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Subduction cycles under western North America during the Mesozoic and Cenozoic eras

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ABSTRACT

An extensive review of geologic and tectonic features of western North America suggests that the interaction of oceanic plates with the continent follows a broad cyclical pattern. In a typical cycle, periods of rapid subduction (7–15 cm/yr), andesitic volcanism, and trench-normal contraction are followed by a shift to trench-normal extension, the onset of voluminous silicic volcanism, formation of large calderas, and the creation of major batholiths. Extension becomes pervasive in metamorphic core complexes, and there is a shift to fundamentally basaltic volcanism, formation of flood basalts, widespread rifting, rotation of terranes, and extensive circulation of fluids throughout the plate margin. Strike-slip faulting becomes widespread with the creation of new tectonostratigraphic terranes. A new subduction zone forms and the cycle repeats. Each cycle is 50–80 m.y. long; cycles since the Triassic have ended and begun at approximately 225, 152, 92, 44, and 15 Ma. The youngest two cycles are diachronous, one from Oregon to Alaska, the other from central Mexico to California. The transitions from one cycle to the next cycle are characterized by rapid and pervasive changes termed, in this chapter, "major chaotic tectonic events." These events appear to be related to the necking or breaking apart of the formerly subducted slab at shallow depth, the resulting delamination of the plate margin, and the onset of a new subduction cycle. These are times of the most rapid apparent and true polar wander of the North American plate, when the plate appears most free to move relative to surrounding plates and relative to the mantle below the asthenosphere. In western North America, magmatism and tectonics during the Jurassic period are quite similar to magmatism and tectonics since mid-Cretaceous time except strike-slip faulting shifted in sense from left lateral to right lateral.

INTRODUCTION

Plate-tectonic models invoked to explain geologic observations in western North America commonly involve one or more of the following assumptions or hypotheses. This chapter suggests that they need to be reconsidered.

1. Subduction beneath western North America was relatively continuous during the Mesozoic and Cenozoic eras.

2. Voluminous calc-alkalic volcanism is evidence for subduction-related volcanic-arc activity.

3. Major batholiths such as the Sierra Nevada of California are the roots of subduction-related volcanic arcs.

4. The East Pacific rise was subducted under California affecting magmatism in the plate margin.

5. Magmatism in western North America was primarily affected by major changes in the dip of the subducted plate.

6. Collision of arc terranes or thickened oceanic crust with the western North American plate margin caused major orogenies within the continental margin.

These concepts were proposed and elaborated early in the history of plate tectonics before detailed data were available on plate motions, magmatic provinces, and the nature of tectono stratigraphic terranes. After more than two decades of very productive research, extensive and detailed data are now available

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to test and quantify these concepts. Plate motions in the northeast Pacific and the rates of convergence of these plates with the North American plate during Cretaceous and Tertiary time have been studied in more detail than anywhere else in the world. Radiometric ages for tens of thousands of rocks provide extensive mileposts for times of change in tectonic and magmatic conditions. Increasingly detailed structural studies are finding many specific periods of deformation and changes in strain, ranging from less than a few million years to some tens of million years in length.

The primary goal of this chapter is to summarize the major geologic events in western North America since the beginning of the Triassic period that bear on the interactions of oceanic plates in the northeast Pacific Ocean with the continent. Evidence is presented for limited periods of rapid subduction during trench-normal contraction, voluminous silicic magmatism during regional extension, and fundamentally basaltic volcanism accompanying major lateral motion. After compiling these data, it becomes clear that they follow a broad cyclical pattern and the evidence for each cycle is discussed. The cycles are separated by sudden changes that are termed "major chaotic tectonic events" in this chapter. The evidence for what happens during these events is summarized. In the last section, a possible model and thoughts about the mechanisms are discussed.

The basic cycle of tectonism and magmatism was first recognized during a study of rapid subduction that slowed as the East Pacific rise arrived close to the trench west of northern Mexico during Tertiary time (Ward, 1991). A transtensional strain regime and one of the largest batholiths in the world, the Sierra Madre Occidental, then formed along the landward side of the former volcanic arc to the east of the trench. Major distension of the crust followed in a narrow but elongate belt of metamorphic core complexes located primarily in southern Arizona between the northwestern tip of the batholith and the trench. This extension culminated in the formation of the Basin and Range province. A new terrane separated from the area to the west of the batholith and began moving to the northwest along the San Andreas fault system.

In this chapter, the evidence for tectonic events and magmatism is compiled in tables and figures accompanied by associated text. The figures contain only the best documented data, the text describes other relevant data, and interpretation is concentrated in the last section of this chapter. In order to keep the list of references to a publishable length, the most recent references are typically cited as places to find the older references. All K/Ar ages reported are corrected for new decay constants where appropriate (Dalrymple, 1979). The correlations of radiometric dates with geologic ages in this chapter are based on the time scale published by Harland et al. (1990). Geologic ages are used in this chapter where the radiometric ages are unknown or not clear. A range of radiometric ages is typically given in parentheses after a geologic age in order to help the reader relate the two types of ages. Such a range means only that the age or age range of interest is thought to be included somewhere within the range given. The term uplift is used in this chapter in the relative sense of a structurally high area typically detected by an unconformity or by the nature of surrounding sedimentary rocks.

EVIDENCE FOR LIMITED INTERVALS OF RAPID SUBDUCTION SINCE THE TRIASSIC

Calculations of relative plate motion

Engebretson et al. (1985) estimated the rates of motion of the Farallon, Kula, and Pacific plates relative to the North American plate, assuming that the Pacific and Atlantic hotspots remained fixed in space relative to each other (Fig. 1A–C). Rea and Duncan (1986) obtained similar results by the same method except they calculated total convergence at rates of 15–20 cm/yr between 80 Ma and 65 Ma under the coast of Oregon (45°N).

Rates at times younger than 84 Ma are relatively well constrained and agree in general with more detailed calculations by Stock and Molnar (1988), who used the plate-circuit approach paying special attention to errors. All three studies agree that the Farallon plate and the Vancouver or Juan de Fuca plate, which broke from it at approximately 55 Ma, were subducted under California at rates of 10–20 cm/yr from approximately 74 Ma to 43 Ma and that convergence has been much slower and has involved some right-lateral strike-slip since that time.

Rates of convergence for periods older than 84 Ma are based on several assumptions that are subject to considerable debate. The first assumption is that the Mid-Pacific Mountains (20°N, 170°–190°W) are the Z-shaped track of a hotspot formed between 145 Ma and 110 Ma and that a similar Z-shaped track is found in the Shatsky and Hess rises to the north (Engebretson et al., 1985). Newer data indicate that the central leg of the Z along the Hess rise formed between 116 Ma and 95 Ma (Vallier et al., 1981; Dalrymple et al., 1990). Windom et al. (1981) argued that the Hess rise was formed by the breakup of a ridge-ridge-ridge triple junction. Winterer and Metzler (1984) suggest that the Mid-Pacific Mountains formed in a linear manner over a hotspot between 130 Ma and 115 Ma. Recent data indicate that the ages of origin for the Resolution and Allison seamounts along the Mid-Pacific Mountains are approximately 15 m.y. younger than predicted by the model assumed by Engebretson et al. (1985; ODP Leg 143 Shipboard Scientific Party, 1993). The ocean floor beneath the central leg of the Z formed between 130 Ma to 124 Ma (Nakanishi et al., 1992), whereas Engebretson et al. (1985) assumed a hotspot formed the seamounts on this seafloor between 135 Ma and 115 Ma. Thus the primary link assumed between the Pacific plate and the hotspot reference frame during most of Cretaceous time is probably not correct. This means that the convergence shown in Figure 1 is probably not correct prior to 84 Ma.

The second critical assumption applies to the period before 145 Ma. Because there were no applicable data, Engebretson et al. (1985, p. 9) extended their "Pacific-hotspot model back to

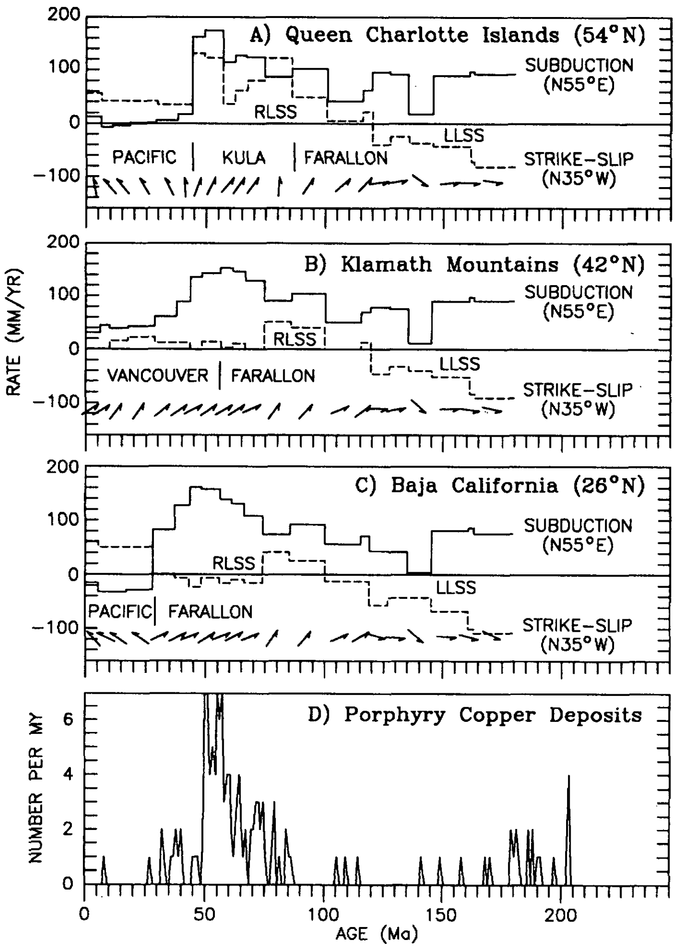


Figure 1. Rates of convergence of the Farallon, Kula, Pacific, and Vancouver plates with respect to North America in the vicinity of the Queen Charlotte Islands (A), Klamath Mountains (B), and Baja California (C) (Table 5 in Engebretson et al., 1985). The components of subduction normal to the trench and strike-slip motion tangential to the trench are calculated assuming that the trench trends N35°W. Arrows show the azimuth of total convergence where north is vertical. Strike-slip faulting is right-lateral (RLSS) for positive rates and left-lateral (LLSS) for negative rates. The Pacific plate was west of the Queen Charlotte Islands from 43 Ma to 0 Ma, the Kula plate from 85 Ma to 43 Ma, and the Farallon plate before 85 Ma. The Farallon plate was probably west of the Klamath Mountains by 55 Ma when part broke off to form the Vancouver plate north of the Pioneer and Mendocino fracture zones. The Vancouver plate became the Juan de Fuca plate during the last 5 m.y. when the Gorda and Explorer plates broke off. D shows the number of dated porphyry copper deposits in western North America per million years for 144 dates published in Sutherland Brown (1976), Hollister (1978), Titley (1982), Damon et al. (1983), and Dilles and Wright (1988).

180 Ma by conjecturing that the Pacific plate was fixed with respect to the hotspots between 180 Ma and 145 Ma." This assumption produced a model to be tested against geologic observations as they claimed, but it is probably not realistic since the Pacific plate has been moving relative to the hotspots at significant rates ever since that time.

A third assumption involves determining how the ocean floor formed during the long, Cretaceous, magnetic-normal period (124–83 Ma). Although topographic features provide some guidance, there appears to have been at least one major plate reorganization near the end of this time (Mammerickx and Sharman, 1988).

A fourth assumption involves the orientation of the trench during Mesozoic time, which was probably roughly north-south, based on its extent and evidence from paleomagnetic data (discussed in a following section) that the North American plate was rotated clockwise during Cretaceous time. In this case, subduction would have been greater than shown in Figure 1 and strike-slip motion smaller.

In summary, the plate-motion calculations provide evidence for a period of very rapid subduction under southern California and northern Mexico from approximately 73 Ma to 36 Ma and under Oregon and Washington beginning and ending perhaps 10 m.y. earlier. Convergence rates may have been moderately high between 135 Ma and 73 Ma with a shift in tangential component from left-lateral to right-lateral strike slip, but these conclusions depend on assumptions that can be seriously questioned. The assumption of little motion of the Pacific plate prior to 145 Ma is consistent with a period of rapid subduction during the Jurassic but cannot be used to prove or disprove the existence of such rapid subduction. In addition, the rates plotted in Figure 1A–C are probably not resolvable to within less than 10–20 mm/yr. The times of change are known only within 20–50 m.y. because of the averaging used to determine the stage poles of rotation, as well as a deliberate attempt to reduce the number of small stages by eliminating or shifting stage boundaries slightly (Engebretson et al., 1985). Thus the calculations of relative plate motions do not provide very accurate estimates of convergence rates prior to 84 Ma and do not provide very accurate estimates of the times when convergence rates changed. We need to examine the geologic evidence.

Arc volcanism and porphyry copper deposits

The clearest geologic evidence for subduction zones active in the Quaternary is arc volcanism, consisting primarily of andesitic volcanoes with some small silicic centers. Andesitic arc volcanoes, although numerous, account for a total of only about 0.5 km^3 of extrusive rocks per year (Crisp, 1984), and most of these are thin layers on top of existing topographic highs. For example, the third largest volcanic eruption in written history occurred during 1912 in the vicinity of Mt. Katmai on the Alaska Peninsula (Hildreth, 1987). The summit of this volcano is at 1,900 m and flat-laying Jurassic sandstone is found nearby at 1,700 m. Such thin veneers of volcanic flows are easily eroded, typically leaving only small dikes and stocks recording accumulation of magma as it moved upward to the main vents. Thus geologic evidence for old andesitic arcs can be subtle. Although major batholiths are typically assumed to be the roots of andesitic arcs, many will be shown below to have formed at different times and in a different regional-strain environment.

Evidence for major andesitic-arc volcanism during Mesozoic time in western North America is listed in Table 1 and is most voluminous during the Early Jurassic. The Early Jurassic arc was primarily oceanic, extending from Alaska to east-central California where it overlapped the continent, much like the modern Aleutian Arc overlaps the Alaskan Peninsula and south-central Alaska. The continental part of the Early Jurassic arc, extending through southeastern California, southern Arizona, and into northern Mexico, was much more silicic and less andesitic than the oceanic part.

Porphyry copper deposits have long been recognized as being concentrated by saline hydrothermal waters at depths of approximately 2 km near andesitic volcanoes (Sillitoe, 1973; Branch, 1976; Hollister, 1978). They formed primarily along the circum-Pacific "ring of fire" and in other regions where subduction was ongoing at the time the deposits formed (Argall and

TABLE 1. EVIDENCE FOR MAJOR ANDESITIC-ARC VOLCANISM DURING THE MESOZOIC IN WESTERN NORTH AMERICA

Location	Composition	Reference*	Location	Composition	Reference*
Early Late Triassic (235-220 Ma)			**Early Jurassic (continued)**		
Nicola Group	Basalt, andesite, pyroclastic rocks	1	Takwahoni facies	Calc-alkaline pyroclastic rocks, breccia, tuffs	2
Kutcho Formation	Basaltic andesite, rhyodacite, calc-alkalic volcanic rocks	2	Toodoggone volcanics	Calc-alkaline to alkaline pyroclastic rocks	2
Shonektaw Formation	Feldspar porphyry flows and pyrocalstic rocks	2	Cold Fish volcanics	Felsic to mafic lava and tuff	10
Takla Group	Augite porphyry basalt	3	Hurwal Formation (part)	Argillite, siltstone, volcanic rocks	11
Lewes River	Coarse andesitic fragmentals, augite porphyry flows	3	Sailor Canyon Formation (part)	Feldspathic turbidites, tuffaceous sandstone	12
Stuhini Group	Volcaniclastic rocks	3	Mount Wrightson Formation	Andesites, dacites, ignimbrites, breccia, sandstones	13
Wild Sheep Creek Formation	Basaltic and andesitic flows, volcaniclastic rocks	3	Fresnal Canyon sequence (part)	Quartz porphyry, andesitic volcanic rocks, arenites	14
Doyle Creek Formation	Basaltic and andesitic flows, volcaniclastic rocks	3	**Earliest Cretaceous (140-124 Ma)**		
Clover Creek Greenstone	Quartz keratophyre tuffs, flows, meta-andesite	3	Chisana Formation	Marine lahars, basalt, andesite flows, volcaniclastic rocks	6
Penon Blanco Formation, lower part	Aphyric basalt, basalt-andesite pillows	4	Part of Gravina-Nutzotin belt	Argillite, graywacke, interbedded andesitic volcanic rocks	15
Early Jurassic (203-178 Ma)			Upper Saint Elias Suite	Small granodiorite, quartz diorite plutons, calc-alkaline	16
Shuyak Formation, upper part	Volcaniclastic sandstone, argillite, tuff	5	Lower Gambier Group	Basaltic, rhyolitic, calc-alkaline to andesitic volcanic rocks	17
Talkeetna Formation	Andesitic, volcaniclastic sandstone, tuffs, flows	6	Fire Lake Group	Volcaniclastic rocks, pyroclastic rocks, intermediate flows	17
Upper Kunga and Maude Groups	Tuffaceous sandstone and shale	7	Longarm Formation	Conglomerate with andesitic volcanic rocks	18
Bonanza Group	Calc-alkaline pyroclastic volcanic rocks	8	Francois Lake Suite	Biotite granite to quartz monzonite, molybdenum deposit	16
Elise Formation, Rossland Group	Augite porphyry flows and pyroclastic rocks	2	Shasta Bally belt Grants Pass belt	Plutons dated between 139 Ma and 131 Ma	19
Telkwa Formation	Pyroclastic and flow volcanic rocks	2	Stony Creek petrofacies	Basaltic and andesitic detritus at its base	20
Nilkitkw Formation	Andesitic to rhyolitic tuff, breccia, basaltic flows	2			
Hazelton Group	Calc-alkaline pyroclastic rocks, breccia, tuffs	9			

*References: 1 = Mortimer, 1987; 2 = Monger et al., 1992; 3 = Mortimer, 1986; 4 = Saleeby, 1990; 5 = Connelly, 1978; 6 = Plafker et al., 1989; 7 = Lewis et al., 1991; 8 = Tipper, 1984; 9 = Marsden and Thorkelson, 1992; 10 = Thorkelson et al., 1991; 11 = Brooks and Vallier, 1978; 12 = Fisher, 1990; 13 = Riggs and Busby-Spera, 1990; 14 = Tosdal et al., 1989; 15 = Haeussler, 1992; also Berg et al., 1972; 16 = Woodsworth et al., 1992; 17 = Woodsworth and Monger, 1992; 18 = Yorath et al., 1992; 19 = Irwin, 1985; 20 = Ingersoll, 1983.

Wyllie, 1983). They are found today in all major, active andesitic arcs except for Japan (Armstrong et al., 1976; Argall and Wyllie, 1983). These mineral deposits can be especially useful for identifying old andesitic arcs because they are not eroded as easily as volcanic rocks on the surface and they have been sought out and studied in detail because of their economic importance.

There are two primary pulses of porphyry coppers in western North America, 85–45 Ma and 203–179 Ma (Fig. 1D). The youngest pulse corresponds closely with the time of rapid subduction (Fig. 1A–C) and the locations of these deposits will be shown to lie on a line parallel to the trench where the volcanic arc most likely formed. By analogy, the older pulse is also assumed to be evidence of rapid subduction. The porphyry copper deposits are concentrated in northern Mexico and southern Arizona between 74 Ma and 46 Ma, in southern British Columbia between 85 Ma and 50 Ma, and in northern Mexico and throughout British Columbia between 203 Ma and 179 Ma (Fig. 2). The Jurassic porphyry copper deposits in Canada are located predominantly within Stikinia (Sutherland Brown, 1976), a tectonostratigraphic terrane extending northwest-southeast through the central third of British Columbia. Stikinia appears to have been accreted to the continent by early Middle Jurassic time (approximately 178 Ma) (Ricketts et al., 1992) but probably has not moved far since the porphyry copper deposits were formed (Vandall and Palmer, 1990).

Times of major contraction

Rapid subduction appears to be contemporaneous with regional trench-normal contraction in the foreland over periods of a few tens of millions of years (Fig. 2). The foreland fold and thrust belt extends from Alaska to Guatemala (Drewes, 1978; Price, 1981; Suter, 1984; Campa, 1985; Allmendinger, 1992). This belt of easterly verging, shallow thrust faulting and décollement folding is typically 100 km wide, but ranges up to 300 km wide. "Thin-skinned" shortening, generally in an east-northeast direction, is commonly 50% (Campa, 1985; Allmendinger, 1992) but decreases northward from central British Columbia (McMechan et al., 1992). Armstrong (1968) called the foreland fold and thrust belt in Nevada and Utah the Sevier orogenic belt and suggested that the Sevier orogeny began in latest Jurassic time extending through earliest Tertiary time. Newer data are allowing definition of several different periods of deformation within one segment and among different segments throughout this long belt (Allmendinger, 1992). The Cretaceous thrusting in Utah and Wyoming began along the western edge of the foreland fold and thrust belt no earlier than Aptian time (less than 124.5 Ma) (Heller et al., 1986) and reached the eastern edge by early Albian time (112 Ma) (Lawton and Trexler, 1991). The major folding and thrusting, however, took place from the Campanian (83–74 Ma), especially during the Paleocene (65.0–56.5 Ma), and possibly into the mid-Eocene (~46 Ma) in southern British Columbia and northern Montana (Price, 1981; Allmendinger, 1992). In central Utah, major thrusting probably began in the late Albian (~100 Ma) (Villien and Kligfield, 1986). From southern Nevada to northern Mexico, the style of faulting changes and the age of deformation is less clear (Allmendinger, 1992). The Mexican thrust belt is thought to have been deformed during early Cenozoic time (Suter, 1984; Campa, 1985).

