence, strong coupling between the upper and lower plates, such as observed and inferred for the Laramide belt. Alternatively, greater lithospheric thinning allows for greater volumes of adiabatically generated melts to form, rise into the collision zone, heat the lower crust, and then rise toward the surface to create the observed volcanic rocks north of the lineament. Thus, not only can slab break-off account for the change from thin-skinned to thick-skinned deformation, but longitudinal variations in lithospheric thinning during break-off could produce the change from thick-skinned deformation without magmatism to the inverse situation: magmatism without thick-skinned deformation. This is exactly what is observed in western North America.

The Sonora segment, south of the Colorado Plateau, contains another magmatic belt that is easily interpreted to represent slab break-off magmas (Fig. 13). These include the so-called Laramide magmatism of southern Arizona and New Mexico, as well as a linear belt of 76–55 Ma plutons that continue southward through much of western Mexico (Damon et al., 1983; Zimmermann et al., 1988; Titley and Anthony, 1989; Barton et al., 1995; McDowell et al., 2001; Henry et al., 2003; Valencia-Moreno et al., 2006, 2007; Ramos-Velázquez et al., 2008).

In addition to the marked lack of slab failure magmas in the Great Basin segment, there are two additional lines of evidence that provide independent support for the idea of a segmented North American plate:

1. Two major fault zones, the Lewis and Clark lineament and the Orofino shear zone, trend northwest across the Rubian superterrane (Figs. 13 and 16 [see below]). The hinterland belt, with its Cordilleran batholiths and metamorphic core complexes, shows several hundred kilometers of sinistral separation across the Orofino shear zone, and if one continues it eastward into the lower plate it lines up well with the northern margin of the geomorphological Colorado Plateau. The Lewis and Clark lineament displays right-lateral separation of the Belt Supergroup, and it clearly fragmented the foredeep between 100 and 75 Ma with thicker and coarser sediments to the south (Wallace et al., 1990). The fault appears to mark the northern limit of Laramide thick-skinned deformation (Fig. 13).
2. During the thrusting, one of the few areas in the entire collision zone to have syncollisional magmatism exists adjacent to the Lewis and Clark lineament and Orofino shear zone. South of the faults, and within the Helena salient, lies the composite Boulder batholith (Figs. 13 and 16 [see below]), which ranges in age from about 80 to 64 Ma; the coeval Elkhorn volcanics; and the 66–64 Ma Butte porphyry copper system (Dilles et al., 2003; Lund et al., 2002; Rutland et al., 1989; Lageson et al., 2001). Within the fold-thrust belt north of the lineament are volcanics of the 80 Ma Two Medicine Formation and the 75 Ma Adel Mountain volcanics (Schmidt, 1978; Roberts and Hendrix, 2000; Harland et al., 2005; Foreman et al., 2008). The interpretation of


60–45 Ma porphyry deposit
85–60 Ma porphyry deposit
Approximate western limit of North American crust in the subsurface as inferred from LITHOPROBE seismic reflection
Early Tertiary plutons
Approximate zone of Paleocene uplift in Coast Plutonic Complex
Alaska
Northwest Territories
Yukon Territory
British Columbia
Alberta
60°
120°
49°
Approximate western limit of North American crust in the subsurface as inferred from LITHOPROBE seismic reflection
SNORCLE LINE 3
Early Tertiary plutons
Tintina Fault
Cordilleran deformation front
200 km
Pacific Ocean
Approximate zone of Paleocene extension in Coastal Complex
LITHOPROBE S. CORDILLERA
Approximate western limit of North American crust in the subsurface as inferred from LITHOPROBE seismic reflection
?
Number of porphyry deposits
0
6
12
15
25
35
45
55
65
75
85
Ma

these rocks has been problematic, but perhaps their syncollisional nature and their occurrence only near the faults indicate that their source was the asthenospheric mantle beneath a postulated transform or STEP fault (Govers and Wortel, 2005) extending just into the North American craton. Magmas were able to upwell through gaps in the lithosphere into the transform zone because of uneven scissors-like movement, or tearing, possibly related to uneven rollback during subduction (Royden, 1983a, 1983b; Rosenbaum and Lister, 2004). Similar tears are imaged tomographically today in the Italian–Tyrrhenian Sea area and appear to have exerted considerable control over magmatism and mineralization during the last 10 Ma (Rosenbaum et al., 2008). Upper Cretaceous sedimentary rocks within the foredeep are different in character and thickness on either side of the Lewis and Clark lineament and reflect synsedimentary activity on the fault during the period 100–75 Ma (Wallace et al., 1990).

The Colorado Mineral Belt (Wilson and Sims, 2003) is a linear belt of Late Cretaceous–early Tertiary magmatism that divides the Laramide basins into two distinct fields (Fig. 13) and appears to comprise magmas with a mantle source. The 75–50 Ma magmatism was correct to have been generated by slab failure and likely represents mixtures of asthenospherically derived basalt and melted Proterozoic crystalline basement (Fig. 14) emplaced into the lower North American plate (Stein and Crock, 1990; Bailley and Farmer, 2007) through a tear in the North American lithosphere that developed along a long-standing lithospheric boundary (McCoy et al., 2005). Furthermore, volcanic rocks of the Oligocene San Juan volcanic field (Lipman, 2007) occur at the junction of the Colorado Mineral Belt and the Rio Grande Rift, with most calderas within the Colorado Mineral Belt (Fig. 13). This attests to the importance of these lithospheric tears in controlling magmatism not only during slab break-off but also during subsequent events many millions of years later.

CORDILLERAN-TYPE BATHOLITHS AND SUBDUCTED CRUST

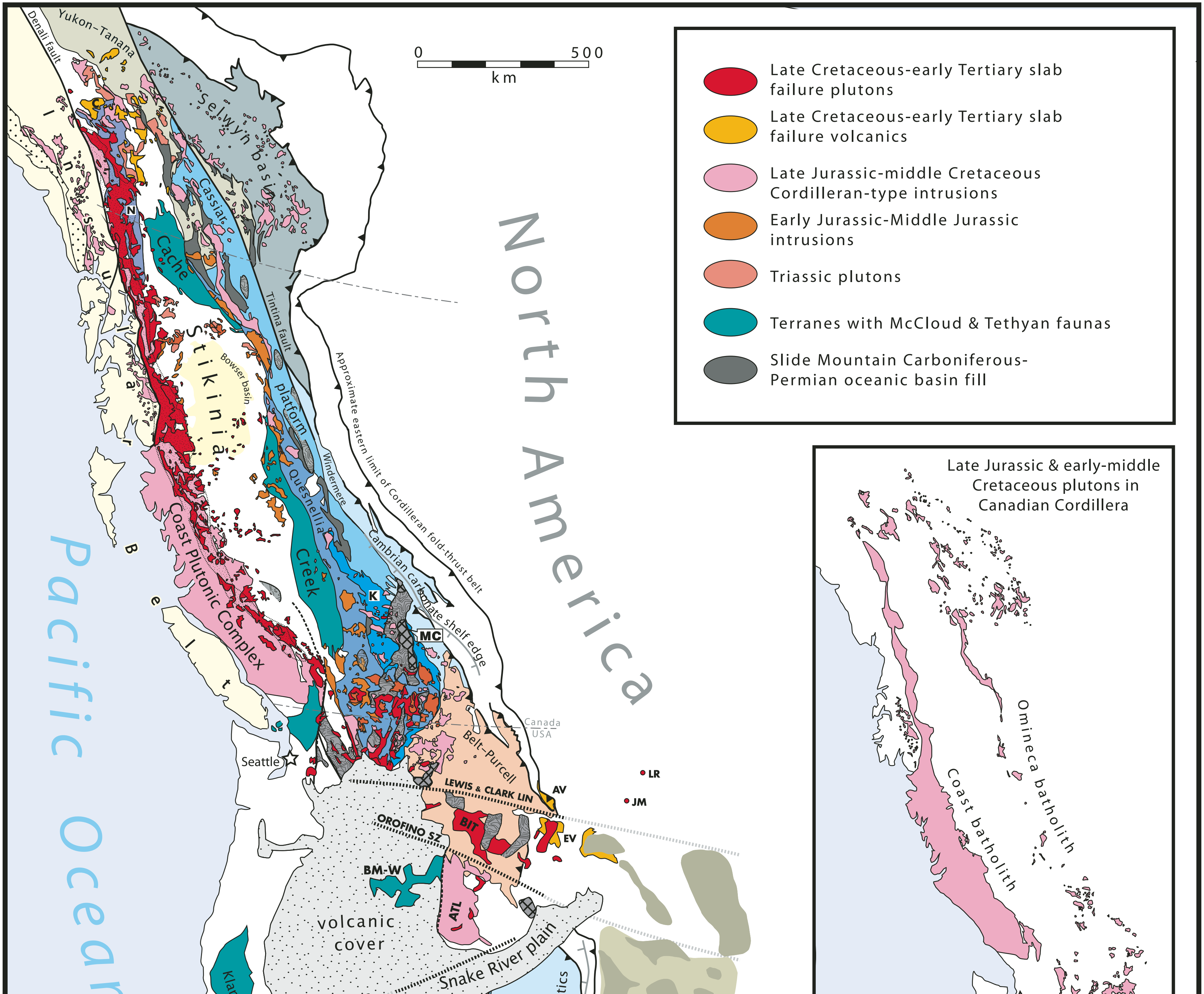
If the North American continent was subducted to the west beneath the superterrane, then it is correct to ask the question: Where are the arc rocks related to westerly directed subduction prior to terminal collision? Although there was separation on strike-slip faults that may have shifted major blocks considerable distances, the obvious choice in the case of the western United States for such an arc would be the Sierra Nevada batholith, the archetypical Cordilleran-type batholith (Bateman and Wahrhaftig, 1966), and other Jurassic-Cretaceous batholiths such as the Coast Plutonic Complex and the Idaho, Peninsular, Sonoran, and Omineca batholiths (Fig. 13). It was the seminal papers by Hamilton (1969a, 1969b) that led to the idea that the Sierra Nevada batholith, and others of western North and South America, were the products of easterly directed subduction of Pacific Ocean floor beneath North America, a concept that has come down to the present more or less unchallenged.

We have already seen, in the case of the latest Cretaceous–early Tertiary development of the Coast Plutonic Complex of western Canada, how great volumes of magma might suddenly arise during collision owing to slab break-off, but apparently there were other, even earlier, magmatic flare-ups in the Sierra Nevada, Coast, and Peninsular Ranges batholiths (Silver and Chappell, 1988; Ducea, 2001; Kimbrough et al., 2001; Ortega-Rivera, 2003; Pearson and Ducea, 2006). These flare-ups correlate reasonably well enough with accretionary events to suggest a causal relationship.

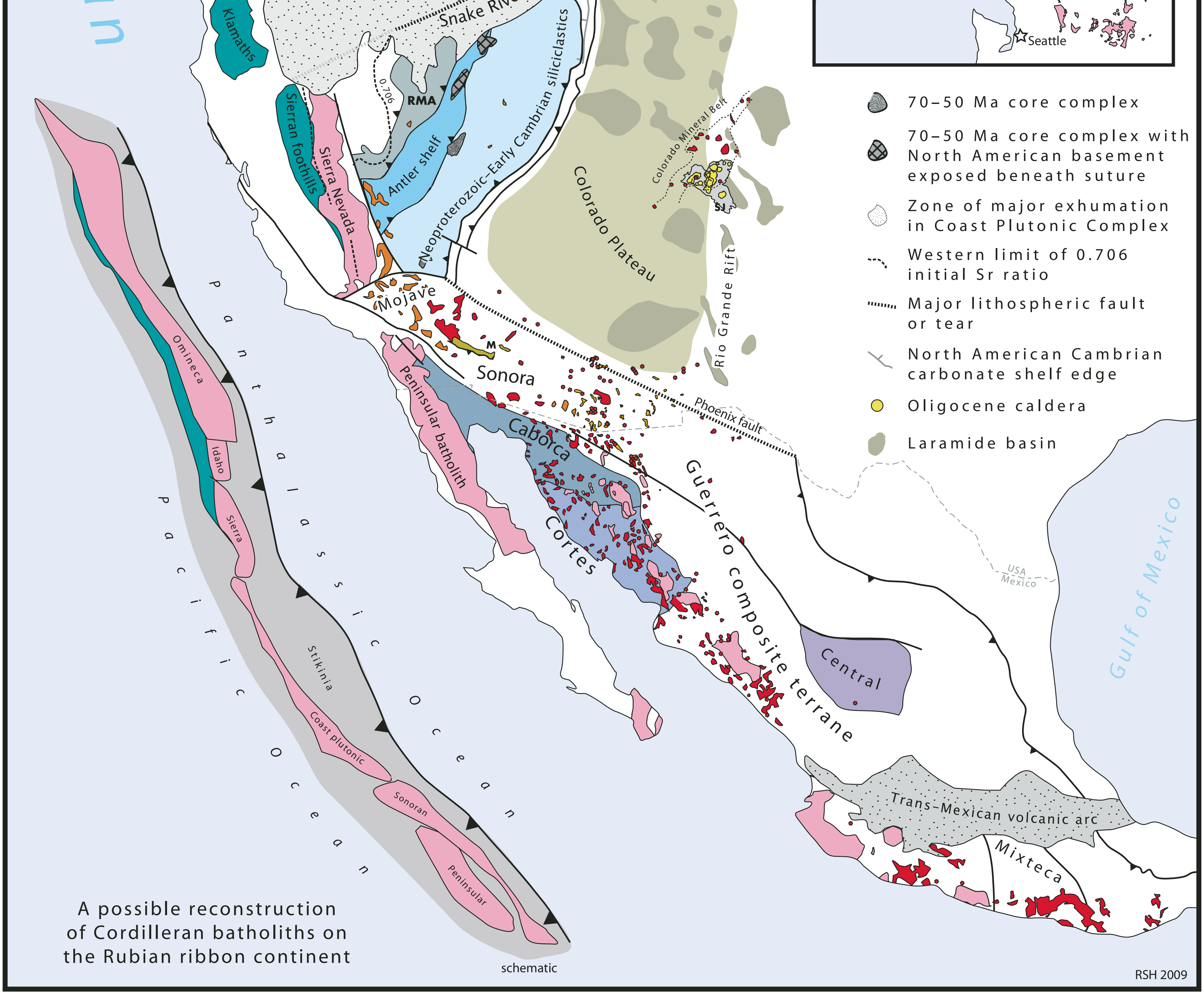
First, consider that "normal" subduction of oceanic crust, even beneath continental crust such as the Alaskan or Kamchatkan peninsulas, doesn't appear to create thick and voluminous Cordilleran batholiths even with 100 m.y. of subduction (Portnyagin et al., 2008). Instead, oceanic subduction generates long-lived centers of magmatism in a broad area of subsidence close to sea level, without much in the way of crustal thickening (Hildebrand and Bowring, 1984). Estimates for volumes of basaltic magma arriving at the base of the crust in typical arcs are poorly constrained but should be the same as magma production in oceanic arcs, which vary widely between 1 and 40 km^3/m.y. per kilometer of arc length (Marsh, 1979; Reymer and Schubert, 1984; Crisp, 1984) on the low end, 60–95 km^3/m.y. per kilometer of arc length (Taira et al., 1998; Holbrook et al., 1999; Larter

Figure 12. Sketch map showing the distribution of early Tertiary slab break-off plutons of the Coast Plutonic Complex after van der Hayden (1992); the approximate zone of Paleocene extension is from Armstrong (1988), and the approximate limit of western North America in the subsurface is inferred from LITHOPROBE seismic reflection (Cook et al., 1988, 2004). The ages and location of porphyry copper deposits are also shown after Godwin (1975).

Figure 13 (*on following two pages*). Geological sketch map of part of the Cordilleran orogen (after Wheeler and McFeely, 1991; Wheeler et al., 1991; Reed et al., 2005; Ramos-Velázquez et al., 2008), showing the distribution of some exotic terranes within the Rubian superterrane, Cordilleran-type batholiths, and various plutonic suites, including slab break-off plutons and volcanic rocks. Insets show the doubled Cordilleran batholiths in the Canadian Cordillera and a possible reconstruction of Cordilleran batholiths on the Rubian supercontinent. Note how the Lewis and Clark lineament appears to control the northern boundary of the Laramide thick-skinned deformation, whereas the northern boundary of the geomorphological Colorado Plateau appears to be controlled by the Orofino shear zone. Both Colorado Plateau and Laramide thick-skinned deformation terminate on the south at the Phoenix fault. AV—Adel volcanics; ATL—Atlanta lobe of Idaho batholith; BIT—Bitterroot lobe of Idaho batholith; BM-W—Blue Mountain–Wallowa terranes; C—Carmacks volcanics; EV—Elkhorn Mountain volcanics; JM—Judith Mountains; K—Kootenay terrane; LR—Little Rocky Mountains; M—McCoy Mountains Formation; MC—Monashee complex; N—Nisling terrane; RMA—Roberts Mountain allochthon; SJ—San Juan volcanic field; SZ—shear zone. Colorado Mineral Belt from Wilson and Sims (2003); calderas in San Juans after Lipman (2007).



Late Cretaceous-early Tertiary slab failure plutons
Late Cretaceous-early Tertiary slab failure volcanics
Late Jurassic-middle Cretaceous Cordilleran-type intrusions
Early Jurassic-Middle Jurassic intrusions
Triassic plutons
Terranes with McCloud & Tethyan faunas
Slide Mountain Carboniferous-Permian oceanic basin fill
Late Jurassic & early-middle Cretaceous plutons in Canadian Cordillera
Omineca batholith
Coast batholith
0
500
km
North America
Pacific Ocean
Yukon-Tanana
Denali fault
Selwyn basin
Cassiar
Cache
Tintina fault
Stikinia
Bowser basin
platform
Approximate eastern limit of Cordilleran fold-thrust belt
Windermere
Quesnellia
Creek
Cambrian carbonate shelf edge
K
MC
N
Coast Plutonic Complex
Insular Belt
Seattle
Canada
USA
Belt–Purcell
LEWIS & CLARK LIN
AV
LR
JM
EV
BIT
OROFINO SZ
BM-W
ATL
volcanic cover
Snake River plain



70–50 Ma core complex
70–50 Ma core complex with North American basement exposed beneath suture
Zone of major exhumation in Coast Plutonic Complex
Western limit of 0.706 initial Sr ratio
Major lithospheric fault or tear
North American Cambrian carbonate shelf edge
Oligocene caldera
Laramide basin
Seattle
Klamaths
Sierran foothills
Sierra Nevada
RMA
0.706
Antler shelf
Neoproterozoic–Early Cambrian siliciclastics
Colorado Plateau
Colorado Mineral Belt
SJ
Rio Grande Rift
Mojave
M
Sonora
Phoenix fault
Caborca
Peninsular batholith
Cortes
Guerrero composite terrane
Central
USA
Mexico
Gulf of Mexico
Trans-Mexican volcanic arc
Mixteca
Panthalassic Ocean
Pacific Ocean
Omineca
Idaho
Sierra
Stikinia
Coast plutonic
Sonoran
Peninsular
A possible reconstruction of Cordilleran batholiths on the Rubian ribbon continent
schematic
RSH 2009

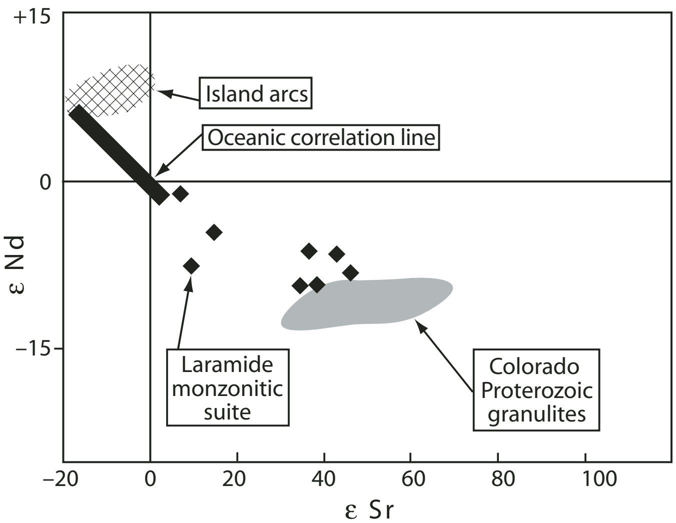


Figure 14. Initial ε Nd vs. ε Sr for Laramide monzonitic intrusions of the Colorado Mineral Belt (from Stein and Crock, 1990), showing that the intrusions could have been derived from a mixture of asthenospheric melts plus Proterozoic granulites of Colorado.

et al., 2001; Dimalanta et al., 2002) in the middle, and a poorly constrained 180 km^3/m.y. per kilometer of arc length (Jicha et al., 2006) on the high end. Because the magmatic flare-ups are at least 2–3 times as voluminous as the "normal" magma production rates in arcs (Ducea, 2001), there must be something unique about the process that caused the flare-ups.

Within the Sierra Nevada batholith the largest flare-up occurred between about 120 and 80 Ma (Chen and Moore, 1982; Ducea, 2001; Irwin, 2002), which is remarkably close to the period of subduction of the North American cratonic margin, estimated here to have taken place between about 124 Ma, when the outer shelf passed over the outer trench bulge, and approximately 70 Ma, when the subducting slab failed. I suggest that it was the melting and/or dewatering of the ancient continental margin slope-rise rocks and their basement that created the magmatic flare-ups. Prior to slab failure, convergence slowed, or even stopped, owing to the difficulty of subducting an old craton, which would explain why magmatism in the Sierra Nevada terminated at about 80 Ma (Chen and Moore, 1982; Bateman, 1992; Saleeby et al., 2008). Similarly, the Coast Plutonic Complex flared markedly during the Cretaceous from about 123 to 85 Ma (Mahoney et al., 2006; Pearson and Ducea, 2006; Hollister and Andronicos, 2006), the Peninsular Ranges Batholith flared between 120 and 90 Ma (Silver and Chappell, 1988; Ortega-Rivera, 2003), and the Salinian block 115–78 Ma (Mattinson, 1990). Given that not every pluton in either batholith has been dated, the ages are only approximations; nevertheless, the timing of the flare-ups coincides remarkably well with the subduction of the North American margin. Subsequent uplift of the batholithic zones exposed a sufficient variety of crustal levels to show that flare-up magmatism essentially reorganized the entire crust (Saleeby et al., 2007).

Water derived from subducted oceanic crust and its overlying sedimentary veneer is generally implicated as the dominant catalyst in the generation of arc magmas (Tatsumi et al., 1986; Moran et al., 1992; Leeman et al., 1994; Stolper and Newman, 1994; Eiler et al., 1998; Caulfield et al., 2008). Old and cold lithosphere adjacent to and in old rifted continental margins would be much cooler than typical oceanic crust and would favor deeper initiation of dehydration reactions, which should promote more efficient transport of fluids to sub-arc depths (Moran et al., 1992; Leeman et al., 1994). Under such conditions a greater volume of subducted sediment would yield a greater volume of water to create abnormal quantities of mafic melts in the mantle wedge. The model suggested here is that arc terranes develop along a crudely steady-state path, adding new crust at a rate that is probably related to the convergence velocity, until the rather abrupt entry of the leading edge of a subducted cratonic margin into the zone of dehydration-melt creation suddenly creates an abnormally large volume of melt to rise into the overriding arc, where it can melt anomalously large volumes of continental crust. Not only does the massive influx of magma create voluminous crustal melts, but the addition of so much rising basalt thickens the crust markedly, for basalt is less dense than mantle. These are entirely different effects than those created during typical steady-state subduction of oceanic crust with its thin veneer of abyssal sediment. Prior to the influx of copious quantities of crustal material into the melt-generation system, as typified by the earlier Cretaceous and Jurassic-Triassic phases of magmatism within the Sierra Nevada batholith, there wasn't extensive crustal thickening, as evidenced by its low-standing nature (Busby-Spera, 1984, 1986; Busby-Spera et al., 1990; Busby et al., 2002; Fiske and Tobisch, 1978; Fisher, 1990; Riggs and Busby-Spera, 1991; Schmidt and Poli, 1998; Ulmer, 2001; Davies and Stephenson, 1992; Grove et al., 2002; Parman and Grove, 2004; Wadsworth et al., 1995; Haxel et al., 2005). Even today in western North America, with >50 m.y. of easterly directed subduction, there is no evidence for the development of voluminous Cordilleran-type batholiths.

In the case of the Sierra Nevada, the Peninsular Ranges Batholith, the Omineca belt, and the Coast Plutonic Complex there is another feature difficult to explain with easterly directed subduction but rather simply explained by westerly directed subduction: the clear and progressive easterly younging of the flare-up magmatism (Fig. 15) (Chen and Moore, 1982; Bateman, 1992; Silver and Chappell, 1988; Ortega-Rivera, 2003; van der Hayden, 1992; Hart et al., 2004). In the westerly directed subduction model presented here, the well-documented mechanism of slab rollback can cause magmatism to migrate toward the trench, which is also migrating (Elsasser, 1971; Dewey, 1980; Garfunkel et al., 1986; Kincaid and Olson, 1987; Royden, 1993a, 1993b). Until recently, many workers interpreted the rollback of the subducting plate as steepening slab dip caused by subduction of progressively older, colder, and denser oceanic lithosphere; however, there seems to be no simple relationship between slab dip and age of the lithosphere (Cruciani et al., 2005). Steeper dips apparently can be

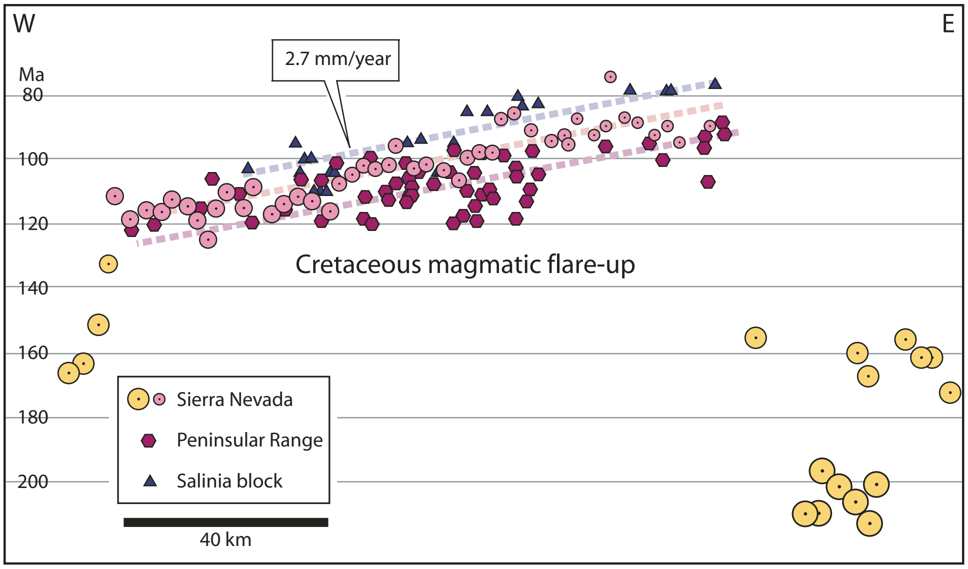


Figure 15. Age vs. distance plots for three flare-up Cordilleran-type batholiths showing dominant 120–80 Ma ages and general eastward younging. Sierra Nevada (modified after Bateman, 1992); Peninsular Ranges (modified from Ortega-Rivera, 2003; Silver and Chappell, 1988), and Salinia block (modified from Mattinson, 1990).

caused by increased hydration and consequent decreased viscosity in the asthenospheric wedge above the slab (Manea and Gurnis, 2008), which, if correct, would dovetail with the model presented here. Whatever the cause of steepening slab dips, rollback in a retreating plate boundary does not necessarily involve any change in slab dip. Instead, rollback occurs when the downgoing plate is sufficiently dense to drive the subduction process (Royden, 1993a, 1993b). This means that not only are old, dense slabs more likely to sink and create a retreating plate boundary, but also that subduction generally stops soon after thick and buoyant continental crust enters the subduction zone.

Possible earlier flare-ups, such as the 170–150 Ma event in the Sierra Nevada, were not as voluminous, and are obviously more difficult to unravel; but they may reflect collisional events in the exotic terranes themselves, such as the joining of the combined Antler–Roberts Mountain–Golconda terrane of western Nevada to a whole host of Permian-Triassic arc terranes and mélanges beneath the western Sierra Nevada, whose complex interactions and amalgamation apparently took place during that time interval (Dickinson, 2008).

No doubt some will argue that Cordilleran-type batholiths cannot have such an origin because there was no collision in South America where the classic Andean batholiths were emplaced; but I would urge some caution because the Cordilleran orogeny, and probably Rubia, continued southward from Mexico into northwestern South America (Toussaint and Restrepo, 1994; Feininger, 1987), and the strong geological and temporal relationships between the western margins of the two continents farther southward suggest that similar processes were active at about the same time (see especially geological maps and pre-batholithic evolution in Cobbing et al., 1981; Pitcher et al., 1985; the structure sections of the Bolivian sub-Andean thrust belt in Roeder and Chamberlain, 1995; and Dunn et al., 1995; and the Late Jurassic to Tertiary magmatic and metallogenic evolution of northern Chile in Bogdanic and Espinoza, 1994). Thus, it is possible—perhaps in my view, even likely—that the western margin of the South American craton was partially subducted westward beneath an exotic block (Rubia?) during the Cordilleran orogeny as the Panthalassic Ocean closed. Thus, the Cordilleras of South America could, just as North America, contain the two possible flare-up phases of collisional Cordilleran-type batholiths: magmatic flare-up and slab break-off flare-up.

It is perhaps worth returning to the North American cases for a moment to point out that the two phases of collisional Cordilleran-type batholiths need not be spatially coincident, even in adjoining segments of the orogen. In the case of the Coast Plutonic Complex, north of the Lewis and Clark lineament, the collisional flare-up phase is overprinted by the younger slab break-off phase as the subducting slab apparently broke off beneath the arc itself. The two phases are partly separated in time by intense uplift and exhumation. In the Sierra Nevada the subducting slab apparently broke off more slowly and more to the east, such that lithospheric necking prevented magmas generated during slab failure from invading the crust in the vicinity of the Sierra Nevada.

Given the possibility of a large amount of strike-slip motion in the Cordilleran orogen, one thing not commonly considered is the original distribution of the Cordilleran batholiths. As they all apparently formed on the Rubian superterrane at the same time, it is reasonable to assume that they originally formed a more or less continuous belt. Within the Canadian Cordillera there are two side-by-side Cretaceous batholiths (Monger et al., 1982), the Coast Plutonic Complex and the Omineca batholith (Fig. 13). Paleomagnetic data from the 70 Ma Carmacks Group, at the north end of the Coast Plutonic Complex (Fig. 13), indicate that rocks of this group lay at the latitude of Oregon ± 700 km when erupted (Johnston et al., 1996; Wynne et al., 1998; Enkin et al., 2006). The Omineca, Idaho, and Sierran batholiths all appear to have parts of the same belt of terranes containing both Tethyan faunas along their western sides, so it is likely that they once formed a continuous belt. The Peninsular Ranges Batholith appears to reasonably restore to the western margin of the Mexican mainland, where it formed a continuous magmatic belt with the Sonoran batholith prior to the opening of the Gulf of California. Thus, I have tentatively restored the Coast Plutonic Complex to a position between the Sierra Nevada and the Peninsular Ranges Batholith (Fig. 13). This places the southern Sierra Nevada and its strongly uplifted southern end (Saleeby et al., 2007) adjacent to the deeply exhumed Coast Plutonic Complex.

POSTCOLLISIONAL MAGMATISM ON NORTH AMERICA

In the collisional model presented here, arc magmatism couldn't begin on the newly amalgamated collision zone until the original oceanic slab attached to North America failed because it was old, thick, cold, strong, and extended to great depths. Once the subducting slab broke off, a new or even a preexisting subduction zone could have propagated beneath the collision zone to create a new arc (Hildebrand and Bowring, 1999; Teng et al., 2000). Slab break-off, as deduced from the generation of the metamorphic core complexes in the Sevier hinterland, the end of thrusting in the fold-thrust belt, and the rapid uplift of the foredeep, occurred in the Late Cretaceous–early Tertiary from about 75 Ma in the Sonoran segment to possibly as young as 60 Ma in the Canadian segment (Fig. 12). After slab failure, new arc magmatism typically starts up within a couple of million years (Dewey, 2005; Suppe, 1987).

Following collision, the first magmatic rocks on or in North America were those of the 54 Ma Bitterroot lobe of the Idaho batholith (Bickford et al., 1981; Foster and Fanning, 1997), volcanic rocks of the Challis volcanic field (Armstrong, 1978), and magmatism from the Washington Cascades through interior British Columbia that extends northward nearly to Alaska (Fig. 16) (Tabor et al., 1984; Ewing, 1981a, 1981b; Matzel et al., 2008; Madsen et al., 2006). A linear band of Eocene magmatism extends >1500 km from southern Arizona to at least the Trans-Mexican arc (Aguirre-Díaz and McDowell, 1991; de Cserna, 1989). In both the Sonoran and Canadian segments the magmatism is the same age, 53–40 Ma, and so together they likely represent the first sign that subduction polarity had flipped and that Pacific oceanic crust was being subducted beneath North America. If subduction had existed beneath the Great Basin segment at that time, arc magmas apparently weren't able to penetrate the lithosphere there.

Some workers (Haeussler et al., 2003; Dostal et al., 2003; Breitsprecher et al., 2003; Madsen et al., 2006) argued that the 53–40 Ma magmatism originated above a slab window (Thorkelson and Taylor, 1989), but oblique subduction of a spreading ridge is unlikely to have created a narrow, linear belt of coeval magmatism extending from Wyoming to Alaska and from southern Arizona to southern Mexico, directly mirroring the segmentation of the orogen.

TRIANGLE ZONE

An interesting feature of the Cordillera, mentioned earlier, is the triangular-shaped area between the Lewis and Clark lineament and the Snake River Plain (Fig. 16). This zone is often called the Columbia Embayment, and on diagrams the northern Sierra is typically connected to the Idaho batholith by a gently sweeping curved line as if there were an actual reentrant in the margin of North America (Dickinson, 2004). In those models the Idaho batholith was emplaced into the North American margin far to the east of the Sierra Nevada along a reentrant in the continental margin. This is unlikely, as both the Sierra Nevada and the Atlanta lobe of the Idaho batholith have similar terranes containing Tethyan faunas along their western margins and appear to be separated in right-lateral fashion across the Snake River Plain (Fig. 16). The 0.706 Sr isopleth shows the same separation. These relations suggest the presence of a northeasterly trending fault within Rubia beneath the lavas of the Snake River Plain. On the north side of the embayment the Orofino shear zone was active from 90 to 70 Ma and clearly separates the Western Idaho shear zone and the 0.706 Sr isopleth in sinistral fashion (Armstrong et al., 1977; Fleck and Criss, 1985; McClelland and Oldow, 2007). Just to the north the Lewis and Clark lineament has dextral separation and was active from 100 to 75 Ma (Wallace et al., 1990).

At the eastern apex of the trianglar zone, the Sevier fold-thrust belt is especially complex and difficult to unravel; yet both the hypothesized Snake River Plain fault and the Orofino shear zone apparently don't continue into the lower North American plate, although southeasterly trending continuations of both the Orofino and Lewis and Clark zones clearly constitute the northern boundaries of the Colorado Plateau and the Laramide thick-skinned deformation, respectively (Figs. 13 and 16). Along most of the Rubian superterrane, both to the north and south of the Columbia triangle and lying east of the Cordilleran batholiths, are extensive terranes containing the Early Cambrian *Archeocyathid*-bearing reefs of the Cassiar and Antler shelves plus the thick Neoproterozoic siliciclastic sections containing diamictons (Fig. 16). As noted by earlier workers, these rocks are missing from the Columbia triangle and may have escaped northward during collision of the Rubian superterrane with North America (Pope and Sears, 1997; Wernicke and Klepacki, 1988). Because the Lewis and Clark lineament was active during the period 100–75 Ma, and because both it and the Orofino shear zone, active from 90 to 70 Ma, clearly affected the distribution of deformation and uplift on North America, these faults were fragmenting the Rubian superterrane during the Cordilleran orogeny at least up until slab failure.

Most of the area of the Columbia triangle is covered by thick Miocene basalts of the Columbia River and Modoc Plateaux (Fig. 16), so there is little opportunity to see what lay west of the Blue Mountan–Wallowa terranes. One possible area where such rocks are visible is the Rimrock Lake Inlier, where mafic plutons and mélange, containing continentally derived clastic rocks and greenstones, formerly lay ~90 km farther south in the middle of the triangle, once strike-slip motion on the Straight Creek–Fraser fault is restored (Miller, 1989). As Miller recognized, the rocks appear to be similar to those of the Klamaths and California Coast Ranges, especially the easternmost Franciscan subterranes. Within the triangle zone the terranes west of the Idaho batholith appear to be 2–3 times as wide as they are to both the north and south, whereas the area to the east of the batholith has been diminished by tectonic escape relative to areas both north and south of the Columbia triangle. The subjacent lithosphere between the two sides is probably very different, given that the western side of the Cordilleran batholiths up and down the Cordillera comprises an amalgam of Triassic to Cretaceous oceanic and accretionary packages (Dickinson, 2008). Presumably the lithosphere inside the western part of the triangle differs from that outside it, and so the faults on both its north and south sides may have formed effective lateral barriers to magmatism and thus confined younger eruptions of plateau basalts to the triangle region.