The onset of the Sevier orogeny coincides in time and space with the intrusion of major batholiths to the west from Alaska to Mexico that will be discussed subsequently. The Sevier orogeny also began when the spreading rate in the central Atlantic Ocean increased from 0.9 cm/yr to 2.4 cm/yr as a spreading system evolved from Rockall Trough west of Scotland to the southern tip of Africa (Klitgord and Schouten, 1986). The onset of major deformation in the foreland fold and thrust belt of Canada and Montana is contemporaneous with the inferred onset of rapid subduction to the west (Fig. 2). Folding and thrusting in Mexico peaked during the time of rapid subduction to the west, but the time of onset is not yet well known.

The thick-skinned Laramide orogeny began in Maastrichtian time (74–65 Ma) just east of the foreland fold and thrust belt from central Montana to southern Arizona (Dickinson et al., 1988). Folding and thrusting ended diachronously (Fig. 2) (Dickinson et al., 1988). This orogeny converted the western part of a broad Albian to Turonian seaway (112–88.5 Ma) extending from the Arctic Ocean to the Gulf of Mexico into numerous nonmarine sedimentary basins separated by basement-cored uplifts with net northeast-southwest contraction and widely varying intensity and vergences of folding. Hamilton (1981) argues that deformation during the Laramide orogeny resulted from clockwise rotation of the Colorado Plateau by several degrees about a pole in western Texas. Paleomagnetic data support this idea and suggest that the rotation was approximately five degrees clockwise (Bryan and Gordon, 1990).

The Nevadan orogeny was defined by Blackwelder (1914, p. 643) as "the folding of the rocks in the Sierra Nevada at the close of the Jurassic" and similar folding in a narrow belt from western Mexico through Alaska. This narrow band of rocks was associated with the Jurassic subduction zone west of the volcanic line. The nature of the deformation was very different from deformation in the Sevier and foreland fold and thrust belts located well east of the volcanic line. The classic Nevadan orogeny resulted in slaty cleavages nearly parallel to the axial surfaces of tight folds. The orogeny is described most thoroughly in rocks of the Foothills metamorphic belt along the west side of the Sierra Nevada. Schweickert et al. (1984) gave an estimate of 155 ± 3 Ma for the age of the Nevadan structures. Metamorphism associated with the Nevadan deformation may have lasted until 147 Ma in the Klamath Mountains (Harper and Wright, 1984). Ductile deformation continued in the foothills of the Sierra Nevada perhaps until 123 Ma (Tobisch et al., 1989). Classic Nevadan slaty cleavages are not well known outside of the Sierra Nevada and Klamath mountains, but the Late Jurassic was a time of widespread deformation from Canada to Mexico and onset of western derived clastic sediments (see Appendix 2).

Major folds did form, for example, at approximately Nevadan time in the Ruby Mountains–East Humboldt Range, metamorphic core complex in Nevada (Hudec, 1992).

A major thrusting event at some time between 200 Ma and 163 Ma has been recognized in the western Sierra Nevada metamorphic belt (Edelman and Sharp, 1989; Girty et al., this volume). The structures appear to be a stack of east-dipping nappes with thrust faults that may have large displacements. The Early to Middle Jurassic Sailor Canyon Formation in the northern Sierra Nevada had been deformed by 166 Ma (Girty et al., this volume), probably during Bajocian time (173.5–166.1 Ma), the time of intrusion of the major Soldier Pass and Palisade Crest Intrusive Suites in the Sierra Nevada described in a following section. This deformation has been confused with Nevadan

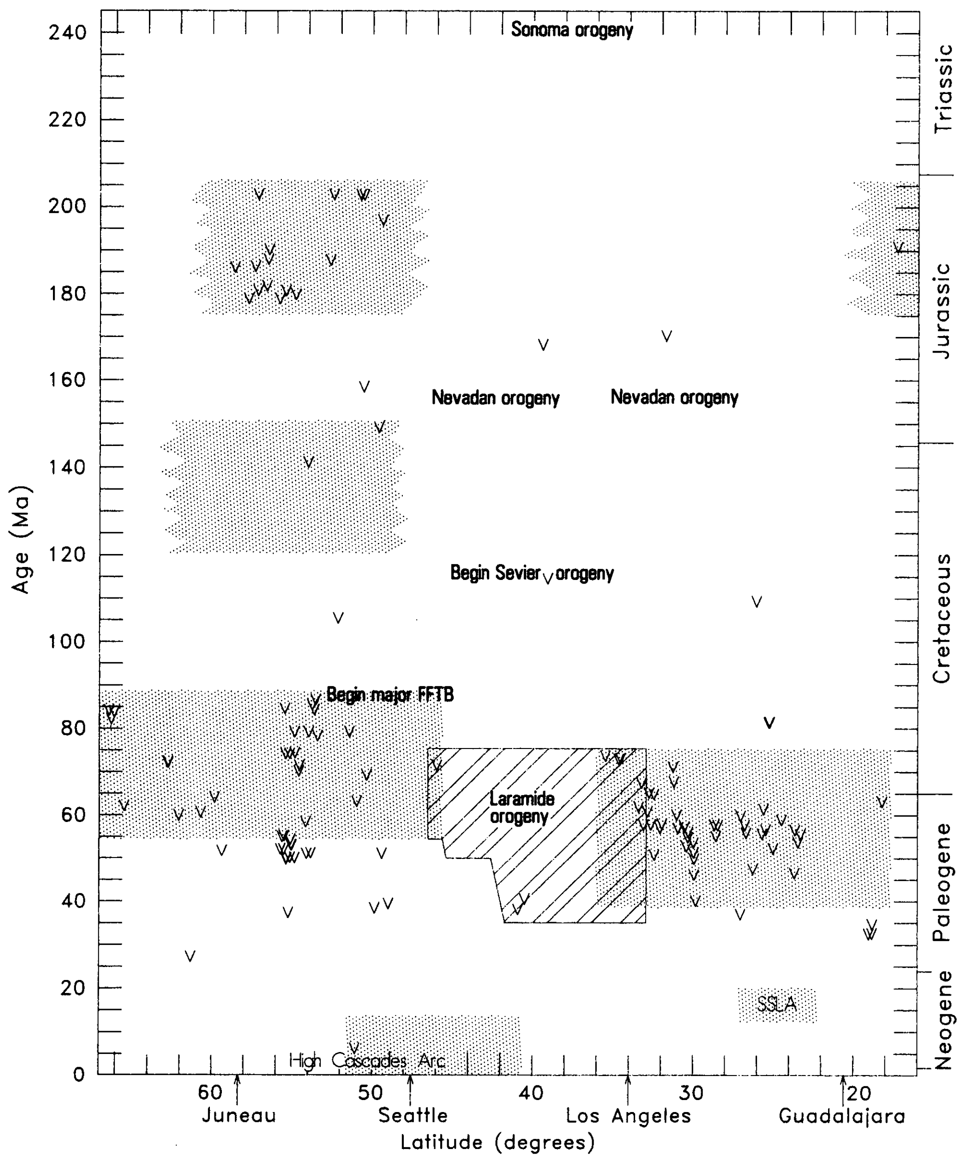


Figure 2. Porphyry copper deposits (V) and times of major contraction plotted by latitude as a function of time. The foreland fold and thrust belt (FFTB) extends from Guatemala to Alaska during the period from 85 Ma to 45 Ma. Only the onset of major deformation in Canada and Montana is shown because the timing is not well known to the south. Latitude is used in this and subsequent figures instead of distance along the trench because it involves the least assumptions, the trend of the entire coastline (N15°W) is more northerly than the trend of the Cenozoic trench along southwestern North America (N35°W), the trend of the western continental margin of North America during the Cretaceous was probably north-south, as shown from paleomagnetic data, Cenozoic magmatism inland seems to project more along the east-west trending fracture zones rather than along lines perpendicular to the trench (Ward, 1991), and primarily at the scale used, the differences in assumed trend of the coast are relatively insignificant. See key on facing page for a description of other symbols.

KEY FOR FIGURES 2, 4, and 5

A	Alkalic igneous rocks, significant outbreaks (Dunne et al., 1978; Miller, 1978; Marvin et al., 1980; Irwin, 1985; Henry et al., 1991)
AL	Atlanta Lobe of the Idaho batholith, Idaho (Vallier and Brooks, 1987)
APW CURVE	Position of the southern border of the Northwest Territories (60° N) as a function of time based on paleomagnetic apparent polar wander summarized in Figure 7A.
BR	Bitterroot Lobe of the Idaho batholith, Idaho (Vallier and Brooks, 1987)
C	Major calderas (Lipman, 1984; Busby-Spera et al., 1990; Lipman and Hagstrum, 1992)
COLO. MB	Colorado Mineral Belt, Colorado
CRFB	Columbia River flood basalts, Oregon (Mangan et al., 1986)
CRO	Coast Range ophiolite, California (Hopson et al., 1981)
CR Ocean Floor	Ocean floor centered around the western Columbia River, Oregon (Duncan, 1982), formed about a ridge striking perpendicular to the plate margin
E	Change from contraction to extension approximately perpendicular to the plate margin (Moore and Hopson, 1961; Chapin and Cather, 1981; Zoback et al., 1981; Aldrich et al., 1986; Brown and Lane, 1988; Janecke, 1992)
FG IS	Fine Gold Intrusive Suite, Sierra Nevada (Bateman, 1992)
KCA	Kamloops-Challis-Absaroka plutonic belt, Washington and British Columbia (Armstrong and Ward, 1991)
KL	Klamath Mountains, California (Irwin, 1985; Hacker and Ernst, 1993)
LLSS	Left-lateral strike-slip faults (Yates, 1968; Graham, 1978; Crouch, 1981; Anderson and Schmidt, 1983; Nokleberg, 1983; Oldow et al., 1984; Kleinspehn, 1985; Blake et al., 1985; Nilsen, 1986; Coleman and Parrish, 1991; Stewart and Crowell, 1992)
M	Time of primary mylonitization in metamorphic core complexes (most references listed in Armstrong and Ward, 1991. Others: Miller and Engels, 1975; Brown and Read, 1983; Isaac et al., 1986; Wust, 1986; Applegate et al., 1992)
O	Time of obduction of ophiolites at current latitude (Wirth and Bird, 1992; Brown, 1977; Saleeby, 1982; Saleeby et al., 1982; Pessagno and Blome, 1990)
R	Times of major rotations of small terranes from paleomagnetic evidence (Coe et al., 1985; Fox and Beck, 1985; Beck et al., 1986; Luyendyk, 1991; Plafker, 1987; Wilson, 1988; Ross et al., 1989)
RLSS	Right-lateral strike-slip faults (see references under LLSS)
S	Pelona, Orocopia, Portal Ridge, and Rand schists (Jacobson, 1990)
S IS	Scheelite Intrusive Suite, Sierra Nevada. Much less voluminous than the other intrusive suites (Bateman, 1992)
SC Ocean Floor	Ocean floor presently west of Santa Cruz, California, formed about a ridge striking perpendicular to the plate margin
SKPR	Skagway-Ketchikan-Prince Rupert plutonic belt (Armstrong, 1988; Brew and Morrell, 1983)
SNAKE RP	Snake River Plain, Idaho
SP-PC IS	Soldier Pass and Palisade Crest Intrusive Suites, Sierra Nevada (Bateman, 1992)
SSLA	Sierra Santa Lucia Arc, Baja, California (Sawlan and Smith, 1984)
SYBMW IS	Shaver, Yosemite Valley, Buena Vista Crest, Merced Peak, and Washburn Lake Intrusive Suites, Sierra Nevada (Bateman, 1992)
T-JM IS	Tuolumne and John Muir Intrusive Suites, Sierra Nevada (Bateman, 1992)
V	Copper porphy deposits interpreted as the shallow roots of arc-related stratovolcanoes (Sutherland Brown, 1976; Hollister, 1978; Titley, 1982; Damon et al., 1983; Dilles and Wright, 1988)

Major batholiths

Ocean floor formed about a ridge trending perpendicular to the plate margin

Subduction, rapid in Paleogene and Jurassic time, moderate in Early Cretaceous time, slow since Miocene time.

Laramide orogeny (Dickinson et al., 1988) deformation primarily because of problems with K/Ar dating. There is also evidence of layer-parallel shortening before 155 Ma in the Newfoundland Mountains of northern Utah (Allmendinger and Jordan, 1984) and other parts of the Great Basin (Miller and Hoisch, this volume). In northeastern Nevada "the evidence for post-Early Triassic thrust faulting accompanied by intense folding is abundant, ubiquitous, and commonly obvious" (Ketner, 1984, p. 483). The Winnemucca deformation belt may have begun forming in Early or Middle Jurassic time (Speed et al., 1988). Uplift in southern Arizona and California represents a major tectonic change probably in Late Triassic to Middle Jurassic time (Reynolds et al., 1989; Marzolf, 1991). This change coincides with the first appearance of western-derived volcanic clasts in lower Mesozoic cratonal stratigraphy and the onset of early Mesozoic thrust faults. In Canada, there was widespread Early Jurassic shortening in the eastern Cordillera (Struik, 1988; Brown et al., 1986) and a fundamental change from westward-verging folds to east-directed breakthrough thrusts about the time of the deep burial and high-grade metamorphism during Middle Jurassic time (Brown and Lane, 1988). This change is recognized southward into central Nevada (Caskey and Schweickert, 1992). All of these studies are hampered by overprinting of extensive deformation since the Early Jurassic orogeny, but they do show that contraction was found throughout the Cordillera in Early and Middle Jurassic time.

The nature and timing of the Sonoma orogeny is uncertain (Gabrielse et al., 1983). It was defined as the Permian to Triassic deformational event that resulted in closely spaced thrust faulting and tight folding of the upper Paleozoic Havallah sequence in the Golconda allochthon (Silberling and Roberts, 1962). Contemporaneous deformation elsewhere in the western United States involved only widespread erosion and very minor local tilting, faulting, and folding (Wyld, 1991). Ketner (1984), Schweickert and Lahren (1987), and Speed (in Miller and Harwood, 1989) suggested that there may have been substantial movement of the Golconda allochthon in Late Triassic or even Early Jurassic time. Snow et al. (1991) argued for large-magnitude shortening from northernmost Nevada to southernmost California during the middle to Late Permian, just before the Sonoman event.

Accretionary complexes

Major accretionary complexes typically contain chert, argillite, limestone, tholeiitic and alkalic basalts, and serpentinized peridotites with severe structural disruption varying from broken formation to mélange. These diverse rocks, which are typically found on the ocean floor, contain or are mixed chaotically with marine micro- and macro-fossils that range in age over periods of 100–200 m.y. Thus these complexes are thought to consist of scrapings from the subducting ocean floor that are in some way plastered against the continent above modern and older subduction zones (Cowan, 1985; Okamura, 1991). These complexes usually contain clear evidence of high-pressure and low-temperature metamorphism and may contain blocks with blueschists thought to be formed in subduction zones as discussed below. Thus the oldest protolith ages of major accretionary complexes are probably indicative of the oldest ocean floor subducted, and the youngest ages are probably indicative of when subduction slowed or stopped. The data summarized in Figure 3 provide clear evidence for major periods of subduction slowing or ending by the Middle Jurassic and during the Eocene. There is also evidence for subduction slowing or ending by mid-Cretaceous time, especially in Alaska.

Schists

High-pressure/low-temperature schists are believed to form in subduction zones. Interpretation of the radiometric age data (Table 2) is complicated by the fact that some are protolith ages, some are ages of primary metamorphism, others relate to late-stage cooling, and some may be reset. The range of ages from 85–39 Ma for the Late Cretaceous to early Cenozoic schists coincides with the best-documented period of rapid subduction (Fig. 1) and these and the Early Jurassic dates (208–178 Ma) coincide with the two peaks in porphyry copper deposits (Fig. 1D). The 165- to 145-Ma dates are predominantly in high-grade blueschist blocks believed to have been mixed with younger protoliths. The significance of the 130- to 90-Ma dates is less clear. Detailed interpretation of these data is beyond the scope of this chapter. Jacobson (1990) showed how complex these dates can be when he calculated three $^{40}Ar/^{39}Ar$ ages of approximately 72 ± 0.3 Ma for the Rand Schist, which is intruded by a granodiorite with a U/Pb age of 79 ± 1 that clearly postdates the prograde metamorphism and deformation. He concludes that the Pelona and Orocopia Schists are no older than 90 to 80 Ma, that what he called the Portal Ridge Schist and Rand Schist are older than 79 Ma, and that if they were all metamorphosed at the same time, their age must be between 90 and 80 Ma. Jacobson (1990) also found strong evidence to suggest that the variation in radiometric ages is more related to differences in cooling history than to differences in age of metamorphism. The U/Pb age of 163 Ma for the Orocopia Schist is for a metadiorite believed to have intruded the protolith (Mukasa et al., 1984).

Summary of intervals of rapid subduction

Calculations of plate motions show that the Farallon plate was being subducted under southern California and northern Mexico at rates close to 15 cm/yr between approximately 74 Ma and 36 Ma. This rapid subduction appears to correlate closely with formation of major porphyry copper deposits, shortening of the foreland fold and thrust belt, minimum ages of protolith in accretionary complexes, and the ages of high-pressure/low-temperature schists. Combining these same data where available shows one interval of rapid subduction from Oregon to Alaska between 87 Ma and 55 Ma and another in the

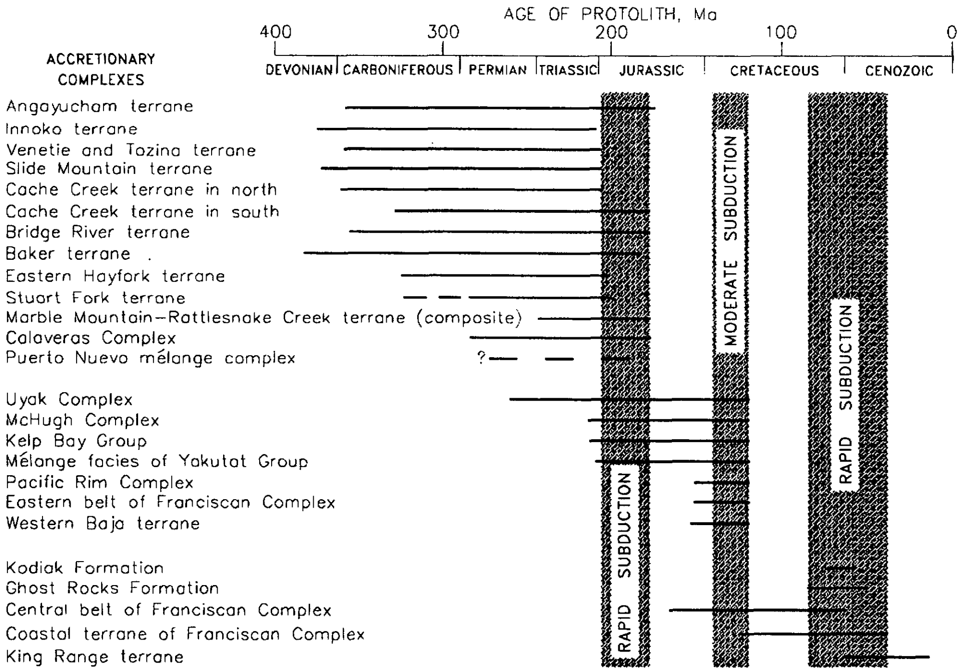


Figure 3. Ages of rocks and fossils found in major accretionary complexes in western North America since the Triassic (Connelly, 1978; Moore et al., 1983; Moore, 1986; Donato, 1987; Frizzell et al., 1987; Jones et al., 1987; Blake et al., 1988; Paterson and Sample, 1988; Baldwin and Harrison, 1989; Bishop and Kays, 1989; Brandon, 1989; Plafker et al., 1989; Goodge, 1990; Hansen, 1990; Mortensen, 1992; Monger et al., 1992; Cordey and Schiarizza, 1993; Goodge and Renne, 1993).

same region during Early Jurassic time (Between 208 Ma and 178 Ma) (Fig. 2). There is also less convincing evidence of moderate rates of subduction during earliest Cretaceous time (~140–120 Ma). These three intervals appear to date the major episodes of moderate and rapid (>7 cm/yr) subduction since the Triassic Period. There were undoubtedly many episodes of much slower subduction not resolvable by these methods, such as seen today west of Oregon and Washington or west of southern Baja California in Miocene time (Ward, 1991).

EVIDENCE FOR VOLUMINOUS SILICIC MAGMATISM DURING REGIONAL EXTENSION

Large calderas and major batholiths

Intervals of rapid subduction are typically followed by the onset of voluminous silicic volcanism and plutonism with large calderas as shown most clearly by Paleogene examples (Fig. 4). Calderas are found in andesitic volcanic arcs, but they are usually smaller than 10 km in diameter and are spaced tens to hundreds of kilometers apart (e.g., Smith and Shaw, 1975). Major continental caldera systems, such as those formed during the Cenozoic from eastern California to Colorado and from northern Mexico to Wyoming, are tens of kilometers in diameter and are typically contiguous to overlapping (C in Fig. 4) (Lipman, 1984). Such calderas in the Andes Mountains of Peru can be traced downward into large granitic plutons similar to those forming major batholiths such as the Sierra Nevada of California (Pitcher et al., 1985). The chemistry of these large silicic systems implies that they are underlain by large plutons of the type observed in major batholiths (Hildreth, 1981).