MOJAVE-SONORAN SEGMENT

I now turn to another segment of the Cordilleran orogen, the region south of the Sevier fold-thrust belt and the Colorado Plateau, where thrust faults, metamorphic terranes, Jurassic arc rocks, subduction complexes, Precambrian crystalline rocks, highly metamorphosed and tectonized Paleozoic metasedimentary rocks, anchizonal sedimentary basin rocks, and metamorphic core complexes trend east-southeasterly from the Transverse Ranges of California across the Mojave Desert and into the Sonoran Desert of southern Arizona (Fig. 5). There is no evidence that north-northeasterly trending faults of the Sevier fold-thrust belt are deformed by the east-southeasterly trending folds and faults, and as rock types and deformational styles change abruptly (Hoisch et al., 1988), there is likely a structural break between the two.

The overall map geometry and the abrupt changes in structural style and rock type suggest that the two areas are separated by a major fault and that a part of the North American craton was sliced off and transported elsewhere (Fig. 5). Crosscutting relationships indicate that at least some separation on the fault must be synchronous or postdate the Sevier thrusts. I term the rocks lying to the southwest of the fault the Sonoran segment, and I suggest that they were juxtaposed against, and/or migrated along, the truncated margin.

Within the Sonoran segment, rock units and their structures trend more westerly than the proposed fault, so their eastern margins are progressively cut out against more northerly parts of the fault (Fig. 5). As the Sevier thrust belt is truncated, at least part of the movement on this hypothesized fault must be younger than about 60 Ma, the minimum age of the thrust belt. The rocks and evolution of the Sonoran segment are sufficiently different from rocks west of the North American craton, and the interpretation presented here is sufficiently new so that a brief description is warranted.

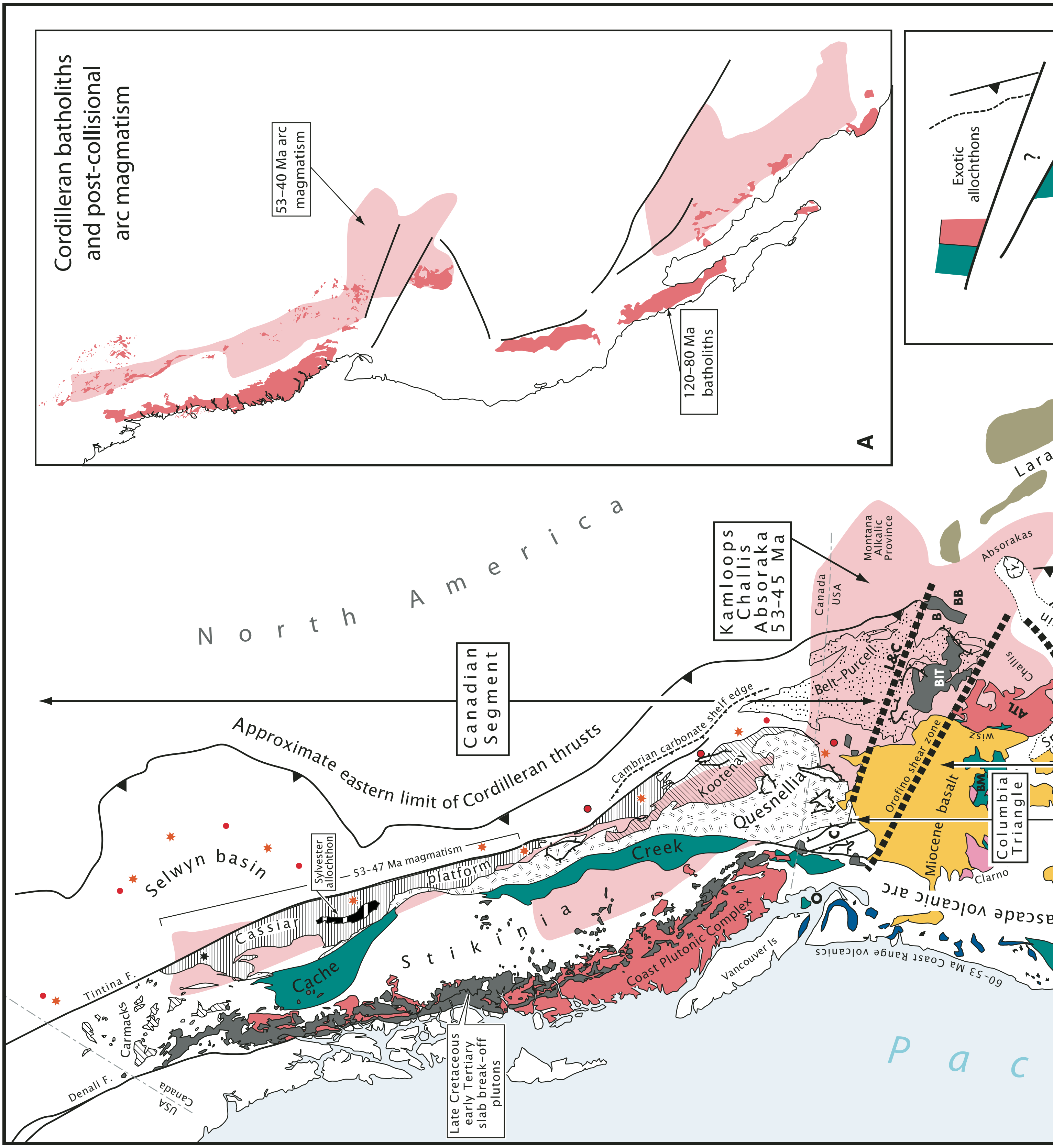
First, miogeoclinal rocks of North America are absent for ~500 km in this region. Second, rocks of the Sonora segment define a series of east-southeasterly–trending fault-bounded domains with thrust faults of various ages and with contrasting rock packages, all of which are very different from those along the western margin of North America, suggesting that they are rocks of the Rubian superterrane. A major compressional belt within the Sonoran segment is known as the Big Maria thrust belt (Fig. 5), which transects the Colorado River area in California and Arizona, and contains both northerly and southerly vergent thrust faults (Hamilton, 1987; Richard et al., 1994; Boettcher et al., 2002). This belt of rocks includes highly metamorphosed and strongly attenuated rocks that some have correlated with North American sections (Stone et al., 1983; Hamilton, 1982), but these rocks were intruded by Mesozoic plutons and, like other parts of the Mojave area, were deformed 8–10 m.y. before the onset of the Cordilleran orogeny (Boettcher et al., 2002).

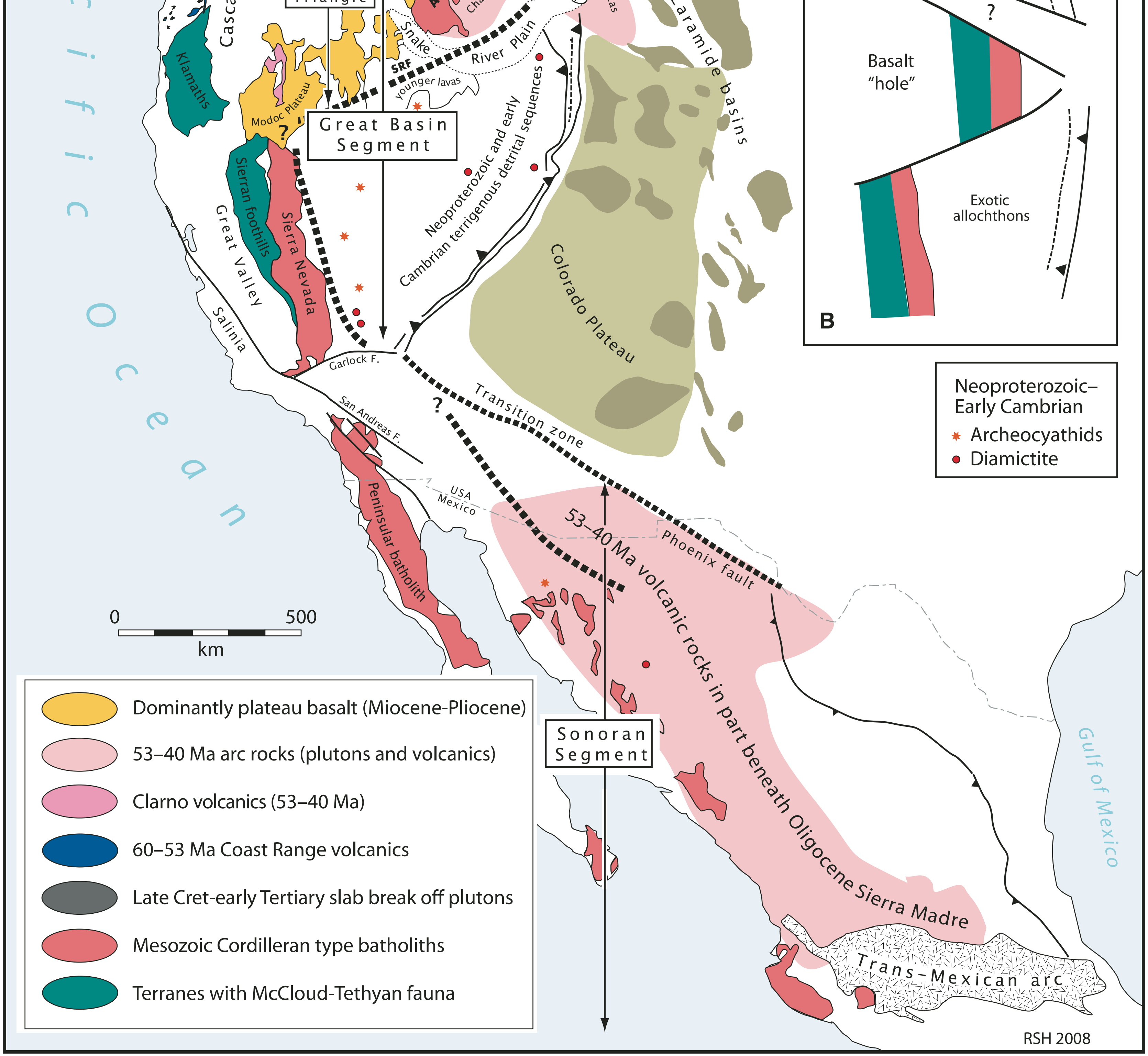
A 7-km-thick section of Upper Jurassic to Upper Cretaceous clastic rocks, known as the McCoy Mountains Formation (Harding and Coney, 1985), appears to lie structurally beneath thrusts along the south side of the Big Maria thrust belt and might represent rocks of a foredeep overridden during thrusting (Tosdal and Stone, 1994) or possibly even a forearc basin. At least part of this group was deposited and deformed after 79 Ma, the age of a rhyolitic tuff within the upper part of the sequence (Tosdal and Stone, 1994). Southwesterly directed thrusting deformed the 79 Ma rocks along with Late Cretaceous plutons and may be part of a more regional event that involved crystalline basement farther west in the eastern Transverse Ranges (Boettcher et al., 2002). A still younger northerly directed thrust event, present in both the Mojave and Sonora Deserts, postdates the earlier deformations and is latest Cretaceous to early Tertiary in age (Tosdal, 1990; Dillon et al., 1990; Haxel et al., 1984).

Apparently related to this younger event is the 500-km-long, east-southeasterly–trending belt of the Orocopia-Pelona schist (Fig. 4), a peculiar, yet distinctive, group of oceanic rocks that contains detrital zircons as young as 60 Ma and was buried to 30 km depth, metamorphosed, and brought to middle crustal depths by 48 Ma (Haxel et al., 2002; Jacobson et al., 2002, 2007). This argues for protolith deposition in a subduction complex, and

→

Figure 16 (*on following two pages*). Geological sketch map showing distribution of postcollisional 53–40 Ma arc magmatism, major faults discussed in the text, named segments of the orogen, and selected features of the Cordilleran orogen (after Wheeler and McFeely, 1991; Reed et al., 2005). Inset (A) Distribution of Cordilleran-type batholiths and 53–40 Ma arc magmatism. Inset (B) separations of Cordilleran batholiths and Tethyan-McCloud terranes along Lewis and Clark lineament (L&C) and the proposed Snake River fault (SRF). Note that the western part of the Columbia triangle is filled with Tertiary basalt. *Archeocyathid*-bearing limestones and Neoproterozoic diamictite occur all along the Cordillera, but they are missing from the Columbia triangle. ATL—Atlanta lobe of Idaho batholith; B—Butte, Montana; BB—Boulder batholith; BIT—Bitterroot lobe of Idaho batholith; BM—Blue Mountain–Wallowa terranes; C—North Cascades; O—Orcas Island; SRF—approximate trace of proposed Snake River fault; wisz—Western Idaho shear zone.


Cordilleran batholiths and post-collisional arc magmatism
53–40 Ma arc magmatism
120–80 Ma batholiths
A
Exotic allochthons
North America
Canadian Segment
Kamloops Challis Absoraka 53-45 Ma
Montana Alkalic Province
Absorakas
Canada
USA
Approximate eastern limit of Cordilleran thrusts
Cambrian carbonate shelf edge
Belt–Purcell
Selwyn basin
Sylvester allochthon
53–47 Ma magmatism
Cassiar platform
Kootenay
Quesnellia
Cache Creek
Stikinia
Coast Plutonic Complex
Vancouver Is
Tintina F.
Carmacks
Denali F.
Late Cretaceous early Tertiary slab break-off plutons
Orofino shear zone
Miocene basalt
Columbia Triangle
Clarno
Challis
Cascade volcanic arc
60–53 Ma Coast Range volcanics
Pac


Great Basin Segment
Sonoran Segment
Snake River Plain
SRF
younger lavas
Modoc Plateau
Klamaths
Sierran foothills
Sierra Nevada
Great Valley
Salinia
Garlock F.
San Andreas F.
Peninsular batholith
USA
Mexico
Neoproterozoic and early Cambrian terrigenous detrital sequences
Laramide basins
Colorado Plateau
Transition zone
Phoenix fault
53–40 Ma volcanic rocks in part beneath Oligocene Sierra Madre
Trans-Mexican arc
Gulf of Mexico
Ocean
0
500
km
Basalt "hole"
Exotic allochthons
B
Neoproterozoic–Early Cambrian
Archeocyathids
Diamictite
Dominantly plateau basalt (Miocene-Pliocene)
53–40 Ma arc rocks (plutons and volcanics)
Clarno volcanics (53–40 Ma)
60–53 Ma Coast Range volcanics
Late Cret-early Tertiary slab break off plutons
Mesozoic Cordilleran type batholiths
Terranes with McCloud-Tethyan fauna
RSH 2008

therefore the schist probably delineates a disrupted oceanic realm formerly located off the western edge of Rubia. In this scenario the Orocopia schist represents sedimentary detritus pulled beneath the Rubian plate and then later exhumed.

Part of the western margin of Rubia is now represented by rocks that in part lie west of the present-day San Andreas fault in the San Gabriel Mountains. Miocene reconstructions show a more or less east-west–trending band of imbricate Proterozoic to Mesozoic basement cut by Late Triassic, Jurassic (164 Ma), and Upper Cretaceous intrusions, which was thrust northward (present coordinates) over the Orocopia schist (Nourse, 2002). This Precambrian crystalline basement appears to continue more or less sporadically throughout southernmost Arizona. Whether it was ever part of Laurentia is unknown, but it was clearly rotated in a clockwise direction (Hornafius et al., 1986; Carter et al., 1987) so that the Orocopia belt lies now along the northern flank of the crystalline basement terrane.

Much of southern Arizona is dismembered by a set of northwesterly trending strike-slip faults, but the north-northeasterly vergent thrust faults continue eastward across southern Arizona in the fault slivers and transport a variety of metamorphosed and mainly Jurassic rocks, which collectively constitute a dismembered arc complex. In many places, primary textures within welded tuff units are still visible (Drewes, 1971), and calderas are locally present (Riggs and Busby-Spera, 1991; Lipman, 1994). In other areas, which reflect deeper structural levels, the rocks are strongly deformed and metamorphosed with local subvolcanic basement of Paleozoic metasedimentary rocks and Precambrian crystalline rocks, both involved in thrusting (Haxel et al., 1984; Reynolds et al., 1988; Hoisch et al., 1988). Throughout the southern Mojave-Sonoran area the overall style and composition of magmatism, along with the occurrence of crystalline basement, indicate that the arc terrane was constructed on continental crust (e.g., Howard et al., 1995), which could once have been part of Laurentia; but if so, it was rifted during the Cambrian and was reaccreted during the Cretaceous. Despite large amounts of shortening and crustal thickening within the Mojave-Sonora block, no complementary foredeep basin is preserved.

Within southern Arizona there are two groups of plutonic rocks: an older belt of metaluminous plutons ranging in age from about 74 to 64 Ma, and a younger grouping of peraluminous plutons with ages between 58 and 53 Ma (Miller et al., 1992). The rocks in the age range 74–64 Ma appear to be part of the slab break-off suite that continues southward through western Mexico (Fig. 13), whereas the younger group appears to be part of the postcollisional arc that also extends down through western Mexico (Fig. 16).

Like the hinterland belt, rocks of the Sonoran segment collapsed to form metamorphic core complexes (Fig. 5). However, instead of doing so in the Paleocene–Eocene, as in the Sevier, the collapse of this belt was in the Miocene (Coney, 1980). In spite of this difference, the rocks of the Sonoran segment have similar ages of deformation, metamorphism, and plutonism, as the rocks of the Rubia superterrane and are included within it. Nevertheless, owing to extensive strike-slip faulting and younger extension, relations are incompletely resolved and require additional work. The thrust front and likely eastern limit of Rubia occurs in east-central Mexico, south of the Big Bend of the Rio Grande, Texas (Figs. 13 and 16).

THE CASE FOR THE PHOENIX FAULT

As stated earlier, rocks of the Sonoran segment are truncated abruptly, but progressively, to the north-northeast (Fig. 13) by a previously unrecognized fault. The line of truncation trends west-northwesterly across Arizona from just north of the Mexico–Arizona–New Mexico triple junction, passing to the north of South Mountain in Phoenix to the Lake Havasu City area and then more or less along the California-Nevada border until it is truncated by the left-lateral Garlock fault. Within much of Arizona the fault trace (Fig. 17A) appears to coincide with a northwesterly line of deep Cenozoic basins, such as the Safford, Higley, Luke, Hassayampa, Congress, and Date Creek basins, which separate the Miocene core complexes to the southwest from the Transition Zone of the Colorado Plateau to the northeast (Spencer et al., 2001). Within southwestern New Mexico the fault passes near Lordsburg, where it separates conspicuous Mesoproterozoic granites from Mesozoic volcanic rocks in both the Pyramid and Little Hatchet mountains to the south. The truncation of the Sevier thrust belt, and the consequent gap south of the Colorado Plateau, have been recognized for decades, and this area contains several northwest-trending faults (Titley, 1976; Nydegger, 1982; Drewes, 1982, 1991). In southeastern Arizona and southwestern New Mexico the trace of the proposed fault approximates the boundary between Drewes's (1991) foreland/subfold-and-thrust-zone to the northeast and his intermediate zones to the southwest.

Besides the abrupt and progressive termination of the thrust belts, several other fundamental changes take place across this line: (1) the extent of Mesozoic-Tertiary metamorphism and its grade drop markedly from widespread amphibolite facies to anchizonal; (2) penetrative deformation is absent to the north and common to the south; (3) Mesozoic and Cretaceous magmatic rocks are absent to the north, whereas they dominate to the south; (4) Miocene metamorphic core complexes are common to the south but are absent to the north; (5) K-Ar and fission-track cooling ages are much younger to the south; (6) highly aluminous metasomatic rocks are widespread south of the line but are absent to the north; (7) conodonts south of the line have a high color-alteration index, whereas those to the north generally have a low color-alteration index; and (8) a change from shallow asthenosphere south of the line to thick lithosphere north of the line (Reynolds et al., 1988; Hendricks and Plescia, 1991).

The line is also prominent (Fig. 17B) on magnetic anomaly maps (Klein, 1982; North American Magnetic Anomaly Group, 2002) where it truncates the prominent northeasterly grain in Precambrian rocks of the American Southwest (Karlstrom and Bowring, 1988). Overall, the juxtaposition of the two regions is so

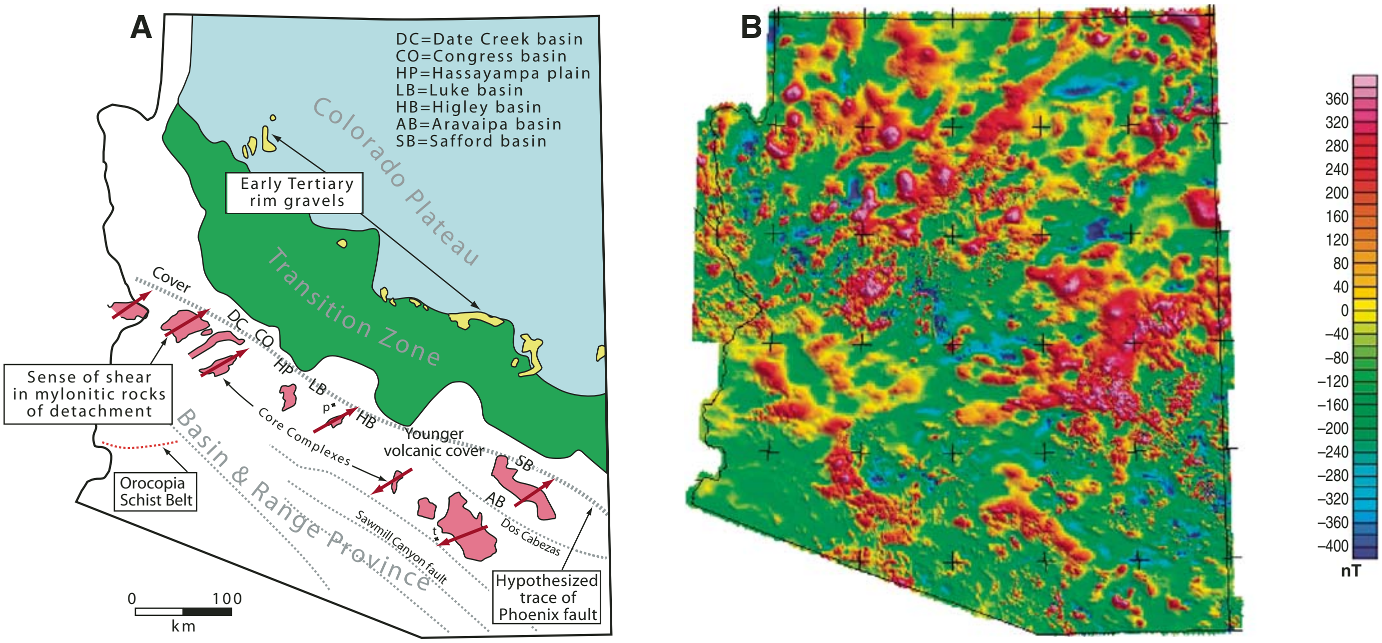


Figure 17. (A) Geological sketch map of Arizona, showing the proposed trace of the Phoenix fault between the Tertiary metamorphic core complexes of the Basin and Range Province and the Transition zone of the Colorado Plateau. Note the occurrence of the deep Tertiary sedimentary basins along the fault trace. Taken in part from Spencer et al. (2001). Several proposed northwest-trending fault zones are shown south of the Phoenix fault after Titley (1976) and Eisele and Isachsen (2001), as well as my own interpretations based on several features such as the termination of the belt of Orocopia schist. p—Phoenix, t—Tucson. (B) Aeromagnetic map of Arizona (North American Magnetic Anomaly Group, 2002), illustrating the abrupt truncation of the prominent northeasterly trending anomalies reflecting the northeasterly grain in Precambrian rocks of the American Southwest (Karlstrom and Bowring, 1988). Anomalies south of the Phoenix fault trend northwesterly and in part likely reflect dismemberment by strike-slip faults.

pronounced and abrupt that the line must represent the approximate surficial trace of a regional structural boundary, most likely a major transcurrent or transform fault. I call the fault the Phoenix fault, mainly because it passes beneath the city of Phoenix.

In addition to the qualities mentioned above, the southern margin of the Colorado Plateau along the Mogollon Rim is very different from its western margin, where large and numerous fault-rotated blocks characterize the transition to the Basin and Range Province (Erskin, 2001). Along the Mogollon Rim, huge rotated normal fault blocks are mostly absent: Instead, nearly flat-lying pediment surfaces are present. Gently dipping sedimentary rocks of Paleozoic age simply end at the rim, and the escarpment is an erosional feature rather than a series of normal faults. Even within the transition zone, horizontal Paleozoic sedimentary rocks occur as erosional remnants sitting unconformably on Precambrian basement. There are some younger faults, such as bound the Verde Valley or occur near Cave Creek (Elston and Young, 1991), but the overall structure of the transition zone is dominantly erosional, a marked difference from the western and eastern margins of the plateau.

In Arizona, it appears that plate interactions along that margin caused at least 1200 m of uplift and shed Paleocene gravels (termed rim gravels) from the rising tectonic welt (Elston and Young, 1991; Holm, 2001; Flowers et al., 2008). This indicates that within the Sonoran segment the original thrust belt, along with most of its foredeep sedimentary basin succession, lay farther to the south and was transported away. The new package of rocks juxtaposed with the southern edge of the Colorado Plateau cuts out the lower plate thrust belt with its imbricated foredeep deposits, and as such now collocates upper-plate arc rocks and their basement with lower-plate cratonic rocks of North America. This is a nearly identical situation to the Caribbean mountain system of Venezuela, where a nonmetamorphosed Cenozoic foreland fold-thrust belt is being diachronously juxtaposed against a mid-Cretaceous metamorphic hinterland owing to oblique convergence (Ostos et al., 2005).

The trace of the Phoenix fault also coincides with several formerly difficult-to-explain changes in depositional facies, jumps in metamorphic grade, and different magmatism along the California-Nevada border. These changes typically occur at nearly right angles to the miogeoclinal and Sevier trends. For example, northeast of the fault Mesozoic eolianites contain no associated volcanic rocks, yet abruptly to the southwest they are interbedded with volcaniclastic sandstones and overlain by volcanic rocks (Marzolf, 1982). Similarly, Mesozoic plutons and volcanic rocks occur directly south of the line, where they are associated with basement-involved thrusts and amphibolite-grade metamorphism of Paleozoic sedimentary rocks (Miller et al., 1982). The age of those thrust faults is also older than those of the Sevier fold-thrust belt just to the north (Walker et al., 1995). Similarly, faults of the East Sierra thrust belt, located mainly northward from the Garlock fault to southern Owens Valley, transported sedimentary, volcanic, and plutonic rocks on northwesterly striking, southwesterly dipping thrust faults that don't continue eastward into southern Nevada (Stevens et al., 1998).

The Phoenix fault may continue north of the Garlock fault along the eastern side of the Argus Range, where it apparently truncates the Independence dike swarm (Moore and Hopson, 1961; Carl and Glazner, 2002). Alternatively, the fault to the north might be a segment of the Mojave-Sonora megashear, which appears to sever and translate the thick Neoproterozoic-Cambrian succession of the White-Inyo Mountains into Mexico (Silver and Anderson, 1974; Anderson and Silver, 2005). Regardless of which major fault continues north of the Sevier thrust belt, its exact path in the Sierra Nevada–Owens Valley–White-Inyos area is problematic, for large-scale displacements in the area have often been proposed, but there has been no general agreement on the trace of such a fault or its age. The most obvious place for such a fault is directly through Owens Valley, where it would explain the absence of the 7.5-km-thick section of White-Inyos Neoproterozoic–lower Paleozoic sedimentary rocks in the Sierra Nevada and would separate the dominantly Jurassic plutons of the White-Inyos from the dominantly Cretaceous plutons of the Sierra Nevada. Stevens et al. (1998) argued that separation of Devonian submarine channels and Permian-Triassic structures limited displacement across Owens Valley to ~65 km, whereas Glazner et al. (2003) suggested that the Independence dike swarm was offset by at least 65 km, and possibly by as much as 130 km, and Kylander-Clark et al. (2005) argued for 65 km of post–83 Ma strike-slip motion in Owens Valley on the basis of matching a single dike across the valley. None of these are definitive as piercing points, because in the case of the dikes they are composite and appear to have emanated from plutons (Hopson, 1988) and not from a regional swarm (Glazner et al., 2008), so matching dikes have been difficult to prove. Correlating a submarine channel across the valley would only be viable if there were only one channel along the ancient margin or if there were something particularly distinctive about those channels. Schweickert and Lahren (1993b) suggested that roof pendants within the Sierra Nevada batholith contained equivalents of the Roberts Mountain and Golconda allochthons and so constrained movement across Owens Valley. However, similar rocks occur over much of the length of the Cordillera (e.g., Turner et al., 1989), and so the value of those rocks as piercing points seems questionable.

Other workers suggested a major Early Cretaceous fault in the Sierra Nevada called the Snow Lake fault, which could have as much as 400 km of dextral displacement (Lahren and Schweickert, 1989; Schweickert and Lahren, 1990, 1993a; Wyld and Wright, 2001, 2005, 2007), or other cryptic intrabatholithic faults with displacements on the order of 100 km (Kistler, 1993; Saleeby and Busby, 1993). Testing these cryptic faults is difficult, as they likely predate the 98–86 Ma Sierra Crest and other Cretaceous magmatism (Coleman and Glazner, 1998; Saleeby and Busby, 1993) and so are now obliterated. The presence of such a fault running right through the arc front would not be surprising, as a huge Fitch-type fault (Fitch, 1972), known as the Semangko, or Barisan Mountain, fault, strikes right through the arc front in Sumatra (van Bemmelen, 1949; Westerveld, 1953; Hildebrand, 1981), but in the case of the Snow Lake fault more data are required to better constrain the proposed fault, which, in any case, doesn't seem to have hundreds of kilometers of separation (Saleeby and Busby, 1993).

At present I suggest that a major fault of great displacement runs through Owens Valley, for the very thick and distinctive 7.5-km-thick Neoproterozoic–early Paleozoic sedimentary section in the White-Inyos simply is not represented in the Sierra Nevada, and there are no definitive piercing points across the valley. The presence of a fault through Owens Valley not only explains why the sections are so different across the valley, but why platform-facies transitions are truncated (Stevens and Stone, 2007), why the Sierra Nevada sits obliquely across the southwest-trending Sevier and older structures of Nevada, and why Jurassic plutons of the White-Inyos are juxtaposed with the dominantly Cretaceous plutons of the Sierra Nevada. Interestingly, the dominant 305°–335° strike of the Independence dike swarm (Hopson et al., 2008) parallels the trend of the Sierran-Mojave-Sonoran arc terrane (Fig. 5).

There are several possible traces for major faults in Mexico, all rather poorly constrained at present. Along the international border a major fault appears to separate rocks of the Chihuahua trough (Haenggi, 2001, 2002), which contains no volcanic rocks, from volcaniclastic rocks of the Bisbee basin to the west, which contain abundant volcanic debris (Fig. 5). Southward, the fault defines the southwestern edge of the Chihuahua trough, delineates that edge of North American crust as identified by Pb isotopes (James and Henry, 1993), and appears to truncate the northeast-trending Ouachita Front (Housh and McDowell, 2005) as shown in Figure 5. Even farther to the south are additional dislocations along the San Marcos fault and Coahuila Island that might be a continuation of the fault (Anderson and Nourse, 2005), but these are more speculative. The simplest solution is to link the two ends of the fold-thrust belt along a fault that passes near the Big Bend of the Rio Grande (Figs. 13 and 16).

Another line of reasoning that supports a syncollisional origin for the fault is the variable cratonic extent of the Western Interior Basin, which appears to be widest where the Rubian allochthons on North American crust are most extensive, as controlled by the location of the Tintina and Phoenix faults (Fig. 18). This could happen only if the region outboard of the faults was decoupled (Fitch, 1972) from the North American craton during sedimentation within the Western Interior Basin.

The proposed Phoenix fault could also explain the enigmatic relationship between the northwesterly trending band of Miocene metamorphic core complexes and the Transition Zone of the Colorado Plateau in Arizona. There, kinematic indicators within the main fault zones of the detachments demonstrate that rocks atop the core complexes slid northeastward during the extensional episode (Shackelford, 1989; Spencer et al., 2001), as

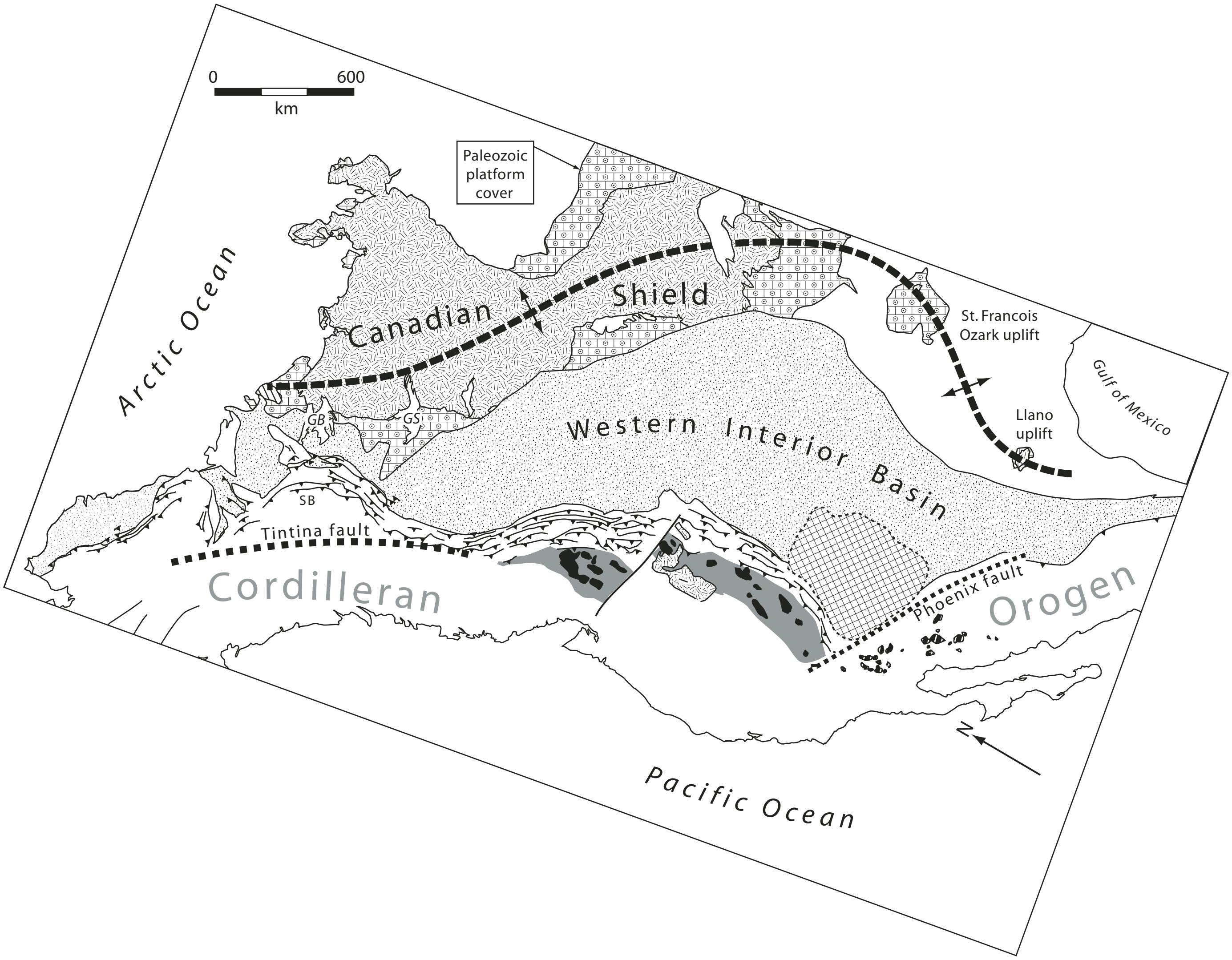


Figure 18. Sketch map illustrating the extent of the Western Interior Basin (modified from Leckie and Smith, 1992) and the approximate locations of the outer bulge, or anticline, and the traces of the Phoenix and Tintina faults. The trace of the outer bulge anticline is defined by the occurrence of Precambrian cored uplifts within the cratonic interior. The anticline, plus older cross-folds, possibly related to the Ouachita orogen, combine to form a dome-and-basin interference pattern over the Midcontinent region. The trace of the anticline within the northern Canadian Shield passes just to the east of Great Bear (GB) and Great Slave (GS) Lakes, where its trace is defined as a broad ridge that forms the eastern margin of the Mackenzie River drainage basin (not shown). The width of the Western Interior Basin is greatest where the hinterland belt is preserved inboard of the proposed Phoenix fault, which suggests that the width of the basin was largely controlled by the load of Rubia on North America, despite there being a possible component of dynamic subsidence. It also suggests that the Phoenix fault was active during sedimentation, as the region outboard of the fault system appears to have been decoupled from North America and does not appear to have affected the width of the basin. Note that except for the Sonora segment, at least part of the thrust belt is preserved everywhere just inboard from the fault system, which rules out subsequent removal of large segments of the foredeep to produce the current breadth. The Selwyn basin (SB) is a thin-skinned belt of exotic rocks, as discussed in the text.

shown in Figures 5 and 17. Whereas the rocks directly to the northeast today are rocks of the transition zone, there should be some evidence, in the form of piercing points, that those rocks formerly lay above the core complexes; yet to my knowledge, none have been found. Additionally, as rocks within the lower plates of the core complexes were uplifted as much as 10 km, it follows that the rocks of the upper plate must have collapsed a more or less equivalent amount, but today there is at most 2 km of structural relief between the Colorado Plateau with its Cretaceous erosional surface and the Transition Zone. Just north of Phoenix, at the margin of the plateau, the base of the southernmost outcrops of rim gravels is at most only 1.5 km lower than the rim of the plateau (Ferguson et al., 1998; Gilbert et al., 1998). Also, as documented by relict fault slivers above the detachment zones, and also by rocks mapped beneath the detachments, variable amounts of Mesozoic plutonic and volcanic rocks occurred throughout the area (Reynolds and Spencer, 1989; Bryant and Wooden, 1989; Hamilton, 1982; Howard et al., 1982); yet these rocks are not known within the transition zone. The proposed fault would pass approximately beneath point 400 on the Arizona COCORP line (Hauser et al., 1987), and the reflection models are not particularly clear in that area, so that sorting out inclined reflectors of the northward-dipping detachment surfaces from those of the Tertiary basins is not straightforward.