A batholith is typically defined as a large, generally discordant, plutonic mass with more than 100 km^2 in surface exposure (Gary et al., 1974). Batholiths can come in many shapes and sizes and have many origins (e.g., Buddington, 1969; Pitcher, 1979). The term "major batholith," as used in this chapter, means a group of plutons formed usually within a few million years that are typically contiguous or overlapping when restored to their original locations prior to subsequent intrusion and tectonism and where individual plutons and their aggregate are typically much longer than they are wide. Some major batholiths, such as the Sierra Nevada batholith of California, are a composite of several distinct major batholithic epochs (Evernden and Kistler, 1980; Bateman, 1992).

The Sierra Madre Occidental (Fig. 4) is the largest silicic volcanic province in North America and most likely overlies the largest batholith in North America. This 1,200 km long and 200 km wide expanse of more than 350 large calderas (Swanson and McDowell, 1984) formed in northern Mexico between 32 Ma and 27 Ma. The vector of motion of the Pacific plate relative to the North American plate between 36 Ma and 20 Ma was 61 ± 7 mm/yr at an azimuth of N64°W ± 12 (Stock and Molnar, 1988). With spreading between the Pacific plate and remnants of the Farallon plate of approximately 50 mm/yr, there

TABLE 2. RADIOMETRIC AGES DETERMINED FOR TRIASSIC AND YOUNGER SUBDUCTION-RELATED SCHISTS IN WESTERNMOST NORTH AMERICA*

Location	Ar/Ar	Rb/Sr	U/Pb	K/Ar	Intruded	Reference
Early Jurassic (208–178 Ma)						
Nome Group, Seward Peninsula, Alaska	>207					Hannula et al., 1991
Raspberry schist, Kodiak Islands, Alaska		208–189	204			Roeske et al., 1989
Seldovia schist terrane, Alaska				198-193		Carden et al., 1977
Iceberg Lake schist, Alaska 186-185						Sisson and Onstott, 1986
Schist of Liberty Creek, Alaska						Metz, 1976
Klondike Schist, Yukon	202?					Metcalfe and Clark, 1983
Pinchi Lake blueschists, British Columbia				223–216		Paterson and Harakal, 1974
Stuart Fork Formation (blueschist), California				223–214		Hotz et al., 1977
Foothills of the Sierra Nevada, California				190–173		Schweickert et al., 1980
Puerto Nuevo mélange complex, Mexico				173?		Moore, 1986
Early Cretaceous (145.6–97 Ma)						
Schist belt, Brooks Range, Alaska	149					Till, 1992
	130–120					Blythe et al., 1990
		105–101		120–116		Armstrong et al., 1986
Schists on Chichagof Island, Alaska				106–91		Decker et al., 1980
Shuksan Greenschist, Darington Phyllite,		160–105		150–97		Armstrong and Misch, 1987
British Columbia		128		164–128		Brown et al., 1982
Settler schist, British Columbia						Monger, 1991
Chilliwack group, British Columbia				155		Armstrong and Misch, 1987
Chiwaukum Schist, British Columbia		90				Longtine and Walker, 1990
		93				Bittenbender and Walker, 1990
May Creek Schist, Oregon	145					Donato, 1992
Colebrooke Schist, Oregon		~128		138–125		Dott, 1965; Coleman, 1972
Bald Mountain Schist, California				141–130		McDowell et al., 1984
South Fork Mountain Schist, California	120–115					Lanphere et al., 1978
				159–158		McDowell et al., 1984
				132–113		McDowell et al., 1984
			165–153			Hopson et al., 1981
				164–154		Lanphere, 1971
Redwood Creek schist, California						Cashman et al., 1986
Condrey Mountain Schist, California				138–128		Helper, 1986
Bald Mountain Schist, California				131–142		McDowell et al., 1984
Goat Mountain Schists, California		141		145–141		Suppe and Foland, 1978
Franciscan Complex, California	143–139					Wakabayashi and Deino, 1989
		154–152				Nelson and DePaolo, 1985
			95–92			Mattinson and Echeverria, 1980
		112?				Peterman et al., 1967
				155–150		Suppe and Armstrong, 1972
Taliaferro Complex, California			162			Mattinson, 1986
				115–90		Suppe and Armstrong, 1972
Catalina schists, California			112			Mattinson, 1986
				112–98		Suppe and Armstrong, 1972
Cadros Island blueschists, California	100–94	99				Baldwin and Harrison, 1989
				112–96		Suppe and Armstrong, 1972
West San Benito Island, California	115–95					Baldwin and Harrison, 1989
Late Cretaceous to Early Cenozoic (97 to 35.4 Ma)						
Bridge River Schist, British Columbia					44	Potter, 1985
Leech River Complex, Washington		42?				Armstrong and Misch, 1987
Cascade River Schist, Washington		45				Babcock et al., 1985
Portal Ridge Schist, California	85					Jacobson, 1990
Schist of Sierra de Salinas, California					85–80	James and Mattinson, 1988
Pelona Schist, California	73–55	59–58		53–52		Jacobson, 1990
Orocopia Schist, California	75–39		163	54–23		Jacobson, 1990
Rand Schist, California	75–72				79	Jacobson, 1990

*Question mark means that analytical error is greater than 5%. Ages are shown in columns that relate to dating technique. The column labeled "Intruded" contains the dates of bodies intruding the schist.

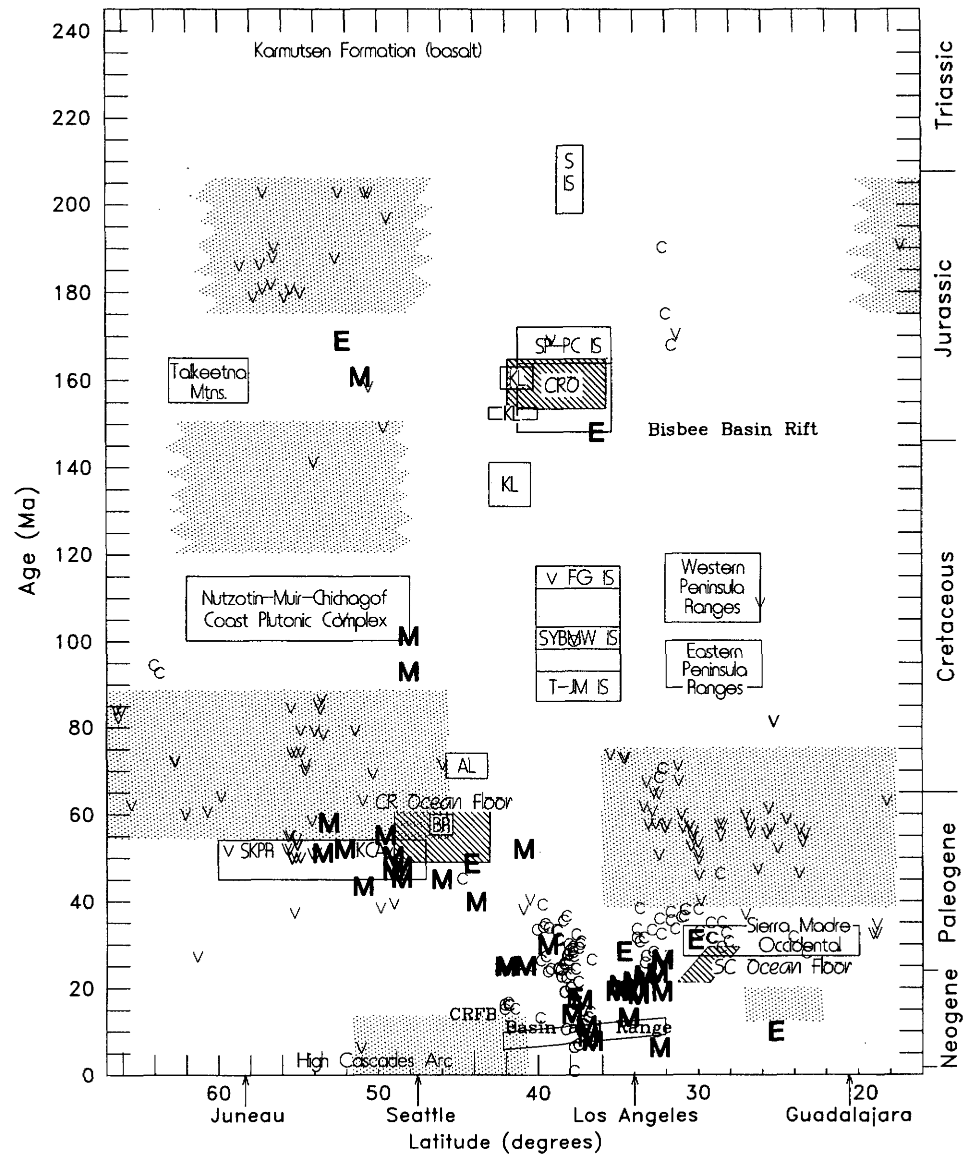


Figure 4. Porphyry copper deposits (V), major calderas (C), changes to trench-normal extension (E), times of major mylonitization in metamorphic core complexes (M), intervals of subduction, and major batholiths plotted by latitude as a function of time. The reasons for choosing the batholiths shown by the rectangles are described in Appendix 1. See key next to Figure 2 for a description of other symbols.

would have been extensional motion of 11 mm/yr at an angle of approximately 27° more westerly from the trend of the trench. If subduction were still active, the extensional component would be increased (Fig. 8 in Ward, 1991). This vector would resolve to approximately 9.6 mm/yr of strike slip parallel to the trench and 5 mm/yr of extension perpendicular to the trench. Although the errors in these calculations are large enough to question whether extension can be resolved, a shift to northeast-southwest trending extension at the northern end of the Sierra Madre Occidental in southwestern New Mexico is inferred from the changes in trends of dikes by 32 Ma (Aldrich et al., 1986). Thus, Ward (1991) concluded that the batholith most likely formed in a transtensional regime along the landward side of the volcanic arc. The older line of andesitic volcanoes and porphyry copper deposits, formed during rapid subduction, is exposed along the western margin of the silicic centers.

The Sierra Nevada of California is another major batholith. Although it contains at least some intrusive rocks of almost every age between 217 Ma and 80 Ma (Stern et al., 1981; Chen and Moore, 1982), Bateman (1992, p. 64) concludes, based on a summary of U-Pb ages and the rock volumes that they represent, that there were three periods of "markedly increased plutonism": 214–201 Ma, 172–148 Ma, and 119–86 Ma. Bateman (1992, p. 26) further subdivides the rocks emplaced during different time spans into intrusive suites (IS) or groups of plutons that "are in some manner cogenetic, though not necessarily comagmatic, and that are the products of a single fusion episode" (Fig. 4).

Such detailed studies and precise dating are not available in most other regions of western North America. Furthermore, the resetting and scatter of many ages based on K-Ar methods complicate the interpretation. The reasons for choosing the major batholiths shown by the rectangles in Figure 4 are described in Appendix 1. The conservative approach of showing only the major batholiths that have been studied in detail, helps distinguish extension-related batholiths from subduction-related plutons, but it may give a false impression about the regional extent of intrusive rocks. For example, intrusion of silicic plutons during the Middle Jurassic (178–157.1 Ma), was widespread from Alaska through Mexico (Armstrong, 1988; van der Heyden, 1992; Armstrong and Ward, 1993) forming a nearly continuous belt, with only the very voluminous batholiths in the Talkeetna Mountains of Alaska and the Sierra Nevada of California shown in Figure 4.

In summary, it is clear from Figure 4 that most major batholiths and continental caldera systems form at distinctly different times from andesitic-arc volcanic rocks and porphyry copper deposits. The batholiths appear to form in a trench-normal extensional environment, whereas the andesitic volcanoes form in a regime of trench-normal contraction. Although these distinctions are clear in most cases, they may be blurred in regions of slow oblique-subduction such as found presently in Sumatra.

Evidence for regional extension

The change from rapid subduction and trench-normal contraction to formation of major batholiths is accompanied by a change to trench-normal extension (E in Fig. 4). Some of the most profound extension is found in metamorphic core complexes that cluster near the westernmost edge of the craton in crust possibly thickened during earlier rapid subduction (M in Fig. 4). Mylonitization formed at many times, but peaked after intrusion of major batholiths and before rifting of the continent. Metamorphic core complexes were formed during the Late Paleocene to Early Eocene from central British Columbia to central Idaho, during the Late Eocene to Miocene from central Idaho through western Utah and eastern Nevada, and during the Miocene in southeastern California and southern Arizona (Armstrong and Ward, 1991).

Extension, forming after the Jurassic batholiths and before the onset of moderate subduction, is found in the Independence dike swarm east of the Sierra Nevada (148 Ma) (Chen and Moore, 1979). Extension is also found in major rift provinces such as the Basin and Range, which opened rapidly between 17 Ma and 14 Ma (Fig. 4) (Schweig, 1989; Zoback et al., 1994), and the Bisbee Basin rift, which began forming in the latest Jurassic as the northwest extension of the Chihuahua Trough in eastern Mexico (Dickinson et al., 1986).

Flood basalts also provide evidence for profound extension. North of the Basin and Range, the flood basalts of the Columbia River Basalt Group formed in Oregon especially between 16.5 Ma and 14 Ma (Mangan et al., 1986), and plateau basalts formed during the same time in the Cariboo Region of British Columbia (Symons, 1969; Bevier, 1983). The Karmutsen Formation of British Columbia and the Nikolai Greenstone, the informally designated Chilkat metabasalt, lower part of the Shuyak Formation, and Chilikadrotna Greenstone of Alaska are sequences of tholeiitic flows up to 6 km thick that formed in a large region from late Ladinian to late Carnian (236–225 Ma), apparently related to rifting (e.g., Muller, 1977; Davis and Plafker, 1985; Andrew and Godwin, 1989; Barker et al., 1989).

EVIDENCE FOR INTERVALS OF MAJOR LATERAL MOTION

Observed strike-slip faulting

Strike-slip faulting with net displacements of hundreds to thousands of kilometers was primarily active during the Late Jurassic, mid-Cretaceous, Eocene, and since the late Miocene (Fig. 5). There is disagreement on the direction of slip, but left lateral was most common during the Jurassic Period (Avé Lallemant and Oldow, 1988) and right lateral was most common since mid-Cretaceous time, in accord with the plate model of Engebretson et al. (1985) (Fig. 1A–C). The strikes of nearly all of these faults are approximately parallel to the plate margin as shown in summary maps by Stewart and Crowell (1992) and Gabrielse et al., 1992). There is considerable debate about the amount of motion, the exact timing of motion and, in some cases, whether motion occurred at two or more separate times. In British Columbia, for example, Coleman and Parrish (1991) argued that strike-slip movement on the Fraser fault began before 48.5 Ma and ended with no more than 100 km of offset between 46.5 Ma and 34 Ma. Kleinspehn (1985) found evidence for approximately 110 km of displacement during Late Cretaceous to early Tertiary time on the Fraser and Straight Creek faults and 150 km of displacement during Cenomanian and Turonian time (97–88.5 Ma) on the Yalakom and Ross Lake faults. Miller (1988) thought this earlier displacement may have been left lateral. Gabrielse (1985) described at least 750 km of right-lateral strike slip on the northern Rocky Mountain Trench with evidence for some Jurassic strike-slip faulting, but primary displacement between mid-Cretaceous and late Eocene or Oligocene time. Price and Carmichael (1986) argued that most of the 450 km of strike-slip displacement on the Tintina Trench–northern Rocky Mountain Trench was during Late Cretaceous and Paleogene time with less than 100 km of displacement during early and middle Eocene time.

Paleomagnetic evidence for lateral motions of the North American plate

The apparent wander of paleomagnetic poles suggests that the North American plate moved laterally with respect to the spin axis of the Earth by large amounts during specific periods of time. The paleomagnetic method can only resolve the north-south component of motion and any rotation. The most reliable paleomagnetic data for cratonal North America are listed in Table 3 and plotted in Figure 6. The North American plate moved northward and rotated approximately 30° counterclockwise between 244 Ma and 203 Ma, rotated about the same amount clockwise between 203 Ma and 158 Ma, moved rapidly northward between 151 Ma and 122 Ma, and rotated approximately 15° counterclockwise between 86 Ma and the present. This standard type of polar plot does not adequately show the rates of motion. One common way to view northward motion through time is to plot the change in distance from a reference point to the paleopoles. Another is to plot the difference between the paleolatitude and the present latitude as a function of age. The data in Table 3, however, range in present longitude from 65°W to 131°W, introducing a distortion because lines of longitude converge at the north pole. To minimize this distortion and emphasize the poleward motion of North America, which is centered near longitude 90°W, I chose a reference point 90° away from this central meridian (0°N and 0°W) and plotted the azimuth to the present north pole minus the azimuth to the paleopole times 111.2 km/degree (Fig. 7A). This calculation gives an estimate of the northward component of motion of the North American plate along the 90°W meridian, roughly the center of the craton, and is equivalent to calculating the shortest angular distance from each paleopole in Figure 6 to the horizontal 180° and 0° lines of longitude.

The data points in Figure 7A do not lie on a single straight line. The dashed line is based on the 10-m.y. mean paleopoles calculated by Irving and Irving (1982) using a 30-m.y. running average of a data set that is slightly smaller than that given in Table 3. Many paleomagnetic studies have been referenced to this curve that, as expected, tends to smooth out extremes in the data. The dot-dashed line shows 20-m.y. running averages based on a more recent dataset (Besse and Courtillot, 1991). But hairpins or cusps in apparent polar wandering curves suggest large and sudden changes in the direction and amount of motion (Fig. 6) (Irving and Park, 1972; Gordon et al., 1984; May and Butler, 1986; Ekstrand and Butler, 1989), limiting the usefulness of any averaged curve for precise work. The dotted line in Figure 7A is based on the paleomagnetic Euler poles of Gordon et al. (1984) who assumed long periods of continuous plate motion separated by abrupt changes in plate movements. Yet the data plotted in Figure 7A show that the changes in motion may have been even more abrupt than Gordon et al. (1984) assumed. The most straightforward way to emphasize abrupt changes in Figure 7A is to plot horizontal lines assuming no north-south motion connected by diagonal lines showing change. Note that such a curve (solid wide lines) fits well within the error bars of all of the data and close to the actual data points for most of the data. The difference between the solid and dashed lines in Figure 7A is responsible for much of the disagreement over the distance that terranes have traveled along the western boundary of North America, especially since the Late Jurassic (e.g., Vandall and Palmer, 1990; Butler et al., 1991). The solid lines are not uniquely determined, and they emphasize where more data are needed!

This analysis assumes that all of the apparent wander of reference poles for North America is caused by motion of the North American plate relative to the Earth's spin axis. Yet the same apparent wander can be caused by motion of the Earth's spin axis relative to the North American plate. In neither case is it necessary that there be any motion of the North American plate relative to other contiguous plates. These times of rapid polar wander, however, coincide with times of major tectonism, described in Appendix 2, caused by relative motion of plates along most of the margins of the North American plate. Thus it seems reasonable to assume that at least part of the apparent polar motion represents true motion of North America relative to surrounding plates.

The solid line in Figure 7A is also plotted in Figure 5, showing the latitude of the southern boundary of the Northwest Territories (60°N) as a function of time. This arbitrary reference latitude was chosen simply to fit the northward motion curve within the figure. The paleomagnetic data suggest that the North American plate moved north to south with respect to the Earth's spin axis least during times of formation of major batholiths in the Middle and Late Jurassic, mid-Cretaceous, and late Paleogene. The most rapid and significant northward motion (1,500–3,000 km) occurred during a time of major strike-slip faulting in the latest Jurassic and earliest Cretaceous, perhaps mainly during the Tithonian (152.1–145.6 Ma). The beginning of this motion is referred to as the J-2 cusp in the polar wandering curve (May and Butler, 1986; May et al., 1989). The Early Cretaceous interval of subduction began soon after this cusp. The J-1 crust formed at approximately 203 Ma, the beginning of the northward motion of approximately 800 km and the onset of rapid subduction during the Early Jurassic. Northward motion of possibly as much as 1,400 km may have occurred during the early Cretaceous period of subduction or simply as part of the motion following the J-2 cusp (heavy dashed line, Fig. 7A). The North American plate appears to have moved 900 km southward during the Late Cretaceous to Eocene interval of rapid subduction, and approximately 400 km northward since the mid-Miocene. These motions of less than 900 km cannot be adequately resolved because the 95% error bars range from ± 80 km to ± 800 km. Note the extensive scatter of data for times younger than 15 Ma.