A series of northeast-trending folds, with wavelengths of 3–10 km and axial traces that are coaxial with the lineation within the detachment fault zones, is present within many of the core complexes and has been difficult to explain by a simple gravitational collapse model (Reynolds and Spencer, 1989). The folds might be more readily explained as structures developed in a transtensional environment (Venkat-Ramani and Tikoff, 2002; C. Ferguson, 2008, personal commun.) along a major transcurrent or transform structure such as the Phoenix fault.

MOJAVE-SONORA MEGASHEAR AND OROCOPIA-PELONA-RAND SCHISTS

Another major northwest-trending structure of the region is the hypothesized Mojave-Sonora megashear (Silver and Anderson, 1974; Anderson and Silver, 2005), which appears to be well south of the Phoenix fault. The presence in the Caborca terrane of Ordovician-Devonian fine-grained siliciclastics, cherts, and barite, coupled with Neoproterozoic, lower Paleozoic, and Lower Jurassic sedimentary rocks—all cut by Jurassic plutons—suggests a reasonable correlation with the Rubian rocks of Nevada and eastern California, including the White-Inyo Mountains, as originally suggested by Silver and Anderson (1974), and more recently by Stewart (2005). The presence of a Neoproterozoic diamicton southeast of the likely White-Inyo equivalents (Stewart et al., 2002) strengthens the case, as Neoproterozoic diamicton of the Kingston Peak Formation occurs in the Death Valley area southeast of the White-Inyo Mountains.

Comparison of rocks between the White-Inyos and the Caborca terrane makes a compelling match (Stewart et al., 2002; Stewart, 2005), but the trace of the fault is problematic, largely because subsequent deformations and magmatism obscure older structures and relationships. However, there are some constraints on its location. First, if the belt of Orocopia-Pelona-Rand schist represents a suture that corresponds to an oceanic realm, as generally accepted, then the fault must pass to the east of the easternmost exposures of the schist, as it defines a more or less continuous belt extending some 500 km from the California coast to western Arizona (Fig. 5). This is consistent with recent work (Amato et al., 2009), which indicates that the Mojave-Sonora megashear must lie farther to the northeast than previously suggested (Anderson and Silver, 2005). There does appear to be an unnamed, but major, northwest-trending fault (Fig. 17) that truncates the belt of schist in western Arizona and juxtaposes different stratigraphic sections on either side (C. Ferguson, 2009, personal commun.). If this is correct, then it opens the possibility that the Orocopia-Pelona-Rand schist belts (Fig. 5) were formerly contiguous and were disrupted by major strike-slip faults as alluded to by other workers (Grove et al., 2003; Nourse, 2002). Overall, the schists have: (1) detrital zircon populations that indicate that a major source for their sedimentary protoliths was the great Cordilleran batholiths and their wall rocks, and (2) accretion ages that young to the east from about 90 to 50 Ma, with the Sierra de Salinas and San Emiglio Mountains outcrops markedly older than the Rand, Pelona, and Orocopia occurrences, which were accreted between 60 and 50 Ma (Grove et al., 2003). From a temporal standpoint, the 50–60 Ma age grouping largely overlaps with slab failure and initiation of easterly directed subduction beneath the newly amalgamated orogen, which suggests that the schists were detritus deposited offshore to the west of Rubia, perhaps in a basin generated during subduction retreat, and that they were partially subducted during the initiation of subduction. This is in keeping with the singular nature of the schist-accretion event; that is, there was only one accretion event, which is difficult to explain in an ongoing, unbroken subduction model. Occurrences of rocks with similar source and burial ages elsewhere along the western margin of Rubia, such as the Swakane gneiss of the Washington Cascades (Matzel et al., 2004) and Catalina schist of the Southern California borderlands (Grove et al., 2008), suggest that the schists and related rocks mark a unique, plate-scale event. Polarity reversal following the thwarted subduction of continental crust beneath an arc is perhaps the mechanically easiest method to generate a subduction zone (Mueller and Phillips, 1991), and this mechanism explains why there was only one burst of schist accretion. Elsewhere along the margin, such as west of the Peninsular Ranges batholith, the emplacement, uplift, and exhumation of the Cordilleran-type batholiths supplied copious quantities of detritus to the western basin (Kimbrough et al., 2001), but apparently any partially subducted material was not regurgitated.

PORPHYRY COPPER DEPOSITS

Porphyry copper deposits are intrusion-related mineralized systems of large size that typically have zoned mineralization and alteration (Titley, 1982). The dominantly calc-alkaline dioritic to quartz monzonitic intrusions have porphyritic to seriate textures, and their disseminated mineralization is mostly fracture-controlled, even on a microscopic scale. Alteration is ubiquitous and widespread but is subject to variability in local structure, wall rock composition, depth and size of intrusion, as well as groundwater availability and volatile evolution of the magma (Gustafson, 1978). The distribution of known deposits reflects not only their origin, but also the wide variety of factors that exposed, modified, and preserved them, so it should be clear that any one model for their origin is unlikely to explain the spectrum of deposits (Barton et al., 1995). Nevertheless, some broad relationships have emerged from the current study.

The largest concentration of porphyry copper deposits within North America occurs in southern Arizona and western Mexico (Figs. 13 and 19). The deposits and their plutonic sources formed

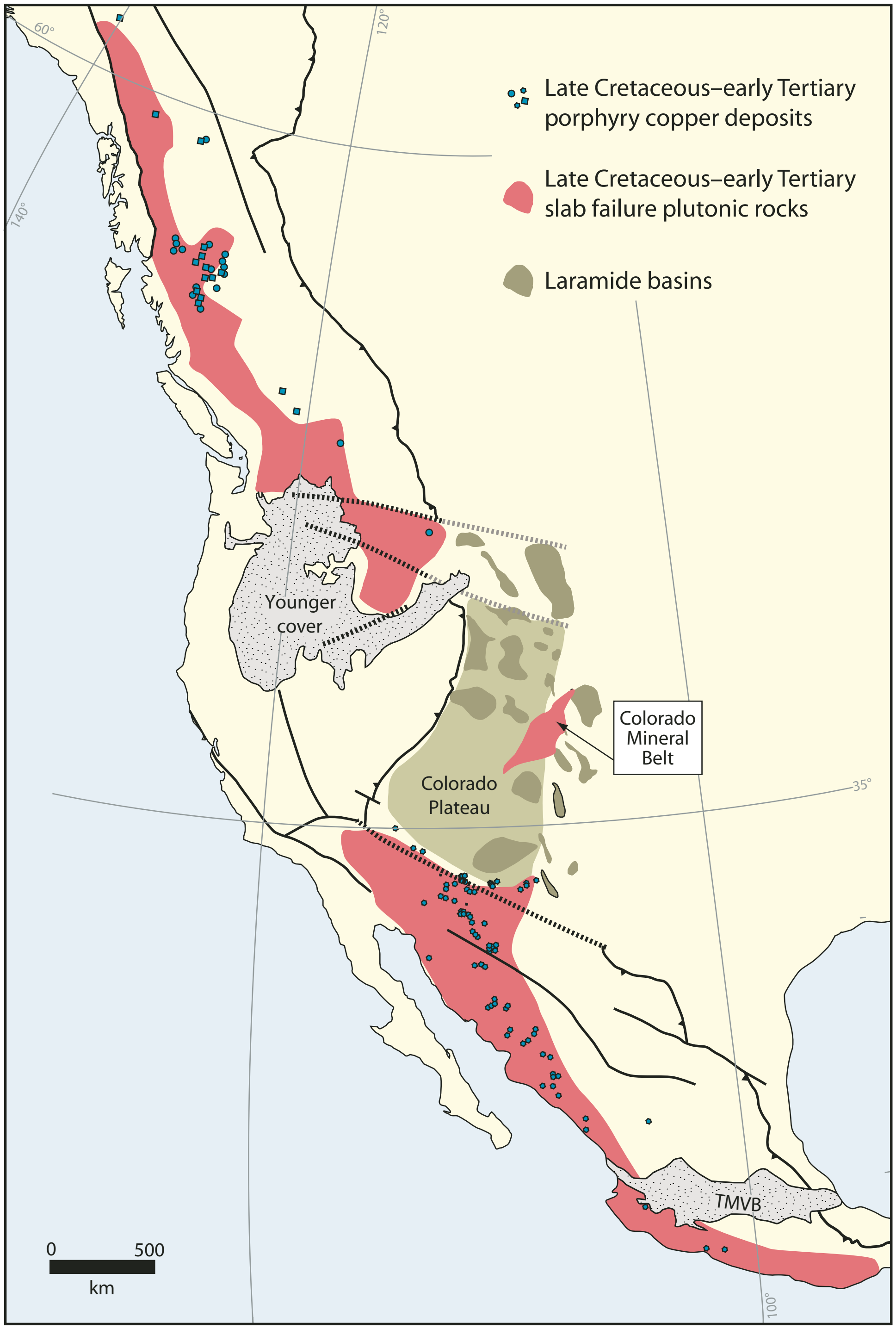


Figure 19. Geological sketch map showing the distribution of Late Cretaceous–early Tertiary porphyry copper deposits and belts of Late Cretaceous–early Tertiary plutonic rocks attributed here to slab failure magmatism. Distribution of porphyries after Titley and Anthony (1989), Titley (1982), Damon et al. (1983), Godwin (1975), Barton et al. (1995), Barra et al. (2005), and Valencia-Moreno et al. (2006, 2007). TMVB—Trans-Mexican volcanic belt.

between about 75 and 55 Ma (Titley and Anthony, 1989; Titley, 1982; Damon et al., 1983; Barton et al., 1995; Barra et al., 2005; Valencia-Moreno et al., 2006, 2007). Many of the intrusions are not accurately dated by zircons, so the precise ages are not well known; nevertheless, the 65 ± 10 Ma age suggests that many porphyry deposits in the Sonoran segment might be related to slab failure as they appear to have been in the Alpine belt (Boorder et al., 1998), Central Range orogeny of Papua New Guinea (Cloos et al., 2005; McDowell et al., 1996), and elsewhere in the southwest Pacific (Solomon, 1990). The main reasons to suggest a genetic relationship between slab failure magmatism and porphyry development are their close temporal and spatial equivalence.

The porphyry deposits of southwestern North America overlap spatially and temporally with the burst of Cretaceous slab-failure magmatism (Titley and Anthony, 1989) south of the Colorado Plateau (Figs. 13 and 19). Although the age of terminal thrusting within the Mexican sector of the orogen is unknown, the progression of slab failure from the U.S. to the Canadian sectors suggests that the slab was progressively tearing from south to north. If so, then it is reasonable to conclude that tearing in the Mexican sector might be as old as 75 Ma.

Like the Sonoran segment, the Canadian segment appears to have concentrations of porphyry copper deposits of similar ages (Godwin, 1975; McMillan et al., 1995) and so also appear to be related to slab beak-off (Fig. 12). The Canadian examples appear to be concentrated along specific zones that are also loci of intrusions, striking obliquely to the trend of the orogen. This is similar to the slab failure magmas along the Colorado Mineral Belt and the Lewis and Clark lineament, such as the Boulder batholith and the Butte porphyry deposits. Overall, many of the porphyry deposits within North America can be accounted for by slab failure magmatism. Some younger deposits might relate to magmas that have scavenged metals from older slab failure plutons and/or relict asthenosphere.

BAJA-BC AND STRIKE-SLIP FAULTS

The Baja-BC (British Columbia) hypothesis was conceived after paleomagnetists discovered anomalously shallow paleomagnetic inclinations in Cretaceous rocks of the Canadian Cordillera, compared with poles from North American cratonic rocks (Beck and Noson, 1972; Irving, 1985). The data implied that a major portion of the British Columbian Cordillera migrated northward some 3000 km between about 90 and 60 Ma (Irving, 1985; Irving et al., 1995; Wynne et al., 1995; Cowan et al., 1997). A number of lines of evidence, including faunal provinciality, basement ages, and contrasting Mesozoic evolution, led Johnston (2008) to suggest that rocks of the Cassiar platform were part of a much larger ribbon continent that was exotic with respect to North America prior to the Cretaceous. Somewhat earlier, Johnston (2001) and Johnston et al. (1996) presented compelling evidence that much of the Canadian and Alaskan Cordillera migrated several thousand kilometers northward prior to docking with North America. That the break occurs well within the foreland, perhaps even at the Kicking Horse Rim, is supported by paleomagnetic data (Enkin et al., 2000; Enkin, 2006), as discussed earlier.

Many scientists couldn't find independent evidence for such large displacements in the field (Mahoney et al., 1999; Butler et al., 2001; Gabrielse et al., 2006) and so had difficulty accepting that thousands of kilometers of translation had occurred (Kerr, 1995). Despite 25 years of intense debate, there is still no clear resolution of the controversy (Umhoefer, 2000). Similarly, some faults, such as the Tintina–Southern Rocky Mountain Trench (Fig. 11), have documented separation of 400–450 km but appear to terminate fairly abruptly, so these faults are difficult to integrate into the geological framework (Gabrielse et al., 2006).

The collisional model presented in this paper has the potential to resolve both the Baja-BC controversy and the vanishing fault conundrum. The reasons involve two of the major differences between the models. In the backarc model, much of the Cordillera was accreted to North America between the Late Devonian–Jurassic, with the Cordilleran orogeny having been caused by backarc intra-plate shortening starting in the Jurassic at about 150 Ma. Implicit in the model is that most of the terranes were already part of North America prior to the Cretaceous and so couldn't have moved northward except along major strike-slip faults. Therefore, it is possible to argue that if there were faults of the magnitudes suggested by the Baja-BC hypothesis, they should be throughgoing and relatively easy to spot. They aren't.

If the exotic terranes did not begin to arrive on the North America margin until about 120 Ma, and were still moving northward at about 70–60 Ma, when thrusting ceased, then the exotic terranes could have moved great distances without leaving any evidence on North America simply because they weren't completely attached to it yet. Thus, a collisional model provides for the possibility of large-scale Cretaceous longitudinal movement in the exotic rocks both before and during collision with North America (Fig. 20). Even though convergence could have been strongly oblique, there need not have been lengthy strike-slip faults within the North American plate because the exotic superterrane was still "at sea." Even when partly docked, strongly oblique convergence would have created major strike-slip faults in the overriding plate, yet would have preserved the orthogonal thrusting in the thrust belt (Fitch, 1972). The collisional model, if correct, reconciles the two opposing views of the Baja-BC controversy (Kerr, 1995; Cowan et al., 1997).

The solution to the vanishing faults is slightly different, but it too is much easier to resolve in an interlaced mosaic of moving fault-bounded terranes. Many faults of the northern Cordillera, possibly even including the Tintina–Southern Rocky Mountain fault, appear to have had most of their strike-slip displacement in the Cretaceous–early Paleocene (Gabrielse et al., 2006; Till et al., 2007). They simply could have ended at a terrane boundary within the exotic collage or possibly have been overridden by another thrust sheet, as illustrated in Figure 21. Thus the collisional model provides a simple method for resolving both the Baja-BC controversy and the vanishing fault problem.

ORIGIN AND SIGNIFICANCE OF EARLY TO MID-TERTIARY EXTENSION

The structural Basin and Range Province (Christiansen and Yeats, 1992) is an extensive area of western North America where the crust was extended, starting in the early to mid-Tertiary (Fig. 22). Geologists have been confounded over the reason for its generally high elevation and its regional extension, so there is little consensus among researchers who have constructed an inordinate number of models to explain its characteristic features (Eaton, 1982; Coney, 1987; Gans and Miller, 1993; Wernicke et al., 1987; Sonder and Jones, 1999). To date, none has garnered universal acceptance. However, the

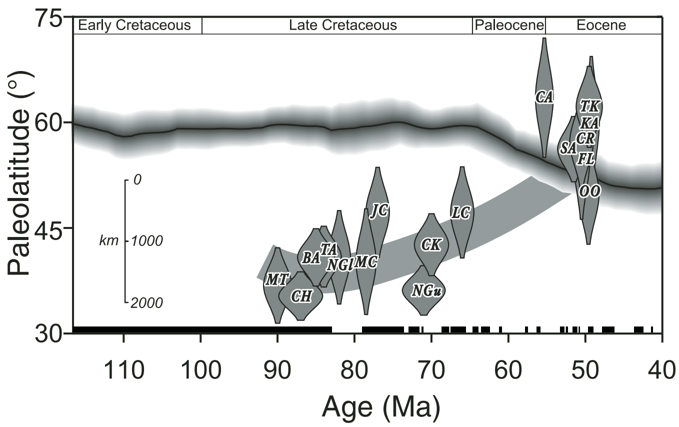


Figure 20. Diagram modified from Enkin (2006) showing the paleolatitudes determined from Cretaceous-Paleocene bedded rocks in the Canadian Cordillera, compared with the calculated paleolatitude evolution curve of North America. Global polarity timescale plotted at bottom (black-normal polarity; white-reverse polarity). Note that although many exotic samples plot 2000 km or more distant from North America, they all could have arrived at their final site by 60–50 Ma, near the end of major contractional deformation of the Cordilleran orogen. This solution potentially reconciles the Baja-BC controversy. CK—Carmacks volcanics; MT—Silverquick and Powell Creek formations at Mount Tatlow, British Columbia; CH—Silverquick and Powell Creek formations at Churn Creek, British Columbia; BA—Powell Creek Formation at Battlement and Amazon creeks, British Columbia; TA—Powell Creek Formation at Tete-Angela, British Columbia; CA—Cantwell Formation volcanic, Alaska; SA—San Poil volcanics, Washington; CR—Crescent Formation volcanics, Washington; OO—Ootsa Lake volcanics, British Columbia; NGl—Lower Nanaimo Group, British Columbia; MC—MaColl Ridge Formation, Alaska; NGu—Upper Nanaimo Group, British Columbia; LC—Lake Clark lavas, Alaska; JC—Late Powell Creek Formation at Jamison Creek, British Columbia; TK—Talkeetna Mountains volcanics, Alaska; KA—Kamloops Group volcanics, British Columbia; FL—Flores volcanics, British Columbia.

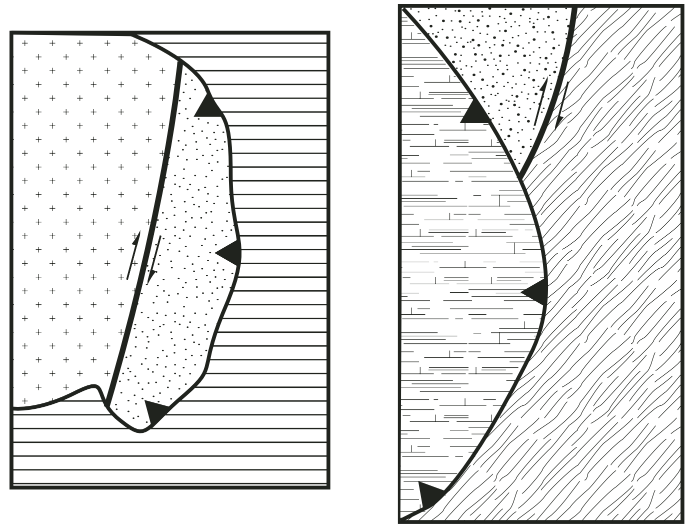


Figure 21. Two possible solutions for the disappearing fault problem often encountered in the Cordillera.

model presented here provides a simple method for generating the generally high-standing nature and subsequent extensional collapse of the region. Figure 22 shows the area of early to mid-Tertiary extension, and it is clear that the area of extension coincides remarkably well with the area of crustal thickening related to underthrusting of the North American continent beneath the arc-bearing Rubian superterrane. For example, within the Great Basin segment the Rubian–North American suture occurs at the Wasatch front, and the Basin and Range extension continues westward to the Owens Valley, the locus of major strike-slip faulting. The only significant difference is the Rio Grande rift area of New Mexico and Colorado.

As much of the Great Basin region has crust of "normal" 30–35 km thickness (Heimgartner et al., 2006) and has undergone more or less 100% extension (Gans and Miller, 1983; Wernicke, 1992), it follows that prior to normal faulting the crust was approximately double normal thickness. Because the distribution of the overthrust region coincides with the extended and collapsed region, I postulate that the early to mid-Tertiary extension resulted directly from the collapse of the region of the crust's doubling during the collisional event. While topography could be the main control on extension, it may be that following collision the hot, and possibly molten, lower crust of the upper plate was more likely to have flowed laterally when sandwiched between cool lower-plate crust and its own cool upper levels (Burov and Watts, 2006). This suggests that the non-extended portion of the lower plate remained fundamentally intact, as suggested during the discussion of slab break-off.

An excellent and well-studied younger analogue is the Tibetan Plateau, which is a region of double-thickness crust formed as a result of convergence between India and Eurasia (Molnar and Tapponnier, 1975). At least part, and perhaps all, of the area of thickened crust can be directly related to subduction of Indian lithosphere beneath Eurasia (Searle et al., 1987). A variety of geophysical data, such as seismic reflectors, highly conductive and low-velocity zones, high heat flow, and strong attenuation of seismic waves, are collectively interpreted to indicate that a partially molten zone exists at depths of 15–20 km beneath the plateau (Nelson et al., 1996; Schilling and Partzsch, 2001).

Driven by the gravitational potential of the thick crust in high plateaus, the thickened region could have thus flowed outward along the partially molten layer, causing the sheetlike region above it to extend (England and Houseman, 1988; Teyssier et al., 2005). For North America, I envision that a rheological gradient existed where the lower part of the Rubian plate was able to flow laterally above the suture zone, whereas the uppermost crust simply broke up in brittle fashion.

The buried edge of North America and strike-slip faults may have combined to limit the western edge of Basin and Range extension by decoupling the area west of the faults from the main mass of Rubia sitting on top of North America. This could explain the lack of obvious Basin and Range–type extension in most of the western Canadian Cordillera.

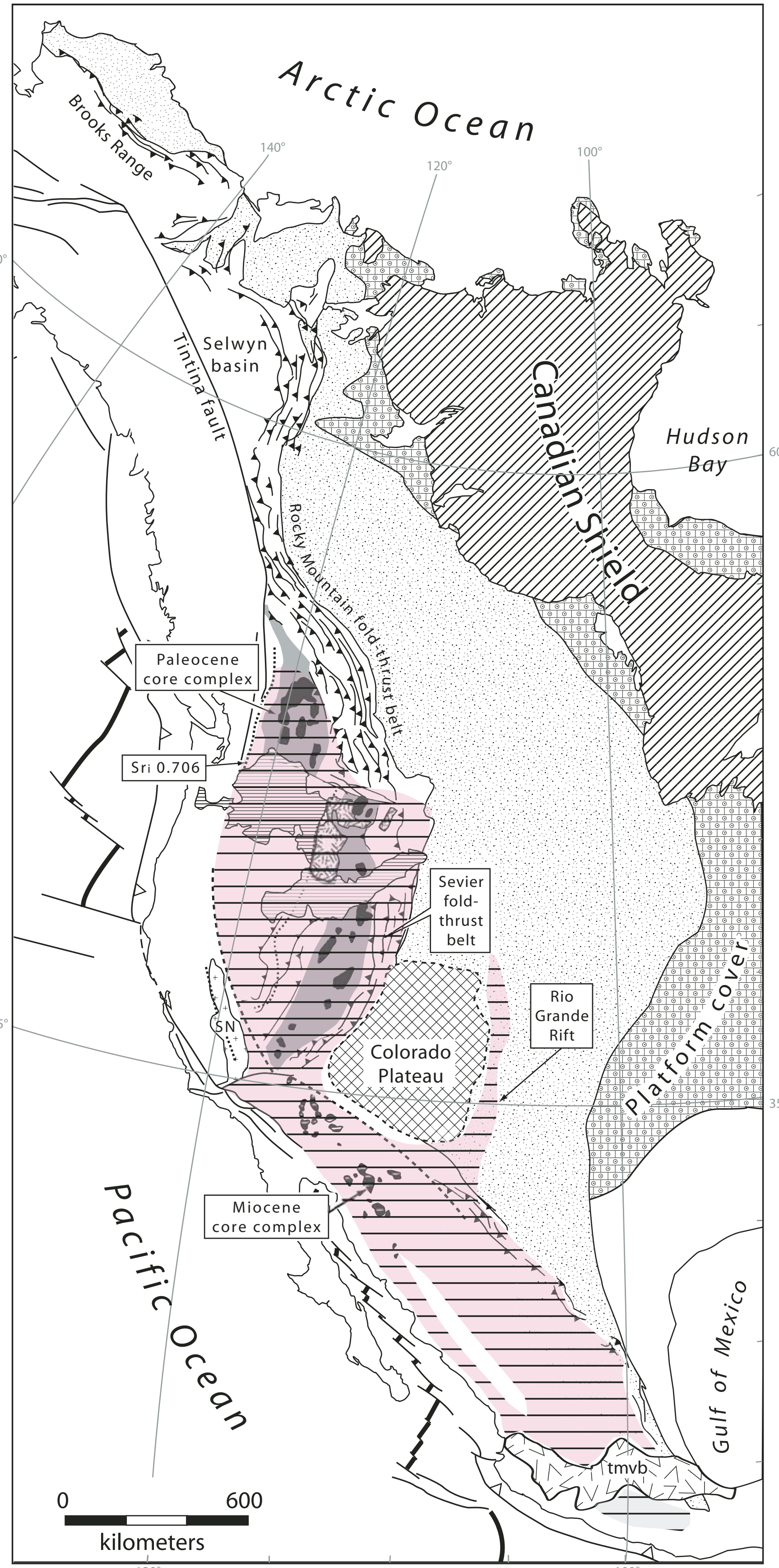


Figure 22. Sketch map showing the distribution of the mid-Tertiary extended region in western North America (ruled and colored area), after Christiansen and Yeats (1992) and Henry and Aranda-Gomez (1992). Note that, except for the Rio Grande rift, the extended area coincides remarkably well with the region of crust possibly doubled in thickness during the Cordilleran orogeny. North American basement continues beneath the allochthonous terranes in the subsurface westward to eastern California as suggested by COCORP and discussed in the text; tmvb—Trans-Mexican volcanic belt, SN—Sierra Nevada.

SUMMARY OF THE EVOLUTION OF THE CORDILLERAN OROGEN

A careful, yet critical, examination of the known geology of western North America reveals that the current backarc model is problematic. Instead, a simple collisional model better explains the geology of the region. A partial time line for the development of the Cordilleran orogen is shown as Figure 23, and a series of developmental cartoons is presented in Figure 24.

In the model presented here the rifted western margin of North America, formed during the Cambrian, collided with, and was partially subducted beneath, a previously amalgamated superterrane (Figs. 13 and 16), which I call Rubia. The superterrane consisted of a diverse collection of terranes, arcs, and seamounts that were united prior to their collision with North America. The first overt sign of collision with North America was the initiation of Cordilleran-type batholiths within Rubia. The batholiths started to develop at about 120 Ma when the outermost parts of the sedimentary wedge of the North American margin were subducted and dewatered to create voluminous melts that rose into the Rubian crust. This was more or less synchronous with the passing of the North American platform over the outer swell to the trench. As the platform emerged, it was eroded, and widespread gravels and conglomerates were spread over the length of the orogen and as far to the east as the Black Hills. When the outermost margin of North America entered the trench it was forced to bend downward and was overrun by fine-grained trench deposits, which, even if not subducted, would have been difficult to separate from unsolidified distal-rise sediments of North America. Abyssal plain, rise, and rift rocks do not appear to have been preserved in the orogen and so were not scraped off the descending plate and incorporated into the accretionary complex. This is not surprising, as the North American ocean plate was about 400 m.y. old and so may have been actively foundering as the plate retreated. This idea is supported by the eastward migration of magmatism within the Cordilleran-type batholiths. It may be that in collisions in which the lower plate is actively retreating that very little slope-rise sediment is incorporated within the accretionary prism simply because the lower plate is sinking faster than its cover can be scraped off.

When rocks of the high-standing Rocky Mountain platform entered the somewhat diminutive accretionary complex, they were folded, "bulldozed" from their basement, transferred to the accretionary complex of the overriding plate, and then translated >100 km eastward onto the craton. Rocks of the upper plate basement formed a backstop; were the structurally highest allochthons, many of crustal dimensions; and were thrust atop the Rocky Mountain shelf edge, burying it in all but a few places. The rapidly thickening accretionary pile flooded the platform and adjacent cratonic cover with eroded debris.

As the leading edge of the North American craton was bent and pulled down beneath the amalgamated superterrane, the pull force generated from the sinking, subducting lithosphere was initially stronger than the buoyancy of the North American craton, so the plate continued to be subducted. However, as greater amounts of buoyant continental lithosphere were subducted, the buoyancy force continually increased until it surpassed the sinking force generated by the oceanic lithosphere. When this happened, the lithosphere of the transitional crust between the strong oceanic lithosphere and the weakly coupled craton started to neck and soon failed. The outermost portion of the craton, and likely all of the transitional crust with its rift deposits, remained attached to the oceanic anchor and were subducted. The failure of the North American plate led to (1) shutdown of the thin-skinned thrusting in the thrust belt; (2) uplift, exhumation, and gravitational collapse in the area just west of the thrust belt known as the hinterland belt; (3) voluminous slab break-off magmatism within the Canadian and Sonoran segments of the orogen; (4) formation of porphyry copper deposits in the Canadian and Sonoran segments; and (5) thick-skinned basement-involved folding and thrusting within the Great Basin segment.

The thick-skinned folds and thrust faults characteristic of the Laramide deformation formed because of continued movement, probably owing to diachronous propagation of the tearing within the subducting plate coupled with rapid isostatic uplift of the collision zone. This led to a strong coupling from frictional forces between the two plates such that compression was partitioned through the entire thickness of crust within the Great Basin segment of the North American craton. This area had little magmatism because the lithospheric mantle had stretched and necked so that the asthenosphere couldn't rise high enough to create a substantial quantity of melt. Both the Canadian and Sonoran segments had torn rapidly, and adiabatically generated magmas were able to flood the collision zone, reduce the frictional forces between plates, and interact with the crust to produce a linear belt of magmatism extending from Wyoming to northern Canada and from Arizona southward through western Mexico. These features demonstrate both the longitudinal variations involved in slab break-off as well as the variations related to speed of break-off. An unresolved question is the source of heat for metamorphism within the hinterland belt. There are a number of small plutons scattered throughout, but whether the region marks the arc front on the upper plate, or reflects residual heat from Jurassic events, is unresolved.

During the collision, a transform fault, here called the Phoenix fault, separated the Great Basin segment from the more variable Sonora segment, with its distinct developmental scheme. Slab failure in the Sonoran and Canadian segments engendered a burst of magmatism, some of which produced the abundant and rich porphyry copper deposits in the area.

A large area of western North America was, and still is, underlain by terranes accreted during the collision. Starting in the Miocene the region of doubled crust began to collapse. This region included not only the classic Basin and Range Province, but also nearly all of the western United States and Mexico outboard of the suture zone. The region probably extended above a partially molten sheet in the lower part of the overthrust Rubian plate. Within the Mojave-Sonoran block the hot arc crust led to Miocene gravitational collapse and creation of metamorphic core complexes.

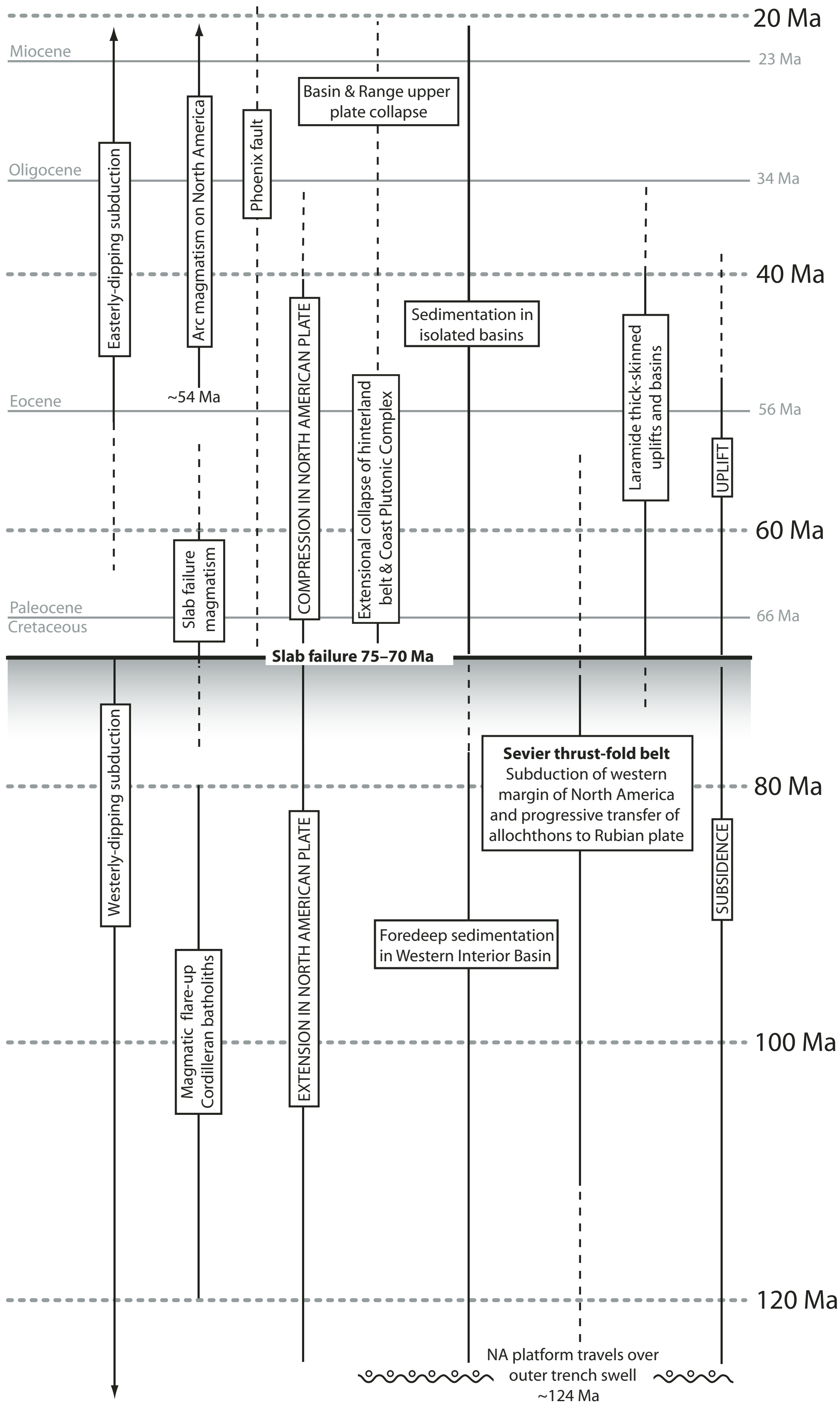


Figure 23. Time line for some of the major events involving North America (NA) and the Rubian superterrane during the Cordilleran orogeny.