Paleolatitude data for the Pacific plate also show northward movement (Table 4 and Figs. 7B and 8). Many of these data are from unoriented drill cores from which only the paleolatitude may be calculated. Therefore only the differences between present latitudes and paleolatitudes are plotted. The solid line shows the northward motion of the Pacific plate relative to the North American plate (Stock and Molnar, 1988) plus the northward motion of the North American plate shown by the solid line in Figure 7A. This line fits the data points well, showing that the paleomagnetic data for the North American plate and

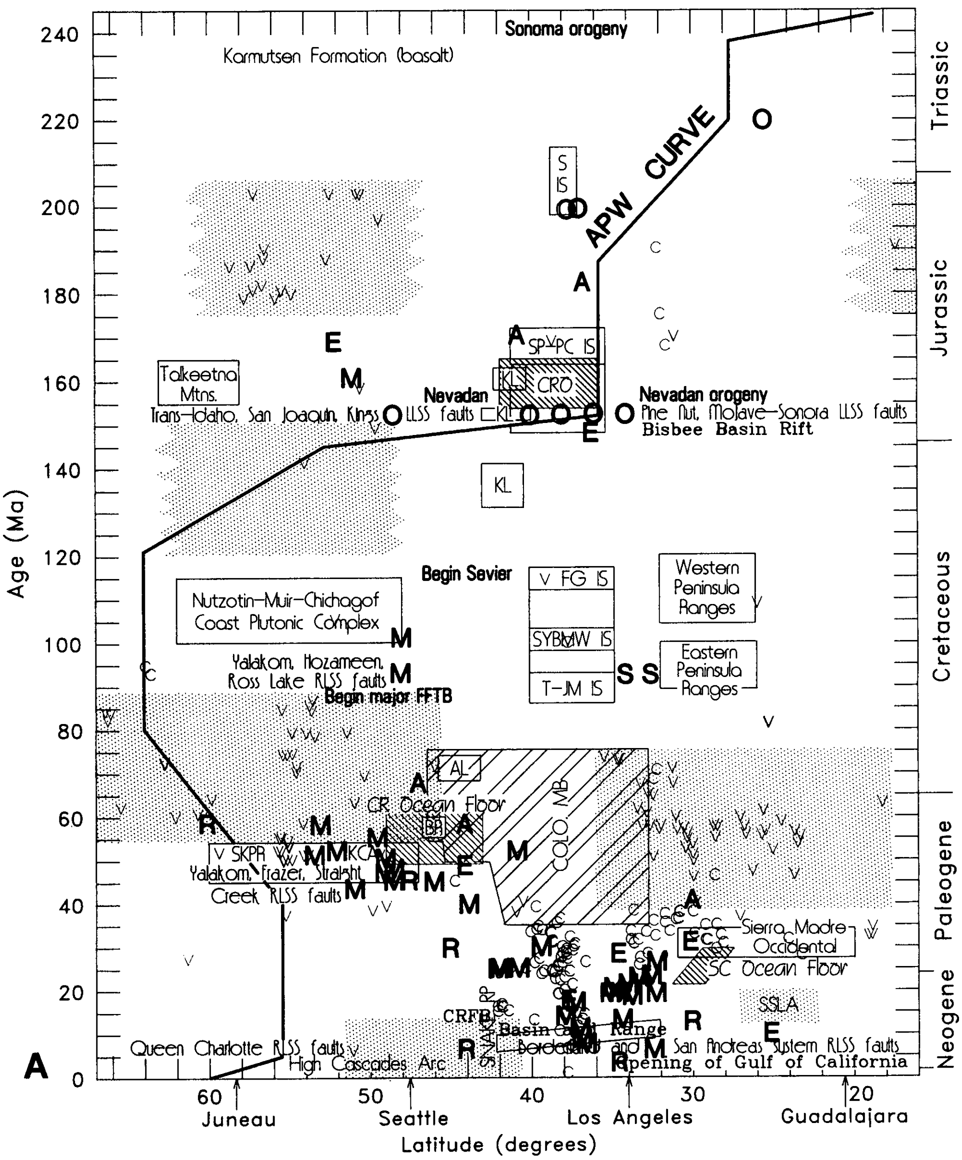
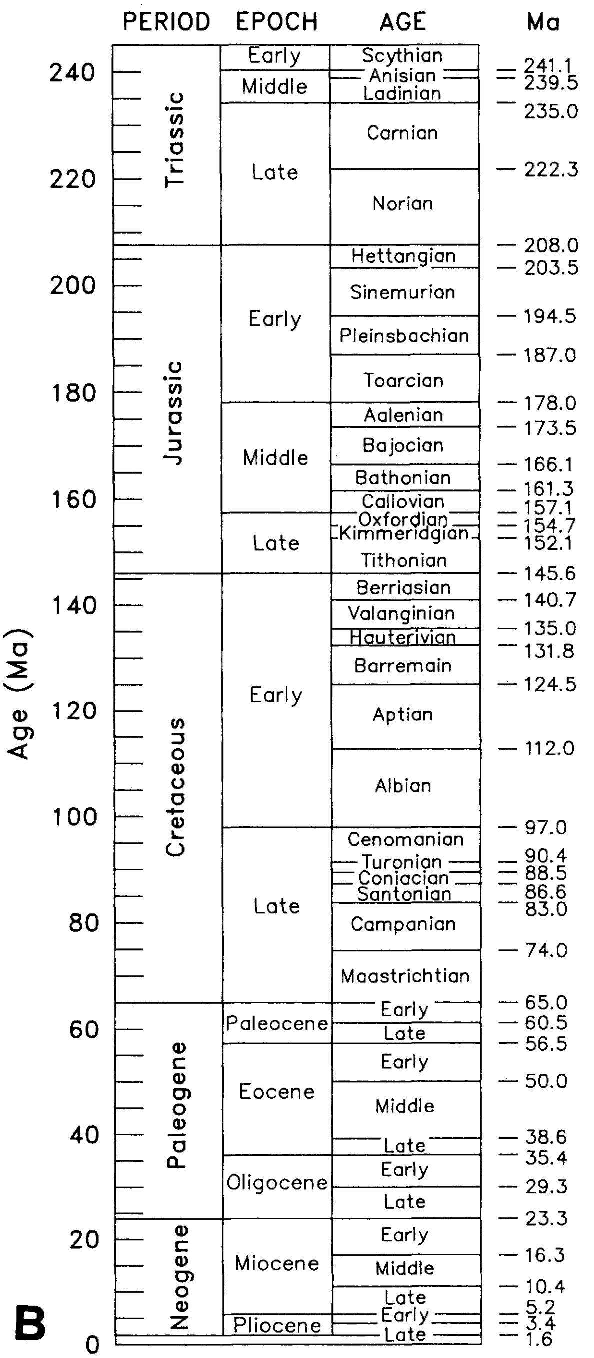


Figure 5(A). Major features of the tectonics of western North America from central Mexico to Alaska since the beginning of the Triassic plotted by latitude as a function of time. See key next to Figure 2 for description of symbols. (B) Time-stratigraphic column (on facing page).

the Pacific plate are consistent with the calculations of relative plate motion. Although the timing of the northward motion of the North American plate since 15 Ma is not clear using data from the craton (Fig. 7A), the three paleomagnetic poles from Hawaii dated between 3 Ma and 5 Ma, when added to the difference in motion between the North American and Pacific plates (Fig. 7B) imply that North America moved north in the last few million years. These data also show that whereas the North American plate was moving northward, the Pacific plate was moving northward even faster, with resultant right-lateral strike slip between these plates. The Pacific plate has moved northward since 128 Ma with a counterclockwise rotation of approximately 20° between about 85–83 Ma (Gordon, 1983) that is contemporaneous with a significant plate reorganization in the northeastern Pacific Ocean (Mammerickx and Sharman, 1988). The dashed line in Figure 7B is the sum of northward motion of the Pacific plate in relation to North America based on the model of Engebretson et al. (1985). The poor agreement for data older than 60 Ma suggests that their model does not adequately account for the plate reorganization at 84 Ma.

Obduction of ophiolites

Ophiolites are interpreted as pieces of oceanic crust and uppermost mantle that are exposed because they were obducted



onto the plate margin or mixed in accretionary complexes. They formed during discrete time intervals. Most well-studied ophiolites of Mesozoic or younger age in western North America from Alaska to California formed during the Middle Jurassic and were obducted during the Late Jurassic, particularly at approximately 152 Ma (Fig 5). Ophiolitic slabs also are commonly found mixed into accretionary complexes from Alaska to Mexico during Triassic or Early Jurassic time. Two well-documented examples are in the western foothills of the central Sierra Nevada of California (dated at ca. 199 Ma) (Saleeby, 1982) and in Baja California (dated at ca. 220 Ma) (Rangin et al., 1983).

EVIDENCE FOR SUBDUCTION CYCLES

The data discussed in the previous sections and summarized in Figure 5 display a broad cyclical pattern for major tectonic events in western North America. Rapid subduction is typically followed by a change from trench-normal contraction to trench-normal extension and the formation of major silicic volcanic systems and batholiths. Extension then increases with major mylonitization in the metamorphic core complexes and the formation of rifts. Strike-slip faulting becomes widespread, and subduction begins again. The evidence for such cycles is exposed most clearly in rocks formed since mid-Cretaceous time because this younger tectonism and magmatism has eroded, intruded, overprinted, and overlain older evidence for older cycles. Yet evidence for the older cycles, often eroded to deeper depths, provides a different perspective on the nature of the younger cycles. The key features of each cycle are summarized in Figure 9.

MEXICAN CYCLE

The best-documented cycle began by 67 Ma in the southwestern United States and northern Mexico. As described in detail by Ward (1991), rapid subduction (>110 mm/yr) of the Farallon plate under northern Mexico occurred between at least 67 Ma and 43 Ma (Fig. 1C), accompanied by widespread arc volcanism, whose roots are best exposed today in the porphyry copper deposits (Fig. 2) that form a line parallel to the trench from central Mexico to Arizona (Fig. 10). At approximately 43 Ma, the East Pacific rise along the easternmost protrusion of the Pacific plate, which had been moving east-northeast toward North America, approached the trench west of the coast of northern Mexico (Fig. 10). The Pacific plate, which had been moving north-northwestward relative to the North American plate, began moving west-northwest, with a component of motion away from North America. Uplift began to the east, and major alkalic volcanism broke out in the Trans-Pecos area of western Texas (Henry et al., 1991), directly inland normal to the trench from the central part of the easternmost part of the Pacific plate and along an eastern extrapolation of the Mendocino and Pioneer fracture zones (Fig. 10). Subduction slowed and the Farallon plate broke into several fragments. Between 37 Ma and 27 Ma, silicic magmatism became widespread from the San Juan Mountains of southern Colorado to Guadalajara, Mexico. The Rio Grande rift began to open and trench-normal extension became dominant by 32 Ma (Aldrich et al., 1986). The Sierra Madre Occidental with its 350 calderas, formed between 32 Ma and 27 Ma in a transtensional environment (Ward, 1991), directly to the east of where the easternmost protrusion of the Pacific plate first reached the trench (Fig. 10). Between 28 Ma and 20 Ma (magnetic anomalies 9 and 6), the small plates east of the East Pacific rise and between the Pioneer and Murray fracture zones rotated clockwise, forming the SC Ocean Floor (Fig. 5) about a ridge striking perpendicular to

TABLE 3. NORTH AMERICA PALEOMAGNETIC REFERENCE POLES AND SOURCES*

Age (Ma)	Site Latitude (N)	Site Longitude (E)	Pole Latitude (N)	Pole Longitude (E)	Error 95%	Symbol	Identification	Source
3	57.7	-130.6	89.1	-31.8	6.6	E	Mt. Edziza Volcano, BC, Canada	Souther and Symons, 1973
4	36.4	-105.7	84.9	90.8	11.1	N	Lavas, Taos, NM	Kono et al., 1967
7	19.2	-98.6	88.8	34.3	7.4	V	Iztaccihuatl Volcanics, Mexico	Steele, 1971
7	20.8	-103.4	80.3	158.8	11.7	R	Rio Grande lavas, Mexico	Watkins et al., 1971
8	19.0	-99.0	86.6	-110.1	7.1	U	Upper Sierra Group, Mexico	Mooser et al., 1974
13	19.0	-99.0	88.4	-44.7	11.0	L	Lower Sierra Group, Mexico	Mooser et al., 1974
14	45.8	-118.0	88.7	171.6	4.0	C	Columbia River Basalt Group	Mankinen et al., 1987
15	42.5	-119.2	88.3	-151.0	6.2	H	High Plateau Lavas, OR	Gromme et al., 1986
16	19.0	-99.0	82.7	138.0	10.5	G	Guadeloupe Group, Mexico	Mooser et al., 1974
25	33.0	-107.0	82.0	146.9	2.9	m	Mogillon-Datil, NM	Diehl et al., 1988
30	40.0	-108.0	83.2	148.0	4.1	D	Oligocene-early Miocene	Diehl et al., 1983
35	33.0	-107.0	80.5	149.4	4.2	M	Mogillon-Datil, NM	Diehl et al., 1988
38	55.9	-63.4	85.5	117.7	3.0	I	Mistastin Impact, LB, Canada	Currie and Larochelle, 1969 Mak et al., 1976
46	42.6	-107.0	79.4	146.2	9.6	R	Rattlesnake Hills, WY	Sheriff and Shive, 1980
47	44.5	-109.5	83.5	177.4	10.1	A	Absaroka Supergroup, WY	Shive and Pruss, 1977
52	48.0	-110.0	82.0	170.2	3.5	P	Alkalic Province, MO	Diehl et al., 1983
60	47.9	-108.6	81.1	153.0	7.0	J	Little Rocky Mountains, MO	Diehl et al., 1983
67	47.2	-109.4	77.8	-144.4	8.6	M	Moccasin-Judith Mountains, MO	Diehl et al., 1983
71	32.0	-112.0	73.6	176.0	7.5	R	Roskruge Volcanics, AZ	Vugteveen et al., 1981
76	47.2	-111.8	82.2	-150.1	6.8	A	Adel Mountains, MO	Gunderson and Sheriff, 1991
86	41.0	-105.0	66.0	-168.0	6.0	N	Niobrara Formation, KS, CO, WY	Shive and Frerichs, 1974
99	34.4	-92.8	72.6	-162.7	6.0	A	Alkalic intrusions, AR	Globerman and Irving, 1988
106	78.8	-103.7	69.0	180.0	14.0	I	Isachsen diabase, NWT	Globerman and Irving, 1988
118	45.5	-74.0	72.4	-169.0	3.2	M	Monteregian Hills, QU, Canada	Foster and Symons, 1979 Eby, 1984
122	43.4	-72.5	71.9	-172.6	6.9	A	White Mountains plutons, NH, VT	Van Fossen and Kent, 1992
145	38.1	-108.2	63.7	164.8	3.9	U	Upper part of Morrison, Fm., CO†	Steiner and Helsley, 1975
147	37.3	-109.3	66.0	159.0	6.6	B	Brushy Basin, Mbr., Morrison Fm., CO	Bazard and Butler, 1992a
149	38.1	-108.2	57.6	147.3	4.2	L	Lower Morrison Formation, CO†	Steiner and Helsley, 1975
151	31.5	-110.5	62.7	131.5	6.3	G	Glance Conglomerate, AZ	Kluth et al., 1982 May and Butler, 1986
158	38.8	-111.1	53.6	133.4	7.2	S	Summerville Formation, UT	Bazard and Butler, 1992b
172	31.4	-110.7	61.8	116.0	6.2	C	Coral Canyon, AZ	May et al., 1986
179	41.5	-73.0	65.3	103.2	1.4	2	Newark Trend G2, Canada	Smith and Noltimier, 1979
190	45.0	-65.0	65.0	85.0	6.0	D	Dikes, New England, Canada	Hodych and Hayatsu, 1988
195	41.8	-73.0	63.0	83.2	2.3	N	Newark Trend G1, Canada	Smith and Noltimier, 1979
196	38.5	-109.6	61.8	80.6	6.3	K	Kayenta Formation, UT†	Steiner and Helsley, 1975
198	38.4	-110.6	59.1	72.7	8.0	W	Wingate Sandstone, UT†	Gordon et al., 1984
203	36.9	-112.4	59.0	61.3	4.5	M	Moenave Formation, AZ†	Ekstrand and Butler, 1989
214	38.4	-110.3	57.7	79.1	7.0	C	Redonda Mbr., Chinle Fm., NM	Reeve and Helsley, 1972 Molina-Garza et al., 1991
215	51.3	-68.7	58.8	89.9	5.8	I	Manicouagan Impact, QU, Canada	Robertson, 1967 Hodych and Dunning, 1992
225	40.3	-75.2	53.6	101.6	4.8	N	Newark Group, red beds, PA	Witte and Kent, 1989
227	34.7	-106.7	59.4	98.5	3.1	c	Bluewater Creek mbr., Chinle, FM, NM†	Molina-Garza et al., 1991
238	34.7	-106.7	55.5	108.5	2.8	m	Moenkopi Formation, NM†	Molina-Garza et al., 1991
242	38.6	-108.9	54.9	108.3	5.3	M	Moenkopi Formation, CO†	May and Butler, 1986
243	39.8	-106.7	52.0	107.0	3.0	S	State Bridge Formation, CO	May and Butler, 1986
243	42.4	-108.5	46.6	113.5	1.9	C	Chugwater Formation, WY	Shive et al., 1984
244	43.4	-109.4	45.4	115.3	4.1	R	Chugwater Formation, WY	Herrero-Bravara and Helsley, 1983

*Poles with a dagger (†) after the identification have been rotated five degrees counterclockwise to correct for apparent rotation of the Colorado Plateau during the Laramide orogeny (Bryan and Gordon, 1990). This list is based on the selections of Irving and Irving (1982), updated by Peter L. Ward for subsequent publications. Selection of poles for the Mesozoic is based primarily on the interpretations of May and Butler (1986) which are still under discussion (Hagstrum, 1993). Besse and Courtillot (1991) compiled a list of poles since 200 Ma that is generally similar to this list. Error is at the 95% confidence level based on the quality and quantity of the data used to calculate the pole. Errors in dating the rock samples vary and are more difficult to quantify, but they are typically at least plus or minus a few million years. In some cases data points represent a suite of rock samples formed throughout a span of several millions of years.

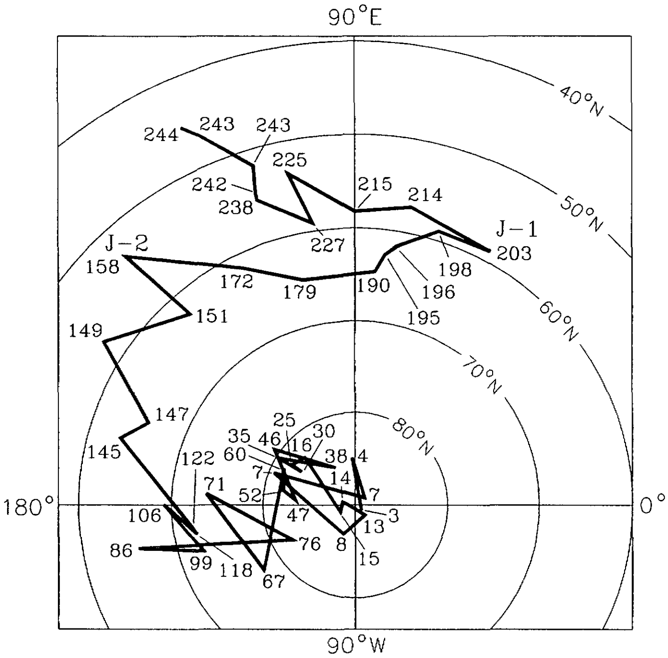


Figure 6. Polar plot of apparent paleomagnetic north poles for the North American craton since the beginning of Mesozoic time. The numbers show the locations and ages (Ma) of the poles listed with errors in Table 3. Errors are omitted from this figure to emphasize the dates but can be thought of as circles with radii varying from 2° to 14.° When errors are taken into account, it is reasonable to assume that the polar-wander curve is more linear than shown.

the plate margin. Mylonitization became widespread in the metamorphic core complexes of southeastern California and southern Arizona. Between 24 Ma and 17 Ma, slow subduction appears to have resumed beneath southern Baja California as shown by the Sierra Santa Lucia arc (Fig. 10 and SSLA in Fig. 5). By 14 Ma, rifting became dominant in the Basin and Range. Strike-slip faulting most likely began at approximately 18 Ma on the Clemens Well–Fenner–San Francisquito fault (CWF, Fig. 10) and the northern part of the San Andreas fault (Smith, 1977; Joseph et al., 1982; Powell, 1993) and became well developed on the San Gregorio (Powell, 1993) and Tosco-Abreojos faults by 10 Ma (Spencer and Normark, 1979). By 5 Ma, rifting was widespread as the Gulf of California began to form between the Sierra Madre Occidental batholith and the former trench. The land west of the Gulf of California and the San Andreas fault became completely detached, moving with the Pacific plate to the northwest relative to North America.