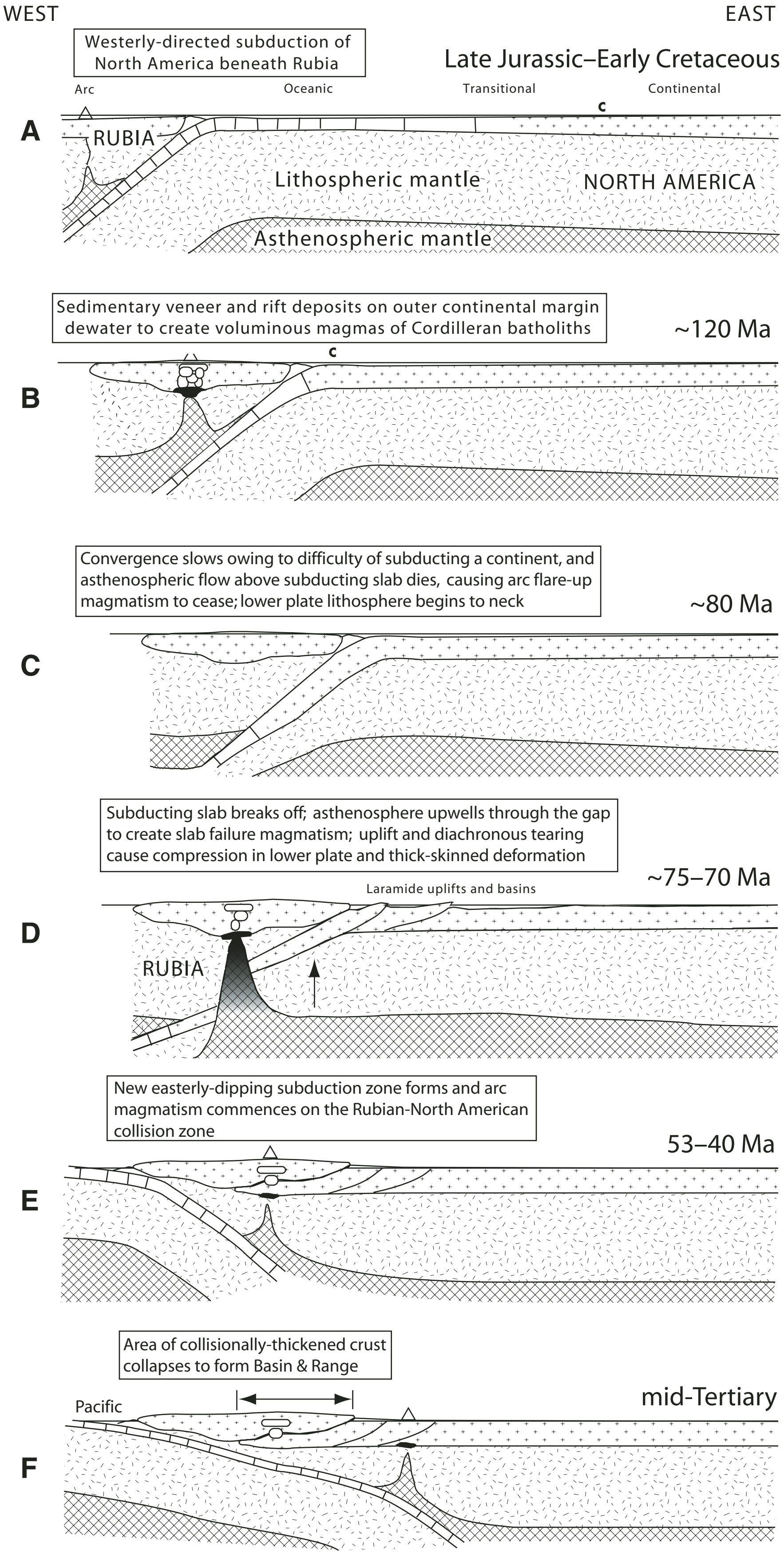


Figure 24. Illustrative cartoons, crudely to scale, showing important developments of the Cordilleran orogeny and subsequent events as developed within the text. (A) West-facing Cambrian passive margin of North America with its rift and overlying passive-margin sediments migrated across the Panthalassic Ocean until about 124–115 Ma. Westerly subduction of the North American plate beneath the Rubian superterrane; c—carbonate platform. (B) The western margin of North America was partially subducted beneath the arc-bearing Rubian superterrane starting at about 124–115 Ma. When the leading edge of North America reached the appropriate depth the sediments of the slope-rise dewatered to create the characteristic Cordilleran-type batholiths over the length of the orogen. The Rocky Mountain platform was riding over the outer swell to the trench at about this time, as documented by widespread deposition of intraformational gravels at the base of the orogenic foredeep. (C) By about 80 Ma, enough continental crust had been subducted so that convergence rates had slowed markedly, the North American lithosphere had begun to neck, and asthenospheric circulation above the subducting slab had stalled. This caused the shutdown of magmatism. (D) Because old and thick cratons are too buoyant to subduct entirely, the subducting slab failed at 75–60 Ma, depending upon the segment, and recycled the rift deposits and their subjacent attenuated basement into the mantle. When freed of its dense oceanic anchor the buoyancy of the North American craton caused it to rise rapidly, which generated strong coupling and intense friction between it and the upper plate. Either owing to plate momentum or to diachronous break-off, the two plates continued to converge, which caused compression in the foreland, and during the Maastrichtian, generated the basement-involved Laramide thrusts and folds. The upper plate hinterland was uplifted and collapsed to form core complexes during the Paleocene–Eocene. As the plate ruptured, asthenosphere upwelled through the tear to melt and invade the Rubian superterrane, where it formed extensive slab break-off magmatism. (E) By 53 Ma a new easterly dipping subduction zone had formed outboard of the amalgamated collision zone, and arc magmatism occurred in both the Canadian and Sonoran segments. (F) During the mid-Tertiary the area of crust that thickened during the Cordilleran orogeny collapsed gravitationally to form the Basin and Range Province.

It is possible that the core complexes formed along the Phoenix fault in a transtensional setting, as there is no evidence that the Transition Zone to the Colorado Plateau slid off the core complexes as had generally been assumed.

I suggest that within the overall tectonic framework of the Cordilleran orogen, it can logically be divided into five different zones from east to west (Fig. 25):

1. a zone of folded autochthonous platformal and foredeep rocks deposited upon the North American craton;
2. a narrow allochthonous zone that occurs from the frontal thrust to the suture and contains eastwardly transported rocks detached from North America during convergence;
3. a transitional zone of considerable complexity that contains a variable assemblage of deformed North American slope-rise rocks, trench-fill deposits, exotic forearc rocks, oceanic rocks, and at least the frontal portions of megathrust slabs;
4. the hinterland zone, in which the North American craton was deeply buried beneath exotic allochthons, and that collapsed to form core complexes; and
5. an interlacing zone of exotic terranes, many of which are still actively migrating along the western margin of North America.

DISCUSSION

Not only does the collision model best explain the evolution of the Cordilleran orogeny, but it explains several features of western North America, which were poorly explained or unresolved in the intraplate model, such as the development and collapse of the hinterland belt, the origin of Cordilleran batholiths and early Tertiary plutonism, the Baja-BC controversy, the Laramide thick-skinned deformation, the origin of the Basin and Range Province, and the puzzling lack of rift deposits on the Cordilleran margin. Furthermore, it unites the various components into an actualistic continuum.

1. The collisional model explains the distribution of the Sevier hinterland with its associated metamorphism and intense contractional deformation because in the collisional model it relates directly to underthrusting of the edge of North America beneath an already amalgamated superterrane.
2. It explains the lack of transitional continental crust and rift basins, presumably once located on the western margin of North America, because the failure of the subducting slab recycled the outer transitional crust and its rift deposits into the mantle.
3. The model clarifies why there are no effects on the North American passive margin shelf from the deformation related to the accretion of the Roberts Mountain allochthon, events in the Luning-Fencemaker thrust belt, and intense Jurassic deformation and metamorphism in the hinterland. This concept also makes interpretations for the allochthons much simpler, because in the model presented here they were amalgamated into a superterrane offshore prior to its docking with North America. This removes the need to transmit 200 km of shortening for hundreds of kilometers through the sedimentary cover without any evidence for it. Furthermore, it removes the necessity to balance ~400 km of shortening in the cover by stuffing an equal length of North American basement beneath the Sierra Nevada.
4. It explains the non–North American isotopic results from Jurassic and Early Cretaceous plutons in the Basin and Range Province of Utah and Nevada, because the plutons were derived from crust of the Rubian superterrane and thus constituted part of the exotic allochthons emplaced upon North America during the collision.
5. The collisional model accounts for the marked change from Jurassic arc magmatism on Rubia to the Cretaceous development of voluminous Cordilleran-type batholiths. Jurassic volcanism was erupted into a generally low-lying area typical of continental arcs, whereas the Cretaceous Cordilleran batholiths were markedly more voluminous and caused rapid

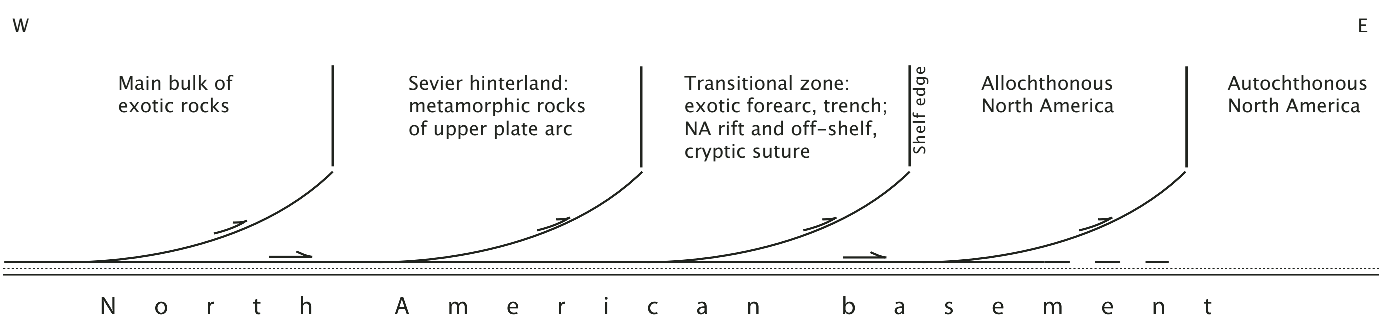


Figure 25. Sketch illustrating the five main zones of the tectonic framework outlined in this paper. From east to west, they are (1) an autochthonous zone comprising rocks of North America; (2) a zone consisting entirely of North American platformal rocks detached from their basement and transported eastward; (3) a transitional zone that might or might not contain a wide variety of rock types, such as slope-rise sediments of North America (NA), trench deposits, exotic forearc rocks, all deformed and in most cases difficult to separate; (4) a hinterland zone comprising metamorphosed and deformed exotic rocks sitting atop North American crust; and (5) rocks entirely exotic with respect to North America, possibly sitting on North American or exotic basement.

thickening of the crust. Steady-state subduction of oceanic crust with its typical thin veneer of sediment simply cannot produce enough magma to have generated Cordilleran batholiths even if subduction had lasted for many tens of millions of years, but the dewatering of sediments deposited on the western margin of North America provided a method for producing voluminous melts rapidly.

6. The collisional model presents a coherent explanation for the collapse of the hinterland belts and the distribution of metamorphic core complexes within western North America because they formed because of isostatic uplift of the collision zone as the result of the break-off of the subducting North American slab.
7. Slab break-off during the collision caused stresses with the partially subducted North American plate to change from extensional to compressive and propagate throughout the entire crust, including crystalline basement, which provided a simple mechanism for generating the thick-skinned Laramide basement-involved uplifts and basins.
8. The linear trend of Late Cretaceous–early Tertiary magmatic rocks extending from Wyoming to Alaska and from Arizona to southern Mexico can readily be explained as products of slab break-off. Asthenosphere was able to rise through the widening gap in the torn North American plate, melt adiabatically, and rise into and through the collision zone.
9. The collisional model provides a simple explanation for regional mid-Tertiary extension in that it occurred only where crust was doubled during the collision.
10. The model appears to resolve the 25-year-long controversy over the Baja-BC hypothesis because final docking of the superterrane did not occur until 65–58 Ma during the Late Cretaceous–early Tertiary, which provides ample time for longitudinal motion along the western margin of North America. Similarly, the timing provides possible answers to the vanishing fault conundrum, because major Cretaceous strike-slip faults may have transected only one or two terranes or blocks within the amalgam.
11. The model reveals that a transform fault, the Phoenix fault, separated the Great Basin segment from the Sonoran segment. This not only explains why the Sevier fold-thrust belt contains a 500-km gap, but it may explain why the Sierra Nevada lies obliquely to the trends of the Sevier thrust belt and the Nevadan thrust belts.
12. The slab break-off likely was largely responsible for the generation of Late Cretaceous–early Tertiary porphyry copper deposits in both the Sonoran and Canadian segments, much as break-off generated similar deposits in New Guinea at about 6 Ma.

PROBLEMS DESERVING ADDITIONAL STUDY

The realization that there are two west-facing platforms in western North America raises the obvious question: Where did the exotic Antler-Cassiar platform come from? Did it come northward from Mexico or South America, or was it originally an east-facing margin that was rotated 180°? Because a contact aureole of a 105 Ma pluton links the Cassiar platform to the 70 Ma Carmacks Group (Johnston, 2008), which, as discussed earlier, migrated ~2000 km north, it is clear that it is far traveled. Paleomagnetic studies of the Cassiar-Antler platforms might resolve its origin.

Overall, there appears to have been so much longitudinal transport along the orogen that much new paleomagnetic data must be collected to better constrain the original locations of individual fault slices. For example, if the Coast Plutonic Complex migrated some 2000 km northward after 70 Ma and was originally located at the latitude of the United States, what are the implications for the paleogeography, and where was the batholith when younger slab-failure magmas were emplaced? Problems such as this abound, but geologists must be more prepared to accept robust paleomagnetic data that indicate large rotations in latitude.

Another vexing problem is the single occurrence of volcanic boulders up to 9 m across within the Jurassic Carmel Formation on the Colorado Plateau in south-central Utah (Chapman, 1989). The boulders are interpreted to have been transported northeasterly at least 250 km over floodplain, tidal-flat, and sabkha deposits in shallow channels by debris flows (Chapman, 1993). Although how this might have happened, without catastrophic floods that should have seriously disrupted the substrate, is difficult to understand. If accepted at face value, the presence of these boulders is puzzling, as the model here demands that the Jurassic arc remained separate from North America until about 124–115 Ma. Perhaps the simplest resolution of the problem is that the volcanic debris was shed northeasterly from across the Phoenix fault. How such outsized clasts might have traveled so far, why they occur in this one locale, and how they accessed North America are all questions that deserve additional consideration.

The complexities between the Lewis and Clark lineament, the Orofino shear zone, and the hypothesized Snake River Plain fault deserve much more study, because the area is critical for understanding the extent of the Colorado Plateau, the Laramide thick-skinned deformation, and the younger eruptions within the Columbia triangle.

NEW DIRECTIONS

The recognition that North America was the lower plate during the Cordilleran orogeny opens up a world of new research possibilities, for the Sevier hinterland belt is still imperfectly understood, and much remains to be learned about how the overriding plate was deformed during collisional orogeny. Likewise, the preservation of a higher structural level within upper-plate rocks in the Sonoran segment allows comparison with deeper structural levels exposed within the Sevier hinterland.

The new model can provide a more realistic picture of the tectonic setting for ore deposits, which could lead to new discoveries. Consider that many deposits were found in rocks formerly considered to be rift and miogeoclinal deposits of North America (Lund, 2008), but which are better interpreted as part of the Rubian superterrane. Many deposits occur within the Roberts Mountain allochthon, and if exotic, as argued here, it might be worthwhile to examine similar rocks, such as those of the Selwyn basin, up and down the Cordillera.

It is obvious that there are considerable along-strike variations within the Cordilleran orogen. Some of these relate to the original shape of the North American continent, such as the area of the Mackenzie Mountains in Canada, where a possible embayment may have prevented the construction of a thick hinterland. Others probably relate to the segmented nature of the subducting North American plate. The along-strike variations within the belt in both upper and lower plates will provide years of fruitful examination for understanding how colliding plates with various components, such as island and continental arcs, respond during collision. Detailed comparisons of these and other along-strike variations should help to illuminate the permutations of collisional orogeny.

The recognition of various segments and transverse shear zones, such as the Orofino shear zone and Phoenix fault, which bound the Colorado Plateau geomorphological province on its north and south margins, suggests a genetic relationship. How an upper plate structure can affect the distribution of the Colorado Plateau in the lower plate provides an interesting problem. How the dextral Lewis and Clark lineament influenced the location of the northern margin of Laramide deformation needs resolution. And does the Colorado Mineral Belt lithospheric tear really divide the Laramide deformation into two different domains as it appears?

The magmatic evolution of the orogen can no longer be simply viewed to have been generated by Mesozoic and Tertiary flat-slab subduction of Pacific oceanic crust beneath North America. In actuality its development is much more complex and started with the subduction of Panthalassic oceanic crust beneath Rubia. As the leading edge of the North American continent entered the subduction zone, huge volumes of water suddenly became available, and from 120 to 80 Ma Cordilleran-type batholiths were created. Because of the difficulty of subducting the North American craton, the subducting slab broke off, and asthenospheric upwelling generated Late Cretaceous–Paleocene slab failure magmas in two segments of the orogen while the Great Basin segment remained relatively amagmatic. Arc magmatism related to easterly dipping subduction of Pacific crust commenced on the amalgamated collision zone at about 53 Ma. Because there are already large amounts of field, petrographic, chemical, and isotopic data for the magmatic rocks of the orogen, placing them in a modern plate tectonic framework will allow more detailed and precise understanding of how these rocks formed.

ACKNOWLEDGMENTS

This paper arose because a question from Sam Bowring caused me to think about the North American Cordillera, a subject I had studiously avoided since my undergraduate days at the University of California at Santa Barbara. Subsequent discussions regarding various aspects of Cordilleran geology with Sam Bowring, Charles Ferguson, Kip Hodges, Paul Hoffman, Stephen Johnston, Dave Kimbrough, Tom Moore, Stephen Richard, Charlie Roots, John Shervais, Brian Wernicke, and Jim Wright have vastly advanced my understanding of important Cordilleran details and improved the paper accordingly. Steve Reynolds, Randy Parrish, Ray Price, and Don Winston graciously replied to questions by email. Sam Bowring, Clark Burchfiel, Kevin Burke, and Stephen Johnston read early drafts of the manuscript and suggested significant improvements. Randy Enkin generously provided a good copy of Figure 20. Bob Miller, Ray Price, Sandra Wyld, Charles Ferguson, Stephen Johnston, and an anonymous scientist formally reviewed the manuscript but do not necessarily agree with my conclusions. Pat Bickford was a wonderfully patient and supportive editor.

REFERENCES CITED

Aguirre-Díaz, G.J., and McDowell, F., 1991, The volcanic section at Nazas, Durango, Mexico, and the possibility of widespread Eocene volcanism within the Sierra Madre Occidental: Journal of Geophysical Research, v. 96, p. 13,373–13,388, doi: 10.1029/91JB00245.

Aitken, J.D., 1971, Control of lower Paleozoic sedimentary facies by the Kicking Horse Rim, southern Rocky Mountains, Canada: Bulletin of Canadian Petroleum Geology, v. 19, p. 557–569.

Allmendinger, R.W., 1992, Fold and thrust tectonics of the western United States exclusive of the accreted terranes, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 583–607.

Allmendinger, R.W., Hauge, T.A., Hauser, E.C., Potter, C.J., and Oliver, J., 1987, Tectonic heredity and the layered lower crust in the Basin and Range Province, western United States, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental Extensional Tectonics: Geological Society [London] Special Publication 28, p. 223–246.

Amato, J.M., Lawton, T.F., Mauel, D.J., Leggett, W.J., González-León, C.M., Farmer, G.L., and Wooden, J.L., 2009, Testing the Mojave-Sonora megashear hypothesis: Evidence from Paleoproterozoic igneous rocks and deformed Mesozoic strata in Sonora, Mexico: Geology, v. 37, p. 75–78, doi: 10.1130/G25240A.1.

Anderson, T.H., and Nourse, J.A., 2005, Pull-apart basins at releasing bends of the sinistral Late Jurassic Mojave-Sonora fault system, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., eds., The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives: Geological Society of America Special Paper 393, p. 97–122, doi: 10.1130/2005.2393(03).

Anderson, T.H., and Silver, L.T., 2005, The Mojave-Sonora megashear—Field and analytical studies leading to the conception and evolution of the hypothesis, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., eds., The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives: Geological Society of America Special Paper 393, p. 1–50, doi: 10.1130/2005.2393(01).

Andronicos, C.L., Chardon, D.H., Hollister, L.S., Gehrels, G.E., and Woodsworth, G.J., 2003, Strain partioning in an obliquely convergent orogen, plutonism and synorogenic collapse: Coast Mountains Batholith, British Columbia, Canada: Tectonics, v. 22, 1012, doi: 10.1029/2001TC001312.

Applegate, J.D.R., and Hodges, K.V., 1995, Mesozoic and Cenozoic extension recorded by metamorphic rocks in the Funeral Mountains, California: Geological Society of America Bulletin, v. 107, p. 1063–1076, doi: 10.1130/0016-7606(1995)107<1063:MACERB>2.3.CO;2.

Armstrong, F.C., and Cressman, E.R., 1963, The Bannock Thrust Zone, Southeastern Idaho: U.S. Geological Survey Professional Paper 374-J, 22 p.

Armstrong, F.C., and Oriel, S.S., 1965, Tectonic development of Idaho-Wyoming thrust belt: American Association of Petroleum Geologists Bulletin, v. 49, p. 1847–1866.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458, doi: 10.1130/0016-7606(1968)79[429:SOBINA]2.0.CO;2.

Armstrong, R.L., 1974, Magmatism, orogenic timing, and orogenic diachronism in the Cordillera from Mexico to Canada: Nature, v. 247, p. 348–351, doi: 10.1038/247348a0.

Armstrong, R.L., 1978, Cenozoic igneous history of the U.S. Cordillera from lat 42° to 48°N, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America Memoir 152, p. 265–282.

Armstrong, R.L., 1982, Cordilleran metamorphic core complexes—From Arizona to southern Canada: Annual Review of Earth and Planetary Sciences, v. 10, p. 129–154, doi: 10.1146/annurev.ea.10.050182.001021.

Armstrong, R.L., 1988, Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera, *in* Clark, S.P., Jr., Burchfiel, B.C., and Suppe, J., eds., Processes in Continental Lithospheric Deformation: Geological Society of America Special Paper 218, p. 55–91.

Armstrong, R.L., Taubeneck, W.H., and Hales, P.O., 1977, Rb-Sr and K-Ar geochronology of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geological Society of America Bulletin, v. 88, p. 397–411, doi: 10.1130/0016-7606(1977)88<397:RAKGOM>2.0.CO;2.

Armstrong, R.L., Parrish, R.R., Van der Hayden, P., Scott, K., Runkle, D., and Brown, R.L., 1991, Early Proterozoic basement exposures in the southern Canadian Cordillera: Core gneiss of Frenchman Cap, Unit I of the Grand Forks Gneiss, and the Vaseaux Formation: Canadian Journal of Earth Sciences, v. 28, p. 1169–1201.

Bailey, E.B., 1968, Tectonic Essays: Mainly Alpine: Oxford, UK, Oxford University Press, 200 p.

Bailley, T.L., and Farmer, G.L., 2007, Reassessing the source of the Colorado Mineral Belt using the Windy Gap conglomerate: Geological Society of America Abstracts with Programs, v. 39, no. 6, p. 467.

Bally, A.W., Gordy, P.L., and Stewart, G.A., 1966, Structure, seismic data, and orogenic evolution of the southern Canadian Rocky Mountains: Canadian petroleum: Geological Society of America Bulletin, v. 14, p. 337–381.

Barker, F., and Arth, J.G., 1990, Two traverses across the Coast batholith, southeastern Alaska, *in* Anderson, J.L., ed., The Nature and Origin of Cordilleran Magmatism: Geological Society of America Memoir 174, p. 395–405.

Barra, F., Ruiz, J., Valencia, V.A., Ochoa-Landin, L., Chesley, J.T., and Zurcher, L., 2005, Laramide porphyry Cu-Mo mineralization in northern Mexico: Age constraints from Re-Os geochronology in molybdenite: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 100, p. 1605–1616.

Barton, M.D., Staude, J.-M.G., Zürcher, L., and Megaw, P.K.M., 1995, Porphyry copper and other intrusion-related mineralization in Mexico, *in* Pierce, F.W., and Bolm, J.G., eds., Porphyry Copper Deposits of the American Cordillera: Arizona Geological Society Digest, v. 20, p. 487–524.

Bateman, P.C., 1992, Plutonism in the Central Part of the Sierra Nevada Batholith: U.S. Geological Survey Professional Paper 1483, 186 p.

Bateman, P.C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada, *in* Bailey, E.H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin 190, p. 106–172.

Beaumont, C., 1981, Foreland basins: Geophysical Journal of the Royal Astronomical Society, v. 65, p. 291–329.

Beck, M.E., Jr., and Noson, L., 1972, Anomalous paleolatitudes in Cretaceous granitic rocks: Nature, v. 235, p. 11–13.

Beck, R.A., Vondra, C.F., Filkins, J.E., and Olander, J.D., 1988, Syntectonic sedimentation and Laramide basement thrusting, Cordilleran foreland: Timing of deformation, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 465–487.

Bickford, M.E., Chase, R.B., Nelson, B.K., Schuster, R.D., and Arruda, E.C., 1981, U-Pb studies on zircon cores and overgrowths, and monazite: Implications for age and petrogenesis of the northeastern Idaho batholith: Journal of Geology, v. 89, p. 433–457.

Bird, P., 1984, Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains: Tectonics, v. 3, p. 741–758, doi: 10.1029/TC003i007p00741.

Bird, P., 1988, Formation of the Rocky Mountains, western United States: A continuum computer model: Science, v. 239, p. 1501–1507, doi: 10.1126/science.239.4847.1501.

Blake, R.B., 1995, Paleogeography and geologic evolution of North America: http://jan.ucc.nau.edu/rcb7/nam.html.

Blakey, R.C., 2008, Pennsylvanian-Jurassic sedimentary basins of the Colorado Plateau and southern Rocky Mountains, *in* Miall, A.D., ed., The Sedimentary Basins of the United States and Canada: Amsterdam, the Netherlands, Elsevier, p. 245–296.

Boettcher, S.S., Mosher, S., and Tosdal, R.M., 2002, Structural and tectonic evolution of Mesozoic basement-involved fold nappes and thrust faults in the Dome Rock Mountains, Arizona, *in* Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Geological Society of America Special Paper 365, p. 73–97.

Bogdanic, C.T., and Espinoza, R.S., 1994, Tectono-sedimentary evolution of the Cretaceous–Early Tertiary and metallogenic scheme of northern Chile, between 20°S and 26°S, *in* Salfity, J.A., ed., Cretaceous Tectonics of the Andes: Wiesbaden, Germany, Vieweb, p. 213–265.

Bond, G., and Kominz, M.A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning: Geological Society of America Bulletin, v. 95, p. 155–173, doi: 10.1130/0016-7606(1984)95<155:COTSCF>2.0.CO;2.

Bott, M.H.P., 1980, Problems of passive margins from the viewpoint of the geodynamics projects: A review, *in* Kent, P., Laughton, A.S., Roberts, D.G., and Jones, E.W.J., eds., The Evolution of Passive Continental Margins in the Light of Recent Deep Drilling Results: Philosophical Transactions of the Royal Society of London, ser. A, v. 294, p. 5–16.

Box, S.E., 1985, Early Cretaceous orogenic belt in northwestern Alaska: Internal organization, lateral extent, and tectonic interpretation, *in* Howell, D.G., ed., Tectonostratigraphic Terranes of the Circum-Pacific Region: Houston, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Ser. 1, p. 137–145.

Bradley, D.C., Dumoulin, J.A., Blodgett, R.B., Harris, A.G., Roeske, S.M., McClelland, W.C., and Layer, P.W., 2006, Geology and affinity of Alaska's Farewell terrane: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 12.

Brady, R.J., Wernicke, B.P., and Niemi, N.A., 2000, Reconstruction of Basin and Range extension and westward motion of the Sierra Nevada block, *in* Lageson, D.R., Peters, S.G., and Lahren, M.M., eds., Great Basin and Sierra Nevada: Boulder, Colorado, Geological Society of America Field Guide 2, p. 75–96.

Breitsprecher, K., Thorkelson, D.J., Groome, W.G., and Dostal, J., 2003, Geochemical confirmation of the Kula-Farallon slab window beneath the Pacific northwest in Eocene time: Geology, v. 31, p. 351–354, doi: 10.1130/0091-7613(2003)031<0351:GCOTKF>2.0.CO;2.

Brewer, J.A., Allmendinger, R.W., Brown, L.D., Oliver, J.F., and Kaufman, S., 1982, COCORP profiling across the Rocky Mountain Front in southern Wyoming, Part 1: Laramide structure: Geological Society of America Bulletin, v. 93, p. 1242–1252, doi: 10.1130/0016-7606(1982)93<1242:CPATRM>2.0.CO;2.

Britt, B.B., Burton, D., Greenhalgh, B., Kowallis, B., Christiansen, E., and Chure, D.J., 2007, Detrital zircon ages for the basal Cedar Mountain Formation (Early Cretaceous) near Moab and Dinosaur National Park, Utah: Geological Society of America Abstracts with Programs, v. 39, no. 5, p. 16.

Brown, R.L., and Journeay, J.M., 1987, Tectonic denudation of the Shuswap metamorphic terrane of southeastern British Columbia: Geology, v. 15, p. 142–146, doi: 10.1130/0091-7613(1987)15<142:TDOTSM>2.0.CO;2.

Brown, R.L., and Lane, L.S., 1988, Tectonic interpretation of west-verging folds in the Selkirk Allochthon of the southern Canadian Cordillera: Canadian Journal of Earth Sciences, v. 25, p. 292–300.

Brown, R.L., Carr, S.D., Johnson, B.J., Coleman, V.J., Cook, F.A., and Varsek, J.L., 1992, The Monashee décollement of the southern Canadian Cordillera: A crustal-scale shear zone linking the Rocky Mountain foreland belt to lower crust beneath accreted terranes, *in* McClay, K.R., ed., Thrust Tectonics: New York, Chapman & Hall, p. 357–364.

Bruhn, R.L., Picard, M.D., and Beck, S.L., 1983, Mesozoic and early Tertiary structure and sedimentology of the central Wasatch Mountains, Uinta Mountains and Uinta Basin, *in* Gurgel, K.D., ed., Geologic Excursions in the Overthrust Belt and Metamorphic Core Complexes of the Intermountain Region: Guidebook, Part 1, Utah Geological and Mineral Survey Special Studies 59, p. 63–106.

Bryant, B., 1984, Reconnaissance Geologic Map of the Precambrian Farmington Canyon Complex and Surrounding Rocks in the Wasatch Mountains between Odgen and Bountiful, Utah: U.S. Geological Survey Miscellaneous Investigations Map I-1447, scale 1:50,000, 1 sheet.

Bryant, B., and Wooden, J.L., 1989, Lower-plate rocks of the Buckskin Mountains, Arizona: A progress report, *in* Spencer, J.E., and Reynolds, S.J., eds., Geology and Mineral Resources of the Buckskin and Rawhide

Mountains, West-Central Arizona: Tucson, Arizona Geological Survey Bulletin 198 (Shackelford Volume), p. 47–50.

Burchfiel, B.C., and Davis, G.A., 1972, Structural framework and structural evolution of the southern part of the Cordilleran orogen, western United States: American Journal of Science, v. 272, p. 97–118.

Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis, western United States: Extension of an earlier synthesis: American Journal of Science, v. 275, p. 363–396.

Burchfiel, B.C., Fleck, R.J., Secor, D.T., Vincelette, R.R., and Davis, G.A., 1974a, Geology of the Spring Mountains, Nevada, *in* Geological Society of America Guidebook for Annual Meeting, 70th, Cordilleran Section, Field Trip 1, p. 17–22.

Burchfiel, B.C., Fleck, R.J., Secor, D.T., Vincelette, R.R., and Davis, G.A., 1974b, Geology of the Spring Mountains, Nevada: Geological Society of America Bulletin, v. 85, p. 1013–1022, doi: 10.1130/0016-7606(1974)85<1013:GOTSMN>2.0.CO;2.

Burchfiel, B.C., Cowan, D.S., and Davis, G.A., 1992, Tectonic overview of the Cordilleran orogen in the western U.S., *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 407–480.

Burchfiel, B.C., Cameron, C.S., and Royden, L.H., 1998, Geology of the Wilson Cliffs–Potosi Mountain area, southern Nevada, *in* Ernst, W.G., and Nelson, C.A., eds., Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall Jr. Volume: Geological Society of America, p. 203–227.

Burov, E.B., and Watts, A.B., 2006, The long-term strength of continental lithosphere: "Jelly sandwich" or "crème-brûlée": GSA Today, v. 16, no. 1, p. 4–10, doi: 10.1130/1052-5173(2006)016<4:TLTSOC>2.0.CO;2.

Busby, C.J., Schermer, E.R., and Mattinson, J.M., 2002, Extensional arc setting and ages of Middle Jurassic eolianites, Cowhole Mountains (Mojave Desert, CA), *in* Glazner, A., Walker, J.D., and Bartley, J.M., eds., Geologic Evolution of the Mojave Desert and Southwestern Basin and Range: Geological Society of America Memoir 195, p. 79–92.

Busby-Spera, C.J., 1984, Large-volume rhyolite ash-flow eruptions and submarine caldera collapse in the lower Mesozoic Sierra Nevada, California: Journal of Geophysical Research, v. 89, p. 8417–8427, doi: 10.1029/JB089iB10p08417.

Busby-Spera, C.J., 1986, Depositional features of rhyolitic and andesitic volcaniclastic rocks of the Mineral King submarine caldera complex, Sierra Nevada, California: Journal of Volcanology and Geothermal Research, v. 27, p. 43–76, doi: 10.1016/0377-0273(86)90080-6.

Busby-Spera, C.J., Mattinson, J.M., Riggs, N.R., and Schermer, E.R., 1990, The Triassic-Jurassic arc in the Mojave-Sonoran deserts and the Sierra-Klamath region: Similarities and differences in paleogeographic evolution, *in* Harwood, D.S., and Miller, M.M., eds., Late Paleozoic and Early Mesozoic Paleogeographic Relations: Klamath Mountains, Sierra Nevada, and Related Rocks: Geological Society of America Special Paper 255, p. 325–337.

Butler, R.F., Gehrels, G.E., and Kodama, K.P., 2001, A moderate translation alternative to the Baja, British Columbia hypothesis: GSA Today, v. 11, no. 6, p. 4–10, doi: 10.1130/1052-5173(2001)011<0004:AMTATT>2.0.CO;2.

Camilleri, P.A., 1992, Mesozoic structural and metamorphic features in the Wood Hills and Pequop Mountains, northeastern Nevada, *in* Wilson, J.R., ed., Field Guide to Geologic Excursions in Utah and Adjacent Areas of Nevada, Idaho, and Wyoming: Utah Geological and Mineral Survey Miscellaneous Publication 92-3, p. 93–105.

Camilleri, P., Yonkee, A., Coogan, J., DeCelles, P., McGrew, A., and Wells, M., 1997, Hinterland to foreland transect through the Sevier Orogen, northeast Nevada to north central Utah: Structural style, metamorphism, and kinematic history of a large contractional orogenic wedge, *in* Link, P.K., and Kowallis, B.J., eds., Proterozoic to Recent Stratigraphy, Tectonics, and Volcanology, Utah, Nevada, Southern Idaho and Central Mexico: Brigham Young University Geology Studies, v. 42, p. 297–309.

Campa U., M.F., 1985, The Mexican thrust belt, *in* Howell, D.G., ed., Tectonostratigraphic terranes of the Circum-Pacific Region: Houston, Texas, Earth Science Series 1, Circum-Pacific Council for Energy and Mineral Resources, p. 299–313.

Carl, B.S., and Glazner, A.F., 2002, Extent and significance of the Independence dike swarm, eastern California, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., eds., Geologic Evolution of the Mojave Desert and Southwestern Basin and Range: Geological Society of America Memoir 195, p. 117–130.

Carr, S.D., 1986, The Valkyr shear zone and the Slocan Lake fault zone: Eocene structures that bound the Valhalla gneiss complex, southeastern British Columbia [M.S. thesis]: Ottawa, Carleton University, 106 p.