Canadian cycle

A second cycle occurred diachronously in the Pacific Northwest and Canada where folding and thrusting began by 89 Ma (Fig. 5). There was a major reorganization of plates in the Pacific between 100 Ma and 84 Ma as shown by the magnetic bight presently located south of the central Aleutian Trench (Mammerickx and Sharman, 1988). This bight is evidence for a ridge-ridge-ridge triple junction located far to the southwest of Mexico at 84 Ma (Engebretson et al., 1985). No one can prove what the orientation of the ridge crest was north of the bight because the paleomagnetic evidence has been subducted, but there does appear to be a strong similarity to geologic events during the Mexican cycle to the south. Like the southern cycle, an eastern protrusion of the Pacific plate may have approached the coast of Oregon and Washington by approximately 67 Ma. The southern end of a possible eastward protrusion of the Pacific plate can be seen along the Aja fracture zone and smaller unnamed fracture zones to the north that are presently being subducted into the Aleutian Trench south of south-central Alaska (Atwater and Severinghaus, 1989). The formation of alkalic volcanism in the Judith, Little Rocky, and Moccasin Mountains of north-central Montana (Marvin et al., 1980), at approximately 67 Ma, implies that the northeastern tip of this eastward protrusion may well have approached the coast of Washington at this time. The Bitterroot lobe of the Idaho batholith formed between 60 Ma and 55 Ma. Metamorphic core complexes represent tens of kilometers of extension between 58 Ma and 45 Ma (Parrish et al., 1988). Beneath and to the west of the Cascade Range, tholeiitic basalts, which range in age from 49 Ma at the Columbia River to 62 Ma in northern Washington and southern Oregon, formed ocean floor about an east-west trending spreading ridge in western Washington and Oregon (Duncan, 1982) (CR Ocean Floor in Fig. 5). This ocean floor forming perpendicular to the plate margin is then directly comparable to the SC Ocean Floor west of Santa Cruz, California, and the ocean floor now forming southwest of the Gulf of California, except that the oceanic terrane in Oregon and Washington has probably been rotated 16° clockwise since its formation (Beck et al., 1986). The spreading ridge west of Oregon most likely became the Kula/Farallon ridge, perhaps generated by opening along the east-west transform fault that made up the northern or possibly the southern edge of this eastern protrusion. Such a ridge would allow rapid counterclockwise rotation of the Kula plate beginning at approximately 55 Ma as observed by Lonsdale (1988), birth of the Aleutian subduction zone (Scholl et al., 1983), separation of the Bering Sea floor from the Pacific Ocean, and rapid motion of terranes to Alaska. The importance of these rotated ocean floors to the creation of terranes will be described below.

The Bitterroot lobe of the Idaho batholith (BR in Fig. 5) is in a similar position and time relative to the period of rapid subduction as the Sierra Madre Occidental batholith. The difference in areal extent may be indicative of lower transtensional strain because the Pacific plate was still moving primarily toward North America until 43 Ma, and the Kula plate was subducting northward under Alaska (Stock and Molnar, 1988). Rather than prolonged rifting of the continent, these other plate motions may have allowed the continent to fracture above the former subduction zone with a large strike-slip fault system that was partially filled in by Skagway-Ketchikan–Prince Rupert and Kamloops-Challis-Absaroka magmatic belts (SKPR and KCA in Fig. 5).

Thus the subduction cycle was perhaps cut short by easy fracture of the continent. This comparison of the two belts formed during Late Cretaceous to Cenozoic time illustrates how the geologic footprints of the basic subduction cycle may vary depending on the motions of nearby plates and may be diachronous along the plate margin. When the oceanic plate seaward of the spreading ridge moved strongly tangential and even slightly away from the continent, volcanism, intrusion, rifting, and strike-slip faulting formed in a broad belt. When the transtentional strain was low and/or more parallel to the plate margin, rifting and magmatism formed in a narrower belt.

The diachronous nature of the Mexican and Canadian cycles has led to the development of a transitional zone affected by both cycles that extends from central Arizona to central Idaho. Many of the features of this zone such as the Colorado Mineral Belt (COLO. MB in Fig. 5A), the Idaho reentrant (vicinity of the Idaho batholith, AL and BR in Fig. 5A), and the Snake River Plain (SNAKE RP in Fig. 5A) are quite different from other regions in western North America. The Laramide orogenic belt similarly extends along the northeastern part of this transitional zone, and thus it may relate to fragmentation of the continent during the Mexican cycle after the Canadian cycle had weakened the continental margin to the northwest.

Early Cretaceous cycle

Engebretson et al. (1985) showed an interval of moderately rapid convergence (>90 mm/yr) between 135 Ma and 119 Ma (Fig. 1A and B), although, as discussed previously, their assumptions regarding plate motions during this interval may not be correct. Many authors describe a magmatic lull between 140 Ma and 125 Ma (e.g., Evernden and Kistler, 1970; Armstrong and Ward, 1993) and note that the most voluminous plutonism during the Cretaceous Period was between 117 Ma and 86 Ma (Bateman, 1992). There is evidence of andesitic volcanism (Table 1), including two dated porphyry copper deposits (Fig. 5) and the largest molybdenum porphyry deposit in Canada at Endako (Sutherland Brown, 1976). Extensive post-Oxfordian and pre-middle Albian (154.7 Ma to 112 Ma) folding in the Skeena Fold Belt of British Columbia (Evenchick, 1991) may be evidence of subduction. The foreland fold and thrust belt from Idaho to Arizona was active between 140 Ma and 110 Ma (Allmendinger, 1992). Thick uppermost Jurassic through Lower Cretaceous molasse deposits accumulated in the foreland of the Canadian Cordillera (Eisbacher et al., 1974) and the Cordillera of the United States (Heller et al., 1986). There are many schists of Early Cretaceous age (Table 2). This sub-

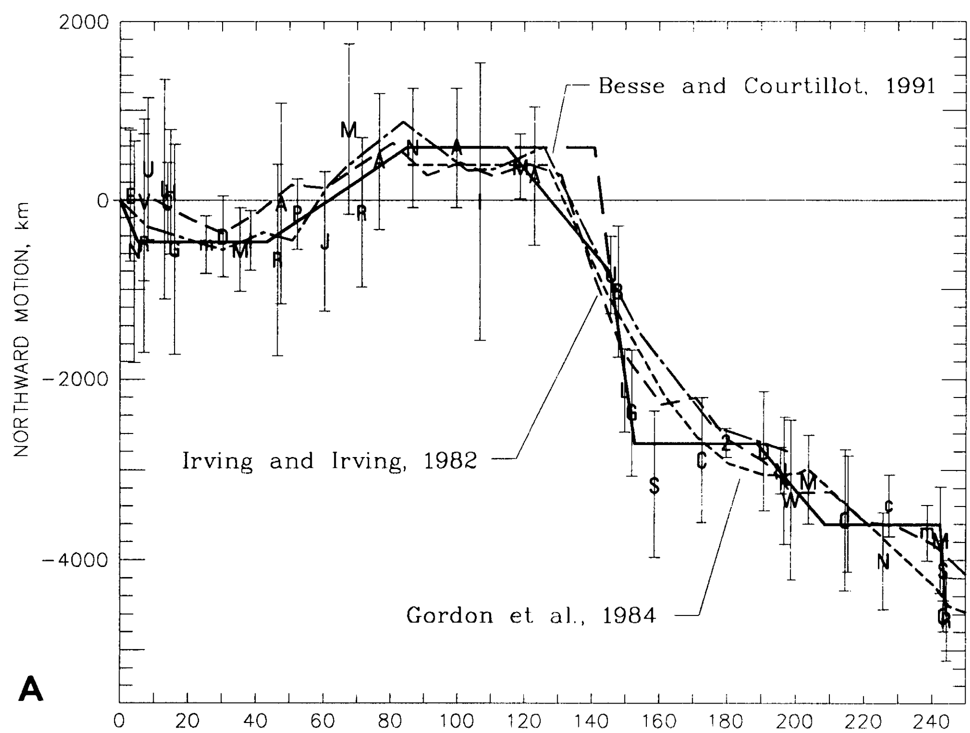


Figure 7A. The net northward component of motion of the North American plate as a function of time. The method of projection is discussed in the text. Symbols, listed in Table 3, are plotted with error bars for paleolatitude. The solid line is the reference curve suggested in this chapter by simply fitting horizontal and sloping line segments to the data. The heavy dashed line is an alternate interpretation for the interval from 115 to 145 Ma. The long-dashed line is the smoothed paleomagnetic reference curve for North America calculated by Irving and Irving (1982). The dot-dashed line is a similar smoothed reference curve calculated by Besse and Courtillot (1991). The short-dashed line is the paleomagnetic Euler pole (PEP) reference curve calculated by Gordon et al. (1984). More data are clearly needed especially between 170 Ma and 120 Ma.

duction cycle appears to have had less associated volcanism and deformation than the Early Jurassic or Cenozoic subduction cycles probably caused by the lower rate of convergence. Spreading in the Atlantic was at a rate of only 7–8 mm/yr between 150 Ma and 115 Ma, whereas it was two to three times faster before and after (Klitgord and Schouten, 1986). Magmatism increased at the end of this cycle with formation of voluminous batholiths from the Peninsula Ranges of northwestern Mexico, to the Sierra Nevada of California, to the Coast Plutonic Complex of British Columbia, to the Nutzotin-Muir-Chichagof belt of Alaska (Fig. 5). Metamorphic core complex activity has been difficult to prove for the mid-Cretaceous because of Eocene overprinting. Complex intrusive masses of two-mica rocks that formed between 101 Ma and 93 Ma in northern Washington are similar to Eocene gneiss domes within core complexes (Miller and Engels, 1975).

One reason for the relative quiescence during the Early Cretaceous interval in western North America is that subduction cycles were well developed in perpendicular directions in the Brooks Range of western Alaska and the southern Caribbean region.

Brookian cycle

The Brookian orogeny, during Early Cretaceous time, deformed northern and western Alaska, the Chukotsk Peninsula, and other parts of northeastern Siberia north of, and including, the South Anyuy suture. The geologic footprints of this orogeny, especially in Alaska, have been imbricated by motions of perhaps hundreds of kilometers along several strike-slip faults including the Kobuk, Kaltag, Iditarod, Farewell, and Susalatna faults. Furthermore, Cenozoic rotations of southern Alaska have been documented from paleomagnetic evidence (Stone and McWilliams, 1989), and rotations of northern Alaska are possible, but difficult to prove or disprove (Stone, 1989). Nevertheless, the geologic and metamorphic relationships (e.g., Patton and Box, 1989; Till, 1992) suggest a subduction cycle.

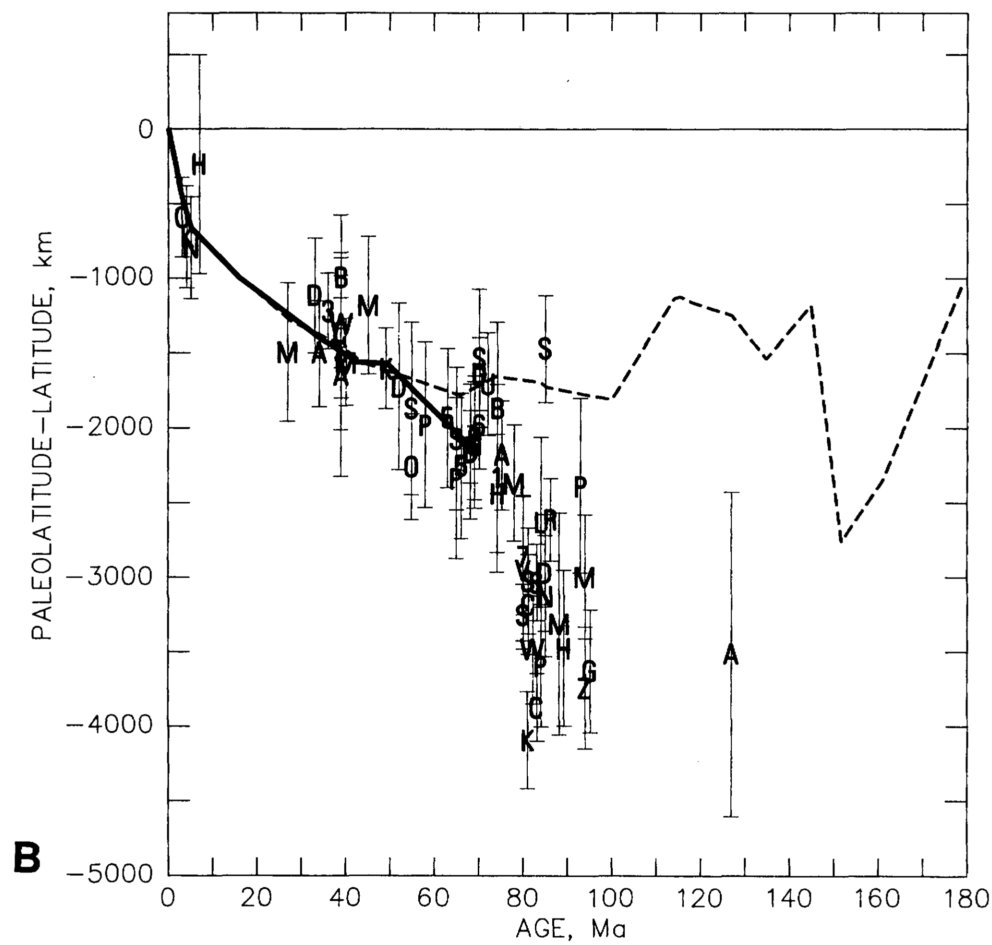


Figure 7B. The net northward component of motion of the Pacific plate as a function of time plotted as paleolatitude minus current latitude. Symbols, listed in Table 4, are plotted with error bars for paleolatitude. The heavy solid line was calculated by adding the northward motion of the Pacific plate relative to the North American plate (Stock and Molnar, 1988) plus the northward motion of the North American plate shown by the heavy solid line in Figure 7A. The dashed line is the sum of northward motion of the Pacific plate in relation to the North American plate based on the model of Engebretson et al. (1985) plus the northward motion of the North American plate shown by the heavy solid line in Figure 7A.

TABLE 4. PACIFIC PLATE PALEOMAGNETIC REFERENCES POLES AND SOURCES*

Age (Ma)	Site Latitude (N)	Site Longitude (E)	Pole Latitude (N)	Pole Longitude (E)	Error 95%	Symbol	Identification	Source
3	21.5	-158.0	84.5	36.1	2.4	O	Oahu, Hawaii	Doell and Dalrymple, 1973
4	22.1	-159.9	80.8	-26.3	3.1	K	Kauai, Makaweli Formation	Doell, 1972a
5	22.1	-159.9	82.1	45.7	3.1	N	Kauai, Napali Formation	Doell, 1972a
7	23.1	-161.9	86.8	-30.8	6.6	H	Nihoa Island	Doell, 1972b
27	28.2	-177.5	14.7	....	4.2	M	Midway drill hole	Gromme and Vine, 1972
33	3.8	-169.8	-6.3	....	3.5	D	DSDP 166	Sager, 1987
34	-2.0	-178.8	-15.6	....	3.2	A	S68-24, NW Nova Trough	Sager and Bleil, 1987
36	39.0	-131.0	78.0	23.0	2.3	3	39131 Seamount	Sager, 1987
39	-2.0	-178.8	-10.6	....	3.4	B	S68-24, NW Nova Trough	Epp et al., 1983
39	8.2	-161.9	75.6	-3.5	4.7	S	Stanley Seamount	Schlanger et al., 1984
39	31.0	176.0	76.8	-27.0	2.1	C	Colahan Seamount	Sager, 1987
39	7.9	-161.9	78.2	14.6	4.4	W	Willoughby Seamount	Sager and Keating, 1984
39	31.8	174.3	75.5	4.6	6.6	A	Abbott Seamount	Sager, 1984
40	-2.5	-173.3	-16.6	....	2.6	M	M70-39	Sager and Bleil, 1987
45	31.9	-141.8	79.4	41.3	4.2	M	Moonless Seamount	Sager, 1987
49	11.4	-168.2	-3.1	....	2.4	K	K78-1012	Sager and Bleil, 1987
52	32.4	157.7	16.8	....	5.0	D	DSDP 577, 50-53, Shatskiy	Sager and Bleil, 1987
55	32.4	157.7	15.5	....	5.2	S	DSDP 577, 54-56, Shatskiy	Sager and Bleil, 1987
55	38.0	170.6	17.6	....	3.2	O	Ojin, DSDP	Kono, 1980
58	32.4	157.7	14.5	....	5.0	P	DSDP 577, 56-61, Shatskiy	Sager and Bleil, 1987
63	32.4	157.7	14.9	....	4.2	5	DSDP 577, 61-65, Shatskiy	Sager and Bleil, 1987
65	44.8	170.0	26.1	....	4.3	S	Suiko, DSDP 433c	Kono, 1980
65	24.9	-157.1	67.7	1.8	4.9	P	Paumakua Seamount	Sager and Pringle, 1988
66	32.4	157.7	12.0	....	4.4	5	DSDP 577, 65-67, Shatskiy	Sager and Bleil, 1987
68	13.5	156.2	-6.0	....	4.1	D	DSDP 199, 63-74, E. Mariana	Sager and Pringle, 1988
68	32.4	157.7	13.2	....	2.2	P	DSDP 577, 66-69, Shatskiy	Sager and Pringle, 1988
69	32.4	157.7	13.6	....	3.6	S	DSDP 577, 67-68, Shatskiy	Sager and Bleil, 1987
69	20.0	180.0	71.0	9.0	4.0	G	Average 65-73	Gordon, 1982
70	4.2	-158.5	-9.7	....	4.2	S	DSDP 315A, 66-74, Xmas Rid	Sager and Pringle, 1988
70	13.5	156.8	-1.3	....	2.2	D	DSDP 585, 66-74, E. Mariana	Sager and Pringle, 1988
70	8.2	-164.9	-9.7	....	2.6	6	DSDP 165, 66-74	Sager and Pringle, 1988
72	-7.5	-151.5	68.5	-14.4	3.1	U	Uyeda/Wageman Seamount	Schlanger et al., 1984
74	26.5	-177.8	68.0	8.9	3.6	H	H11 Seamount, SW Midway	Sager and Pringle, 1988
74	28.1	-171.2	7.0	....	5.7	1	H13 Seamount	Sager and Bleil, 1987
74	26.6	-159.9	9.7	....	5.2	B	Bach Ridge	Sager and Bleil, 1987
75	26.6	-161.3	69.2	-2.1	3.3	A	Haydn Seamount	Sager and Pringle, 1988
78	25.1	-161.7	68.3	6.8	3.5	M	Mendelssohn-E Seamount E	Sager and Pringle, 1988
80	40.9	144.9	56.4	-0.6	2.0	S	Sisoev/Erimo Seamount	Gordon, 1983
80	11.8	177.6	-13.9	....	3.6	7	DSDP 170, 78-83	Sager and Pringle, 1988
80	7.3	172.3	63.2	2.2	4.4	V	Von Valtier SM Marshall I	Sager and Pringle, 1988
81	22.2	-162.6	60.0	-1.3	3.0	C	Chataqua Seamount	Gordon, 1983
81	17.9	-152.7	56.5	-9.9	3.2	S	Show Seamount E	Gordon, 1983
81	17.1	-154.2	49.8	1.5	2.9	K	Kona 5S Seamount	Gordon, 1983
82	25.1	-162.8	57.8	3.1	3.3	W	Mendelssohn-W Seamount	Sager and Pringle, 1988
83	25.7	-160.2	59.2	-10.1	2.3	S	Schumann-W Seamount E	Sager and Pringle, 1988
83	14.9	-172.3	55.0	1.8	2.0	C	C6 Seamount	Sager and Pringle, 1988
84	12.0	-165.8	47.5	-26.5	3.7	P	Kapsitotwa Seamount	Schlanger et al., 1984
84	29.0	-162.3	59.2	-26.2	5.1	L	Liszt Seamount E	Sager and Pringle, 1988
85	12.5	-167.0	61.6	4.0	3.7	N	Nagata Seamount	Schlanger et al., 1984
85	19.1	-169.5	-7.8	....	3.5	D	DSDP 171, 82-88, Karin SM	Sager and Pringle, 1988
85	-11.0	-162.3	-24.3	....	3.2	S	DSDP 317A, 82-88, Manahiki	Sager and Pringle, 1988
86	29.6	-163.3	55.6	-35.4	2.5	R	Rachmaninov Seamount E	Sager and Pringle, 1988
88	31.8	-165.0	56.0	-17.4	6.7	M	Mahler Seamount	Sager and Pringle, 1988
89	18.3	-161.8	52.0	-18.0	4.7	H	HD-1 Seamount	Gordon, 1983
93	4.2	-158.5	-17.4	....	5.3	P	DSDP 315A, Xmas Ridge E	Sager, 1987
94	27.1	148.7	55.9	-37.0	3.3	Z	Z43 Seamount	Sager and Pringle, 1988
94	29.5	153.5	63.4	-28.7	3.4	M	Makarov Seamount	Sager and Pringle, 1988
95	21.3	153.2	57.3	-29.9	3.7	G	Golden Dragon Seamount	Sager and Pringle, 1988
127	20.0	180.0	51.4	-36.9	9.8	A	Mean lineations and DSDP	Gordon, 1990

*Pole longitude cannot be calculated for unoriented drill cores.

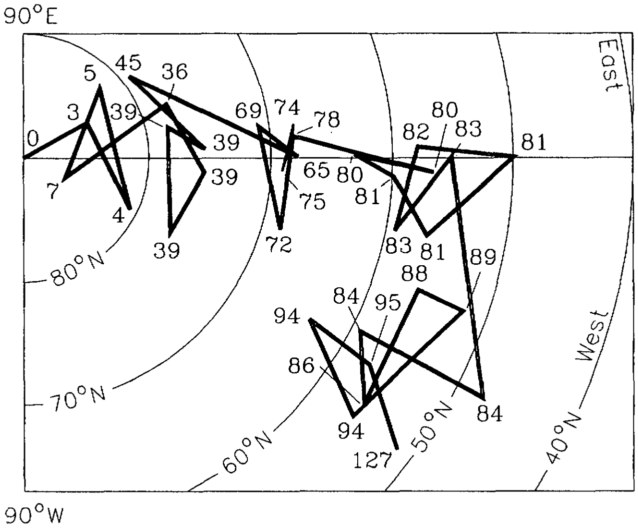


Figure 8. Polar plot of apparent paleomagnetic north poles for the Pacific plate since Early Cretaceous time. Number shows ages (Ma) of the poles listed in Table 4. The Greenwich meridian is indicated by 0°. Errors are omitted from this figure to emphasize the dates but can be thought of as circles with radii varying from 2° to 14°. When errors are taken into account, it is reasonable to assume that the polar-wander curve is more linear than shown.