Carr, S.D., 1995, The southern Omineca Belt, British Columbia: New perspectives from the Lithoprobe Geoscience Program: Canadian Journal of Earth Sciences, v. 32, p. 1720–1739.

Carr, S.D., and Simony, P.S., 2006, Ductile thrusting versus channel flow in the southeastern Canadian Cordillera: Evolution of a coherent crystalline thrust sheet: Geological Society [London] Special Publication 268, p. 561–587.

Carter, E.S., Orchard, M.J., Ross, C.A., Ross, J.R.P., Smith, P.L., and Tipper, H.W., 1992, Paleontological signatures of terranes, *in* Gabrielse, H., and Yorath, C.J., eds., Geology of the Cordilleran Orogen of Canada: Geological Survey of Canada, Geology of Canada: J.O. Wheeler (ed.), v. 4, p. 3–11 (also Geological Society of America, Geology of North America, v. G-2, p. 28–38).

Carter, J.N., Luyendyk, B.P., and Terres, R.R., 1987, Neogene clockwise tectonic rotation of the eastern Transverse Ranges, California, as suggested by paleomagnetic vectors: Geological Society of America Bulletin, v. 98, p. 199–206, doi: 10.1130/0016-7606(1987)98<199:NCTROT>2.0.CO;2.

Cather, S.M., 2004, Laramide orogeny in central and northern New Mexico and southern Colorado, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: Albuquerque, New Mexico Geological Society Special Publication 11, p. 203–248.

Caulfield, J.T., Turner, S.P., Dosseto, A., Pearson, N.J., and Beier, C., 2008, Source depletion and extent of melting in the Tongan sub-arc mantle: Earth and Planetary Science Letters, v. 273, p. 279–288.

Centeno-Garcia, E., and Silva-Romo, G., 1997, Petrogenesis and tectonic evidence of central Mexico during Triassic–Jurassic time: Revista Mexicana de Ciencias Geológicas, v. 14, p. 244–260.

Centeno-Garcia, E., Ruíz, J., Coney, P.J., Patchett, P.J., and Ortega-Gutiérrez, F., 1993, Guerrero terrane of Mexico: Its role in the southern Cordillera from new geochemical data: Geology, v. 21, p. 419–422, doi: 10.1130/0091-7613(1993)021<0419:GTOMIR>2.3.CO;2.

Centeno-Garcia, E., Guerrero-Suastegui, M., and Talavera-Mendoza, O., 2008, Guerrero Composite Terrane of western Mexico: Collision and subsequent rifting in a supra-subduction zone, *in* Draut, A., Clift, P.D., and Scholl, D.W., eds., Formation and Applications of the Sedimentary Record in Arc Collision Zones: Geological Society of America Special Paper 436, p. 279–308.

Chapman, M.G., 1989, Implications of rhyolitic ignimbrite boulders in the Middle Jurassic Carmel Formation of southern Utah: Geology, v. 17, p. 281–284, doi: 10.1130/0091-7613(1989)017<0281:IORIBI>2.3.CO;2.

Chapman, M.G., 1993, Catastrophic floods during the Middle Jurassic: Evidence in the upper member and Crystal Creek member of the Carmel Formation, southern Utah, *in* Dunn, G., and McDougall, K., eds., Mesozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section Symposium, v. 2, p. 407–416.

Chase, R.B., Bickford, M.E., and Tripp, S.E., 1978, Rb-Sr and U-Pb isotopic studies of the northeastern Idaho batholith and border zone: Geological Society of America Bulletin, v. 89, p. 1325–1334, doi: 10.1130/0016-7606(1978)89<1325:RAUISO>2.0.CO;2.

Chen, J.H., and Moore, J.G., 1982, Uranium-lead isotope ages from the Sierra Nevada batholith, California: Journal of Geophysical Research, v. 87, p. 4761–4784, doi: 10.1029/JB087iB06p04761.

Christiansen, R.L., and Yeats, R.S., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 261–406.

Christie-Blick, N., 1982, Upper Proterozoic and Lower Cambrian rocks of the Sheeprock Mountains, Utah: Regional correlation and significance: Geological Society of America Bulletin, v. 93, p. 735–750, doi: 10.1130/0016-7606(1982)93<735:UPALCR>2.0.CO;2.

Christie-Blick, N., 1983, Structural geology of the southern Sheeprock Mountains, Utah: Regional significance, *in* Miller, D.M., Todd, V.R., and Howard, D.A., eds., Tectonic and Stratigraphic Studies in the Eastern Great Basin: Geological Society of America Memoir 157, p. 101–124.

Christie-Blick, N., 1997, Neoproterozoic sedimentation and tectonics in west-central Utah, *in* Link, P.K., and Kowallis, B.J., eds., Proterozoic to Recent Stratigraphy, Tectonics, and Volcanology, Utah, Nevada, Southern Idaho and Central Mexico: Provo, Brigham Young University Geology Studies, v. 42, pt. 1, p. 1–30.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737, doi: 10.1130/0016-7606(1993)105<0715:LBACOS>2.3.CO;2.

Cloos, M., and Shreve, R.L., 1988a, Subduction-channel model of prism accretion, mélange formation, sediment subduction, and subduction erosion at convergent plate margins: 1. Background and description: Pure and Applied Geophysics, v. 128, p. 455–500, doi: 10.1007/BF00874548.

Cloos, M., and Shreve, R.L., 1988b, Subduction-channel model of prism accretion, mélange formation, sediment subduction, and subduction erosion at convergent plate margins: 2. Implications and discussion: Pure and Applied Geophysics, v. 128, p. 501–545, doi: 10.1007/BF00874549.

Cloos, M., Sapiie, B., van Ufford, A.Q., Weiland, R.J., Warren, P.Q., and McMahon, T.P., 2005, Collisional delamination in New Guinea: The Geotectonics of Subducting Slab Breakoff: Geological Society of America Special Paper 400, 51 p.

Cobbing, E.J., Pitcher, W.S., Wilson, J.J., Baldock, J.W., Taylor, W.P., McCourt, W., and Snelling, N.J., 1981, The Geology of the Western Cordillera of northern Peru: London, Institute of Geological Sciences Overseas Memoir 5, Her Majesty's Stationery Office, 143 p.

Coleman, D.S., and Glazner, A.F., 1998, The Sierra Crest magmatic event: Rapid formation of juvenile crust during the Late Cretaceous in California, *in* Ernst, W.G., and Nelson, C.A., eds., Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall Jr. Volume: Boulder, Colorado, Geological Society of America, p. 253–272.

Coleman, D.S., Briggs, S., Glazner, A.F., and Northrup, C.J., 2003, Timing of plutonism and deformation in the White Mountains of eastern California: Geological Society of America Bulletin, v. 115, p. 48–57, doi: 10.1130/0016-7606(2003)115<0048:TOPADI>2.0.CO;2.

Colpron, M., and Price, R.A., 1995, Tectonic significance of the Kootenay terrane, southeastern Canadian Cordillera: An alternative model: Geology, v. 23, p. 25–28, doi: 10.1130/0091-7613(1995)023<0025:TSOTKT>2.3.CO;2.

Colpron, M., Price, R.A., Archibald, D.A., and Carmichael, D.M., 1996, Middle Jurassic exhumation along the western flank of the Selkirk fan structure: Thermobarometric and thermochronometric constraints from the Illecillewaet synclinorium, southeastern British Columbia: Geological Society of America Bulletin, v. 108, p. 1372–1392, doi: 10.1130/0016-7606(1996)108<1372:MJEATW>2.3.CO;2.

Colpron, M., Warren, M.J., and Price, R.A., 1998, Selkirk fan structure, southeastern Canadian Cordillera: Tectonic wedging against an inherited basement ramp: Geological Society of America Bulletin, v. 110, p. 1060–1074, doi: 10.1130/0016-7606(1998)110<1060:SFSSCC>2.3.CO;2.

Colpron, M., Nelson, J.L., and Murphy, D.C., 2006, A tectonostratigraphic framework for the pericratonic terranes of the northern Canadian Cordillera, *in* Colpron, M., and Nelson, J.L., eds., Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America, Canadian and Alaskan Cordillera: St. John's, Newfoundland, Geological Association of Canada Special Paper 45, p. 1–23.

Colpron, M., Nelson, J.L., and Murphy, D.C., 2007, Northern Cordilleran terranes and their interactions through time: GSA Today, v. 17, no. 4/5, p. 4–10, doi: 10.1130/GSAT01704-5A.1.

Compton, R.R., 1972, Geologic Map of the Yost Quadrangle, Box Elder County, Utah, and Cassia County, Idaho: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-672, scale 1:31,680, 7 p.

Compton, R.R., 1980, Fabrics and strains in quartzites of a metamorphic core complex, Raft River Mountains, Utah, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 385–398.

Coney, P.J., 1980, Cordilleran metamorphic core complexes: An overview, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran Metamorphic Core Complexes: Geological Society of America Memoir 153, p. 7–31.

Coney, P.J., 1987, The regional tectonic setting and possible causes of Cenozoic extension in the North American Cordillera, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental Extensional Tectonics: Geological Society [London] Special Publication 28, p. 177–186.

Coney, P.J., and Evenchick, C.A., 1994, Consolidation of the American Cordilleras: Journal of South American Earth Sciences, v. 7, p. 241–262, doi: 10.1016/0895-9811(94)90011-6.

Coney, P.J., and Harms, T., 1984, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression: Geology, v. 12, p. 550–554, doi: 10.1130/0091-7613(1984)12<550:CMCCCE>2.0.CO;2.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p. 329–333, doi: 10.1038/288329a0.

Conrad, C.P., and Lithgow-Bertelloni, C., 2002, How mantle slabs drive plate motions: Science, v. 298, p. 207–209, doi: 10.1126/science.1074161.

Coogan, J.C., 1992, Structural evolution of piggyback basins in the Wyoming-Idaho-Utah thrust belt, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional Geology of Eastern Idaho and Western Wyoming: Geological Society of America Memoir 179, p. 55–81.

Cook, D.G., 1970, A Cambrian facies change and its effect on structure, Mount Stephens–Mount Dennis area, Alberta–British Columbia, *in* Wheeler, J.O., ed., Structure of the Southern Canadian Cordillera: Toronto, Geological Association of Canada Special Paper 6, p. 27–39.

Cook, F.A., and van der Velden, A.J., 1995, Three-dimensional crustal structure of the Purcell anticlinorium in the Cordillera of southwestern Canada: Geological Society of America Bulletin, v. 107, p. 642–664.

Cook, F.A., Green, A.G., Simony, P.S., Price, R.A., Parrish, R.R., Milkereit, B., Gordy, P.L., Brown, R.L., Coflin, K.C., and Patenaude, C., 1988, LITHOPROBE seismic reflection structure of the southeastern Canadian Cordillera: Initial results: Tectonics, v. 7, p. 157–180, doi: 10.1029/TC007i002p00157.

Cook, F.A., Varsek, J.L., Clowes, R.M., Kanasewich, E.R., Spencer, C.S., Parrish, R.R., Brown, R.L., Carr, S.D., Johnson, B.J., and Price, R.A., 1992, LITHOPROBE crustal reflection structure of the southern Canadian Cordillera 1, foreland thrust and fold belt to Fraser River fault: Tectonics, v. 11, p. 12–35, doi: 10.1029/91TC02332.

Cook, F.A., Clowes, R.M., Snyder, D.B., van der Veldon, A.J., Hall, K.W., Erdmer, P., and Evanchick, C.A., 2004, Precambrian crust beneath the Mesozoic northern Canadian Cordillera discovered by Lithoprobe seismic reflection profiling: Tectonics, v. 23, TC2010, doi: 10.1029/2002TC001412.

Corsetti, F.A., and Hagadorn, J.W., 2003, The Precambrian-Cambrian transition in the southern Great Basin, USA: The Sedimentary Record, v. 1, p. 4–8.

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: American Journal of Science, v. 297, p. 117–173.

Crawford, M.L., Klepeis, K.A., Gehrels, G., and Isachsen, C., 1999, Batholith emplacement at mid-crustal levels and its exhumation within an obliquely convergent margin: Tectonophysics, v. 312, p. 57–78, doi: 10.1016/S0040-1951(99)00170-5.

Crisp, J.A., 1984, Rates of magma emplacement and volcanic activity: Journal of Volcanology and Geothermal Research, v. 20, p. 177–211, doi: 10.1016/0377-0273(84)90039-8.

Crowley, J.L., and Brown, R.L., 1994, Tectonic links between the Clachnacudainn terrane and Selkirk allochthon, southern Omineca Belt, Canadian Cordillera: Tectonics, v. 13, p. 1035–1051, doi: 10.1029/94TC00627.

Crowley, P.D., Reiners, P.W., Reuter, J.M., and Kaye, G.D., 2002, Laramide exhumation of the Bighorn Mountains, Wyoming: An apatite (U-Th)/He thermochronology study: Geology, v. 30, p. 27–30, doi: 10.1130/0091-7613(2002)030<0027:LEOTBM>2.0.CO;2.

Cruciani, C., Carminati, E., and Doglioni, C., 2005, Slab dip vs. lithosphere age: No direct function: Earth and Planetary Science Letters, v. 238, p. 298–310, doi: 10.1016/j.epsl.2005.07.025.

Curray, J.R., Emmel, F.J., and Moore, D.G., 2002, The Bengal Fan: Morphology, geometry, stratigraphy, history and processes: Marine and Petroleum Geology, v. 19, p. 1191–1223, doi: 10.1016/S0264-8172(03)00035-7.

Currie, B.S., 1997, Sequence stratigraphy of nonmarine Jurassic-Cretaceous rocks, central Cordilleran foreland-basin system: Geological Society of America Bulletin, v. 109, p. 1206–1222, doi: 10.1130/0016-7606(1997)109<1206:SSONJC>2.3.CO;2.

Currie, B.S., 1998, Upper Jurassic–Lower Cretaceous Morrison and Cedar Mountain formations, NE Utah–NW Colorado: Relationships between nonmarine deposition and early Cordilleran foreland-basin development: Journal of Sedimentary Research, v. 68, p. 632–652.

Currie, B.S., 2002, Structural configuration of the Early Cretaceous Cordilleran Foreland-Basin System and Sevier Thrust Belt, Utah and Colorado: Journal of Geology, v. 110, p. 697–718, doi: 10.1086/342626.

Dahlen, F.A., and Suppe, J., 1988, Mechanics, growth, and erosion of mountain belts, *in* Clark, S.P., Burchfiel, B.C., and Suppe, J., eds., Processes in Continental Lithospheric Deformation: Geological Society of America Special Paper 218, p. 161–178.

Dahlstrom, C.D.A., 1970, Structural geology on the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332–406.

Dahlstrom, C.D.A., 1977, Structural geology in the eastern margin of the Canadian Rocky Mountains, *in* Heisey, E.L., and Lawson, D.E., eds., Rocky Mountain Thrust Belt Geology and Resources: Casper, Wyoming Geological Association, Annual Field Conference, 29th, p. 407–439.

Damon, P.E., Shafiqullah, M., and Clark, K.F., 1983, Geochronology of the porphyry copper deposits and related mineralization of Mexico: Canadian Journal of Earth Sciences, v. 20, p. 1052–1071.

Davies, J.H., 2002, Breaking plates: Nature, v. 418, p. 736–737, doi: 10.1038/418736a.

Davies, J.H., and Stephenson, D.J., 1992, Physical model of source region of subduction zone volcanics: Journal of Geophysical Research, v. 97, no. B2, p. 2037–2070.

Davies, J.H., and von Blanckenburg, F., 1995, Slab break-off: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens: Earth and Planetary Science Letters, v. 129, p. 85–102, doi: 10.1016/0012-821X(94)00237-S.

de Boorder, H., Spakman, W., White, S.H., and Wortel, M.J.R., 1998, Late Cenozoic mineralization, orogenic collapse and slab detachment in the European Alpine belt: Earth and Planetary Science Letters, v. 164, p. 569–575.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: American Journal of Science, v. 304, p. 105–168, doi: 10.2475/ajs.304.2.105.

DeCelles, P.G., and Coogan, J.C., 2006, Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah: Geological Society of America Bulletin, v. 118, p. 841–864, doi: 10.1130/B25759.1.

DeCelles, P.G., and Currie, B.S., 1996, Long-term sediment accumulation in the middle Jurassic–early Eocene Cordilleran retroarc foreland basin system: Geology, v. 24, p. 591–594, doi: 10.1130/0091-7613(1996)024<0591:LTSAIT>2.3.CO;2.

DeCelles, P.G., Lawton, T.F., and Mitra, G., 1995, Thrust timing, growth of structural culminations, and synorogenic sedimentation in the type area of the Sevier orogenic belt, central Utah: Geology, v. 23, p. 699–702, doi: 10.1130/0091-7613(1995)023<0699:TTGOSC>2.3.CO;2.

de Cserna, Z., 1989, An outline of the geology of Mexico, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America—An Overview: Boulder, Colorado, Geological Society of America, Geology of North America, v. A, p. 233–264.

Dewey, J.F., 1980, Episodicity, sequence and style at convergent plate boundaries, *in* Strangway, D., ed., The Continental Crust and Its Mineral Deposits: Toronto, Geological Association of Canada Special Paper 20, p. 553–573.

Dewey, J.F., 2005, Orogeny can be very short: Proceedings of the National Academy of Sciences of the United States of America, v. 102, p. 15,286–15,293, doi: 10.1073/pnas.0505516102.

Dewey, J.F., and Bird, J.M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647, doi: 10.1029/JB075i014p02625.

Dewey, J.F., and Burke, K.C.A., 1973, Tibetan, Variscan and Precambrian basement reactivation: Products of continental collision: Journal of Geology, v. 81, p. 683–692.

Dickinson, W.R., 1977, Paleozoic plate tectonics and the evolution of the Cordilleran continental margin, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic Paleogeography of the Western United States: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, 1st, p. 137–156.

Dickinson, W.R., 1981, Plate tectonic evolution of the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 113–135.

Dickinson, W.R., 2000, Geodynamic interpretation of Paleozoic tectonic trends oriented oblique to the Mesozoic Klamath-Sierran continental margin in California, *in* Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic Paleogeography and Tectonics of Western Nevada and Northern California: Geological Society of America Special Paper 347, p. 209–245.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 32, p. 13–45, doi: 10.1146/annurev.earth.32.101802.120257.

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, p. 353–368, doi: 10.1130/GES00054.1.

Dickinson, W.R., 2008, Accretionary Mesozoic-Cenozoic expansion of the Cordilleran continental margin in California and adjacent Oregon: Geosphere, v. 4, p. 329–353, doi: 10.1130/GES00105.1.

Dickinson, W.R., and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America Memoir 152, p. 355–366.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039, doi: 10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2.

Dilek, Y., and Moores, E.M., 1995, Geology of the Humboldt igneous complex, Nevada, and tectonic implications for the Jurassic magmatism in the Cordilleran orogen, *in* Miller, D.M., and Busby-Spera, C., eds., Jurassic Magmatism and Tectonics of the North American Cordillera: Geological Society of America Special Paper 299, p. 229–248.

Dilles, J.H., Martin, M.W., Stein, H., and Rusk, B., 2003, Re-Os and U-Pb ages for the Butte copper district, Montana: A short- or long-lived hydrothermal system?: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 400.

Dillon, J.T., Haxel, G.B., and Tosdal, R.M., 1990, Structural evidence for northeastward movement on the Chocolate Mountains thrust, southeasternmost California: Journal of Geophysical Research, v. 95, p. 19,953–19,971, doi: 10.1029/JB095iB12p19953.

Dimalanta, C., Taira, A., Yumul, G.P., Jr., Tokuyama, H., and Mochizuki, K., 2002, New rates of western Pacific island arc magmatism from seismic and gravity data: Earth and Planetary Science Letters, v. 202, p. 105–115, doi: 10.1016/S0012-821X(02)00761-6.

Doelling, H.H., 1980, Geology and Mineral Resources of Box Elder County, Utah: Utah Geological and Mineral Survey Report 115, 251 p.

Dostal, J., Breitsprecher, K., Church, B.N., Thorkelson, D., and Hamilton, T.S., 2003, Eocene melting of Precambrian lithospheric mantle: Analcime-bearing volcanic rocks from the Challis-Kamloops belt of south central British Columbia: Journal of Volcanology and Geothermal Research, v. 126, p. 303–326, doi: 10.1016/S0377-0273(03)00153-7.

Doughty, P.T., and Chamberlain, K., 2007, Age of the Paleoproterozoic basement and related rocks in the Clearwater complex, northern Idaho, U.S.A., *in* Link, P.K., and Lewis, R.S., eds., Proterozoic Geology of Western North America and Siberia: Tulsa, Oklahoma, SEPM (Society for Sedimentary Geology) Special Publication 86, p. 9–35.

Doughty, P.T., and Chamberlain, K., 2008, Protolith age and timing of Precambrian magmatic and metamorphic events in the Priest River complex, northern Rockies: Canadian Journal of Earth Sciences, v. 45, p. 99–116, doi: 10.1139/E07-067.

Doughty, P.T., and Price, R.A., 1999, Tectonic evolution of the Priest River complex, northern Idaho and Washington: A reappraisal of the Newport fault with new insights on metamorphic core complex formation: Tectonics, v. 18, p. 375–393, doi: 10.1029/1998TC900029.

Doughty, P.T., Price, R.A., and Parrish, R.R., 1998, Geology and U-Pb geochronology of Archean basement and Proterozoic cover in the Priest River complex, northwestern United States, and their implications for Cordilleran structure and Precambrian Continent reconstructions: Canadian Journal of Earth Sciences, v. 35, p. 39–54, doi: 10.1139/cjes-35-1-39.

Doughty, P.T., Chamberlain, K.R., Foster, D.A., and Sha, G.S., 2007, Structural, metamorphic, and geochronologic constraints on the origin of the Clearwater core complex, northern Idaho, *in* Sears, J.W., Harms, T.A., and Evenchik, C.A., eds., Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 211–241.

Drewes, H., 1971, Mesozoic Stratigraphy of the Santa Rita Mountains, Southeast of Tucson: U.S. Geological Survey Professional Paper 658-C, 81 p.

Drewes, H., 1982, Northwest-trending basement flaws—A control to fluid movement and possible measure of rate of plate convergence, *in* Powers, R.B., ed., Geologic Studies of the Cordilleran Thrust Belt: Denver, Rocky Mountain Association of Geologists, p. 421–423.

Drewes, H., 1991, Description and development of the Cordilleran Orogenic Belt in the Southwestern United States and Northern Mexico: U.S. Geological Survey Professional Paper 1512, 92 p.

DuBois, D.P., 1982, Tectonic framework of basement thrust terrane, northern Tendoy Range, southwest Montana, *in* Powers, R.B., ed., Geologic Studies of the Cordilleran Thrust Belt: Denver, Rocky Mountain Association of Geologists, p. 145–158.

Ducea, M., 2001, The California arc: Thick granite batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups: GSA Today, v. 11, no. 11, p. 4–10, doi: 10.1130/1052-5173(2001)011<0004:TCATGB>2.0.CO;2.

Dunn, J.F., Hartshorn, K.G., and Hartshorn, P.W., 1995, Structural styles and hydrocarbon potential of the Sub-Andean thrust belt of southern Bolivia, *in* Tankard, A.J., Suárez Soruco, R., and Welsink, H.J., eds., Petroleum Basins of South America: American Association of Petroleum Geologists Memoir 62, p. 523–543.

Dusel-Bacon, C., Hopkins, M.J., Mortensen, J.K., Dashevsky, S.S., Bressler, J.R., and Day, W.C., 2006, Paleozoic tectonic and metallogenic evolution of the pericratonic rocks of east-central Alaska and adjacent Yukon Territory, *in* Colpron, M., and Nelson, J.L., eds., Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America, Canadian and Alaskan Cordillera: St. John's, Newfoundland, Geological Association of Canada Special Paper 45, p. 25–74.

Eaton, G.P., 1982, The Basin and Range Province: Origin and tectonic significance: Annual Review of Earth and Planetary Sciences, v. 10, p. 409–440, doi: 10.1146/annurev.ea.10.050182.002205.

Eberth, D.A., Britt, B.B., Scheetz, R.D., Stadtman, K.L., and Brinkman, D.B., 2006, Dalton Wells—Geology and significance of debris-flow-hosted dinosaur bonebeds (Cedar Mountain Formation, eastern Utah, USA): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 236, p. 217–245, doi: 10.1016/j.palaeo.2005.11.020.

Eiler, J.M., McInnes, B., Valley, J.W., Graham, C.M., and Stolper, E.M., 1998, Oxygen isotope evidence for slab-derived fluids in the sub-arc mantle: Nature, v. 393, p. 777–781, doi: 10.1038/31679.

Eisele, J., and Isachsen, C.E., 2001, Crustal growth in southern Arizona: U-Pb geochronologic and Sm-Nd isotopic evidence for addition of the Paleoproterozoic Cochise block to the Mazatzal province: American Journal of Science, v. 301, p. 773–797, doi: 10.2475/ajs.301.9.773.

Elison, M.W., Speed, R.C., and Kistler, R.W., 1990, Geologic and isotopic constraints on the structure of the northern Great Basin: Geological Society of America Bulletin, v. 102, p. 1077–1092, doi: 10.1130/0016-7606(1990)102<1077:GAICOT>2.3.CO;2.

Elsasser, W.M., 1971, Sea floor spreading and thermal convection: Journal of Geophysical Research, v. 76, p. 1101–1111, doi: 10.1029/JB076i005p01101.

Elston, D.P., and Young, R.A., 1991, Cretaceous-Eocene (Laramide) landscape development and Oligocene-Pliocene drainage reorganization of transition zone and Colorado Plateau, Arizona: Journal of Geophysical Research, v. 96, p. 12,389–12,406, doi: 10.1029/90JB01978.

Elston, D.P., Enkin, R.J., Baker, J., and Kisilevsky, D., 2000, Tightening the Belt: Paleomagnetic constraints on deposition and deformation of the Middle Proterozoic Belt-Purcell Supergroup, U.S. and Canada, *in* Schalla, R.A., and Johnson, E.H., eds., Montana/Alberta Thrust Belt and Adjacent Foreland: Billings, Montana Geological Society Anniversary Symposium, 50th, v. 2, p. 10–12.

England, P.C., and Houseman, G.A., 1988, The mechanics of the Tibetan Plateau: Philosophical Transactions of the Royal Society of London, ser. A, Mathematical and Physical Sciences, v. 326, p. 301–320, doi: 10.1098/rsta.1988.0089.

Enkin, R.J., 2006, Paleomagnetism and the case for Baja British Columbia, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence for and against Large-Scale Displacements: St. John's, Newfoundland, Geological Association of Canada Special Paper 46, p. 233–253.

Enkin, R.J., Osadetz, K.G., Baker, J., and Kisilevsky, D., 2000, Orogenic remagnetizations in the Front Ranges and Inner Foothills of the southern Canadian Cordillera: Chemical harbinger and thermal handmaiden of Cordilleran deformation: Geological Society of America Bulletin, v. 112, p. 929–942, doi: 10.1130/0016-7606(2000)112<0929:ORITFR>2.3.CO;2.

Enkin, R.J., Johnston, S.T., Larson, K.P., and Baker, J., 2006, Paleomagnetism of the 70 Ma Carmacks Group at Solitary Mountain, Yukon, confirms and extends controversial results: Further evidence for the Baja British Columbia model, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence for and against Large-Scale Displacements: St. John's, Newfoundland, Geological Association of Canada Special Paper 46, p. 221–232.

Erdmer, P., Ghent, E.D., Archibald, D.A., and Stout, M.Z., 1998, Paleozoic and Mesozoic high-pressure metamorphism at the margin of ancestral North America in central Yukon: Geological Society of America Bulletin, v. 110, p. 615–629, doi: 10.1130/0016-7606(1998)110<0615:PAMHPM>2.3.CO;2.

Ernst, W.G., Coleman, D.S., and Van de Ven, C.M., 2003, Petrochemistry of granitic rocks in the Mount Barcroft area—Implications for arc evolution, central White Mountains, easternmost California: Geological Society of America Bulletin, v. 115, p. 499–512, doi: 10.1130/0016-7606(2003)115<0499:POGRIT>2.0.CO;2.

Erskin, M.C., 2001, Colorado Plateau tectonostratigraphic unit, *in* Erskine, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., eds., The Geologic Transition, High Plateaus to Great Basin—A Symposium and Field Guide: Salt Lake City, Utah Geological Association Publication 30, p. 39–56.

Evans, J.G., Griscom, A., Halvorson, P.F., and Cummings, M.L., 2002, Tracking the western margin of the North American Craton beneath southeastern Oregon: A multidisciplinary approach, *in* Bonnichsen, B., White, C.M., and McCurry, M., eds., Tectonic and Magmatic Evolution of the Snake River Plain Volcanic Province: Moscow, Idaho, Idaho Geological Survey Bulletin 30, p. 35–57.

Evenchick, C.A., McMechan, M.F., McNicholl, V.J., and Carr, S.D., 2007, A synthesis of the Jurassic–Cretaceous tectonic evolution of the central and southeastern Canadian Cordillera: Exploring links across the orogen, *in* Sears, J.W., Harms, T.A., and Evenchik, C.A., eds., Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 117–145.

Ewing, T.E., 1981a, Regional stratigraphy and structural setting of the Kamloops Group, south-central British Columbia: Canadian Journal of Earth Sciences, v. 18, p. 1464–1477.

Ewing, T.E., 1981b, Petrology and geochemistry of the Kamloops Group volcanics, British Columbia: Canadian Journal of Earth Sciences, v. 18, p. 1478–1491.

Feininger, T., 1987, Allochthonous terranes in the Andes of Ecuador and northwestern Peru: Canadian Journal of Earth Sciences, v. 24, p. 266–278.

Ferguson, C.A., Gilbert, W.G., and Leighty, R.S., 1998, Geology of the New River Mesa 7.5′ Quadrangle, Maricopa and Yavapai Counties, Arizona: Arizona Geological Survey Open-File Report 98-12, 29 p., map scale 1:24,000, and cross sections.

Fermor, P.R., and Moffat, I.W., 1992, Tectonics and structure of the Western Canada foreland basin, *in* MacQueen, R.W., and Leckie, D.A., eds., Foreland Basins and Fold Belts: American Association of Petroleum Geologists Memoir 55, p. 81–105.

Finney, S.C., and Perry, B.D., 1991, Depositional setting and paleogeography of Ordovician Vinini Formation, central Nevada, *in* Cooper, J.D., and Stevens, C.H., eds., Paleozoic Paleogeography of the Western U.S., II: Los Angeles, SEPM (Society for Sedimentary Geology), Pacific Section, p. 747–766.

Finney, S.C., Noble, P., and Cluer, J.K., 2000, Lower Paleozoic stratigraphy of central Nevada: Comparisons and contrasts between the lower and upper plates of the Roberts Mountains thrust, *in* Lageson, D.R., Peters, S.G., and Lahren, M.M., eds., Great Basin and Sierra Nevada: Boulder, Colorado, Geological Society of America Field Guide 2, p. 279–300.

Fisher, G.R., 1990, Middle Jurassic syntectonic conglomerate in the Mt. Tallac roof pendant, northern Sierra Nevada, California, *in* Harwood, D.S., and Miller, M.M., eds., Late Paleozoic and Early Mesozoic Paleogeographic Relations: Klamath Mountains, Sierra Nevada, and Related Rocks: Geological Society of America Special Paper 255, p. 339–350.

Fiske, R.S., and Tobisch, O.T., 1978, Paleogeographic significance of volcanic rocks of the Ritter Range pendant, central Sierra Nevada, California, *in* Howell, G., and McDougall, A.K., eds., Mesozoic Paleogeography of the Western United States: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, 2nd, p. 209–222.

Fitch, T., 1972, Plate convergence, transcurrent faults and internal deformation adjacent to southeast Asia and the western Pacific: Journal of Geophysical Research, v. 77, p. 4432–4460, doi: 10.1029/JB077i023p04432.

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, v. 90, p. 291–308, doi: 10.1007/BF00378269.

Flowers, R.M., Wernicke, B.P., and Farley, K.A., 2008, Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry: Geological Society of America Bulletin, v. 120, p. 571–587, doi: 10.1130/B26231.1.

Foley, S., 1992, Vein-plus-wall-rock melting mechanisms in the lithosphere and the origin of potassic alkaline magmas: Lithos, v. 28, p. 435–453, doi: 10.1016/0024-4937(92)90018-T.

Foreman, B.Z., Rogers, R.R., Deino, A.L., Wirth, K.R., and Thole, J.T., 2008, Geochemical characterization of bentonite beds in the Two Medicine formation (Campanian, Montana), including a new ^{40}Ar/^{39}Ar age: Cretaceous Research, v. 29, p. 373–385, doi: 10.1016/j.cretres.2007.07.001.

Foster, D.A., and Fanning, C.M., 1997, Geochronology of the northern Idaho batholith and the Bitterroot metamorphic core complex: Magmatism preceding and contemporaneous with extension: Geological Society of America Bulletin, v. 109, p. 379–394, doi: 10.1130/0016-7606(1997)109<0379:GOTNIB>2.3.CO;2.

Foster, D.A., Mueller, P.A., Mogk, D.W., Wooden, J.L., and Vogl, J.J., 2006, Proterozoic evolution of the western margin of the Wyoming craton: Implications for the tectonic and magmatic evolution of the northern Rocky Mountains: Canadian Journal of Earth Sciences, v. 43, p. 1601–1619, doi: 10.1139/E06-052.

Foster, D.A., Doughty, P.T., Kalakay, T.J., Fanning, C.M., Coyner, S., Grice, W.C., and Vogl, J., 2007, Kinematics and timing of exhumation of metamorphic core complexes along the Lewis and Clark fault zone, northern Rocky Mountains, USA, *in* Till, A.B., Roeske, S.M., Sample, J.C., and Foster, D.A., eds., Exhumation Associated with Continental Strike-Slip Fault Systems: Geological Society of America Special Paper 434, p. 207–232.

Fuentes, F., DeCelles, P.G., and Gehrels, G.E., 2009, Jurassic onset of foreland basin deposition in northwestern Montana, USA: Implications for along-strike synchroneity of Cordilleran orogenic activity: Geology, v. 37, p. 379–382.

Gabrielse, H., 1992, Okanagan-Kootenay region, *in* Part E. Foreland Belt, *in* Gabrielse, H., and Yorath, C.J., eds., Structural Styles, Chapter 17, of Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, Geology of Canada, no. 4, p. 607–609.

Gabrielse, H., and Yorath, C.J., 1991, Geology of the Cordilleran Orogen, *in* Canada: Geological Survey of Canada, Geology of Canada Number 4, 847 p. (also Geological Society of America, Geology of North America, v. G-2).

Gabrielse, H., Murphy, D.C., and Mortensen, J.K., 2006, Cretaceous and Cenozoic dextral orogen-parallel displacements, magmatism, and paleogeography, north-central Canadian Cordillera, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence for and against Large-Scale Displacements: St. John's, Newfoundland, Geological Association of Canada Special Paper 46, p. 255–276.

Gans, P.B., and Miller, E.L., 1983, Style of mid-Tertiary extension in east-central Nevada, *in* Gurgel, K.D., ed., Geologic Excursions in the Overthrust Belt and Metamorphic Core Complexes of the Intermountain Region: Salt Lake City, Utah Geological Survey and Mineral Survey, p. 107–139.

Gans, P.B., and Miller, E.L., 1993, Extension in the Basin and Range Province: Late orogenic collapse or something else?: Montpellier, France, Proceedings of the International Conference on Late Orogenic Extension in Mountain Belts, http://www.geol.ucsb.edu/faculty/gans/abstracts/gans1993.html.

Garfunkel, Z., Anderson, C.A., and Schubert, G., 1986, Mantle circulation and the lateral migration of subducted slabs: Journal of Geophysical Research, v. 91, p. 7205–7223, doi: 10.1029/JB091iB07p07205.

Gehrels, G.E., Dickinson, W.R., Riley, B.C.D., Finney, S.C., and Smith, M.T., 2000a, Detrital zircon geochronology of the Roberts Mountains allochthon, Nevada, *in* Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic Paleogeography and Tectonics of Western Nevada and Northern California: Geological Society of America Special Paper 347, p. 19–42.

Gehrels, G.E., and 15 others, 2000b, Tectonic implications of detrital zircon data from Paleozoic and Triassic strata in western Nevada and northern California, *in* Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic Paleogeography and Tectonics of Western Nevada and Northern California: Geological Society of America Special Paper 347, p. 133–150.

Gibb, R.A., Thomas, M.D., LaPointe, P.L., and Mukhopadhyay, M., 1983, Geophysics of proposed Proterozoic sutures in Canada: Precambrian Research, v. 19, p. 349–384, doi: 10.1016/0301-9268(83)90021-9.

Gibson, D.W., 1985, Stratigraphy, Sedimentology, and Depositional Environments of the Coal-Bearing Jurassic-Cretaceous Kootenay Group, Alberta and British Columbia: Geological Survey of Canada Bulletin 357, 108 p.

Gilbert, W.G., Ferguson, C.A., and Leighty, R.S., 1998, Geology of the Humboldt Mountain 7.5′ Quadrangle, Maricopa and Yavapai Counties, Arizona: Arizona Geological Survey Open-File Report 98-11, 17 p., map scale 1:24,000, and cross sections.

Ginsberg, R.N., and James, N.P., 1974, Holocene carbonate sediments of continental shelves, *in* Burk, C.A., and Drake, C.L., eds., The Geology of Continental Margins: New York, Springer-Verlag, p. 137–156.

Glazner, A.F., Bartley, J.M., Coleman, D.S., and Kylander-Clark, A., 2003, Evidence from the Independence dike swarm for 65 km or more of post-Jurassic dextral offset across Owens Valley, California: Geological Society of America Abstracts with Programs, v. 35, no. 4, p. 80.

Glazner, A.F., Carl, B.S., Coleman, D.S., Miller, J.S., and Bartley, J.M., 2008, Chemical variability and the composite nature of dikes from the Jurassic Independence dike swarm, eastern California, *in* Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs and Batholiths: A Tribute to Cliff Hopson: Geological Society of America Special Paper 438, p. 455–480, doi: 10.1130/2008.2438(16).

Godwin, C.I., 1975, Imbricate subduction zones and their relationship with Upper Cretaceous to Tertiary porphyry deposits in the Canadian Cordillera: Canadian Journal of Earth Sciences, v. 12, p. 1362–1378.

Goldstrand, P.M., 1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, p. 145–154, doi: 10.1130/0016-7606(1994)106<0145:TDOUCT>2.3.CO;2.

Goodfellow, W.D., Cecile, M.P., and Leybourne, M.I., 1995, Geochemistry, petrogenesis, and tectonic setting of lower Paleozoic alkalic and potassic volcanic rocks, Northern Canadian Cordilleran Miogeocline: Canadian Journal of Earth Sciences, v. 32, p. 1236–1254.

Govers, R., and Wortel, M.J.R., 2005, Lithosphere tearing at STEP faults: Response to edges of subduction zones: Earth and Planetary Science Letters, v. 236, p. 505–523, doi: 10.1016/j.epsl.2005.03.022.

Greenhalgh, B.W., and Britt, B.B., 2007, Stratigraphy and sedimentology of the Morrison–Cedar Mountain Formation boundary, east-central Utah, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., eds., Central Utah—Diverse Geology of a Diverse Landscape: Salt Lake City, Utah Geological Association Publication 36, p. 81–100.

Grose, L.T., 1974, Tectonics of the Rocky Mountain region, *in* Mallory, W.W., ed., Geologic Atlas of the Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 34–44.

Grove, M., Jacobson, C.E., Barth, A.P., and Vucic, A., 2003, Temporal and spatial trends of Late Cretaceous–early Tertiary underplating of Pelona and related schists beneath southern California and southwestern Arizona, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., and Martin-Barajas, A., eds., Tectonic Evolution of Northwestern Mexico and the Southwestern USA: Geological Society of America Special Paper 374, p. 381–406.

Grove, M., Bebout, G.E., Jacobson, C.E., Barth, A.P., Kimbrough, D.L., King, R.L., Zou, H., Lovera, O.M., Mahoney, B.J., and Gehrels, G.E., 2008, The Catalina Schist: Evidence for middle Cretaceous subduction erosion of southwestern North America, *in* Draut, A., Clift, P.D., and Scholl, D.W., eds., Formation and Applications of the Sedimentary Record in Arc Collision Zones: Geological Society of America Special Paper 436, p. 335–361, doi: 10.1130/2008.2436(15).

Grove, T.L., Parman, S.W., Bowring, S.A., Price, R.C., and Baker, M.B., 2002, The role of an H_2O-rich fluid component in the generation of primitive basaltic andesites and andesites from the Mount Shasta region, Northern California: Contributions to Mineralogy and Petrology, v. 142, p. 375–396.

Gustafson, L.B., 1978, Some major factors of porphyry copper genesis: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 73, p. 600–607.

Haenggi, W.T., 2001, Tectonic history of the Chihuahua Trough, Mexico, and adjacent USA, Part I: The pre-Mesozoic setting: Boletín de La Sociedad Geológica Mexicana, v. 54, p. 28–66.

Haenggi, W.T., 2002, Tectonic history of the Chihuahua trough, Mexico, and adjacent USA, Part II: Mesozoic and Cenozoic: Boletín de la Sociedad Geológica Mexicana, v. 55, p. 38–94.

Haeussler, P.J., Bradley, D.C., Wells, R.E., and Miller, M.L., 2003, Life and death of the Resurrection plate: Evidence for its existence and subduction in the northeastern Pacific in Paleocene–Eocene time: Geological Society of America Bulletin, v. 115, p. 867–880, doi: 10.1130/0016-7606(2003)115<0867:LADOTR>2.0.CO;2.

Hamilton, W.B., 1978, Mesozoic tectonics of the western United States, *in* Howell, G., and McDougall, A.K., eds., Mesozoic Paleogeography of the Western United States: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, 2nd, p. 33–61.

Hamilton, W.B., 1982, Structural evolution of the Big Maria Mountains, northeastern Riverside County, southeastern California, *in* Frost, E.G., and

Martin, D.L., eds., Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 1–27.

Hamilton, W.B., 1987, Mesozoic geology and tectonics of the Big Maria Mountains region, southeastern California: Arizona Geological Society Digest, v. 18, p. 33–47.

Hamilton, W.B., 1988, Laramide crustal shortening, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 27–39.

Hamilton, W.B., and Myers, W.B., 1966, The Nature of Batholiths: U.S. Geological Survey Professional Paper 544C, 30 p.

Hamilton, W.O., 1969a, Mesozoic California and the underflow of Pacific mantle: Geological Society of America Bulletin, v. 80, p. 2409–2430, doi: 10.1130/0016-7606(1969)80[2409:MCATUO]2.0.CO;2.

Hamilton, W.O., 1969b, The volcanic central Andes, a modern model for the Cretaceous batholiths and tectonics of western North America: Oregon Department of Geology and Mineral Industries Bulletin, v. 65, p. 175–184.

Hanan, B.B., Shervais, J.W., and Vetter, S.K., 2008, Yellowstone plume-continental lithosphere interaction beneath the Snake River Plain: Geology, v. 36, p. 51–54, doi: 10.1130/G23935A.1.

Haney, E.M., 2008, Pressure-temperature evolution of metapelites within the Anaconda metamorphic core complex, southwestern Montana [M.S. thesis]: Missoula, University of Montana, 100 p.

Hansen, A.R., 1976, Jurassic salts of the hingeline area, southern Rocky Mountains: Denver, Rocky Mountain Association of Geologists, 1976 Symposium, p. 261–266.

Harding, L.E., and Coney, P.J., 1985, The geology of the McCoy Mountains formation, southeastern California and southwestern Arizona: Geological Society of America Bulletin, v. 96, p. 755–769, doi: 10.1130/0016-7606(1985)96<755:TGOTMM>2.0.CO;2.

Harland, S.S., Snee, L.W., Reynolds, M.W., Mehnert, H.H., Schmidt, R.G., Sheriff, S.D., and Irving, A.J., 2005, ^{40}Ar/^{39}Ar and K/Ar Geochronology and Tectonic Significance of the Upper Cretaceous Adel Mountain Volcanics and Spatially Associated Tertiary Igneous Rocks, Northwestern Montana: U.S. Geological Survey Professional Paper 1696, 29 p.

Harper, G.D., and Link, P.K., 1986, Geochemistry of upper Proterozoic rift-related volcanics, northern Utah and southeastern Idaho: Geology, v. 14, p. 864–867, doi: 10.1130/0091-7613(1986)14<864:GOUPRV>2.0.CO;2.

Harris, M.T., and Sheehan, P.M., 1998, Early Silurian stratigraphic sequences of the eastern Great Basin (Utah and Nevada), *in* Landing, E., and Johnson, M.E., eds., Silurian Cycles: Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes: Albany, New York State Museum Bulletin 491, p. 51–61.

Hart, C.J.R., Goldfarb, R.J., Lewis, L.L., and Mair, J.L., 2004, The Northern Cordillera Mid-Cretaceous Plutonic Province: Ilmenite/magnetite-series granitoids and intrusion-related mineralization: Resource Geology, v. 54, p. 253–280, doi: 10.1111/j.1751-3928.2004.tb00206.x.

Haschke, M.R., Scheuber, E., Günther, A., and Reutter, K.-J., 2002, Evolutionary cycles during the Andean orogeny: Repeated slab breakoff and flat subduction: Terra Nova, v. 14, p. 49–55, doi: 10.1046/j.1365-3121.2002.00387.x.

Hauser, E.C., Gephart, J., Latham, T., Oliver, J., Kaufman, S., Brown, L., and Lucchita, I., 1987, COCORP Arizona transect: Strong crustal reflections and offset Moho beneath the transition zone: Geology, v. 15, p. 1103–1106, doi: 10.1130/0091-7613(1987)15<1103:CATSCR>2.0.CO;2.

Haxel, G.B., Tosdal, R.M., May, D.J., and Wright, J.E., 1984, Latest Cretaceous and early Tertiary orogenesis in south-central Arizona: Thrust faulting, regional metamorphism, and granitic plutonism: Geological Society of America Bulletin, v. 95, p. 631–653, doi: 10.1130/0016-7606(1984)95<631:LCAETO>2.0.CO;2.

Haxel, G.B., Jacobson, C.E., Richard, S.M., Tosdal, R.M., and Grubensky, M.J., 2002, The Oricopia Schist in southwest Arizona: Early Tertiary oceanic rocks trapped or transported far inland, *in* Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Geological Society of America Special Paper 365, p. 99–128.

Haxel, G.B., Wright, J.E., Riggs, N.R., Tosdal, R.M., and May, D.M., 2005, Middle Jurassic Topawa Group, Boboquivari Mountains, south-central Arizona: Volcanic and sedimentary record of deep basins within the Jurassic magmatic arc, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., eds., The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives: Geological Society of America Special Paper 393, p. 329–357, doi: 10.1130/2005.2393(12).

Heck, F.R., and Speed, R.C., 1987, Triassic olistostrome and shelf-basin transition in the western Great Basin: Paleogeographic implications: Geological Society of America Bulletin, v. 99, p. 539–551, doi: 10.1130/0016-7606(1987)99<539:TOASTI>2.0.CO;2.

Heimgartner, M., Lovie, J.N., Scott, J.B., Thelen, W., Lopez, C.T., and Coolbaugh, M., 2006, The crustal thickness of the Great Basin: Using seismic refraction to assess regional geothermal potential: Geothermal Research Transactions, v. 30, p. 83–86.

Heller, P.L., and Paola, C., 1989, The paradox of Lower Cretaceous gravels and the initiation of thrusting in the Sevier orogenic belt, United States Western Interior: Geological Society of America Bulletin, v. 101, p. 864–875, doi: 10.1130/0016-7606(1989)101<0864:TPOLCG>2.3.CO;2.

Heller, P.L., Bowler, S.S., Chambers, H.P., Coogan, J.C., Hagen, E.S., Shuster, M.W., Winslow, N.S., and Lawton, T.F., 1986, Time of initial thrusting in the Sevier orogenic belt, Idaho-Wyoming and Utah: Geology, v. 14, p. 388–391, doi: 10.1130/0091-7613(1986)14<388:TOITIT>2.0.CO;2.

Heller, P.L., Ducker, K., and McMillan, M.E., 2003, Post-Paleozoic alluvial gravel transport as evidence of continental tilting in the U.S. Cordillera: Geological Society of America Bulletin, v. 115, p. 1122–1132, doi: 10.1130/B25219.1.

Helwig, J., 1974, Eugeosynclinal basement and a collage concept of orogenic belts, *in* Dott, R.H., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 359–380.

Hendricks, J.D., and Plescia, J.B., 1991, A review of the regional geophysics of the Arizona Transition Zone: Journal of Geophysical Research, v. 96, p. 12,351–12,373, doi: 10.1029/90JB01781.

Henry, C.D., and Aranda-Gomez, J.J., 1992, The real southern Basin and Range: Mid- to late Cenozoic extension in Mexico: Geology, v. 20, p. 701–704, doi: 10.1130/0091-7613(1992)020<0701:TRSBAR>2.3.CO;2.

Henry, C.D., McDowell, F.W., and Silver, L.T., 2003, Geology and geochronology of granitic batholithic complex, Sinaloa, Mexico: Implications for Cordilleran magmatism and tectonics, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., and Martin-Barajas, A., eds., Tectonic Evolution of Northwestern Mexico and the Southwestern USA: Geological Society of America Special Paper 374, p. 237–273.

Hildebrand, R.S., 1981, Early Proterozoic LaBine Group of Wopmay orogen: Remnant of a continental volcanic arc developed during oblique convergence, *in* Campbell, F.H.A., ed., Proterozoic Basins in Canada: Ottawa, Geological Survey of Canada Paper 81-10, p. 133–156.

Hildebrand, R.S., 2005, Autochthonous and allochthonous strata of the El Callao greenstone belt: Implications for the nature of the Paleoproterozoic Trans-Amazonian orogeny and the origin of gold-bearing veins in the El Callao mining district, Guayana shield, Venezuela: Precambrian Geology, v. 143, p. 75–86, doi: 10.1016/j.precamres.2005.09.009.

Hildebrand, R.S., and Bowring, S.A., 1984, A non-extensional model for the origin of continental intra-arc depressions, with a Proterozoic example from Wopmay orogen, Northwest Territories, Canada: Geology, v. 12, p. 73–77, doi: 10.1130/0091-7613(1984)12<73:CIDANM>2.0.CO;2.

Hildebrand, R.S., and Bowring, S.A., 1999, Crustal recycling by slab failure: Geology, v. 27, p. 11–14, doi: 10.1130/0091-7613(1999)027<0011:CRBSF>2.3.CO;2.

Hildebrand, R.S., Paul, D., Pietikäinen, P., Hoffman, P.F., Bowring, S.A., and Housh, T., 1991, New geological developments in the internal zone of Wopmay orogen, District of Mackenzie, *in* Current Research, Part C: Geological Survey of Canada Paper 91-1C, p. 157–164.

Hildebrand, R.S., Ferguson, C.A., and Skotnicki, S., 2008, Preliminary Geologic Map of the Silver City 7.5 min. Quadrangle, Grant County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Map OSGM-164, scale 1:24,000, 1 sheet.

Hintze, L.F., 1988, Geologic History of Utah: Provo, Brigham Young University Geology Studies Special Publication 7, 202 p.

Hite, R.J., and Cater, F.W., 1972, Pennsylvanian rocks and salt anticlines, Paradox basin, Utah and Colorado: Geologic Atlas of the Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 133–138.

Hodges, K.V., and Applegate, J.D., 1993, Age of Tertiary extension in the Bitterroot metamorphic core complex, Montana and Idaho: Geology, v. 21, p. 161–164, doi: 10.1130/0091-7613(1993)021<0161:AOTEIT>2.3.CO;2.

Hodges, K.V., and Walker, J.D., 1990, Petrologic constraints on the unroofing history of the Funeral Mountain metamorphic core complex, California: Journal of Geophysical Research, v. 95, p. 8437–8445.

Hodges, K.V., and Walker, J.D., 1992, Extension in the Cretaceous Sevier orogen, North American Cordillera: Geological Society of America Bulletin, v. 104, p. 560–569, doi: 10.1130/0016-7606(1992)104<0560:EITCSO>2.3.CO;2.

Hodges, K.V., Snoke, A., and Hurlow, H., 1992, Thermal evolution of a portion of the Sevier hinterland: The northern Ruby Mountains–East Humboldt range and Wood Hills, northeastern Nevada: Tectonics, v. 11, p. 154–164, doi: 10.1029/91TC01879.

Hoffman, P.F., 1988, United Plates of America, the birth of a craton—Early Proterozoic assembly and growth of Laurentia: Annual Review of Earth and Planetary Sciences, v. 16, p. 22–46, doi: 10.1146/annurev.ea.16.050188.002551.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America—An Overview: Boulder, Colorado, Geological Society of America, Geology of North America, v. A, p. 447–511.

Hoffman, P.F., Tirrul, R., King, J.E., St-Onge, M.R., and Lucas, S.B., 1988, Axial projections and modes of crustal thickening, eastern Wopmay orogen, northwest Canadian shield, *in* Clark, S.P., Jr., ed., Processes in Continental Lithospheric Deformation: Geological Society of America Special Paper 218, p. 1–29.

Hoisch, T.D., Miller, C.F., Heizler, M.T., Harrison, T.M., and Stoddard, E.F., 1988, Late Cretaceous regional metamorphism in southeastern California, *in* Ernst, W.G., ed., Metamorphic and Crustal Evolution of the Western United States: Englewood Cliffs, New Jersey, Prentice Hall, p. 538–571.

Holbrook, W.S., Lizzarralde, D., McGeary, S., Bangs, N., and Diebold, J., 1999, Structure and composition of the Aleutian island arc and implications for continental crustal growth: Geology, v. 27, p. 31–34, doi: 10.1130/0091-7613(1999)027<0031:SACOTA>2.3.CO;2.

Hollister, L.S., 1982, Metamorphic evidence for rapid (2mm/yr) uplift of a portion of the Central Gneiss Complex, Coast Mountains, B.C.: Canadian Mineralogist, v. 20, p. 319–332.

Hollister, L.S., and Andronicos, C.L., 2000, The Central Gneiss Complex, Coast Mountains, British Columbia, *in* Stowell, H.H., and McClelland, W.C., eds., Tectonics of the Coast Mountains, Southeastern Alaska and British Columbia: Geological Society of America Special Paper 343, p. 45–59.

Hollister, L.S., and Andronicos, C.L., 2006, Formation of new continental crust in Western British Columbia during transpression and transtension: Earth and Planetary Science Letters, v. 249, p. 29–38, doi: 10.1016/j.epsl.2006.06.042.

Hollister, L.S., Diebold, J., and Triparna, D., 2008, Whole crustal response to Late Tertiary extension near Prince Rupert, British Columbia: Geosphere, v. 4, p. 360–374, doi: 10.1130/GES000144.1.

Holm, R.F., 2001, Cenozoic paleogeography of the central Mogollon Rim–southern Colorado Plateau region, Arizona, revealed by Tertiary gravel deposits, Oligocene to Pleistocene lava flows, and incised streams: Geological Society of America Bulletin, v. 113, p. 1467–1485, doi: 10.1130/0016-7606(2001)113<1467:CPOTCM>2.0.CO;2.

Hopson, C.A., 1988, Independence dike swarm: Origin and tectonic significance: Eos (Transactions, American Geophysical Union), v. 69, p. 1479.

Hopson, R.F., Hillhouse, J.W., and Howard, K.A., 2008, Dike orientations in the Late Jurassic Independence dike swarm and implications for vertical-axis tectonic rotations in eastern California, *in* Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson: Geological Society of America Special Paper 438, p. 481–498, doi: 10.1130/2008.2438(17).

Hornafius, J.S., Luyendyk, B.P., Terres, R.R., and Kamerling, M.J., 1986, Timing and extent of Neogene tectonic rotation in the western Transverse Ranges, California: Geological Society of America Bulletin, v. 97, p. 1476–1487, doi: 10.1130/0016-7606(1986)97<1476:TAEONT>2.0.CO;2.

House, M.A., Hodges, K.V., and Bowring, S.A., 1997, Petrological and geochronological constraints on regional metamorphism along the northern border of the Bitterroot batholith: Journal of Metamorphic Geology, v. 15, p. 753–764, doi: 10.1111/j.1525-1314.1997.00052.x.

House, M.A., Bowring, S.A., and Hodges, K.V., 2002, Implications of middle Eocene epizonal plutonism for the unroofing history of the Bitterroot metamorphic core complex, Idaho-Montana: Geological Society of America Bulletin, v. 114, p. 448–461, doi: 10.1130/0016-7606(2002)114<0448:IOMEEP>2.0.CO;2.

Housh, T.B., and McDowell, F.W., 2005, Isotope provinces and mid-Tertiary igneous rocks of northwestern Mexico (Chihuahua and Sonora) and their relation to basement configuration, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., eds., The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives: Geological Society of America Special Paper 393, p. 671–692, doi: 10.1130/2005.2393(25).

Housh, T.B., and McMahon, T.P., 2000, Ancient isotopic characteristics of Neogene potassic magmatism in western New Guinea (Irian Jaya, Indonesia): Lithos, v. 50, p. 217–239, doi: 10.1016/S0024-4937(99)00043-2.

Howard, K.A., 1980, Metamorphic infrastructure in the northern Ruby Mountains, Nevada, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran Metamorphic Core Complexes: Geological Society of America Memoir 153, p. 335–347.

Howard, K.A., Kistler, R.W., Snoke, A.W., and Willden, R., 1979, Geologic Map of the Ruby Mountains, Nevada: U.S. Geological Survey Miscellaneous Geological Investigations Map I-1136, scale 1:125,000, 1 sheet.

Howard, K.A., Goodge, J.W., and John, B.E., 1982, Detached crystalline rocks of the Mohave, Buck, and Bill Williams mountains, western Arizona, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 377–390.

Howard, K.A., McCaffrey, K.J.W., Wooden, J.L., Foster, D.A., and Shaw, S.E., 1995, Jurassic thrusting of Precambrian basement over Paleozoic cover in the Clipper Mountains, southeastern California, *in* Miller, D.M., and Busby-Spera, C., eds., Jurassic Magmatism and Tectonics of the North American Cordillera: Geological Society of America Special Paper 299, p. 375–392.

Huang, C.Y., Yuan, P.B., and Tsao, S.J., 2006, Temporal and spatial records of active arc-continent collision in Taiwan: A synthesis: Geological Society of America Bulletin, v. 118, p. 274–288, doi: 10.1130/B25527.1.

Hudec, M.R., 1992, Mesozoic structural and metamorphic history of the central Ruby Mountains metamorphic core complex, Nevada: Geological Society of America Bulletin, v. 104, p. 1086–1100, doi: 10.1130/0016-7606(1992)104<1086:MSAMHO>2.3.CO;2.

Hyndman, D.W., and Sears, J.W., 1988, Post-Archean metamorphism and tectonic evolution of western Montana and northern Idaho, *in* Ernst, W.G., ed., Metamorphism and Crustal Evolution of the Western United States: Englewood Cliffs, New Jersey, Prentice Hall, Rubey Volume 7, p. 332–361.

Hyndman, R.D., 1972, Plate motions relative to the deep mantle and the development of subduction zones: Nature, v. 238, p. 263–265, doi: 10.1038/238263b0.

Irving, E., 1985, Whence British Columbia: Nature, v. 314, p. 673–674, doi: 10.1038/314673a0.

Irving, E., and Wynne, P.J., 1992, Paleomagnetism: Review and tectonic implications, *in* Gabrielse, H., and Yorath, C.J., eds., Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, Geology of Canada, J.O. Wheeler (ed.), v. 4, p. 81–86 (also Geological Society of America, Geology of North America, v. G-2, p. 63–86).

Irving, E., Monger, J.W.H., and Yole, R.W., 1980, New paleomagnetic evidence for displaced terranes: Geological Association of Canada Special Paper 20, p. 441–456.

Irving, E., Thorkelson, D.J., Wheadon, P.M., and Enkin, R.J., 1995, Paleomagnetism of the Spences Bridge group and northward displacement of the Intermontane belt, British Columbia: Journal of Geophysical Research, v. 100, p. 6057–6071, doi: 10.1029/94JB03012.

Irwin, W.P., 2002, Correlation of the Klamath Mountains and Sierra Nevada: U.S. Geological Survey Open-File Report 02-490, 2 sheets.

Jacobson, C.E., Grove, M., Stamp, M.M., Vicic, A., Oyarzabal, F.R., Haxel, G.B., Tosdal, R.M., and Sherrod, D.R., 2002, Exhumation history of the Orocopia Schist and related rocks in the Gavilan Hills area of southeasternmost California, *in* Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Geological Society of America Special Paper 365, p. 129–154.

Jacobson, C.E., Grove, M., Vućić, A., Pedrick, J.N., and Ebert, K.A., 2007, Exhumation of the Orocopia Schist and associated rocks of southeastern California: Relative roles of erosion, synsubduction tectonic denudation, and middle Cenozoic extension, *in* Cloos, M., Carlson, W.D., Gilbert, M.C., Liou, J.G., and Sorensen, S.S., eds., Convergent Margin Terranes and Associated Regions: A Tribute to W.G. Ernst: Geological Society of America Special Paper 419, p. 1–37, doi: 10.1130/2007.2419(01).

James, E.W., and Henry, C.D., 1993, Pb isotopes of ore deposits in Trans-Pecos Texas and northeastern Chihuahua, Mexico: Basement, igneous and sedimentary sources of metals: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 88, p. 934–947.

James, N.P., and Mountjoy, E.W., 1983, Shelf-slope break in fossil carbonate platforms: An overview, *in* Stanley, D.J., and Moore, G.T., eds., The Shelfbreak: Critical Interface on Continental Margins: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication 33, p. 189–206.

Jicha, B.R., Scholl, D.W., Singer, B.S., Yogodzinski, G.M., and Kay, S.M., 2006, Revised age of Aleutian island arc formation implies high rate of magma production: Geology, v. 34, p. 661–664, doi: 10.1130/G22433.1.

Johnston, D.H., Williams, P.F., Brown, R.L., Crowley, J.L., and Carr, S.D., 2000, Northeastward extrusion and extensional exhumation of crystalline rocks of the Monashee complex, southeastern Canadian Cordillera: Journal of Structural Geology, v. 22, p. 603–625, doi: 10.1016/S0191-8141(99)00185-6.

Johnston, S.J., 2008, The Cordilleran ribbon continent of North America: Annual Review of Earth and Planetary Sciences, v. 36, p. 495–530, doi: 10.1146/annurev.earth.36.031207.124331.

Johnston, S.T., 2001, The great Alaskan terrane wreck: Oroclinal orogeny and reconciliation of paleomagnetic and geological data in the northern Cordillera: Earth and Planetary Science Letters, v. 193, p. 259–272, doi: 10.1016/S0012-821X(01)00516-7.

Johnston, S.T., and Borel, G.D., 2007, The odyssey of the Cache Creek terrane, Canadian Cordillera: Implications for accretionary orogens, tectonic setting of Panthalassa, the Pacific superswell, and the break-up of Pangea: Earth and Planetary Science Letters, v. 253, p. 415–428, doi: 10.1016/j.epsl.2006.11.002.

Johnston, S.T., and Erdmer, P., 1995, Hot-side-up aureole in southwest Yukon and limits on terrane assembly of the northern Canadian Cordillera: Geology, v. 23, p. 419–422, doi: 10.1130/0091-7613(1995)023<0419:HSUAIS>2.3.CO;2.

Johnston, S.T., Wynne, P.J., Francis, D., Hart, C.J.R., Enkin, R.J., and Engebretson, D.C., 1996, Yellowstone in Yukon: The Late Cretaceous Carmacks Group: Geology, v. 24, p. 997–1000, doi: 10.1130/0091-7613(1996)024<0997:YIYTLC>2.3.CO;2.

Journeay, J.M., 1986, Stratigraphy, internal strain, and thermo-tectonic evolution of northern Frenchman Cap dome: An exhumed duplex structure, Omineca hinterland, S.E. Canadian Cordillera [Ph.D. thesis]: Kingston, Ontario, Queen's University.

Journeay, M., 1992, Geology of north central Frenchman Cap Dome: Geological Survey of Canada, Open-File Report 2447, 5 sheets.

Karlstrom, K.E., and Bowring, S.A., 1988, Early Proterozoic assembly of tectonostratigraphic terranes in southwestern North America: Journal of Geology, v. 96, p. 561–576.

Kauffman, E.G., 1977, Geological and biological overview: Western Interior Cretaceous basin: Mountain Geologist, v. 14, p. 75–99.

Keen, C.E., and Dehler, S.A., 1997, Extensional styles and gravity anomalies at rifted continental margins: Some North Atlantic examples: Tectonics, v. 16, p. 744–754, doi: 10.1029/97TC01765.

Kepper, J.C., 1981, Sedimentology of a middle Cambrian outer shelf margin with evidence for syndepositional faulting, eastern California and western Nevada: Journal of Sedimentary Petrology, v. 51, p. 807–821.

Kerr, R.A., 1995, How far did the west wander?: Science, v. 268, p. 635, doi: 10.1126/science.268.5211.635.

Kimbrough, D.L., Smith, D.P., Mahoney, J.B., Moore, T.E., Grove, M., Gastil, R.G., Ortega-Rivera, A., and Fanning, C.M., 2001, Forearc-basin sedimentary response to rapid Late Cretaceous batholith emplacement in the Peninsular Ranges of southern and Baja California: Geology, v. 29, p. 491–494, doi: 10.1130/0091-7613(2001)029<0491:FBSRTR>2.0.CO;2.

Kincaid, C., and Olson, P., 1987, An experimental study of subduction and slab migration: Journal of Geophysical Research, v. 92, p. 13,832–13,840, doi: 10.1029/JB092iB13p13832.

Kistler, R.W., 1993, Mesozoic intrabatholithic faulting, Sierra Nevada, California, *in* Dunne, G.C., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States—II: Los Angeles, SEPM (Society for Sedimentary Geology), Pacific Section, p. 247–262.

Klein, D.P., 1982, Regional gravity and magnetic evidence for a tectonic weakness across southwestern Arizona, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 61–67.

Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the ancestral Rocky Mountains: Geology, v. 9, p. 10–15, doi: 10.1130/0091-7613(1981)9<10:PTOTAR>2.0.CO;2.

Koch, W.J., 1976, Lower Triassic facies in the vicinity of the Cordilleran hingeline: Western Wyoming, southeastern Idaho and Utah: Denver, Rocky Mountain Association of Geologists, 1976 Symposium, p. 203–217.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, F., Turner, C.E., Kunk, M.J., and Obradovich, J.D., 1998, The age of the Morrison Formation: Modern Geology, v. 22, p. 235–260.

Kowallis, B.J., Britt, B.B., Greenhalgh, B.W., and Spinkel, D.A., 2007, New U-Pb zircon ages from an ash bed in the Brushy Basin Member of the Morrison Formation near Hanksville, Utah, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., eds., Central Utah—Diverse Geology of a Diverse Landscape: Salt Lake City, Utah Geological Association Publication 36, p. 75–80.

Kruse, S., and Williams, P.F., 2007, The Monashee reflection: Re-examination of a Lithoprobe crustal-scale seismic reflection in the southern Canadian Cordillera: Geosphere, v. 3, p. 26–41, doi: 10.1130/GES00049.1.

Kulik, D.M., and Schmidt, C.J., 1988, Region of overlap and styles of deformation of Cordilleran thrust belt and Rocky Mountain foreland, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 75–98.

Kylander-Clark, A.R.C., Coleman, D.S., Glazner, A.F., and Bartley, J.M., 2005, Evidence for 65 km of dextral slip across Owens Valley, California, since 83 Ma: Geological Society of America Bulletin, v. 117, p. 962–968, doi: 10.1130/B25624.1.

Lageson, D.R., and Schmitt, J.G., 1994, The Sevier orogenic belt of the western United States: Recent advances in understanding its structural and sedimentologic framework, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds., Mesozoic Systems of the Rocky Mountain Region, U.S.A.: Denver, SEPM (Society for Sedimentary Geology), Rocky Mountain Section, p. 27–64.

Lageson, D.R., Schmitt, J.G., Horton, B.K., Kalakay, T.J., and Burton, B.R., 2001, Influence of Late Cretaceous magmatism on the Sevier orogenic wedge, western Montana: Geology, v. 29, p. 723–726, doi: 10.1130/0091-7613(2001)029<0723:IOLCMO>2.0.CO;2.

Lahren, M.M., and Schweickert, R.A., 1989, Proterozoic and Lower Cambrian miogeoclinal rocks of Snow Lake pendant, Yosemite-Emigrant Wilderness, Sierra Nevada, California: Evidence for major Early Cretaceous dextral translation: Geology, v. 17, p. 156–160, doi: 10.1130/0091-7613(1989)017<0156:PALCMR>2.3.CO;2.

Lallemand, S., Liu, C.-S., Angelier, J., and Tsai, Y.-B., 2001, Active subduction and collision in Southeast Asia: Tectonophysics, v. 333, p. 1–7, doi: 10.1016/S0040-1951(00)00263-8.

Lamerson, P.R., 1982, The Fossil Basin and its relationship to the Absaroka thrust system, Wyoming and Utah, *in* Powers, R.B., ed., Geologic Studies of the Cordilleran Thrust Belt: Denver, Colorado, Rocky Mountain Association of Geologists, p. 279–337.

Larter, R.D., Vanneste, L.E., and Bruguier, N.J., 2001, Structure, composition and evolution of the South Sandwich island arc: Implications for rates of arc magmatic growth and subduction erosion: Eos (Transactions, American Geophysical Union), v. 82, F1187.

Lawton, T.F., and Trexler, J.H., Jr., 1991, Piggyback basin in the Sevier orogenic belt, Utah: Implications for development of the thrust wedge: Geology, v. 19, p. 827–830, doi: 10.1130/0091-7613(1991)019<0827:PBITSO>2.3.CO;2.

Lawton, T.F., Sprinkel, D., DeCelles, P.G., Mitra, G., and Sussman, A.J., 1997, Thrusting and synorogenic sedimentation in the central Utah Sevier thrust belt and foreland basin, *in* Link, P.K., and Kowallis, B.J., eds., Mesozoic to Recent Geology of Utah: Provo, Brigham Young University Geology Studies, v. 42, pt. 2, p. 33–67.

Leckie, D.A., and Smith, D.G., 1992, Regional setting, evolution, and depositional cycles of the western Canada foreland basin, *in* MacQueen, R.W., and Leckie, D.A., eds., Foreland Basins and Fold Belts: Tulsa, Oklahoma, American Association of Petroleum Geologists Memoir 55, p. 9–46.

Leeman, W.P., Oldow, J.S., and Hart, W.K., 1992, Lithosphere-scale thrusting in the western U.S. Cordillera as constrained by Sr and Nd isotopic transitions in Neogene volcanic rocks: Geology, v. 20, p. 63–66, doi: 10.1130/0091-7613(1992)020<0063:LSTITW>2.3.CO;2.

Leeman, W.P., Carr, M.J., and Morris, J.D., 1994, Boron geochemistry of the Central American volcanic arc: Constraints on the genesis of subduction-related magmas: Geochimica et Cosmochimica Acta, v. 58, p. 149–168, doi: 10.1016/0016-7037(94)90453-7.