Shortening in the Brooks Range fold and thrust belt was north directed and active from Late Jurassic to Albian time (157.1–97 Ma) (Mayfield et al., 1988). A flood of magmatic-arc and mafic rock debris was shed northward onto the Arctic Alaska terrane beginning in the Tithonian (152.1–145.6 Ma) (Patton and Box, 1989). The deposition of these clastic rocks implies tectonism contemporaneous with the sudden northward motion of North America seen in the paleomagnetic data (Fig. 5). Subduction was apparently underway, stacking several thrust plates in the manner observed today by seismic methods (Fuis et al., 1991), throughout the Berriasian and Valanginian (145.6–135 Ma) with some volcanism lasting until 118 Ma (Patton and Box, 1989). Onset of extension between 131 Ma and 119 Ma is shown by a regional unconformity indicating uplift, widespread extensional structures, and magma types related to extensional terranes (Miller and Hudson, 1991). As subduction-related contraction changed to extension, the relative positions of surrounding plates were apparently such that rather than forming a transtensional zone near the volcanic line, the volcanic line rifted, cutting off sedimentary deposits from the north to the North Slope (Molenaar, 1983) and forming the Canadian Basin. Widespread rifting in the Canadian Basin, possibly by counterclockwise rotation of northern Alaska, began in Hauterivian time (135–131.8 Ma) (Sweeney, 1985), and although the

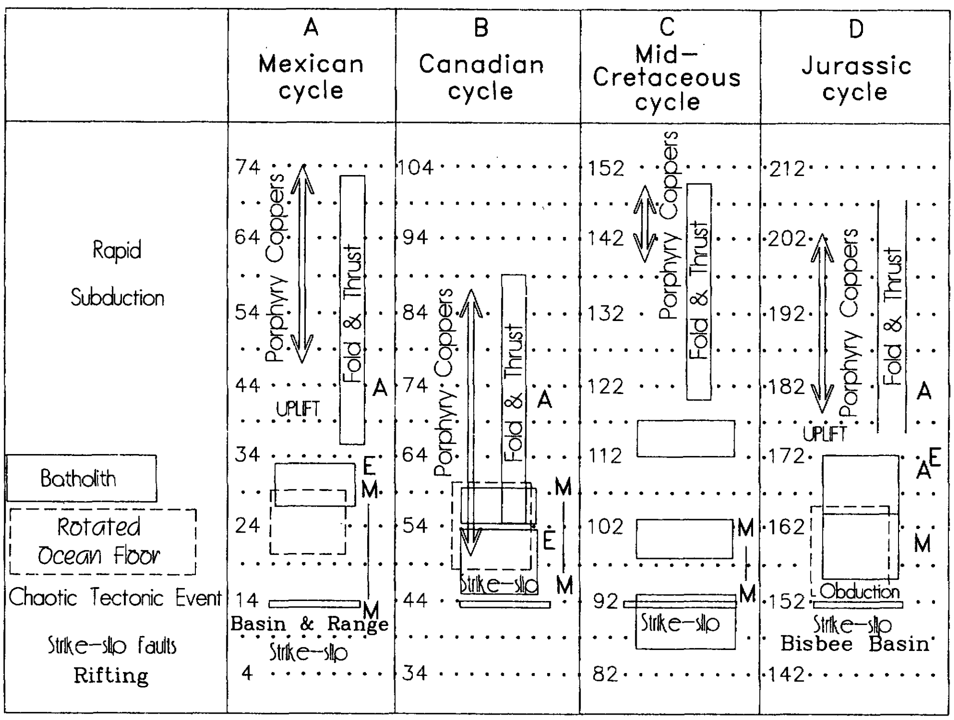


Figure 9. Comparison of four subduction cycles with the time scales adjusted such that all four major chaotic tectonic events line up horizontally. In all four cases, rapid subduction inferred from folding and thrusting and arc-volcanic rocks exposed in porphyry copper deposits is followed by localized alkalic volcanism (A), a change to trench-normal extension (E), batholith formation, rotation of oceanic magnetic anomalies near land, distension in metamorphic core complexes (M), a major chaotic tectonic event, and strike-slip faulting and rifting. No rotated oceanic magnetic anomalies are observed for the mid-Cretaceous event probably because they would have formed during the long normal-magnetic approach.

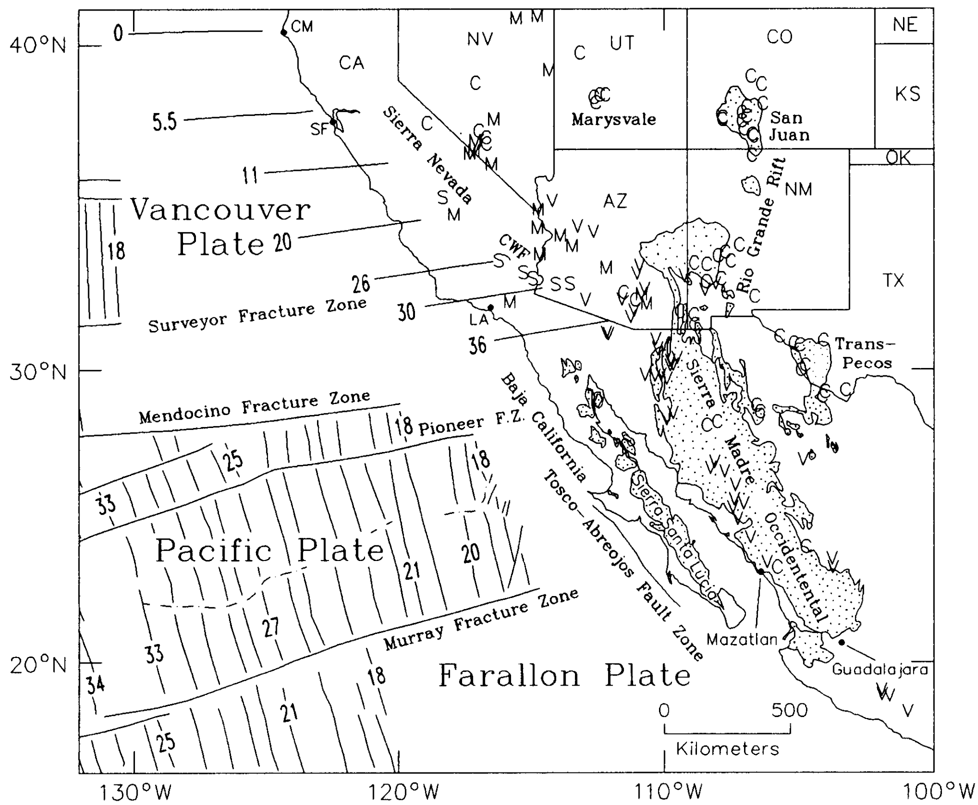


Figure 10. Map of the southwestern U.S. and northern Mexico showing the location of the Sierra Madre Occidental batholith and related volcanic fields, major calderas (C), porphyry copper deposits (V), major Miocene metamorphic core complexes in the vicinity of southern Arizona (M) and the undivided Pelona, Orocopia, Rand Schists (S). Only features younger than 71 Ma are shown. CM = Cape Mendocino, SF = San Francisco, and LA = Los Angeles. Land west of the San Andreas fault has been rotated to close the Gulf of California. The magnetic anomalies on the Pacific plate that formed before 42 Ma (anomaly 18) (Atwater and Severinghaus, 1989) are shown in their position relative to North America at 42 Ma as calculated by Stock and Molnar (1988). A short segment of the Mendocino fracture zone west of Cape Mendocino, California, is shown rotated to its former positions at 5.5, 11, 20, 26, 30, and 36 Ma. Shading shows major outcrop areas of primarily Tertiary volcanic rocks in the vicinity of the Sierra Madre Occidental (King, 1969). CWF is the Clemens Wall fault.

age of its ocean floor and mode of formation is highly debated (Lawver and Scotese, 1990), most authors seem to be converging on dates of 118–84 Ma. The Ruby batholith formed at approximately 110 Ma and is isotopically more similar to the Idaho batholith than to other batholiths in western North America (Arth et al., 1989). Continued formation of thick turbidites and molassoid conglomerates through Albian and Cenomanian time (112–90.4 Ma) indicate high rates of erosion. At approximately 84 Ma, the strain field changed to east-west shortening accompanied by a significant realignment of plates in the northern Pacific Ocean (Mammerickx and Sharman, 1988) and the onset of rapid subduction under western North America.

Early Cretaceous Caribbean cycle

Limited outcrops in the Caribbean region provide evidence of complex, multiple motions and the tectonic history is actively debated (e.g., Dengo and Case, 1990). The proto-Caribbean Ocean opened during Late Jurassic and Early Cretaceous time as discussed in Appendix 2. In northern Venezuela, at least six fault-separated nappes or terranes range on the south from a thick Coniacian (88.5–86.6 Ma) flysch, to Late Jurassic and Early Cretaceous metasedimentary rocks, ophiolite, and eclogite, to a chain of granitic plutons on the north (Maresch, 1974; Bellizzia and Dengo, 1990). Some schists have K/Ar dates of 117–100 Ma, and the granite on Aruba Island formed approximately between 90 Ma and 85 Ma (Beets et al., 1984; Donnelly et al., 1990). This subduction zone was probably active from the Late Jurassic until approximately the Aptian (157.1–112 Ma) while the North American plate moved away from the South American plate, and the mid-Proto-Caribbean ridge approached the northern coast of South America. The spreading rate increased at this time in the South Atlantic Ocean (Savostin et al., 1986), and a significant plate reorganization occurred throughout the Caribbean and Pacific at approximately 84 Ma (Mammerickx and Sharman, 1988; Pindell and Barrett, 1990). There are many details to be worked out concerning subduction cycles in the Brooks Range and the Caribbean region, but these few observations show that during the Early Cretaceous subduction cycles were probably better developed in these two areas than in the region in between along the western coast of North America.

Jurassic cycle

During Carnian time (235–222.3 Ma), basaltic, andesitic, and rhyodacitic lava flows and pyroclastic rocks, with some alkalic and shoshonitic rocks, formed from northern British Columbia to southern California (Table 1) (Schweickert, 1978; Mortimer, 1986), inland from the contemporaneous flood basalts in western British Columbia and Alaska (Karmutsen Formation and related rocks, Fig. 4). The role of this short-lived arc is unclear. It was followed by widespread formation of up to 400 m of Carnian to Norian limestone in a shallow-water environment. At some time between the early Norian and late Sinemurian (222.3 Ma and 194.5 Ma), there was a rapid, but conformable shift to deep-water conditions as shown most clearly by the Sailor Canyon Formation in the northern Sierra Nevada of California (Fisher, 1990; Girty et al., this volume). This turbiditic sandstone and carbonaceous siltstone indicates the onset of a subduction environment by Early Jurassic time. At the same time there was thrusting and uplift of the craton, forming the J-0 regional unconformity from at least Idaho to Arizona (Reynolds et al., 1989; Marzolf, 1991). Andesitic volcanism was widespread during the Early Jurassic (Table 1). The decrease in porphyry coppers by the end of the Early Jurassic (178 Ma) (Fig. 2) implies that subduction slowed. Alkalic plutons formed in the White and Inyo Mountains and the Mojave Desert of southern California primarily between 185 Ma and 167 Ma (Dunne et al., 1978). Alkalic plutons with similar ages are found in the Klamath Mountains of northern California and in central British Columbia (Miller, 1978). Much more voluminous calc-alkalic and alkali-calcic magmatism began by 172 Ma (e.g., Tosdal et al., 1989; Bateman, 1992) with the possible onset of trench-normal extension (Busby-Spera et al., 1990). Busby-Spera (1988) suggested that the Early Jurassic arc lay within a graben, implying extension, but evidence for significant extension prior to 178 Ma is controversial (e.g., Marzolf, 1990). There is evidence for Middle Jurassic extension and normal faulting near the arc and inland (e.g., Oldow and Bartel, 1987; Miller and Allmendinger, 1991; Miller and Hoisch, 1992). Metamorphic core complex mylonitization began in British Columbia by 161 Ma (Brown and Read, 1983). Crustal shortening then was widespread at least from Idaho to southern California (Allmendinger and Jordan, 1984; Walker et al., 1990; Hudec, 1992), ending by 148 Ma with the onset of the Independence and related dike swarms (Chen and Moore, 1979).

A number of strike-slip faults may have been active during the Tithonian (152.1–145.6 Ma). The proposed Mojave-Sonora megashear in California and northern Mexico is thought to have been active from approximately 155–145 Ma, accumulating about 800 km of left-lateral strike slip (Anderson and Schmidt, 1983). Left-lateral slip on the Pine Nut fault and closing of the Luning-Fencemaker fold and thrust belt in western Nevada during Middle or Late Jurassic through Early Cretaceous time (Oldow, 1984) are consistent with northwestward movement of the North American plate. Right-lateral strike-slip motion has been proposed along the Foothills fault system, the Kings River fault, and the San Joaquin River fault west of the Sierra Nevada during Nevadan time (Nokleberg, 1983; Saleeby, 1981; Clark, 1960), but the direction of motion is not well established and the inferred motion may simply reflect the youngest sense of motion along these multiply deformed sutures. Left-lateral shear motion may have occurred along the Walker Lane belt in Nevada during the Jurassic (Stewart, 1988). Major left-lateral motion is inferred on the Trans-Idaho discontinuity (Yates, 1968) in the middle Mesozoic.

The primary difference between the Jurassic and Mexican sequences is polarity. During the Jurassic, the strike-slip faulting was left lateral and the Bisbee Basin rift was south of the arc volcanoes and major batholiths. During the Cenozoic, the faulting was right lateral and the Basin and Range was north of the arc volcanoes and batholiths. A second difference is that few Jurassic porphyry copper deposits have been reported in the vicinity of the Sierra Nevada batholith. The Cenozoic porphyry copper deposits (Fig. 10) formed west of the Cenozoic batholiths. The Jurassic counterparts may have been eroded deeply, severed by strike-slip faults, and overlain in part by sedimentary deposits of the Great Valley of California. A third difference is that geologic evidence for the Jurassic cycle is less readily observed because of subsequent activity. There are insufficient data to tell whether there were two diachronous cycles during the Jurassic as there were during the Cenozoic.

EVIDENCE FOR MAJOR CHAOTIC TECTONIC EVENTS BETWEEN SUBDUCTION CYCLES

The beginning and end of each subduction cycle in western North America is marked by rapid change along the boundary between the North American and oceanic plates. Geologic evidence for the nature of each of these major chaotic tectonic events varies depending on the level of erosion, the extent of the plate boundary involved, and the amount of overprinting by more recent events. Taken as a group, however, the evidence for these events suggests the occurrence of a fundamental process lasting typically less than ten million years.

Miocene (ca. 15 Ma)

Distension, rifting, and rotation of small terranes from Canada to Mexico was profound in the wedge of continent above the former subduction zone between the former volcanic line and the former trench. Deformation was particularly intense from the Sierra Madre Occidental batholith in Mexico northwestward to the region east of the Mendocino fracture zone located at about 35°N at this time (Fig. 10). Tectonic fragmentation started in southern California with rapid formation of major basins beginning about 23 Ma (Dickinson et al., 1987). Subduction of the small Guadalupe plate, a fragment of the former Farallon plate, began under the Sierra Santa Lucia Arc in southern Baja California and lasted only until approximately 17 Ma (Fig. 10 and SSLA in Fig. 5). Mylonitization reached a peak in the metamorphic core complexes of southern California and southern Arizona between 20 Ma and 15 Ma (Fig. 5). Diabase dikes and sills were widespread in the Los Angeles Basin especially at 15 Ma (Crowell, 1987). Terranes throughout the Transverse Ranges of southern California rotated 5° to 6° clockwise per million years from 17 Ma to the present (Luyendyk, 1991). Major strike-slip movement began at approximately 14 Ma on the Tosco-Abreojos fault west of Baja California (Spencer and Normark, 1979). Other steep faults that formed along the coast in the King Range terrane, presently located in northern California, were filled with adularia-bearing veins dated at 13.8 Ma (McLaughlin et al., 1985). More than 400 km of the spreading ridge west of the coast of Baja California became extinct, and the spreading center jumped southward and rotated to become perpendicular to the trench west of the southern end of the Sierra Madre Occidental batholith and near the southernmost end of what was to become the Gulf of California (Mammerickx and Klitgord, 1982). The Basin and Range province from northern Mexico to southern Oregon opened significantly between 17 Ma and 14 Ma (Zoback et al., 1994). Just north of the Basin and Range, the flood basalts of the Columbia River Basalt Group formed in Oregon especially between 16.5 Ma and 14 Ma (Mangan et al., 1986) and plateau basalts formed in the Cariboo Region of southern British Columbia (Bevir, 1983). Parts of western Oregon rotated clockwise as much as 16° (Beck et al., 1986). Beginning by approximately 18 Ma, magmas in the Basin and Range became fundamentally basaltic, and in Arizona the $^{87}Sr/^{86}Sr$ ratio had dropped abruptly by 13 Ma below 0.7055 (Keith and Wilt, 1986; Reynolds et al., 1986). The Basin and Range province and all the continent to the west began to move in part with the Pacific plate. Even today, approximately 15% of the motion between the North American plate and the Pacific plate is taken up by opening in the Basin and Range province (Eddington et al., 1987).

Eocene (ca. 44 Ma)

There was a major transition in the Pacific Northwest during Middle Eocene time (50–38.6 Ma) (Fig. 5) that ends the Canadian cycle. Primarily between 50 Ma and 45 Ma, large volumes of calc-alkalic andesite to dacite erupted in the Challis magmatic belt from northeastern Washington through southern Idaho (Christiansen and Yeats, 1992). Beginning by 43 Ma, volcanism shifted westward to form the andesitic Cascades of western Oregon and Washington. Extension, which had begun inland in the metamorphic core complexes at approximately 55 Ma (Parrish et al., 1988), culminated in the forearc with coarse clastic sediments filling rapidly forming grabens between 50 Ma and 40 Ma (Heller et al., 1987). Many small coastal blocks in Oregon rotated clockwise approximately 25° between 48 Ma and 40 Ma (Wells and Coe, 1985; Fox and Beck, 1985). Normal faulting predominated. The Mission fault in southern British Columbia had 10.4–18.4 km of downdip displacement bringing schist to the surface after 46.5 Ma (Coleman and Parrish, 1991). These changes were localized in the Pacific Northwest but were contemporaneous with the change to a more westerly direction of motion for the Pacific plate at 43 Ma (Stock and Molnar, 1988).

Cenomanian (ca. 92 Ma)

The mid-Cretaceous orogeny was important from coastal California to southeastern Alaska (Rubin et al., 1990), forming in northwestern Washington one of the most impressive stacks of thrust sheets found in western North America. During Albian time (112 Ma to 97 Ma), there was a dramatic increase in tectonic subsidence with the deposition of more than 8 km of sedimentary materials in the Methow Basin. The blueschists and greenschists of the Shuksan Metamorphic Suite of Misch (1966) were then "uplifted and/or cooled, indicating they had departed the subduction environment" (McGroder, 1991, p. 201). A major angular unconformity formed during part of Cenomanian time (97.1–90.4 Ma) and thrusting began. This deformation in northern Washington and southern British Columbia was contemporaneous with the Coast Range orogeny in Oregon (Blake et al., 1985).

To the north, in the western metamorphic belt of the Coast Plutonic Complex in southeastern Alaska, Stowell and Hooper (1990) interpreted structures related to a thermal peak between 100 Ma and 90 Ma west of the Coast Range megalineament to show a complex history involving underthrusting, normal motion on the former thrust, and strike-slip motion.

Tithonian (ca. 152 Ma)

The short-lived Nevadan orogeny and the sudden and rapid northward movement of the North American plate near the end of the Jurassic (Figs. 5 and 7) are parts of the major terminal event for the Jurassic subduction cycle. Much of the evidence for this event is found in the western metamorphic belt of the Sierra Nevada in California that contains Paleozoic through Early Jurassic ocean floor, sedimentary rocks, and mélange (Day et al., 1985; Hacker, 1993). Six terranes, which had been juxtaposed along east-dipping thrust faults active before approximately 165 Ma, were covered with Callovian to Kimmeridgian (161.3–152.1 Ma) flysch, the Mariposa Formation, in rapidly deforming basins (Bogen, 1984). Folding and faulting involving rigid rotation of these beds began sometime between 151 Ma and 150 Ma (Tobisch et al., 1989). The primary Nevadan deformation involves northwest-trending penetrative slaty cleavage in mudstones and a spaced cleavage in graywacke that shows a remarkable regional consistency (Schweickert et al., 1984). A characteristic "crenulation cleavage developed in the phyllites as the rocks to the west acquired their slaty cleavage" (Schweickert et al., 1984, p. 971). The deformation was enhanced by migrating fluids associated with metamorphism. Tobisch et al. (1989, p. 406) note that chemical changes during mylonitization were substantial, suggesting "large fluid/rock interchange during deformation." Metamorphism was highest along regions such as the Bear Mountain fault zone, which apparently acted as a channel for fluid-transported heat. Although the main deformation probably lasted for less than a few million years (Schweickert et al., 1984) and appears to coincide at least with the beginning of the rapid northward motion of the North American plate discussed above, some regional ductile deformation may have continued until 123 Ma (Tobisch et al., 1989), through the compressive part of the Cretaceous subduction cycle. One effect of the fluid-driven metamorphism was extensive secondary magnetization of the rocks (Bogen et al., 1985). The Nevadan deformation and metamorphism were contemporaneous, within current temporal resolution, with obduction of the Coast Range ophiolite at 152 Ma (Hopson et al., 1981) and the beginning of the rapid northward movement of the North American plate (Fig. 5). Evidence has not been reported for widespread strike-slip motion within the western metamorphic belt during Late Jurassic or Early Cretaceous time, but left-lateral strike-slip motion was widespread throughout western North America (Fig. 5).