Levin, V., Shapiro, N., Park, J., and Ritzwoller, M., 2002, Seismic evidence for catastrophic slab loss beneath Kamchatka: Nature, v. 418, p. 763–766.
Lewis, C.J., Wernicke, B.P., Selverstone, J., and Bartley, J.M., 1999, Deep burial of the footwall of the northern Snake Range décollement, Nevada: Geological Society of America Bulletin, v. 111, p. 39–51, doi: 10.1130/0016-7606(1999)111<0039:DBOTFO>2.3.CO;2.
Lewis, R.S., Bush, J.H., Burmester, R.F., Kauffman, J.D., Garwood, D.L., Myers, P.E., and Othberg, K.L., 2005, Geologic Map of the Potlach 30 × 60 Minute Quadrangle, Idaho: Idaho Geological Survey: Geologic Map 41, scale 1:100,000, map plus notes (30 p.).
Link, P.K., Durk, K.M., and Fanning, C.M., 2007, SHRIMP U-Pb ages from Archean orthogneiss, Mesoproterozoic paragneiss and Eocene Boulder Creek Pluton, Pioneer Mountains, south-central Idaho, part of the 2600 Ma Grouse Creek block: Geological Society of America Abstracts with Programs, v. 39, no. 6, p. 613.
Lipman, P.W., 1994, Tucson Mountains caldera—A Cretaceous ash-flow caldera in southern Arizona, *in* Thorman, C.H., and Lane, D.E., eds., Ninth V.E. McKelvey Forum on Mineral and Energy Resources: Guidebook for Field Trips: U.S. Geological Survey Circular 1103-B, p. 89–102.
Lipman, P.W., 2007, Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field: Geosphere, v. 3, p. 42–70, doi: 10.1130/GES00061.1.
Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1991, Detachment models for the formation of passive continental margins: Tectonics, v. 10, p. 1038–1064, doi: 10.1029/90TC01007.
Lund, K., 2008, Geometry of the Neoproterozoic and Paleozoic rift margin of western Laurentia: Implications for mineral deposit settings: Geosphere, v. 4, p. 429–444, doi: 10.1130/GES00121.1.
Lund, K., and Snee, L.W., 1988, Metamorphism, structural development, and age of the continent–island arc juncture in west-central Idaho, *in* Ernst, W.G., ed., Metamorphism and Crustal Evolution of the Western United States: Englewood Cliffs, New Jersey, Prentice Hall, Rubey Volume 7, p. 297–331.
Lund, K., Aleinikoff, J.N., Kunk, M.J., Unruh, D.M., Zeihen, G.D., Hodges, W.C., duBray, E.A., and O'Neill, J.M., 2002, SHRIMP U-Pb and $^{40}Ar/^{39}Ar$ age constraints for relating plutonism and mineralization in the Boulder batholith region, Montana: Economic Geology and Bulletin of the Society of Economic Geologists, v. 97, p. 241–267.
Lund, K., Aleinikoff, J.N., Yacob, E.Y., Unruh, D.M., and Fanning, C.M., 2008, Coolwater culmination: Sensitive high-resolution ion microprobe (SHRIMP) U-Pb and isotopic evidence for continental delamination in the Syringa Embayment, Salmon River suture, Idaho: Tectonics, v. 27, TC2009, doi: 10.1029/2006TC002071.
Lush, A.P., McGrew, A.J., Snoke, A.W., and Wright, J.E., 1988, Allochthonous Archean basement in the northern East Humboldt Range, Nevada: Geology, v. 16, p. 349–353, doi: 10.1130/0091-7613(1988)016<0349:AABITN>2.3.CO;2.
Madsen, J.K., Thorkelson, D.J., Friedman, R.M., and Marshall, D.D., 2006, Cenozoic to Recent plate configurations in the Pacific Basin: Ridge subduction and slab window magmatism in western North America: Geosphere, v. 2, p. 11–34, doi: 10.1130/GES00020.1.
Mahoney, J.B., Mustard, P.S., Haggart, J.W., Friedman, R.M., Fanning, M., and McNicholl, V.J., 1999, Archean and Proterozoic zircons in Cretaceous sediments of the western Canadian and northwest U.S. Cordillera: The "Baja B.C." hypothesis fails a "crucial test": Geology, v. 27, p. 195–198, doi: 10.1130/0091-7613(1999)027<0195:AZICSO>2.3.CO;2.
Mahoney, J.B., Gordee, S., Haggart, J.W., Friedman, R.M., Diakow, L., and Woodsworth, G.J., 2006, Jurassic–Tertiary evolution of the Central Coast Plutonic Complex: Controls on over 120 million years of magmatism: Geological Society of America Abstracts with Programs, Specialty Meeting No. 2, p. 24.
Mair, J.L., Hart, C.J.R., and Stephens, J.R., 2006, Deformation history of the northwestern Selwyn Basin, Yukon, Canada: Implications for orogen evolution and mid-Cretaceous magmatism: Geological Society of America Bulletin, v. 118, p. 304–323, doi: 10.1130/B25763.1.
Mallory, W.M., 1972, Pennsylvanian arkose and the ancestral Rocky Mountains, *in* Geologic Atlas of the Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 131–132.
Manea, V.C., and Gurnis, M., 2008, The quest for a missing key parameter: Controlling the slab dip evolution in subduction systems: Geophysical Research Abstracts, v. 10, EGU2008, p. A-04883.
Marsh, B.D., 1979, Island-arc volcanism: American Scientist, v. 67, p. 161–172.
Marzolf, J.E., 1982, Paleogeographic implications of early Jurassic(?) Navajo and Aztec sandstones, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 493–501.
Mattinson, C.G., Colgan, J.P., Metcalf, J.R., Miller, E.L., and Wooden, J.L., 2007, Late Cretaceous to Paleocene metamorphism and magmatism in the Funeral Mountains metamorphic core complex, Death Valley, California, *in* Cloos, M., Carlson, W.D., Gilbert, M.C., Liou, J.G., and Sorensen, S.S., eds., Convergent Margin Terranes and Associated Regions: A Tribute to W.G. Ernst: Geological Society of America Special Paper 419, p. 205–223, doi: 10.1130/2006.2419(11).
Mattinson, J.M., 1990, Petrogenesis and evolution of the Salinian magmatic arc, *in* Anderson, J.L., ed., The Nature and Origin of Cordilleran Magmatism: Geological Society of America Memoir 174, p. 237–250.
Matzel, J.E.P., Bowring, S.A., and Miller, R.B., 2004, Protolith age of the Swakane Gneiss, North Cascades, Washington: Evidence of rapid underthrusting of sediments beneath an arc: Tectonics, v. 23, TC6009, doi: 10.1029/2003TC001577.
Matzel, J.E.P., Bowring, S.A., and Miller, R.B., 2008, Spatial and temporal variations in Nd isotopic signatures across the crystalline core of the North Cascades, Washington, *in* Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs and Batholiths: A Tribute to Cliff Hopson: Geological Society of America Special Paper 438, p. 499–516, doi: 10.1130/2008.2348(18).
McClelland, W.C., and Oldow, J.S., 2007, Late Cretaceous truncation of the western Idaho shear zone in the central North American Cordillera: Geology, v. 35, p. 723–726, doi: 10.1130/G23623A.1.
McCollum, L.B., and McCollum, M.B., 1984, Comparison of a Cambrian medial shelf sequence with an outer shelf margin sequence, northern Great Basin, *in* Kerns, G.J., and Kerns, R.L., eds., Geology of Northwest Utah, Southern Idaho and Northeast Nevada: Salt Lake City, Utah Geological Association Publication 13, p. 35–44.
McCoy, A.M., Karlstrom, K.E., Shaw, C.A., and Williams, M.L., 2005, The Proterozoic ancestry of the Colorado Mineral Belt: 1.4 Ga shear zone system in central Colorado, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region: An Evolving Lithosphere, Tectonics, Geochemistry, and Geophysics: Washington, D.C., American Geophysical Union Monograph 154, p. 71–90.
McDonald, R.E., 1972, Eocene and Paleocene rocks of the southern and central basins, *in* Geologic Atlas of the Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 243–256.
McDowell, F.W., McMahon, T.P., Warren, P.Q., and Cloos, M., 1996, Pliocene Cu-Au-bearing igneous intrusions of the Gunung Bijih (Ertsberg) district, Irian Jaya, Indonesia: K-Ar geochronology: Journal of Geology, v. 104, p. 327–340.
McDowell, F.W., Roldán-Quintana, J., and Connelly, J.N., 2001, Duration of Late Cretaceous–early Tertiary magmatism in east-central Sonora, Mexico: Geological Society of America Bulletin, v. 113, p. 521–531, doi: 10.1130/0016-7606(2001)113<0521:DOLCET>2.0.CO;2.
McGrew, A.J., Peters, M.T., and Wright, J.E., 2000, Thermobarometric constraints on the tectonothermal evolution of the northern East Humboldt Range metamorphic core complex, Nevada: Geological Society of America Bulletin, v. 112, p. 45–60, doi: 10.1130/0016-7606(2000)112<0045:TCOTTE>2.3.CO;2.
McIlreath, I.A., 1977, Accumulation of a Middle Cambrian, deep-water limestone debris apron adjacent to a vertical, submarine carbonate escarpment, southern Rocky Mountains, Canada, *in* Cook, H.E., and Enos, P., eds., Deep-Water Carbonate Environments: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication 25, p. 113–124.
McMechan, M.E., Thompson, R.I., Cook, D.G., Gabrielse, H., and Yorath, C.J., 1992, Part E. Foreland Belt, *in* Gabrielse, H., and Yorath, C.J., eds., Structural Styles, chap. 17 of Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, Geology of Canada, no. 4, p. 634–650.
McMillan, W.J., Thompson, J.F.H., Hart, C.J.R., and Johnston, S.T., 1995, Regional geological and tectonic setting of porphyry deposits in British Columbia and Yukon Territory, *in* Schroeter, T.G., ed., Porphyry Deposits of the Northwestern Cordillera of North America: Montreal, Canadian Institute of Mining and Metallurgy, Special Volume 46, p. 40–57.
Menzies, M., Rogers, N., Tindle, A., and Hawkesworth, C.J., 1987, Metasomatism and enrichment processes in lithospheric peridotites, an effect of asthenosphere-lithosphere interaction, *in* Menzies, M.A., and

Hawkesworth, C.J., eds., Mantle Metasomatism: London, Academic Press, p. 313–361.

Middleton, L.T., 2001, Middle Cambrian offshore microbialites and shoaling successions, western Wyoming: Implications for regional paleogeography: Rocky Mountain Geology, v. 36, p. 81–98, doi: 10.2113/gsrocky.36.2.81.

Miller, C.F., Howard, K.A., and Hoisch, T.D., 1982, Mesozoic thrusting, metamorphism and plutonism, Old Woman-Piute range, southeastern California, *in* Frost, E.G., and Martin, D.L., eds., Mesozoic–Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, Cordilleran Publishers, p. 561–581.

Miller, D.M., 1980, Structural geology of the northern Albion Mountains, south-central Idaho, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran Metamorphic Core Complexes: Geological Society of America Memoir 153, p. 399–423.

Miller, D.M., and Hoisch, T.D., 1995, Jurassic tectonics of northeastern Nevada and northwestern Utah from the perspective of barometric studies, *in* Miller, D.M., and Busby-Spera, C., eds., Jurassic Magmatism and Tectonics of the North American Cordillera: Geological Society of America Special Paper 299, p. 267–294.

Miller, D.M., Hillhouse, W.C., Zartman, R.E., and Lanphere, M.A., 1987, Geochronology of intrusive and metamorphic rocks in the Pilot Range, Utah and Nevada, and comparison with regional patterns: Geological Society of America Bulletin, v. 99, p. 866–879, doi: 10.1130/0016-7606(1987)99<866:GOIAMR>2.0.CO;2.

Miller, D.M., Nilson, T.H., and Bilodeau, W.L., 1992, Late Cretaceous to early Eocene geologic evolution of the U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 205–260.

Miller, E.L., and Hudson, T.L., 1991, Mid-Cretaceous extensional fragmentation of a Jurassic–early Cretaceous compressional orogen, Alaska: Tectonics, v. 10, p. 781–796, doi: 10.1029/91TC00044.

Miller, E.L., Holdsworth, B.K., Whiteford, W.B., and Rogers, D., 1984, Stratigraphy and structure of the Schoonocer sequence, northern Nevada: Implications for Paleozoic plate margin tectonics: Geological Society of America Bulletin, v. 95, p. 1063–1076, doi: 10.1130/0016-7606(1984)95<1063:SASOTS>2.0.CO;2.

Miller, R.B., 1989, The Mesozoic Rimrock Lake inlier, southern Washington Cascades: Implications for the basement to the Columbia Embayment: Geological Society of America Bulletin, v. 101, p. 1289–1305, doi: 10.1130/0016-7606(1989)101<1289:TMRLIS>2.3.CO;2.

Miller, R.B., and Bowring, S.A., 1990, Structure and chronology of the Oval Peak batholith and adjacent rocks: Implications for the Ross Lake fault zone, North Cascades, Washington: Geological Society of America Bulletin, v. 102, p. 1361–1377, doi: 10.1130/0016-7606(1990)102<1361:SACOTO>2.3.CO;2.

Molnar, P., and Tapponnier, P., 1975, Cenozoic tectonics of Asia: Effects of a continental collision: Science, v. 189, p. 419–426, doi: 10.1126/science.189.4201.419.

Monger, J., and Price, R., 2002, The Canadian Cordillera: Geology and tectonic evolution: CSEG Recorder, February 2002, p. 17–36.

Monger, J.W.H., and Ross, C.A., 1971, Distribution of fusulinaceans in the western Canadian Cordillera: Canadian Journal of Earth Sciences, v. 8, p. 259–278.

Monger, J.W.H., Price, R.A., and Templeman-Kluitt, D., 1982, Tectonic accretion and the origin of two metamorphic and plutonic welts in the Canadian Cordillera: Geology, v. 10, p. 70–75, doi: 10.1130/0091-7613(1982)10<70:TAATOO>2.0.CO;2.

Montañez, I.P., and Osleger, D.A., 1996, Contrasting sequence boundary zones developed within cyclic carbonates of the Bonanza King Formation, Middle to Late Cambrian, southern Great Basin, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, p. 7–21.

Moore, J.G., and Hopson, C.A., 1961, The Independence dike swarm in eastern California: American Journal of Science, v. 259, p. 241–259.

Moore, T.E., Wallace, W.K., Bird, K.J., Karl, S.M., Mull, C.G., and Dillon, J.T., 1994, Geology of northern Alaska, *in* Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-1, p. 49–140.

Moore, T.E., Aleinkoff, J.N., and Harris, A.G., 1997a, Stratigraphic and structural implications of conodont and detrital zircon U-Pb ages from metamorphic rocks of the Coldfoot terrane, Brooks Range, Alaska: Journal of Geophysical Research, v. 102, p. 20,797–20,820, doi: 10.1029/96JB02351.

Moore, T.E., Wallace, W.K., Mull, C.G., Adams, K.E., Plafker, G., and Nokleberg, W.J., 1997b, Crustal implications of bedrock geology along the Trans-Alaska Crustal Transect (TACT) in the Brooks Range, northern Alaska: Journal of Geophysical Research, v. 102, p. 20,645–20,684, doi: 10.1029/96JB03733.

Moore, T.E., Potter, C.J., O'Sullivan, P.B., Shelton, K.L., and Underwood, M.B., 2004, Two stages of deformation and fluid migration in the west-central Brooks Range fold and thrust belt, northern Alaska, *in* Swennen, R., Roure, F., and Granath, J.W., eds., Deformation, Fluid Flow, and Reservoir Appraisal in Foreland Fold and Thrust Belts: Tulsa, Oklahoma, American Association of Petroleum Geologists Hedberg Ser., no. 1, p. 157–186.

Moran, A.E., Sisson, V.B., and Leeman, W.P., 1992, Boron depletion during progressive metamorphism: Implications for subduction processes: Earth and Planetary Sciences, v. 111, p. 331–349, doi: 10.1016/0012-821X(92)90188-2.

Morgan, S.S., and Law, R.D., 1998, An overview of Paleozoic–Mesozoic structures developed in the central White-Inyo Range, eastern California, *in* Ernst, W.G., and Nelson, C.A., eds., Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall Jr. Volume: Boulder, Colorado, Geological Society of America, p. 161–172.

Morrow, J.R., and Sandberg, C.A., 2008, Evolution of Devonian carbonate-shelf margin, Nevada: Geosphere, v. 4, p. 445–458, doi: 10.1130/GES00134.1.

Mortensen, J.K., 1992, Pre-mid-Mesozoic tectonic evolution of the Yukon-Tanana terrane, Yukon and Alaska: Tectonics, v. 11, p. 836–853, doi: 10.1029/91TC01169.

Mougenot, D., Boillot, G., and Rehault, J.-P., 1983, Prograding shelfbreak types on passive continental margins: Some European examples, *in* Stanley, D.J., and Moore, G.T., eds., The Shelfbreak: Critical Interface on Continental Margins: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication 33, p. 61–77.

Mount, J.F., and Bergk, K.J., 1998, Depositional sequence stratigraphy of Lower Cambrian grand cycles, southern Great Basin, U.S.A., *in* Ernst, W.G., and Nelson, C.A., eds., Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall Jr. Volume: Boulder, Colorado, Geological Society of America, p. 180–202.

Mudge, M.R., 1982, A resume of the structural geology of the northern disturbed belt, northwestern Montana, *in* Powers, R.B., ed., Geologic Studies of the Cordilleran Thrust Belt: Denver, Rocky Mountain Association of Geologists, p. 91–122.

Mudge, M.R., and Earhart, R.L., 1980, The Lewis Thrust Fault and Related Structures in the Disturbed Belt, Northwestern Montana: U.S. Geological Survey Professional Paper 1174, 18 p.

Mueller, S., and Phillips, R.J., 1991, On the initiation of subduction: Journal of Geophysical Research, v. 96, p. 651–665, doi: 10.1029/90JB02237.

Mulch, A., Teyssier, C., Cosca, M.A., Vanderhaeghe, O., and Venneman, T.W., 2004, Reconstructing paleoelevation in eroded orogens: Geology, v. 32, p. 525–528, doi: 10.1130/G20394.1.

Murchey, B.L., 1990, Age and depositional setting of siliceous sediments in the upper Paleozoic Havallah sequence near Battle Mountain, Nevada: Implications for the paleogeography and structural evolution of the western margin of North America, *in* Harwood, D.S., and Miller, M.M., eds., Late Paleozoic and Early Mesozoic Paleogeographic Relations: Klamath Mountains, Sierra Nevada, and Related Rocks: Geological Society of America Special Paper 255, p. 137–155.

Murphy, D.C., Mortensen, J.K., Piercey, S.J., Orchard, M.J., and Gehrels, G.E., 2006, Mid-Paleozoic to early Mesozoic tectonostratigraphic evolution of Yukon-Tanana and Slide Mountain terranes and affiliated overlap assemblages, Finlayson Lake massive sulphide district, southeastern Yukon, *in* Colpron, M., and Nelson, J.L., eds., Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America, Canadian and Alaskan Cordillera: St. John's, Newfoundland, Geological Association of Canada Special Paper 45, p. 75–105.

Murphy, J.B., Hynes, A.J., Johnston, S.T., and Keppie, J.D., 2003, Reconstructing the ancestral Yellowstone plume from accreted seamounts and its relationship to flat-slab subduction: Tectonophysics, v. 365, p. 185–194, doi: 10.1016/S0040-1951(03)00022-2.

Nelson, C.A., 1962, Lower Cambrian–Precambrian succession, White-Inyo Mountains, California: Geological Society of America Bulletin, v. 73, p. 139–144, doi: 10.1130/0016-7606(1962)73[139:LCSWMC]2.0.CO;2.

Nelson, C.A., 1978, Late Precambrian–Early Cambrian stratigraphic and faunal succession of eastern California and the Precambrian-Cambrian boundary: Geological Magazine, v. 115, p. 121–126.

Nelson, J.L., 1993, The Sylvester allochthon: Upper Paleozoic and Mesozoic marginal-basin and island-arc terranes in northern British Columbia: Canadian Journal of Earth Sciences, v. 30, p. 634–643.

Nelson, K.D., Wenjin Zhao, Brown, L.D., Kuo, J., Jinkai Che, Xianwen Liu, Klemperer, S.L., Makovsky, Y., Melssner, R., Mechie, J., Kind, R., Wenzel, F, Ni, J., Nabele, J., Chen Leshou, Handong Tan, Wenbo Wie, Jones, A.G., Booker, J., Unsworth, M., Kidd, W.S.F., Hauck, M., Alsdorf, D., Ross, A., Cogan, M., Changde Wu, Sandvol, E., and Edwards, M., 1996, Partially molten middle crust beneath Southern Tibet: Synthesis of project INDEPTH results: Science, v. 274, p. 1684–1688.

North American Magnetic Anomaly Group (NAMAG), 2002, The Magnetic Anomaly Map of North America: U.S. Geological Survey Open-File Report 02-414, http://pubs.usgs.gov/of/2002/ofr-02-414/.

Nourse, J.A., 2002, Middle Miocene reconstruction of the central and eastern San Gabriel Mountains, southern California, with implications for the evolution of the San Gabriel fault and Los Angeles basin, *in* Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Geological Society of America Special Paper 365, p. 161–185.

Nydegger, G.L., 1982, The Las Vegas–El Paso gap: A review of the southern part of the Cordilleran overthrust belt, *in* Powers, R.B., ed., Geologic Studies of the Cordilleran Thrust Belt: Denver, Rocky Mountain Association of Geologists, p. 391–407.

Okulitch, A.V., Wanless, R.K., and Loveridge, W.D., 1975, Devonian plutonism in south-central British Columbia: Canadian Journal of Earth Sciences, v. 12, p. 1760–1769.

Oldow, J.S., Bally, A.W., Avé Lallemant, H.G., and Leeman, W.P., 1989, Phanerozoic evolution of the North American Cordillera (United States and Canada), *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America: An Overview: Boulder, Colorado, Geological Society of America, Geology of North America, v. A, p. 139–232.

O'Neill, J.M., Lonn, J.D., Lageson, D.R., and Kunk, M.J., 2004, Early Tertiary Anaconda metamorphic core complex, southwestern Montana: Canadian Journal of Earth Sciences, v. 41, p. 63–72, doi: 10.1139/e03-086.

O'Neill, J.M., Ruppel, E.T., and Lopez, D.A., 2005, Newly recognized Chief Joseph metamorphic core complex and younger structures in the north-central Beaverhead mountains, Idaho and Montana—Expanding the temporal and spatial limits of post-contractional extension in the northern Rocky mountains: Geological Society of America Abstracts with Programs, v. 37, no. 6, p. 4.

O'Neill, J.M., Ruppel, E.T., and Lopez, D.A., 2007, Great Divide megashear, Montana, Idaho and Washington: An intraplate lithospheric shear zone and its impact on Mesoproterozoic depositional basins: Geological Society of America Abstracts with Programs, v. 39, no. 5, p. 36.

Oriel, S.S., and Armstrong, F.C., 1971, Uppermost Precambrian and lowest Cambrian rocks in southeastern Idaho: U.S. Geological Survey Professional Paper 394, 52 p.

Ortega-Rivera, A., 2003, Geological constraints on the tectonic history of the Peninsular Ranges batholith of Alta and Baja California: Tectonic implications for western Mexico, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., and Martin-Barajas, A., eds., Tectonic Evolution of Northwestern Mexico and the Southwestern USA: Geological Society of America Special Paper 374, p. 297–335.

Ostos, M., Yoris, F., and Avé Lallemant, H.G., 2005, Overview of the southeast Caribbean–South American plate boundary zone, *in* Avé Lallemant, H.G., and Sisson, V.B., eds., Caribbean–South American Plate Interactions, Venezuela: Geological Society of America Special Paper 394, p. 53–89, doi: 10.1130/2005.2394(02).

O'Sullivan, P.B., Moore, T.E., Wallace, W.K., and Potter, C.J., 2006, Timing of Brooks Range and North Slope uplift and denudation: A summary of the fission-track results: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 24.

Otteman, A.S., and Snoke, A.W., 2004, Structural analysis of a Laramide-age, basement-involved, foreland fault zone, Rawlins uplift, south-central Wyoming: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 268.

Palmer, A.R., and Hintze, L.F., 1992, Middle Cambrian to Lower Ordovician rocks, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 20–22.

Parman, S.W., and Grove, T.L., 2004, Harzburgite melting with and without H_2O: Experimental data and predictive modeling: Journal of Geophysical Research, v. 109, B02201, doi: 10.1029/2003JB002566.

Parrish, R.R., 1992, Miscellaneous U-Pb zircon dates from southeast British Columbia, *in* Radiogenic Age and Isotopic Studies, Report 5: Geological Survey of Canada Paper 91-2, p. 143–153.

Parrish, R.R., 1995, Thermal evolution of the southeastern Canadian Cordillera: Canadian Journal of Earth Sciences, v. 32, p. 1618–1642.

Parrish, R., Carr, S.D., and Parkinson, D.L., 1988, Eocene extensional tectonics and geochronology of the southern Omineca Belt, British Columbia and Washington: Tectonics, v. 7, p. 181–212, doi: 10.1029/TC007i002p00181.

Paterson, S.R., Miller, R.B., Alsleben, H., Whitney, D.L., Valley, P.M., and Hurlow, H., 2004, Driving mechanisms for >40 km of exhumation during contraction and extension in a continental arc, Cascades core, Washington: Tectonics, v. 23, TC3005, doi: 10.1029/2002TC001440.

Pearson, D.M., and Ducea, M.N., 2006, How do you build the largest batholith in the Phanerozoic? Evidence for three magmatic flare-ups in the Coast Plutonic Complex of British Columbia, Canada: Geological Society of America Abstracts with Programs, Specialty Meeting No. 2, p. 24.

Perry, W.J., Jr., and Flores, R.M., 1997, Sequential Laramide deformation and Paleocene depositional patterns in deep gas-prone basins of the Rocky Mountain region: U.S. Geological Survey Bulletin 2146-E, p. 49–59.

Peterson, J.A., 1977, Paleozoic shelf-margins and marginal basins, western Rocky Mountains—Great Basin, United States, *in* Heisey, E.L., and Lawson, D.E., eds., Rocky Mountain Thrust Belt Geology and Resources: Wyoming Geological Association, Annual Field Conference, 29th, p. 135–153.

Pitcher, W.S., Atherton, M.P., Cobbing, E.J., and Beckinsale, R.D., 1985, Magmatism at a Plate Edge: New York, Halstad Press, 328 p.

Poole, F.G., Sandberg, C.A., and Boucot, A.J., 1977, Silurian and Devonian paleogeography of the western United States, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic Paleogeography of the Western United States: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, 1st, p. 39–65.

Poole, F.G., Stewart, J.H., Palmer, A.R., Sandberg, C.A., Madrid, R.J., Ross, R.J., Jr., Hintze, L.F., Miller, M.M., and Wrucke, C.T., 1992, Latest Precambrian to latest Devonian time: Development of a continental margin, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 9–56.

Poole, W.G., and Sandberg, C.A., 1977, Mississippian paleogeography and tectonics of the western United States, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic Paleogeography of the Western United States: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, 1st, p. 67–85.

Pope, M.C., and Sears, J.W., 1997, Cassiar platform, north-central British Columbia: A miogeoclinal fragment from Idaho: Geology, v. 25, p. 515–518, doi: 10.1130/0091-7613(1997)025<0515:CPNCBC>2.3.CO;2.

Portnyagin, M., Savelyev, D., Hoernle, K., Hauff, F., and Garbe-Schönberg, D., 2008, Mid-Cretaceous Hawaiian tholeiites preserved in Kamchatka: Geology, v. 36, p. 903–906, doi: 10.1130/G25171A.1.

Potter, C.J., and Moore, T.E., 2006, Frontal detachment folds on Alaska's North Slope: Geological Society of America Abstracts with Programs, v. 38, no. 5, p. 24.

Poulton, T.P., Christopher, J.E., Hayes, B.J.R., Losert, J., Tittemore, J., and Gilchrist, R.D., 1994, Jurassic and lowermost Cretaceous strata of the Western Canada Sedimentary Basin, *in* Mossop, G.D., and Shetsen, I., eds., Geological Atlas of the Western Canada Sedimentary Basin: Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 297–316.

Powell, W.G., Johnston, P.A., Collom, C.J., and Johnston, K.J., 2006, Middle Cambrian brine seeps on the Kicking Horse Rim and their relationship to Talc and Magnesite mineralization and associated dolomitization, British Columbia, Canada: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 101, p. 431–451.

Price, N.J., and Audley-Charles, M.G., 1987, Tectonic collision after plate rupture: Tectonophysics, v. 140, p. 121–129, doi: 10.1016/0040-1951(87)90224-1.

Price, R.A., 1981, The Cordilleran foreland thrust and fold belt in the southern Canadian Rockies, *in* McClay, H.R., and Price, N J., eds., Thrust and

Nappe Tectonics: Geological Society [London] Special Publication 9, p. 427–448.

Price, R.A., 1994, Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin, *in* Mossop, G.D., and Shetsen, I., compilers, Geologic Atlas of the Western Canada Sedimentary Basin: Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 13–24.

Price, R.A., 2000, The Southern Canadian Rockies: Evolution of a foreland thrust and fold belt: Calgary, GeoCanada 2000, Field Trip Guidebook, 246 p.

Price, R.A., and Fermor, P.R., 1985, Structure section of the Cordilleran foreland thrust and fold belt west of Calgary, Alberta: Geological Survey of Canada Paper 84-14, 1 sheet.

Price, R.A., and Mountjoy, E.W., 1970, Geologic structure of the Canadian Rocky Mountains between Bow and Athabasca Rivers: A progress report, *in* Wheeler, J.O., ed., Structure of the Southern Canadian Cordillera: Geological Association of Canada Special Publication 6, p. 7–25.

Price, R.A., and Mountjoy, E.W., 1972, Geology, Banff (West Half): Geological Survey of Canada Map 1295A, scale 1:50,000, 1 sheet.

Price, R.A., and Sears, J.W., 2000, A preliminary palinspastic map of the Mesoproterozoic Belt-Purcell Supergroup, Canada and USA: Implications for the tectonic setting and structural evolution of the Purcell anticlinorium and the Sullivan deposit, *in* Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E., eds., The Geological Environment of the Sullivan Deposit, British Columbia: Geological Association of Canada Special Publication 1, p. 61–81.

Quarles van Ufford, A., and Cloos, M., 2005, Cenozoic tectonics of New Guinea: American Association of Petroleum Geologists Bulletin, v. 89, p. 119–140.

Raeside, R.P., and Simony, P.S., 1983, Stratigraphy and deformational history of the Scripp Nappe, Monashee Mountains, British Columbia: Canadian Journal of Earth Sciences, v. 20, p. 639–650.

Ramos-Velázquez, E., Calmus, T., Valencia, V., Iriondo, A., Valencia-Moreno, M., and Bellon, H., 2008, U-Pb and $^{40}Ar/^{39}Ar$ geochronology of the coastal Sonora batholith: New insights on Laramide continental arc magmatism: Revista Mexicana de Ciencias Geológicas, v. 25, p. 314–333.

Raynolds, R.G., and Johnson, K.R., 2003, Synopsis of the stratigraphy and paleontology of the uppermost Cretaceous and lower Tertiary strata in the Denver Basin, Colorado: Rocky Mountain Geology, v. 38, p. 171–181, doi: 10.2113/gsrocky.38.1.171.

Reed, J.C., Wheeler, J.O., and Tucholke, B.E., 2005, Geologic Map of North America: Boulder, Colorado, Geological Society of America, Decade of North American Geology Continental Scale Map 1, scale 1:5,000,000, 3 sheets.

Reymer, A., and Schubert, G., 1984, Phanerozoic addition rates to the continental crust and crustal growth: Tectonics, v. 3, p. 63–77, doi: 10.1029/TC003i001p00063.

Reynolds, S.J., 2007, Connections between the Maria fold and thrust belt and adjacent regions: Ores and orogenesis, Circum-Pacific tectonics, geologic evolution and ore deposits: Tucson, Arizona Geological Society abstract 253.

Reynolds, S.J., and Spencer, J.E., 1989, Pre-Tertiary rocks and structures in the upper plate of the Buckskin detachment fault, west-central Arizona, *in* Spencer, J.E., and Reynolds, S.J., eds., Geology and Mineral Resources of the Buckskin and Rawhide Mountains, west-central Arizona: Arizona Geological Survey Bulletin 198 (Shackelford Volume), p. 67–102.

Reynolds, S.J., Richard, S.M., Haxel, G.B., Tosdal, R.M., and Laubach, S.E., 1988, Geologic setting of Mesozoic and Cenozoic metamorphism in Arizona, *in* Ernst, W.G., ed., Metamorphic and Crustal Evolution of the Western United States: Englewood Cliffs, New Jersey, Prentice Hall, p. 467–501.

Richard, S.M., Ballard, S.N., Boettcher, S.S., Hamilton, W.B., Hoisch, T.D., and Tosdal, R.M., 1994, Mesozoic tectonics of the Maria Belt, west-central Arizona and southeastern California, *in* McGill, S.F., and Ross, T.M., eds., Geological Investigations of an Active Margin: Redlands, California, San Bernardino County Museum Association and Geological Society of America, Cordilleran Section Guidebook, p. 272–292.

Richards, D.R., Butler, R.F., and Harms, T.A., 1993, Paleomagnetism of the late Paleozoic Slide Mountain terrane, northern and central British Columbia: Canadian Journal of Earth Sciences, v. 30, p. 1898–1913.

Riggs, N.R., and Busby-Spera, C.J., 1990, Evolution of a multi-vent volcanic complex within a subsiding arc graben depression: Mount Wrightson Formation, southern Arizona: Geological Society of America Bulletin, v. 102, p. 1114–1135, doi: 10.1130/0016-7606(1990)102<1114:EOAMVV>2.3.CO;2.

Riggs, N.R., and Busby-Spera, C.J., 1991, Facies analysis of an ancient, dismembered large caldera complex and implications for intra-arc subsidence—Middle Jurassic strata of Cobre ridge, southern Arizona, U.S.A., *in* Cas, R.A.F., and Busby-Spera, C.J., eds., Volcaniclastic Sedimentation: Sedimentary Geology, v. 74, p. 39–67.

Rigo, R.J., 1968, Middle and Upper Cambrian stratigraphy in the autochthon and allochthon in northern Utah: Brigham Young University Geology Studies, v. 15, pt. 1, p. 31–66.

Roberts, E.M., and Hendrix, M.S., 2000, Taphonomy of a petrified forest in the Two Medicine formation (Campanian), northwest Montana: Implications for palinspastic restoration of the Boulder batholith and Elkhorn Mountains volcanics: Palaios, v. 15, p. 476–482.

Robinson, P., 1972, Tertiary history, *in* Geologic Atlas of the Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 233–242.

Roca, X., and Nadon, G.C., 2007, Tectonic control on the sequence stratigraphy of nonmarine retroarc foreland basin fills: Insights from the Upper Jurassic of central Utah, U.S.A.: Journal of Sedimentary Research, v. 77, p. 239–255, doi: 10.2110/jsr.2007.021.

Rodgers, D.W., 1989, Geologic Map of the Deep Creek Mountains Wilderness Study Area, Tooele and Juab Counties, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF2099, scale 1:50,000, 1 sheet.

Rodgers, J., 1987, Basement uplifts within cratons marginal to orogenic belts: American Journal of Science, v. 287, p. 661–692.

Rodgers, J., 1997, Exotic nappes in external parts of orogenic belts: American Journal of Science, v. 297, p. 174–219.

Roeder, D., and Chamberlain, R.L., 1995, Structural geology of Sub-Andean fold and thrust belt in northwestern Bolivia, *in* Tankard, A.J., Suárez Soruco, R., and Welsink, H.J., eds., Petroleum Basins of South America: American Association of Petroleum Geologists Memoir 62, p. 459–479.

Roots, C.F., 1983, Mount Harper Complex, Yukon: Early Paleozoic volcanism at the margin of the Mackenzie Platform, *in* Current Research, Part A: Geological Survey of Canada Paper 83-1A, p. 423–427.

Roots, C.F., Nelson, J.L., Simard, R.-L., and Harms, T.A., 2006, Continental fragments, mid-Paleozoic arcs and overlapping late Paleozoic arc and Triassic sedimentary strata in the Yukon-Tanana terrane of northern British Columbia and southern Yukon, *in* Colpron, M., and Nelson, J.L., eds., Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America, Canadian and Alaskan Cordillera: Geological Association of Canada Special Paper 45, p. 153–177.

Rose, P.R., 1977, Mississippian carbonate shelf margins, western United States, *in* Hill, J.G., ed., Geology of the Cordilleran Hingeline: Denver, Rocky Mountain Association of Geologists, p. 135–151.

Rosenbaum, G., and Lister, G.S., 2004, Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides: Tectonics, v. 23, TC1013, doi: 10.1029/2003TC001518.

Rosenbaum, G., Gasparon, M., Lucente, F.P., Peccarillo, A., and Miller, M.S., 2008, Kinematics of slab tear faults during subduction segmentation and implications for Italian magmatism: Tectonics, v. 27, TC2008, doi: 10.1029/2007TC002143.

Ross, G.M., Villeneuve, M.E., Parrish, R.R., and Bowring, S.A., 1991, Geophysics and geochronology of the crystalline basement of the Alberta Basin, Western Canada: Canadian Journal of Earth Sciences, v. 28, p. 512–522.

Ross, G.M., Patchett, R.J., Hamilton, M., Heaman, L., DeCelles, P.G., Rosenberg, E., and Giovanni, M.K., 2005, Evolution of the Cordilleran orogen (southwestern Alberta, Canada) inferred from detrital mineral geochronology, geochemistry, and Nd isotopes in the foreland basin: Geological Society of America Bulletin, v. 117, p. 747–763, doi: 10.1130/B25564.1.

Royden, L.H., 1993a, Evolution of retreating subduction boundaries formed during continental collision: Tectonics, v. 12, p. 629–638, doi: 10.1029/92TC02641.

Royden, L.H., 1993b, The tectonic expression of slab pull at continental convergent boundaries: Tectonics, v. 12, p. 303–325, doi: 10.1029/92TC02248.

Royse, F., Jr., 1993a, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir 5, p. 272–311.

Royse, F., Jr., 1993b, Case of the phantom foredeep: Early Cretaceous in west-central Utah: Geology, v. 21, p. 133–136, doi: 10.1130/0091-7613(1993)021<0133:COTPFE>2.3.CO;2.

Royse, F., Jr., Warner, M.A., and Reese, D.L., 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho–northern

Utah, *in* Bolyard, D.W., ed., Deep Drilling Frontiers of the Central Rocky Mountains: Denver, Rocky Mountain Association of Geologists, p. 41–54.