Carnian (ca. 230 Ma)

The voluminous Karmutsen Formation, Nikolai Greenstone, and related flood basalts that formed in British Columbia and Alaska between 236 Ma and 225 Ma are evidence of major extension and extrusion. These may record a chaotic tectonic event at the beginning of the Jurassic cycle.

Summary of the properties of the major chaotic tectonic events

Major chaotic tectonic events seem to follow the *onset* of batholith formation by approximately 20 m.y., although batholith formation may continue during a chaotic event (Fig. 9). They typically begin with the rapid formation of tectonic basins and extensive mylonitization in the metamorphic core complexes. They often involve flood basalts, a change to fundamentally basaltic volcanism, and a drop in the ratio $^{87}Sr/^{86}Sr$, implying sudden thinning of the lithosphere. They involve sudden rotation of terranes and rifting, implying the strength of the boundary between the oceanic and continental plates goes through a minimum as the continental margin is profoundly extended, the earlier subduction zone breaks up, and a new subduction zone is established. They involve substantial strike-slip motion along the plate margin and rapid motion of the paleomagnetic pole and, most likely, of the continent.

Another distinctive feature of these terminal events may be the major role of fluids seen in adularia-bearing veins formed in the Miocene, in pervasive serpentinization between the Coast Range ophiolite and the Franciscan Complex, and in alteration of the western metamorphic belt of the Sierra Nevada. Peak metamorphism and remagnetization associated with these old subduction zones extends over narrow but elongate regions, implying heating from fluids.

This summary shows that subduction cycles are separated by major chaotic tectonic events. A great deal of work is needed to resolve the details of these events so that the mechanisms can be brought into focus.

DISCUSSION OF A POSSIBLE MODEL

There appears to be general agreement that the negative buoyancy of subducting slaps creates a force at least twice as great as any other force on the plates and thus is primarily responsible for plate motion (Forsyth and Uyeda, 1975; Chapple and Tullis, 1977; Richardson et al., 1979; Backus et al., 1981; Richardson and Cox, 1984). Documentation of the subduction cycle in this chapter shows that geology in orogenic belts correlates closely in time and space with subduction and with changes to extension and to strike-slip motion later in the proposed subduction cycles. The periods of very rapid subduction, at least in the northeast Pacific Ocean, only last for approximately 30 m.y. and are separated by periods of approximately the same length where subduction is slow or nonexistent. The basic phases of a subduction cycle model are shown in cross section in Figure 11.

"Collision" of the North American plate with a mid-ocean ridge

The primary event to trigger a change in the subduction environment under southwestern North America during the Cenozoic was the approach of the East Pacific rise to the trench (Figs. 10 and 11B) (Ward, 1991). The ridge was not subducted, as shown by short lengths of old ridge crest found along the coast of California and Mexico (Mammerickx and Klitgord, 1982; Atwater and Severinghaus, 1989; Lonsdale, 1991). Uplift observed on land was probably caused by the buoyancy of the young oceanic lithosphere being subducted (Fig. 11B). Alkalic magmatism broke out approximately 800 km inland (subtracting 200 km for subsequent Basin and Range extension). Coney and Reynolds (1977) argued that the eastern outbreak of magmatism was caused by the shallowing of the dip of the subducted plate, but volcanic rocks and a porphyry copper deposit were formed at the same time halfway between western Texas and the trench, implying that the dip of the slab was not so shallow as to shut off access of magma to the former arc region. I

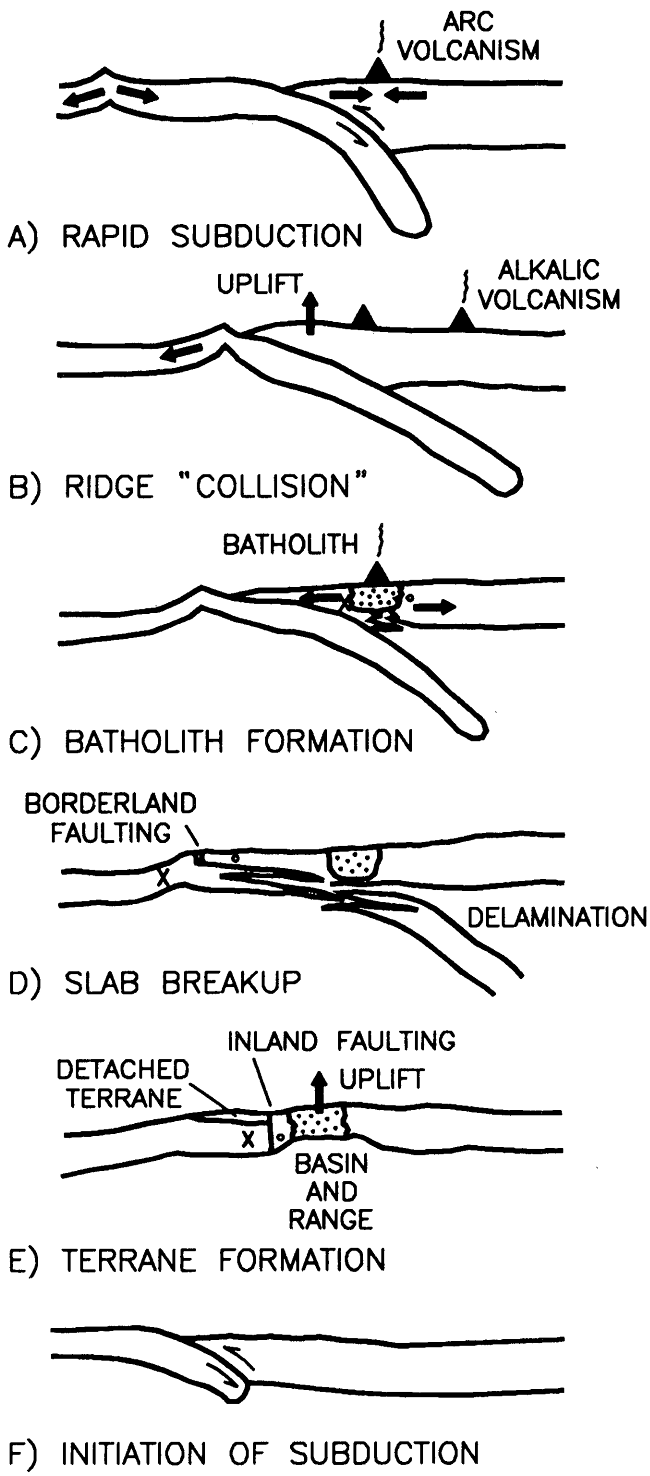


Figure 11. A model of the interaction of a mid-ocean ridge with a trench where the trend of the ridge is at a small angle with the trend of the trench. See description in text. Shear parallel to the trench is shown in parts D and E by dots (tips of arrows) and Xs (tails of arrows).

know of no direct evidence for the dip of the subducted plate at 40 Ma. I have shown that a plot of ages of magmatism versus distance along a profile similar to that shown by Coney and Reynolds (1977), but drawn perpendicular to theirs, implies the same type of magmatic sweep and thus slab dip but along the volcanic arc rather than perpendicular to it (Ward, 1991) Although many young slabs have low dips, Jarrard (1986) shows that the correlation of slab dip with slab age is not statistically significant. The alkalic magmatism in western Texas may simply be the mechanical effect inland of the interaction of the ridge with the trench or may relate in some way to the eastward extension of the Mendocino or Pioneer fracture zones. The alkalic nature of the magmatism is likely to be caused by many factors including the thickness of the lithosphere, assimilation of crustal rocks, and depth to the underlying plate (e.g., Verma and Nelson, 1989).

Transtentional origin of granites

In each of the best-documented subduction cycles, periods of subduction are followed by changes in regional strain from trench-normal contraction to trench-normal extension and by the formation of major batholiths (Fig. 11C). Several authors have noted the importance of extension and transtension in the formation of granites. Hutton et al. (1990) concluded that rapakivi granite in Greenland intruded along ductile, extensional shear zones. Tobisch and others (1986) emphasized the evidence for extension during Late Jurassic and Early Cretaceous plutonism in the Sierra Nevada of California. Evidence for major strike-slip faulting within and during formation of the Sierra Nevada batholith is described by Busby-Spera and Saleeby (1990), Lahren et al. (1990), and Kistler (1990). Saleeby (1991) proposed the term "transtitching batholithic belt" to emphasize that fundamentally different terranes appear to be stitched together by an elongated batholith, presumably filling the faulted and extended boundary. One of the clearest examples of such transtitching is the combined 1,500 km length of the Skagway-Ketchikan–Prince Rupert and Kamloops-Challis-Absaroka belts (SKPR and KCA in Fig. 5) that lay at or near the eastern boundary of the Kula plate as it moved rapidly northward. Kriens and Wernicke (1990) argued that the Ross Lake fault in northern Washington is a slightly tectonized intrusive contact even though regional relations suggest a fault. The Skagit Complex of Kriens and Wernicke (1990) that intrudes the area was dated at approximately 90 Ma, the time of the major chaotic tectonic event in this area. Thus this well-studied area may be a classic example of a synplutonic intrusive complex stitching two terranes together.

Several authors have proposed that contraction-induced crustal thickening related to subduction is important in the origin of granite (e.g., Sandiford et al., 1991; Hutton and Reavy, 1992). This proposal is not supported by the observation in Fig. 5 that the most voluminous and extensive batholiths formed between 120 Ma and 86 Ma after the interval of moderate subduction during the Early Cretaceous. Although the batholith was coeval with the fold and thrust belt, Laramide-type crustal thickening took place after the magmatism ceased. I infer that the width of the batholith may be most affected by the magnitude of the extensional component of motion between the two plates involved.

The role of highly mobile fluids during major chaotic tectonic events has been emphasized above. Fluids may also be mobilized when the crust is severely fractured during the early stages of batholith development. Gold-bearing quartz veins in southeastern Alaska formed along the Coast Range megalineament between 56.1 Ma and 55 Ma, the time when the Skagway-Ketchikan–Prince Rupert belt of granitic rocks (SKPR in Fig. 5) began intruding (Goldfarb et al., 1991). Similar veins were formed within the western metamorphic belt of the Sierra Nevada in California primarily between 120 Ma and 110 Ma, the time during which the Fine Gold Intrusive Suite was emplaced (FG IS in Fig. 5) (Bohlke and Kistler, 1986).

Breaking apart of the subducted slab

There is little evidence for old subducted plates hanging from old subduction zones (Grand, 1987; Grand and Engebretson, 1992; Richards and Engebretson, 1992). The plates must become detached at some point, and because the downgoing motion of the subducted plates appears to be the dominant force driving plate motions and causing shortening on the continental margin and foreland, the detachment of these plates probably relieves contraction and introduces extension. Such extensional collapse of a contractile orogen is observed in orogenic belts around the world (e.g., Dewey, 1988).

The crust appears to have been thickened significantly by contraction during subduction (Bird, 1988). Then during the major chaotic tectonic event in the Miocene, the wedge of crust that overlay the former subduction zone between the trench and the volcanic arc appears to have been extended so pervasively that it has thinned and collapsed. While rifting and extension was widespread in the Basin and Range, mostly to the east of the former volcanic line, the most profound thinning was located, for reasons yet to be understood, in the extensional corridor of southern California and southern Arizona, between the northern end of the Sierra Madre Occidental batholith and the trench (Fig. 10).

The outbreak of flood basalts and fundamentally basaltic volcanism from British Columbia to Mexico at approximately 10 Ma to 15 Ma, together with the sudden decrease in $^{87}Sr/^{86}Sr$ initial ratio, implies rapid thinning of the lithosphere over a very wide area (Fig. 11D). Bird (1979) introduced the concept of lithospheric delamination under the Basin and Range where, because of inherent gravitational instability, the dense, lower lithosphere breaks away from the upper lithosphere. Sacks and Secor (1990) and Nelson (1992), among others, discussed the implications of delamination for subducted slabs. Philippot and van Roermund (1992) described a rheological model for ocean-crust delamination based on mapping of structures in omphacite in the Alps. The effect of the subducted slab breaking apart (Fig. 11D) is to delaminate the lithosphere under the Basin and Range, leading to the high heatflow, extensive rifting, thin crust and other well-known features of this province (e.g., Eaton, 1982). After subduction slows (Fig. 11B), the slab is likely to heat up, causing significant weakening at depths in excess of 40 km (Philippot and van Roermund, 1992). and allowing the slab to pull apart in the 20-m.y. time lapse observed. Release of the downward-pulling slab would relax forces in the shallow part of the subduction zone, allowing extension and possibly even reverse motion or normal faulting on the uppermost part of the former subduction zone. Such motion can be expected to disturb this zone, especially toward its distal end, much like pulling a rug out from under numerous books laid side by side. The thicker parts of this zone may collapse along former thrusts, distending and uplifting as observed in the metamorphic core complexes.

Severinghaus and Atwater (1990) argued that the slab is heated and simply becomes assimilated in the asthenosphere. I do not see this as a viable option for several reasons. Most of the slab consists of refractory mantle material left over after the low-melting components have been removed (Dickinson and Luth, 1971). These parts of the slab cannot melt in the asthenosphere. Secondly, there is seismic evidence for old slabs in the upper mantle (Grand, 1987; Grand and Engebretson, 1992). Thirdly, the regional geology and tectonics described in this chapter show evidence for a punctuated process rather than the steady-state process that Severinghaus and Atwater (1990) propose.

Anchoring of the plates

Paleomagnetic data (Fig. 5) show that during the 20 m.y. immediately following rapid subduction, when major batholiths are formed, the north-south motion of the North American plate is minimal. In the beginning of the subduction cycle, both oceanic and continental plates appear to move relatively easily, but by the end of the interval of rapid subduction, motion becomes difficult, as if the downgoing slab becomes stuck in the lower mantle. Between 68 Ma and 42 Ma, approximately 3,500 km of oceanic plate was subducted under North America (Stock and Molnar, 1988). This plate may have been stacked up in the mantle in slices, may have been laid out horizontally at some depth, or may have gone vertically toward the core boundary at a depth of approximately 5,000 km. In any case, the likelihood that the subducting slab penetrates the asthenosphere suggests that it can become an anchor that must be broken apart before rapid plate motions can resume. The breaking apart of the upper subducting plate suggested above during the major chaotic tectonic events may have as much to do with mechanical failure as with thermal weakening and ductile straining. Such anchoring would limit the length of intervals of rapid subduction. If such anchoring takes place, then identification of graveyards of subducted plates (Richards and Engebretson, 1992) would provide a way to calibrate east-west continental motion much as paleomagnetism provides a way to calibrate north-south motion.

Such anchoring might explain the difference between apparent polar wander, which is the motion of plates relative to the Earth's spin axis, and true polar wander, which is the motion of the mantle hotspots relative to the Earth's spin axis. True polar wander is episodic with motions as fast as 4.3–9 cm/yr from 200–180 Ma, 120–100 Ma, 80–50 Ma, and 10–0 Ma, motion of 3.6 cm/yr between 150–140 Ma, and otherwise motion of less than 3 cm/yr (Besse and Courtillot, 1991). Calculation of true polar wander involves significant smoothing of noisy data. Nevertheless, I am impressed by the correlation of four of these five global episodes with times of rapid subduction under western North America following major chaotic tectonic events, when the coupling of the plates through the asthenosphere to the mantle by subducted plates is proposed here to be at a minimum.

Gulfs, creation of terranes, and obduction of ophiolites

Following the major chaotic tectonic event and the apparent collapse of the lithosphere along the plate margin in Miocene time, rifting began in the Gulf of California (Stock and Hodges, 1989), turning into sea-floor spreading by 3.2 Ma (Lonsdale, 1989). The fundamental footprint of this change on the ocean floor is magnetic anomalies that show the ridge crest perpendicular to the margin and the transform faults parallel to the margin. On land the fundamental footprint is the creation of a new tectonostratigraphic terrane riding on the adjacent oceanic plate and moving along strike-slip faults parallel to the continental margin (Fig. 11E). Such rotated ocean-floor magnetic anomalies are observed at other times and places (Fig. 5). The SC Ocean Floor (Fig. 5A), presently west of Santa Cruz, California, formed between 29 Ma and 20 Ma after most of the Sierra Madre Occidental batholith formed and may be related to formation of the King Range terrane in northern California (Blake et al., 1988). The CR Ocean Floor (Fig. 5A), presently underlying westernmost Washington and Oregon, formed between 62 Ma and 49 Ma, at the same time as the Bitterroot lobe and probably other parts of the Idaho batholith formed. This is the time that the Yakutat terrane most likely began its journey northward (Bruns, 1983). Similarly, although subduction under the Bering Sea began in early Tertiary time (Scholl et al., 1986), the ocean floor of the Bering Sea formed earlier between magnetic anomalies M13 and M1 (138–125 Ma) (Cooper et al., 1976) and may be related to ocean floor under the Yukon-Koyukuk Basin and formation of the Ruby batholith at approximately 110 Ma.

During formation of the Sierra Nevada batholith in Late Jurassic time, the ocean floor exposed today in the Coast Range and Josephine ophiolites of northern California (CRO, Fig. 5) formed between 165 Ma and 153 Ma (Hopson et al., 1981; Harper et al., 1985). This ocean floor underlies at least the western part of the Great Valley of California, which is filled with sedimentary deposits of Late Jurassic and younger age. The Great Valley is located west of the Jurassic part of the Sierra Nevada batholith in the same way that the Gulf of California is located west of the Sierra Madre Occidental batholith (Fig. 10). Harper et al. (1985) conclude that the Josephine ophiolite, presently located north of the Great Valley, formed about spreading ridge segments perpendicular to the plate margin with transform faults parallel to the plate margin just as ocean floor is forming today in the Gulf of California. The marine sedimentary materials were deposited in submarine-fan environments, primarily by turbidity currents, as are observed in the Gulf of California today (Lonsdale, 1989). The Great Valley of California thus appears to be a sediment-filled version of the Gulf of California.

It took 12 m.y. to form the Coast Range ophiolite. The Gulf of California has been opening for only 3 m.y. In another 9 m.y., the southern tip of Baja California is likely to lie several hundred kilometers closer to Los Angeles, California, changing the Gulf of California into a bay. Subsequent right-lateral strike-slip motion along the continental margin and through this bay, followed by the onset of a new subduction zone, would leave an ophiolite, i.e., part of the oceanic crust currently under the Gulf of California, attached to the continent and underthrust by mélange formed in a future subduction zone. Similarly during the Tithonian, rapid northward motion of the North American plate and the onset of a new subduction zone would leave the presently exposed geologic relations of the Coast Range ophiolite underthrust by mélange of the Franciscan Complex that was formed in a Cretaceous and Cenozoic subduction zone. Thus obduction would not have involved movement of the ophiolite relative to North America. The terranes that moved in a left-lateral sense during the Jurassic when this rotated ocean floor formed would have been moving southward toward Mexico. The ocean floor that once lay across the mouth of this Jurassic bay is likely to be the Guerrero terrane in Mexico (Centeno-Garcia et al., 1993) or similar oceanic terranes farther south. Reconstructions of the Caribbean region show that much of Mexico must be made up of terranes that moved into their current position since Jurassic time (Pindell and Barrett, 1990).

This scenario explains how the Coast Range ophiolite was "obducted" at 152 Ma as suggested by Hopson et al. (1981), but was attached to North America since its creation. Obduction would then involve thrusting a new subducting plate under the ophiolite rather than thrusting the ophiolite onto the continent. Hopson et al. (1986) argued that the ophiolite moved rapidly northward on the ocean plates before obduction, but, as discussed in Appendix 2 of this chapter and shown in Figures 5 and 7, it was North America that moved rapidly northward at the end of the Jurassic Period.

The terminal event in Late Jurassic time involved extensive ophiolite obduction and major northward motion of the North American plate. The observation that mid-Cretaceous and Miocene ophiolites are not found suggests either that major strike-slip motion between the continental and oceanic plates is required for obduction or that the ophiolites have not yet been eroded to the surface. I think the latter explanation is correct because the CR Ocean Floor (Fig. 5A) making up western Washington and Oregon is already exposed but not upturned like the Coast Range ophiolite. Continued uplift and erosion along this margin is likely to expose this ocean floor more clearly.

Although this model explains the formation and obduction of massive ophiolites such as the Coast Range and Josephine ophiolites, ophiolitic fragments are widespread in mélange belts such as the Central Metamorphic belt of the northwestern Sierra Nevada of California. Such fragments have dates close to the onset of subduction, suggesting they are blocks of ocean floor broken loose during the mechanical process involved in the initiation of subduction.