Rutland, C., Smedes, H.W., Tilling, R.I., and Greenwood, W.R., 1989, Volcanism and plutonism at shallow crustal levels: The Elkhorn Mountain volcanics and the Boulder batholith, southwestern Montana, *in* Chapin, C.E., and Zidek, J., eds., Field Excursions to Volcanic Terranes in the Western United States, Volume II: Cascades and Intermountain West: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 264–276.

Sacks, P.E., and Secor, D.T., 1990, Delamination in collisional orogens: Geology, v. 18, p. 999–1002, doi: 10.1130/0091-7613(1990)018<0999:DICO>2.3.CO;2.

Saleeby, J.B., and Busby-Spera, C., 1992, Early Mesozoic tectonic evolution of the western U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 107–168.

Saleeby, J.B., and Busby, C., 1993, Paleogeographic and tectonic setting of axial and western metamorphic framework rocks of the southern Sierra Nevada, California, *in* Dunne, G.C., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States—II: Los Angeles, SEPM (Society for Sedimentary Geology), Pacific Section, p. 197–226.

Saleeby, J., Farley, K.A., Kistler, R.W., and Fleck, R.J., 2007, Thermal evolution and exhumation of deep-level batholithic exposures, southernmost Sierra Nevada, California, *in* Cloos, M., Carlson, W.D., Gilbert, M.C., Liou, J.G., and Sorensen, S.S., eds., Convergent Margin Terranes and Associated Regions: A Tribute to W.G. Ernst: Geological Society of America Special Paper 419, p. 39–66.

Saleeby, J., Ducea, M.N., Busby, C., Nadin, E., and Wetmore, P.H., 2008, Chronology of pluton emplacement and regional deformation in the southern Sierra Nevada batholith, California, *in* Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson: Geological Society of America Special Paper 438, p. 397–427, doi: 10.1130/2008.2438(14).

Samson, S.D., Patchett, P.J., McClelland, W.C., and Gehrels, G.E., 1991, Isotopic constraints on the petrogenesis of the west side of the northern Coast Mountains batholith, Alaskan and Canadian Cordillera: Canadian Journal of Earth Sciences, v. 28, p. 939–946.

Schilling, F.R., and Partzsch, G.M., 2001, Quantifying partial melt fraction in the crust beneath the central Andes and the Tibetan Plateau: Physics and Chemistry of the Earth, v. 26, p. 239–246, doi: 10.1016/S1464-1895(01)00051-5.

Schirmer, T.W., 1985, Basement thrusting in north-central Utah: A model for the development of the northern Utah highland, *in* Kerns, G.J., and Kerns, R.L., Jr., eds., Orogenic Patterns and Stratigraphy of North-Central Utah and Southeastern Idaho: Salt Lake City, Utah Geological Association Publication 14, p. 129–143.

Schmidt, M.W., and Poli, S., 1998, Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation: Earth and Planetary Science Letters, v. 163, p. 361–379.

Schmidt, R.G., 1978, Rocks and Mineral Resources of the Wolf Creek Area, Lewis and Clark and Cascade Counties, Montana: U.S. Geological Survey Bulletin 1441, 91 p.

Scholten, R., 1982, Continental subduction in the northern U.S. Rockies—A model for back-arc thrusting in the western Cordillera, *in* Powers, R.B., ed., Geologic Studies of the Cordilleran Thrust Belt: Denver, Rocky Mountain Association of Geologists, p. 123–136.

Schuchert, C., 1923, Sites and nature of North American geosynclines: Geological Society of America Bulletin, v. 34, p. 151–229.

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, v. 9, p. 1609–1629, doi: 10.1029/TC009i006p01609.

Schweickert, R.A., and Lahren, M.M., 1993a, Triassic-Jurassic magmatic arc in eastern California and western Nevada: Arc evolution, cryptic tectonic breaks, and significance of the Mojave–Snow Lake fault, *in* Dunne, G.C., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States—II: Los Angeles, SEPM (Society for Sedimentary Geology), Pacific Section, p. 227–246.

Schweickert, R.A., and Lahren, M.M., 1993b, Tectonics of the east-central Sierra Nevada—Saddlebag Lake and northern Ritter Range pendants, *in* Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., eds., Crustal Evolution of the Great Basin and Sierra Nevada: Reno, Geological Society of America, Cordilleran/Rocky Mountain Section Guidebook, Department of Geological Sciences, University of Nevada, p. 313–351.

Schweickert, R.A., and Snyder, W.S., 1981, Paleozoic plate tectonics of the Sierra Nevada and adjacent regions, *in* Ernst, W.G., ed., The Geotectonic Evolution of California: Rubey Volume 1: Englewood Cliffs, New Jersey, Prentice Hall, p. 182–202.

Searle, M.P., Windley, B.F., Coward, M.P., Cooper, D.J.W., Rex, A.J., Rex, D., Tingdong, L., Xuchang, X., Jan, M.Q., Thakur, V.C., and Kumar, S., 1987, The closing of Tethys and the tectonics of the Himalaya: Geological Society of America Bulletin, v. 98, p. 678–701, doi: 10.1130/0016-7606(1987)98<678:TCOTAT>2.0.CO;2.

Sears, J.W., 1988, Two major thrust slabs in the west-central Montana Cordillera, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 165–170.

Sears, J.W., 2001, Emplacement and denudation history of the Lewis-Eldorado-Hoadley thrust slab in the northern Montana Cordillera, USA: Implications for steady-state orogenic processes: American Journal of Science, v. 301, p. 359–373, doi: 10.2475/ajs.301.4-5.359.

Sears, J.W., 2006, Montana transform: A tectonic cam surface linking thin- and thick-skinned Laramide shortening across the Rocky Mountain foreland: Rocky Mountain Geology, v. 41, p. 65–76, doi: 10.2113/gsrocky.41.2.65.

Sears, J.W., 2007, Belt Purcell basin: Keystone of the Rocky Mountain fold-and-thrust belt, United States and Canada, *in* Sears, J.W., Harms, T.A., and Evenchik, C.A., eds., Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 147–166, doi: 10.1130/2007.2433(07).

Shackelford, T.J., 1989, Structural geology of the Rawhide Mountains, Mohave County, Arizona, *in* Spencer, J.E., and Reynolds, S.J., eds., Geology and Mineral Resources of the Buckskin and Rawhide Mountains, West-Central Arizona: Arizona Geological Survey Bulletin 198, p. 15–46.

Sheehan, P.M., 1986, Late Ordovician and Silurian carbonate-platform margin near Bovine and Lion mountains, northwestern Utah: Late Ordovician and Silurian of the eastern Great Basin, Part 7: Milwaukee Public Museum Contributions in Biology and Geology 70, 16 p.

Silberling, N.J., Nichols, K.M., Trexler, J.H., Jr., Jewell, P.W., and Crosbie, R.A., 1997, Overview of Mississippian depositional and paleotectonic history of the Antler foreland, eastern Nevada and western Utah, *in* Link, P.K., and Kowallis, B.J., eds., Proterozoic to Recent Stratigraphy, Tectonics, and Volcanology, Utah, Nevada, Southern Idaho and Central Mexico: Provo, Brigham Young University Geology Studies, v. 42, p. 161–196.

Silver, L.T., and Anderson, T.H., 1974, Possible left-lateral early to middle Mesozoic disruption of the southwestern North American craton margin: Geological Society of America Abstracts with Programs, v. 6, no. 7, p. 955–956.

Silver, L.T., and Chappell, B., 1988, The Peninsular Ranges batholith: An insight into the Cordilleran batholiths of southwestern North America: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 79, p. 105–121.

Silverberg, D.S., 1990, The tectonic evolution of the Pioneer metamorphic core complex, south-central Idaho [Ph.D. thesis]: Cambridge, Massachusetts Institute of Technology, 289 p.

Simony, P.S., 1992, Ancestral North America and Kootenay arc, *in* Geological Survey of Canada, Geology of Canada, no. 4 (also Geological Society of America, Geology of North America, v. G-2), p. 615–620.

Skipp, B., 1987, Basement thrust sheets in the Clearwater orogenic zone, central Idaho and western Montana: Geology, v. 15, p. 220–224, doi: 10.1130/0091-7613(1987)15<220:BTSITC>2.0.CO;2.

Skipp, B., and Hait, M.H., Jr., 1977, Allochthons along the northeast margin of the Snake River plain, Idaho, *in* Heisey, E.L., and Lawson, D.E., eds., Rocky Mountain thrust belt geology and resources: Casper, Wyoming Geological Association, Annual Field Conference, 29th, p. 499–516.

Smith, D.L., Wyld, S.J., Wright, J.E., and Miller, E.L., 1993, Progression and timing of Mesozoic crustal shortening in the northern Great Basin, western U.S.A., *in* Dunne, G., and McDougall, K., eds., Mesozoic Paleogeography of the Western United States—II: Los Angeles, SEPM (Society for Sedimentary Geology), Pacific Section, Book 71, p. 389–406.

Smith, M.L., and Gehrels, G.E., 1992a, Structural geology of the Lardeau Group near Trout Lake, British Columbia: Implications for the structural evolution of the Kootenay Arc: Canadian Journal of Earth Sciences, v. 29, p. 1305–1319.

Smith, M.L., and Gehrels, G.E., 1992b, Stratigraphic comparison of the Lardeau and Covada groups: Implications for revision of stratigraphic relations in the Kootenay Arc: Canadian Journal of Earth Sciences, v. 29, p. 1320–1329.

Smithson, S.B., Brewer, J.A., Kaufman, S., Oliver, J.E., and Hurich, C.A., 1979, Structure of the Laramide Wind River Uplift, Wyoming, from COCORP deep reflection data and from gravity data: Journal of Geophysical Research, v. 84, p. 5955–5972, doi: 10.1029/JB084iB11p05955.

Snoke, A.W., 1980, Transition from infrastructure to suprastructure in the northern Ruby Mountains, Nevada, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran Metamorphic Core Complexes: Geological Society of America Memoir 153, p. 287–333.

Snoke, A.W., and Miller, D.M., 1988, Metamorphic and tectonic history of the northeastern Great Basin, *in* Ernst, W.G., ed., Metamorphic and Crustal Evolution of the Western United States: Englewood Cliffs, New Jersey, Prentice Hall, p. 606–648.

Snow, J.K., 1992, Large-magnitude Permian shortening and continental-margin tectonics in the southern Cordillera: Geological Society of America Bulletin, v. 104, p. 80–105, doi: 10.1130/0016-7606(1992)104<0080:LMPSAC>2.3.CO;2.

Solomon, M., 1990, Subduction, arc reversal, and the origin of porphyry copper-gold deposits in island arcs: Geology, v. 18, p. 630–633, doi: 10.1130/0091-7613(1990)018<0630:SARATO>2.3.CO;2.

Sonder, L.J., and Jones, C.H., 1999, Western United States extension: How the west was widened: Annual Review of Earth and Planetary Sciences, v. 27, p. 417–462, doi: 10.1146/annurev.earth.27.1.417.

Speed, R.C., 1977, Island arc and other paleogeographical terranes of late Paleozoic age in the western Great Basin, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic Paleogeography of the Western United States: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, 1st, p. 349–362.

Spence, W., 1987, Slab pull and the seismotectonics of subducting lithosphere: Reviews of Geophysics, v. 25, p. 55–69, doi: 10.1029/RG025i001p00055.

Spencer, J.E., Richard, S.M., and Ferguson, C.A., 2001, Cenozoic structure and evolution of the boundary between the Basin and Range and Transition Zone provinces in Arizona, *in* Erskin, M.C., Faulds, J.E., Bartley, J.M., and Rowley, P.D., eds., The Geologic Transition, High Plateaus to Great Basin—A Symposium and Field Guide: Salt Lake City, Utah Geological Association Publication 30, p. 273–289.

Stein, H.J., and Crock, J.G., 1990, Late Cretaceous–Early Tertiary magmatism in the Colorado Mineral Belt: Rare earth element and samarium-neodymium isotopic studies, *in* Anderson, J.L., ed., The Nature and Origin of Cordilleran Magmatism: Geological Society of America Memoir 174, p. 195–223.

Stevens, C.H., and Stone, P., 2007, The Pennsylvanian–Early Permian Bird Spring Carbonate Shelf, Southeastern California: Fusulinid Biostratigraphy, Paleogeographic Evolution, and Tectonic Implications: Geological Society of America Special Paper 429, 82 p.

Stevens, C.H., Stone, P., and Kistler, R.W., 1992, A speculative reconstruction of the middle Paleozoic continental margin of southwestern North America: Tectonics, v. 11, p. 405–419, doi: 10.1029/91TC02884.

Stevens, C.H., Stone, P., Dunne, G.C., Greene, D.C., Walker, J.D., and Swanson, B.J., 1998, Paleozoic and Mesozoic evolution of east-central California, *in* Ernst, W.G., and Nelson, C.A., eds., Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall Jr. Volume: Boulder, Colorado, Geological Society of America, p. 119–160.

Stewart, J.H., 1970, Upper Precambrian and Lower Cambrian Strata in the Southern Great Basin, California and Nevada: U.S. Geological Survey Professional Paper 620, 206 p.

Stewart, J.H., 1972, Initial deposits of the Cordilleran geosyncline—Evidence of late Precambrian (<850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, p. 1345–1360, doi: 10.1130/0016-7606(1972)83[1345:IDITCG]2.0.CO;2.

Stewart, J.H., 2005, Evidence for Mojave-Sonora megashear—Systematic left-lateral offset of Neoproterozoic to Lower Jurassic strata and facies, western United States and northwestern Mexico, *in* Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., eds., The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives: Geological Society of America Special Paper 393, p. 209–231, doi: 10.1130/2005.2393(05).

Stewart, J.H., and Poole, F.G., 1974, Lower Paleozoic and uppermost Precambrian Cordilleran miogeocline, Great Basin, western United States, *in* Dickinson, W.R., ed., Tectonics and Sedimentation: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 28–57.

Stewart, J.H., Gehrels, G.E., Barth, A.P., Link, P.K., Christie-Blick, N., and Wrucke, C.T., 2001, Detrital zircon provenance of Mesoproterozoic to Cambrian arenites in the western United States and northwestern Mexico: Geological Society of America Bulletin, v. 113, p. 1343–1356, doi: 10.1130/0016-7606(2001)113<1343:DZPOMT>2.0.CO;2.

Stewart, J.H., Amaya-Martinez, R., and Palmer, A.R., 2002, Neoproterozoic and Cambrian strata of Sonora, Mexico: Rodinian supercontinent to Laurentian Cordilleran margin, *in* Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Geological Society of America Special Paper 365, p. 5–48.

Stewart, W.D., Dixon, O.A., and Rust, B.R., 1993, Middle Cambrian carbonate-platform collapse, southeastern Canadian Rocky Mountains: Geology, v. 21, p. 687–690, doi: 10.1130/0091-7613(1993)021<0687:MCCPCS>2.3.CO;2.

Stöcklin, J., 1974, Possible ancient continental margins in Iran, *in* Burke, C.A., and Drake, C.L., eds., The Geology of Continental Margins: New York, Springer-Verlag, p. 873–887.

Stockmal, G.S., Beaumont, C., and Boutilier, R., 1986, Geodynamic models of convergent margin tectonics: Transition from rifted margin to overthrust belt and consequence of foreland basin development: American Association of Petroleum Geologists Bulletin, v. 70, p. 181–190.

Stockmal, G.S., Cant, D.J., and Bell, J.S., 1992, Relationship of the stratigraphy of the western Canada foreland basin to Cordilleran tectonics: Insights from geodynamic models, *in* MacQueen, R.W., and Leckie, D.A., eds., Foreland Basins and Fold Belts: Tulsa, Oklahoma, American Association of Petroleum Geologists Memoir 55, p. 107–124.

Stokes, W.L., 1976, What is the Wasatch Line? *in* Hill, J.G., ed., Geology of the Cordilleran Hingeline: Denver, Rocky Mountain Association of Geologists, p. 11–25.

Stolper, E., and Newman, S., 1994, The role of water in the petrogenesis of Mariana trough magmas: Earth and Planetary Science Letters, v. 121, p. 293–325, doi: 10.1016/0012-821X(94)90074-4.

Stone, P., Howard, K.A., and Hamilton, W., 1983, Correlation of metamorphosed Paleozoic strata of the southeastern Mojave Desert region, California and Arizona: Geological Society of America Bulletin, v. 94, p. 1135–1147, doi: 10.1130/0016-7606(1983)94<1135:COMPSO>2.0.CO;2.

Suppe, J., 1984, Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan: Beijing, Geological Society of China Memoir 6, p. 21–33.

Suppe, J., 1987, The active Taiwan mountain belt, *in* Schaer, J.P., and Rodgers, J., eds., Anatomy of Mountain Ranges: Princeton, New Jersey, Princeton University Press, p. 277–293.

Suter, M., 1987, Structural traverse across the Sierra Madre Oriental fold-thrust belt in east-central Mexico: Geological Society of America Bulletin, v. 98, p. 249–264, doi: 10.1130/0016-7606(1987)98<249:STATSM>2.0.CO;2.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: Application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26–44, doi: 10.1130/0016-7606(1984)95<26:AASOLA>2.0.CO;2.

Taira, A., Saito, S., Aoike, K., Morita, S., Tokuyama, H., Suyehiro, K., Takahashi, N., Shinohara, M., Kiyokawa, S., Naka, J., and Klaus, A., 1998, Nature and growth rate of the northern Izu-Bonin (Ogasawara) arc crust and their implications for continental crust formation: Island Arc, v. 7, p. 395–407.

Tardy, M., Lapierre, H., Freydier, C., Coulon, C., Gill, J.-B., Mercier de Lepinay, B., Beck, C., Martinez, R.J., Talavera, M.O., Ortiz, H.E., Stein, G., Bourdier, J.-L., and Yta, M., 1994, The Guerrero suspect terrane (western Mexico) and coeval arc terranes (the Greater Antilles and the Western Cordillera of Columbia): A late Mesozoic intra-oceanic arc accreted to cratonal America during the Cretaceous: Tectonophysics, v. 230, p. 49–73.

Tatsumi, Y., Hamilton, D.L., and Nesbitt, R.W., 1986, Chemical characteristics of fluid phase released from a subducted lithosphere and origin of arc magmas: Evidence from high-pressure experiments and natural rocks: Journal of Volcanology and Geothermal Research, v. 29, p. 293–309, doi: 10.1016/0377-0273(86)90049-1.

Taylor, W.J., Bartley, J.M., Martin, M.W., Geissman, J.W., Walker, J.D., Amstrong, P.A., and Fryxell, J.E., 2000, Relations between hinterland and foreland shortening: Sevier orogeny, central North American Cordillera: Tectonics, v. 19, p. 1124–1143, doi: 10.1029/1999TC001141.

Teng, L.S., Lee, C.T., Tsai, Y.B., and Hsiao, L., 2000, Slab breakoff as a mechanism for flipping of subduction polarity in Taiwan: Geology, v. 28, p. 155–158, doi: 10.1130/0091-7613(2000)28<155:SBAAMF>2.0.CO;2.

Teyssier, C., Ferré, E.C., Whitney, D.L., Norlander, B., Vanderhaeghe, O., and Parkinson, D., 2005, Flow of partially molten crust and origin of detachments during collapse of the Cordilleran Orogen, *in* Bruhn, D., and Burlini, L., eds., High-Strain Zones: Structure and Physical Properties: Geological Society [London] Special Publication 245, p. 39–64.

Thorkelson, D.J., and Taylor, R.P., 1989, Cordilleran slab windows: Geology, v. 17, p. 833–836, doi: 10.1130/0091-7613(1989)017<0833:CSW>2.3.CO;2.

Till, A.B., Roeske, S.M., Bradley, D.C., Friedman, R., and Layer, P.W., 2007, Early Tertiary transtension-related deformation and magmatism along the Tintina fault system, Alaska, *in* Till, A.B., Roeske, S.M., Sample, J.C., and Foster, D.A., eds., Exhumation Associated with Continental Strike-Slip Fault Systems: Geological Society of America Special Paper 434, p. 233–264, doi: 10.1130/2007.2434(11).

Titley, S.R., 1976, Evidence for a Mesozoic linear tectonic pattern in southeastern Arizona: Arizona Geological Society Digest, v. 10, p. 71–101.

Titley, S.R., 1982, Geologic setting of porphyry copper deposits: Southeastern Arizona, *in* Titley, S.R., ed., Advances in Geology of the Porphyry Copper Deposits: Southwestern United States: Tucson, University of Arizona Press, p. 37–58.

Titley, S.R., and Anthony, E.Y., 1989, Laramide mineral deposits in Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Arizona Geological Society Digest, v. 17, p. 485–514.

Todd, S.P., Murphy, F.C., and Kennan, P.S., 1991, On the trace of the Iapetus suture in Ireland and Britain: Journal of the Geological Society [London], v. 148, p. 869–880, doi: 10.1144/gsjgs.148.5.0869.

Todd, V.R., 1980, Structure and petrology of a Tertiary gneiss complex in northwestern Utah, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran Metamorphic Core Complexes: Geological Society of America Memoir 153, p. 349–383.

Tosdal, R.M., 1990, Tectonics of the Mule Mountains thrust system, southeast California and southwest Arizona: Journal of Geophysical Research, v. 95, p. 20,035–20,048, doi: 10.1029/JB095iB12p20025.

Tosdal, R.M., and Stone, P., 1994, Statigraphic relations and U-Pb geochronology of the Upper Cretaceous McCoy Mountains Formation, southwestern Arizona: Geological Society of America Bulletin, v. 106, p. 476–491, doi: 10.1130/0016-7606(1994)106<0476:SRAUPG>2.3.CO;2.

Toth, M.I., and Stacey, J.S., 1992, Constraints on the Formation of the Bitterroot Lobe of the Idaho Batholith, Idaho, and Montana from U-Pb Zircon Geochronology and Feldspar Pb Isotopic Data: U.S. Geological Survey Bulletin 2008, 14 p.

Toussaint, J.F., and Restrepo, J.J., The Colombian Andes during Cretaceous times, *in* Salfity, J.A., ed., Cretaceous Tectonics of the Andes: Wiesbaden, Germany, Vieweb, p. 61–100.

Tucker, E.W., 1983, Variations in structural style and correlation of thrust plates in the Sevier foreland thrust belt, Great Salt Lake area, Utah, *in* Miller, D.M., Todd, V.R., and Howard, D.A., eds., Tectonic and Stratigraphic Studies in the Eastern Great Basin: Geological Society of America Memoir 157, p. 101–124.

Turner, R.J.W., Madrid, R.J., and Miller, E.L., 1989, Roberts Mountain allochthon: Stratigraphic comparison with lower Paleozoic outer continental margin strata of the northern Canadian Cordillera: Geology, v. 17, p. 341–344, doi: 10.1130/0091-7613(1989)017<0341:RMASCW>2.3.CO;2.

Ulmer, P., 2001, Partial melting in the mantle wedge—The role of H_2O in the genesis of mantle-derived "arc-related" magmas: Physics of the Earth and Planetary Interiors, v. 127, p. 215–232.

Umhoefer, P.J., 2000, Where are the missing faults in translated terranes?: Tectonophysics, v. 326, p. 23–35, doi: 10.1016/S0040-1951(00)00144-X.

Umhoefer, P.J., 2003, A model for the North American Cordillera in the Early Cretaceous: Tectonic escape related to arc collision of the Guerrero terrane and a change in North American plate motion, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., and Martin-Barajas, A., eds., Tectonic Evolution of Northwestern Mexico and the Southwestern USA: Geological Society of America Special Paper 374, p. 117–134.

Vail, P.R., Mitchum, R.M., Jr., Shipley, T.H., and Buffler, R.T., 1980, Unconformities of the North Atlantic, *in* Kent, P., Laughton, A.S., Roberts, D.G., and Jones, E.W.J., eds., The Evolution of Passive Continental Margins in the Light of Recent Deep Drilling Results: Philosophical Transactions of the Royal Society of London, ser. A, v. 294, p. 137–155.

Valencia-Moreno, M., Ochoa-Landín, L., Noguez-Alcántara, B., Ruiz, J., and Pérez-Segura, E., 2006, Caracterîsticas metalogenéticas de los dépositos de tipo pórfido cuprífero en México y su situacíon en el contexto mudial: Boletín de la Sociedad Geológica Mexica, v. 63, p. 1–26.

Valencia-Moreno, M., Ochoa-Landín, L., Noguez-Alcántara, B., Ruiz, J., and Pérez-Segura, E., 2007, Geological and metallogenetic characteristics of the porphyry copper deposits of Mexico and their situation in the world context, *in* Alaniz-Alvarez, S.A., and Nieto-Samaniego, Á.F., eds., Geology of Mexico: Celebrating the Centenary of the Geological Society of Mexico: Geological Society of America Special Paper 422, p. 433–458, doi: 10.1130/2007.2422(16).

Valley, P.M., Whitney, D.L., Paterson, S.R., Miller, R.B., and Alsleben, H., 2003, Metamorphism of the deepest exposed arc rocks in the Cretaceous to Paleogene Cascades belt, Washington: Evidence for large-scale vertical motion in a continental arc: Journal of Metamorphic Geology, v. 21, p. 203–220, doi: 10.1046/j.1525-1314.2003.00437.x.

Van Bemmelen, R.W., 1949, The Geology of Indonesia: The Hague, Martinus Nijhoff, 732 p.

van der Heyden, P., 1992, A Middle Jurassic to Early Tertiary Andean-Sierran arc model for the coast belt of British Columbia: Tectonics, v. 11, p. 82–97, doi: 10.1029/91TC02183.

Venkat-Ramani, M., and Tikoff, B., 2002, Physical models of transtension folding: Geology, v. 30, p. 523–526, doi: 10.1130/0091-7613(2002)030<0523:PMOTF>2.0.CO;2.

Verstappen, H.Th., 1959, Geomorphology and crustal movements of the Aru islands in relation to the Pleistocene drainage of the Sahul shelf: American Journal of Science, v. 257, p. 491–502.

Vogl, J.J., Calvert, A.T., and Gans, P.B., 2002, Mechanisms and timing of exhumation of collision-related metamorphic rocks, southern Brooks Range, Alaska: Insights from ^{40}Ar/^{39}Ar thermochronology: Tectonics, v. 21, 1011, doi: 10.1029/2000TC001270.

Wadsworth, W.B., Ferriz, H., and Rhodes, D.D., 1995, Structural and magmatic development of the Middle Jurassic magmatic arc in the Cowhole Mountains, central-eastern Mojave Desert, California, *in* Miller, D.M., and Busby-Spera, C., eds., Jurassic Magmatism and Tectonics of the North American Cordillera: Geological Society of America Special Paper 299, p. 327–349.

Walker, J.D., Burchfiel, B.C., and Davis, G.A., 1995, New age controls on initiation and timing of foreland belt thrusting in the Clark Mountains, southern California: Geological Society of America Bulletin, v. 107, p. 742–750, doi: 10.1130/0016-7606(1995)107<0742:NACOIA>2.3.CO;2.

Wallace, C.A., Lidke, D.J., and Schmidt, R.G., 1990, Faults of the central part of the Lewis and Clark line and fragmentation of the Late Cretaceous foreland basin in west-central Montana: Geological Society of America Bulletin, v. 102, p. 1021–1037, doi: 10.1130/0016-7606(1990)102<1021:FOTCPO>2.3.CO;2.

Watts, A.B., Karner, G.D., and Steckler, M.S., 1982, Lithospheric flexure and the evolution of sedimentary basins, *in* Kent, P., Bott, M.H.P., McKenzie, D.P., and Williams, C.A., eds., The Evolution of Sedimentary Basins: Philosophical Transactions of the Royal Society of London, ser. A., v. 305, p. 249–281.

Wells, M.L., 1992, Kinematics and timing of sequential deformations in the eastern Raft River Mountains, *in* Wilson, J.R., ed., Field Guide to Geologic Excursions in Utah and Adjacent Areas of Nevada, Idaho, and Wyoming: Geological Society of America Miscellaneous Publication 92-3, p. 59–78.

Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-3, p. 553–581.

Wernicke, B., and Klepacki, D.W., 1988, Escape hypothesis for the Stikine block: Geology, v. 16, p. 461–464, doi: 10.1130/0091-7613(1988)016<0461:EHFTSB>2.3.CO;2.

Wernicke, B.P., Christiansen, R.L., England, P.C., and Sonder, L.J., 1987, Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental Extensional Tectonics: Geological Society [London] Special Publication 28, p. 203–221.

Wernicke, B., Axen, G.J., and Snow, J.K., 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738–1757, doi: 10.1130/0016-7606(1988)100<1738:BARETA>2.3.CO;2.

Westerveld, J., 1953, Eruptions of acid pumice tuffs and related phenomena along the Great Sumatran Fault-Trough systems: Proceedings of the Pacific Science Congress, 7th, v. 2, p. 411–438.

Wheeler, J.O., and McFeely, P., 1991, Tectonic Assemblage Map of the Canadian Cordillera and Adjacent Parts of the United States of America: Geological Survey of Canada Map 1712A, scale 1:2,000,000, 2 sheets.

Wheeler, J.O., Brookfield, A.J., Gabrielse, H., Monger, J.W.H., Tipper, H.W., and Woodsworth, G.J., 1991, Terrane Map of the Canadian Cordillera: Geological Survey of Canada Map 1713A, scale 1:2,000,000, 2 sheets.

White, T., Furlong, K., and Arthur, M., 2002, Forebulge migration in the Cretaceous Western Interior Basin of the central United States: Basin Research, v. 14, p. 43–54, doi: 10.1046/j.1365-2117.2002.00165.x.

Whiteford, W.B., 1990, Paleozoic setting of the Schoonover sequence, Nevada, and implications for the late Paleozoic margin of western North America, *in* Harwood, D.S., and Miller, M.M., eds., Late Paleozoic and Early Mesozoic Paleogeographic Relations: Klamath Mountains, Sierra Nevada, and Related Rocks: Geological Society of America Special Paper 255, p. 115–136.

Wilson, A.B., and Sims, P.K., 2003, Colorado Mineral Belt revisited—An analysis of new data: U.S. Geological Survey Open-File Report 03-046, 7 p.

Wright, J.E., and Wooden, J.L., 1991, New Sr, Nd, and Pb isotopic data from plutons in the northern Great Basin: Implications for crustal structure and granite petrogenesis in the hinterland of the Sevier thrust belt: Geology, v. 19, p. 457–460, doi: 10.1130/0091-7613(1991)019<0457:NSNAPI>2.3.CO;2.

Wright, J.E., and Wyld, S.J., 2006, Gondwanan, Iapetan, Cordilleran interactions: A geodynamic model for the Paleozoic tectonic evolution of the North American Cordillera, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence for and against Large-Scale Displacements: St. John's, Newfoundland, Geological Association of Canada Special Paper 46, p. 377–408.

Wust, S.L., 1986, Regional correlation of extension directions in Cordilleran metamorphic core complexes: Geology, v. 14, p. 828–830.

Wust, S.L., and Link, P.K., 1988, Field guide to the Pioneer Mountains core complex, south-central Idaho, *in* Link, P.K., and Hackett, W.R., eds., Guidebook to the Geology of Central and Southern Idaho: Idaho Geological Survey Bulletin 27, p. 43–54.

Wyld, S.J., 1990, Paleozoic and Mesozoic rocks of the Pine Forest Range, northwest Nevada, and their relation to volcanic arc assemblages of the western U.S. Cordillera, *in* Harwood, D.S., and Miller, M.M., eds., Late Paleozoic and Early Mesozoic Paleogeographic Relations: Klamath Mountains, Sierra Nevada, and Related Rocks: Geological Society of America Special Paper 255, p. 219–237.

Wyld, S.J., 2000, Triassic evolution of the arc and backarc of northwestern Nevada, the evidence for extensional tectonism, *in* Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic Paleogeography and Tectonics of Western Nevada and Northern California: Geological Society of America Special Paper 347, p. 185–207.

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: American Journal of Science, v. 301, p. 150–181, doi: 10.2475/ajs.301.2.150.

Wyld, S.J., and Wright, J.E., 2005, Early Cretaceous, margin-parallel, dextral faulting and terrane translation in the U.S. Cordillera: Geological Society of America Abstracts with Programs, v. 37, no. 4, p. 102.

Wyld, S.J., and Wright, J.E., 2007, Cretaceous dextral strike-slip faulting in the North American Cordillera: Where do we go from here?: Geological Society of America Abstracts with Programs, v. 39, no. 4.

Wyld, S.J., Quinn, M.J., and Wright, J.E., 1996, Anomalous(?) Early Jurassic deformation in the western U.S. Cordillera: Geology, v. 24, p. 1037–1040, doi: 10.1130/0091-7613(1996)024<1037:AEJDIT>2.3.CO;2.

Wyld, S.J., Rogers, J.W., and Copeland, P., 2003, Metamorphic evolution of the Luning-Fencemaker fold-thrust belt, Nevada: Illite crystallinity, metamorphic petrology, and ^{40}Ar^{39}Ar geochronology: Journal of Geology, v. 111, p. 17–38, doi: 10.1086/344663.

Wyld, S.J., Umhoefer, P.J., and Wright, J.E., 2006, Reconstructing northern Cordilleran terranes along known Cretaceous and Cenozoic strike-slip faults: Implications for the Baja British Columbia hypothesis and other models, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence for and against Large-Scale Displacements: St. John's, Newfoundland, Geological Association of Canada Special Paper 46, p. 277–298.

Wynne, P.J., Irving, E., Maxson, J.A., and Kleinspehn, K.L., 1995, Paleomagnetism of the Upper Cretaceous strata of Mount Tatlow: Evidence for 3000 km of northward displacement of the eastern Coast Belt, British Columbia: Journal of Geophysical Research, v. 100, p. 6073–6091.

Wynne, P.J., Enkin, R.J., Baker, J., Johnston, S.T., and Hart, C.J.R., 1998, The big flush: Paleomagnetic signature of a 70 Ma regional hydrothermal event in displaced rocks of the northern Canadian Cordillera: Canadian Journal of Earth Sciences, v. 35, p. 657–671, doi: 10.1139/cjes-35-6-657.

Yingling, V.L., and Heller, P.L., 1992, Timing and record of foreland sedimentation during the initiation of the Sevier orogenic belt in central Utah: Basin Research, v. 4, p. 279–290, doi: 10.1111/j.1365-2117.1992.tb00049.x.

Yonkee, W.A., 1992, Basement-cover relations, Sevier orogenic belt, northern Utah: Geological Society of America Bulletin, v. 104, p. 280–302, doi: 10.1130/0016-7606(1992)104<0280:BCRSOB>2.3.CO;2.

Yonkee, W.A., Parry, W.T., Bruhn, R.L., and Cashman, P.C., 1989, Thermal models of thrust faulting: Constraints from fluid inclusion observations, Willard thrust sheet, Idaho-Utah-Wyoming thrust belt: Geological Society of America Bulletin, v. 101, p. 304–313, doi: 10.1130/0016-7606(1989)101<0304:TMOTFC>2.3.CO;2.

Yonkee, W.A., Parry, W.T., and Bruhn, R.L., 2003, Relations between progressive deformation and fluid-rock interaction during shear zone growth in a basement-cored thrust sheet, Sevier orogenic belt, Utah: American Journal of Science, v. 303, p. 1–59, doi: 10.2475/ajs.303.1.1.

Yu, H.-S., and Chou, Y.-W., 2001, Characteristics and development of the flexural forebulge and basal unconformity of Western Taiwan Foreland Basin: Tectonophysics, v. 333, p. 277–291, doi: 10.1016/S0040-1951(00)00279-1.

Zaleha, M.J., 2006, Sevier orogenesis and nonmarine basin filling: Implications of new stratigraphic correlations of Lower Cretaceous strata throughout Wyoming, USA: Geological Society of America Bulletin, v. 118, p. 886–896, doi: 10.1130/B25715.1.

Zaleha, M.J., and Wiesemann, S.A., 2005, Hyperconcentrated flows and gastroliths: Sedimentology of diamictites and wackes of the Cloverly Formation, Lower Cretaceous, Wyoming, U.S.A.: Journal of Sedimentary Research, v. 75, p. 43–54, doi: 10.2110/jsr.2005.005.

Zen, E., and Hammarstrom, J.A., 1984, Magmatic epidote and its petrologic significance: Geology, v. 12, p. 515–518, doi: 10.1130/0091-7613(1984)12<515:MEAIPS>2.0.CO;2.

Zimmermann, J.L., Stussi, J.M., Gonzalez Partida, E., and Arnold, M., 1988, K-Ar evidence for age and compositional zoning in the Puerta Vallerta–Rio Santiago Batholith (Jalisco, Mexico): Journal of South American Earth Sciences, v. 1, p. 267–274, doi: 10.1016/0895-9811(88)90005-3.

Manuscript Accepted by the Society 2 March 2009

Printed in the USA

Contents

THE GEOLOGICAL SOCIETY OF AMERICA®

3300 Penrose Place ▪ P.O. Box 9140
Boulder, CO 80301-9140, USA

ISBN 978-0-8137-2457-7
9 780813 724577