Initiation of subduction and orthogonal subduction cycles

How subduction begins has been the subject of a great deal of thought with little consensus (e.g., McKenzie, 1977; England and Wortel, 1980; Karig, 1982; Cloetingh et al., 1984; Ellis, 1988; Mueller and Phillips, 1991; Gurnis, 1992; Erickson, 1993). In the case of an Atlantic-type margin, subduction could conceivably be started by loading the oceanic lithosphere with sedimentary deposits over several hundred million years, severing the boundary, and pushing the oceanic plate down (Cloetingh et al., 1984). On a Pacific-type margin, however, subduction starts and stops much more frequently. Recognition in this chapter that a subduction cycle typically ends with a major chaotic tectonic event, commonly with the continent moving rapidly relative to the adjacent oceanic plate, suggests that subduction initiates along the resulting fractured boundary. The mechanism may simply be sinking of the oceanic plate as the continent overrides it. A more likely explanation for the rapid onset of subduction associated with the rapid but conformal deepening of marginal basins would be that an existing trench, such as the current one southwest of central Mexico, or at least a small flap of oceanic lithosphere, such as the one presently under the Transverse Ranges in southern California (Humphreys et al., 1984), is slid horizontally along the plate margin, perhaps with a component of compression. England and Wortel (1980) estimate that a slab must be pushed to a depth of about 130 km before slab pull will become large enough to allow subduction to continue on its own. This type of mechanism would better explain formation of a subduction zone along an old transform fault within an ocean basin. For example, the Bering Sea appears to have been separated from the Pacific Ocean at 55 Ma (Scholl et al., 1983) by converting a transform fault on the ocean floor into a trench. Mueller and Phillips (1991, p. 662) discuss the mechanics involved and conclude that "transform faults and fracture zones represent the favored sites of trench formation." Strike-slip faulting of terranes appears best developed immediately following the major chaotic tectonic events.

Conversion of transform margins to trenches and subduction zones and back to transform margins implies that plates such as the Farallon and Kula plates have moved successively northeastward under the western United States, northwestward under Alaska and Kamchatka, northeastward again, and so forth. This interleaving of subduction cycles in perpendicular directions is suggested by the discussion above of well-developed subduction during Early Cretaceous time in the Brooks Range and the Caribbean but less well-developed subduction in the western United States and Canada. Motions of single plates within these broader cycles show such orthogonal interleaving even more clearly. Subduction was rapid under Canada between 83 Ma and 55 Ma (Fig. 5) while a transform fault in Alaska was apparently becoming a new subduction zone south of the Bering Sea (Scholl et al., 1983) and while silicic magmatism was occurring in the Alaska Range and Kuskowim Mountains (Hudson, 1983; Wallace and Engebretson, 1984). Strike-slip faulting became dominant in western Canada between 55 Ma and 45 Ma, when the Kula plate was rotating counterclockwise and moving to the north at a rate of at least 20 cm/yr relative to the North American plate (Engebretson et al., 1985). To the south of the Kula ridge, subduction was rapid under southwestern North America from 74–40 Ma (Fig. 1). As continental volcanism began erupting throughout Mexico, the southwestern United States, and the Cascades, early Aleutian volcanism, and by inference, subduction, was active from 42–21 Ma (Wallace and Engebretson, 1984). Then andesitic-arc volcanism and probably subduction resumed west of Baja California from 20–14 Ma and in the Cascade Range from 17–9 Ma (Wells et al., 1984). Meanwhile, the Aleutians arc was uplifted, folded, and extended between 14 Ma and 9 Ma (Scholl et al., 1976) and strike-slip faulting became important along the western margin of northern Mexico and southern California. Major volcanism returned to the Aleutians beginning at 3 Ma, as the Gulf of California opened with major strike-slip motion on the San Andreas fault. The Pacific plate is presently being subducted under Alaska at a rate of about 7 cm per year so that the current slab with a length of at least 400 km (Reyners and Coles, 1982) could have been subducted within the past 6 m.y.

Mechanisms for the exhumation of schists

Blueschists, eclogites, coesite, and even diamonds in narrow metamorphic belts are typically on the seaward side and lower plate of major thrust faults (e.g., Sobolev and Shatskii, 1987; Blake et al., 1988; Wang et al., 1989; Jacobson, 1990) and have long been recognized as evidence that crustal rocks can be thrust to depths of as great as 100 km and then returned to the surface fast enough to prevent significant retrograde metamorphism. Several authors (e.g., Ernst, 1975; Cloos, 1982; England and Holland, 1979; Platt, 1986; Hsü, 1991) have proposed mechanisms for the upward motion of these metamorphic rocks, but they have typically been restricted by the conventional wisdom that subduction is quasi-continuous. Identification of subduction cycles and major chaotic tectonic events in this chapter, as well as increasing evidence for normal faulting on former thrust faults, discussed subsequently, provide some new insight.

In southern California and southwestern Arizona, the Pelona, Orocopia, Rand, and Portal Ridge Schists lie below the Vincent, Chocolate Mountains, Orocopia, and Rand thrusts. Tosdal et al. (1989, p. 415) argued that the protolith of the Orocopia Schist is "sandstone, largely graywacke, with subordinate to rare basalt, ferromanganiferous chert and siliceous limestone and peridotite . . . accumulated in a marine basin formed by ocean spreading within or along a continental margin" in Late Jurassic and possibly earliest Cretaceous time. These schists were metamorphosed at pressures of 6–9 kb (inferred depths of 20–30 km) and at temperatures of approximately 480–650°C (Jacobson et al., 1988; Jacobson, 1990). Such conditions are typical for the geothermal gradient currently observed in the nearby Basin and Range province (Lachenbruch and Sass, 1977). Transitional blueschists-greenschists in the Rand Mountains and relict crossite observed in several of the mafic schists are evidence of an earlier low-temperature metamorphism. Although the radiometric ages range from 85–23 Ma (Table 2), Jacobson (1990) argued that the differences primarily reflect different cooling histories, that the Pelona and Orocopia Schists are not likely to be older than 90–80 Ma, and that the Portal Ridge and Rand Schists have minimum ages of approximately 80 Ma. Thus at least some of these schists probably reached their peak in pressure of initial prograde metamorphism during or soon after the major chaotic tectonic event at approximately 92 Ma, when rapid subduction began west of British Columbia and before rapid subduction was underway beneath southern California (Fig. 5). Platt (1975) inferred from the Catalina schists that the observed inverted thermal gradient developed below the hot hanging-wall peridotite during the initiation of subduction. Thrusting of a new slab under the remnants of the former slab, or at least under the accretionary wedge that lay above the former slab, is likely to cause initial uplift of the schists, thrust fault, and hanging wall. Pervasive circulation of fluids, as best observed associated with the Jurassic major chaotic tectonic event, would raise the temperatures. Development of rapid subduction (Peacock, 1988) and restriction of fluid circulation would rapidly lower the temperature of the schists, although uplift may have continued related to underplating in the subduction zone (Rubie, 1984). There does not appear to have been post-metamorphic movement on the Vincent thrust, but there is clear evidence of normal faulting on the Orocopia "thrust" after some cooling, bringing the Orocopia Schist to shallow depths by 60 Ma (see references in Jacobson, 1990). This normal faulting could simply be related to upthrust of the accretionary wedge due to underplating during subduction. By 32 Ma, the Orocopia Schist had reached the surface because the Quechan Volcanics were deposited on it (Haxel and Dillon, 1978). Continued uplift is likely during the metamorphic core complex distension culminating at approximately 15 Ma.

In northern California, the South Fork Mountain Schist and the Valentine Spring Formation of Worral (1981), which together form the uppermost part of the Franciscan Complex, are thrust under the older Coast Range ophiolite along the Coast Range fault. There is clear evidence of subsequent motion on the fault, however, with top-to-the-east motion, i.e., normal faulting with an extensional offset (Harms et al., 1992). Younger rocks are downfaulted over older rocks with omission of structural section along low-angle normal faults just like faulting observed in the Basin and Range. The contacts between the Franciscan and both the Del Puerto ophiolite and the Cedar Mountain ophiolite outlier can be clearly observed over large distances and are sub-horizontal. Kinematic indicators consistently show "hanging wall to the east, that is, displacement of the Coast Range ophiolite to the east relative to the underlying Franciscan Complex" (Harms et al., 1992, p. 233). The timing of the normal faulting was most likely between 60 Ma and 70 Ma (Harms et al., 1992), similar to inferred normal faulting in southern California and soon after rapid subduction began at approximately 75 Ma.

Sedimentary rocks in the Eastern belt of the Franciscan Complex include deep sea cherts and sandstones from a continental source area that differs fundamentally from the Great Valley sequence to the east (Blake et al., 1984, 1985). Sedimentary rocks of the Central belt to the west, on the other hand, have close affinities with the base of the Great Valley sequence and appear to be a more distal facies of the same fan system. Normal faulting may have juxtaposed the Eastern belt between the Great Valley sequence and Central belt. A distinctive feature of the Central belt of the Franciscan Complex are blueschist, eclogite, and amphibolite exotic blocks that have yielded K/Ar dates of 154 Ma (Coleman and Lanphere, 1971) and 162 Ma (Mattinson, 1986). These blocks came from greater depths than the rest of the schist and thus must have been brought up by an additional process, such as by extensive strike-slip faulting during the rapid northward motion of the North American plate in Tithonian time or by the initiation of subduction.

Thus there is increasing evidence that blueschists and other schists thought to be related to subduction may in fact form during the initiation of subduction. Uplift of these schists appears to have been a complicated and multi-step process involving chilling near the place of formation, uplift in response to an oceanic plate and accretionary wedge being thrust under them, normal faulting along the former thrust fault above the schists, and denudation from extension and upwarping.

Where are we currently in the subduction cycle?

Our view of what is typical in plate tectonics is distorted by the fact that we have been in a period of very rapid change since the Miocene major chaotic tectonic event and especially during the past 7 m.y. All of the subducted slabs around the world, at least to the base of the seismogenic zone, could have been subducted during the past 7 m.y. based on current rates.

From Figure 5, we can conclude that we are now in the beginning of a new subduction cycle.

Periods of very rapid subduction are separated by periods of extension, batholith formation, and major chaotic tectonic events. But does subduction continue in between the times of rapid subduction or does it stop? When a subducting margin converts to a strike-slip margin, such as the current margin of southern California and northern Mexico, then there is no subduction zone. But what about to the north and south? There is evidence of subduction-related magmatism between 24 Ma and 17 Ma in Baja California (Sawlan and Smith, 1984) and between 17 Ma and 9 Ma in the Cascades (Wells et al., 1984). Relatively slow subduction continues today west of the Cascades and southwest of Mexico. Detailed studies will be needed to sort out the locations and times of these episodes of relatively slow subduction under relatively small areas.

The primary difference between times of very rapid subduction and times of slow subduction appears to be a matter of the size of the subducting plates. In latest Cretaceous time, the large Farallon plate was subducting rapidly under most of western North America. The rate stayed high after the Vancouver plate broke from the Farallon plate, but began to drop rapidly as these plates fragmented into smaller and smaller pieces such as the Monterey, Cocos, Nazca, Arguello, Guadalupe, and Magdelena plates (Lonsdale, 1991). We are currently in a time interval when very small plates such as the Rivera plate, located west of central Mexico, and the Explorer plate, located west of central British Columbia, are being subducted slowly under western North America while the large Pacific plate is being subducted more rapidly under Alaska and Asia. When most of the East Pacific rise has reached the trench, a new subduction zone may then be formed along the length of North America and a large plate in the Pacific may begin to be subducted rapidly, beginning a new major cycle under the western North America equivalent to cycles that begin during Early Jurassic and Late Cretaceous time.

CONCLUSIONS

1. Calculated plate motions, ages of andesitic volcanism and porphyry copper deposits, periods of trench-normal contraction, ages of rocks and fossils in accretionary complexes, and ages of schists provide evidence that the times of rapid (>10 cm/yr) subduction of ocean plates under western North America were between 208 Ma and 178 Ma and between 87 Ma and 36 Ma, with more moderate subduction between 140 Ma and 120 Ma.

2. The most voluminous silicic magmatism in western North America formed large calderas and batholiths primarily from 214–201 Ma, 172–148 Ma, 119–86 Ma, and 32–27 Ma, in a trench-normal extensional environment.

3. Major strike-slip faults with net displacements of hundreds to thousands of kilometers formed during the Late Jurassic, mid-Cretaceous, Eocene, and since the late Miocene. The sense of motion was left lateral during the Jurassic Period and right lateral since mid-Cretaceous time.

4. The apparent wandering of paleomagnetic poles for North America was minimal during intervals when batholiths formed, moderate during intervals of rapid subduction, and most rapid just preceding the onset of such intervals of rapid subduction.

5. These basic observations suggest a typical cycle of tectonic events. Rapid subduction is followed by a change from trench-normal contraction to trench-normal extension and the formation of major silicic volcanic systems and batholiths. Extension then increases with major mylonitization in the metamorphic core complexes and the formation of rifts. Strike-slip faulting becomes widespread, and subduction typically begins again. The length of each cycle is 50–80 m.y., depending on all of the boundary conditions.

6. A cycle in Canada and a separate cycle in the southwestern United States and northern Mexico, separated by a mid-ocean ridge off shore, occurred diachronously since the mid-Cretaceous. Previous cycles were during the Jurassic and the Early Cretaceous.

7. Cycles were separated by major chaotic tectonic events. Such events follow the onset of batholith formation by approximately 20 m.y. Major chaotic tectonic events since the Triassic were approximately 225, 152, 92, 44, and 15 Ma.

8. Major chaotic tectonic events follow the rapid formation of tectonic basins and extensive mylonitization in the metamorphic core complexes. They involve flood basalts, a change to fundamentally basaltic volcanism, sudden rotation of terranes, and rifting. They appear to be related to the final breaking apart of an earlier subduction zone and formation of a new subduction zone. During these events blueschists and other metamorphosed rocks are brought rapidly to the surface, and fluids permeate the upper crust along the former subduction zone, forming pervasive serpentinization, causing metamorphism, and resetting magnetizations.

9. Both apparent and true polar wander are greatest following the major chaotic tectonic events, implying that these are times when the plates are most free to move relative to the mantle below the asthenosphere.

In the introduction to this chapter, I suggested that several commonly invoked plate-tectonic models need to be reconsidered. In this chapter, I have shown that rapid subduction was not continuous under western North America but occurred during a few relatively short periods of time. A primary contribution of this chapter is to draw a distinction between subduction-related arc-magmatism and voluminous silicic magmatism that is not related directly to rapid subduction. Both types of magmatism are calc-alkalic. Distinction of these types makes it clear that major silicic batholiths are not the roots of subduction-related volcanic arcs, but are formed typically in the same location, but at a later time after subduction has slowed or stopped. The East Pacific rise was not subducted under western North America as shown by fossil pieces of the rise along the coast. Thus subduction of the rise cannot be used to explain magmatism along the plate margin. While the dip of the subducting slab is likely to change with time, the distribution and nature of magmatism appears to be effected primarily by the interaction of a spreading ridge and young oceanic lithosphere with the continental margin. Finally, major contractional orogenies in western North America since the Triassic appear to be related to rapid subduction, motion of North America relative to other continents, and major chaotic tectonic events separating subduction cycles.

The cycles described in this chapter are major features related to the very rapid subduction of very large plates. As a mid-ocean ridge approaches the trench, the plates break up into smaller and smaller pieces. Although the basic cycle seems to apply in a general way to each of these smaller plates, the footprints of the cycle are exposed in smaller and smaller regions and the distinctions between times of subduction, batholith formation, and strike-slip faulting become less clear. Thus elaboration of the details may take some time.

Similar subduction cycles are observed during the Paleozoic era in western North America and during Phanerozoic time in other orogenic belts, but these will need to be described in future papers. This chapter outlines a basic framework that appears useful for relating studies in different oceanic-continental plate margins to each other and to fundamental tectonic processes. We have barely begun to scratch the surface of what we should ultimately be able to understand about the details of these regions.

ACKNOWLEDGMENTS

In 1986, I wrote to Dick Armstrong requesting access to his computerized database of radiometric ages in Canada to add to my compilation for the United States and Mexico. His warm response led to many stimulating and productive years of collaboration. Dick has had a profound influence not only on earth science, but on many other earth scientists. I am particularly pleased that my contribution to this tribute helps put into a plate-tectonic and hemispheric context many of the fruits of Dick's labor, from defining the Sevier orogeny in 1968 to three decades of dating rocks throughout western North America.

More than a decade ago, I set out to try to understand why geologists talked in terms of processes changing on the scale of millions of years and plate-tectonicists spoke in terms of tens to even hundreds of millions of years. Both had to be talking about the same processes. This chapter is the second result of a decade of invigorating and often confusing and overwhelming compilation of geologic data and tectonic interpretations. I wish especially to thank the authors of the tens of thousands of papers that document data in western North America and wrestle with broader interpretations. I apologize if I have left out some of your papers that seem important, but in a compilation of this breadth, I have certainly missed a few papers, have not always found the most definitive paper on a topic, and have had to select references carefully, in order to keep the list to a publishable length. I tend to favor recent references that contain the older references.

The staff of the U.S. Geological Survey library in Menlo Park provided extensive, efficient, and courteous help. Over the years, my thoughts were stimulated and focused by thoughtful reviews by and discussions with Dick Armstrong, Paul Bateman, Bob Christiansen, John Crowell, Bill Dickinson, Sherman Gromme, Warren Hamilton, Dave Howell, King Huber, Porter Irwin, Dave Miller, Walter Mooney, Bonnie Murchey, Bob Simpson, Chris Stevens, Jack Stewart, Art Sylvester, Dick Tosdal, Bob Wallace, Ray Wells, and Mary Lou Zoback. This chapter was substantially improved by thoughtful reviews by Paul Bateman, Keith Howard, Peter Molnar, Jim Monger, Dave Miller, Art Sylvester, and Mary Lou Zoback. Careful editing was provided by Ron Le Conte and Louise Walsh.

APPENDIX 1: MAJOR BATHOLITHS IN WESTERN NORTH AMERICA

One goal in Figures 4 and 5 is to show the ages and latitudes of major batholiths as defined in the section entitled "Large calderas and major batholiths." This appendix describes the sources of information and the choices made in deciding which intrusions to include outside of the Sierra Nevada of California.

Ages for rocks in the Peninsular Ranges batholith of southwestern California range from 120–65 Ma, but the U-Pb ages based on zircons fall into two distinct groups of 120–104 Ma and 100–89 Ma (Krummenacher et al., 1975; Silver et al., 1979) (Fig. 4). The older group that forms the western part of the batholith consists of scattered small epizonal plutons, whereas the younger group to the east is more similar to the major Sierran intrusive suites consisting of larger mesozonal plutons that are mutually contiguous and become younger to the east (Silver et al., 1979; Chen and Moore, 1982). The eastern half of the Peninsular Ranges batholith compares morphologically to the Tuolumne and John Muir Intrusive Suites (T-JM IS in Fig. 4) in the Sierra Nevada. Intrusions in the Salinian block of western California are similar in age to the rocks in the Peninsular Ranges and the Sierra Nevada (Mattinson and James, 1985).

In the Klamath Mountains of northwestern California, all of the plutons are scattered among the country rocks, and perhaps none should therefore be included in Figure 4. For completeness, however, I include times of the most widespread plutonism (Irwin, 1985; Hacker and Ernst, 1993). The plutons in the 207-Ma to 189-Ma range in the Rattlesnake Creek terrane are not included in Figure 4 because they appear to be blocks surrounded by a mélange in a subduction zone.

Radiometric ages in the Idaho batholith are complicated by resetting, but the times of formation of the Atlanta (AL) and Bitterroot (BR) lobes are shown in Figure 4 (Vallier and Brooks, 1987). The Pioneer batholith of southwestern Montana is a composite body formed between 76 Ma and 65 Ma (Arth et al., 1986) and the nearby Boulder batholith was intruded between 80 Ma and 70 Ma (Smedes et al., 1988). These batholiths, the related Elkhorn volcanics, and the Atlanta lobe of the Idaho batholith formed at the beginning of the Laramide orogeny and lie near 46°N at the northern end of the region deformed in the orogeny. They also coincide in space and time with the arrival of the ridge crest at the trench to the west proposed above in the section on the Canadian Cycle. These batholiths in Idaho and southwestern Montana do not appear to be similar in setting or chemistry to others shown in Figure 4.

The Kamloops-Challis-Absaroka (KCA in Fig. 4) volcanic episode was a very voluminous magmatic event extending from northwestern Wyoming to southern Yukon between 54 Ma and 45 Ma (Armstrong, 1988; Brew and Morrell, 1983; Armstrong and Ward, 1991). Farther north, this activity is referred to as the Skagway-Ketchikan–Prince Rupert belt (SKPR in Fig. 4). It is contemporaneous with the time that much of southern Alaska apparently moved approximately 20° northward (Coe et al., 1985; Stone and McWilliams, 1989) and may stitch together much of the strike-slip boundary that was active at that time.

The Talkeetna Mountains–Aleutian Range plutonic belt consists of closely spaced plutons whose concordant ages range from 175–145 Ma and are concentrated between 165–155 Ma (Hudson, 1983). At the time of formation, the latitude of these rocks was probably about 20° farther south, near the Sierra Nevada and Klamath Mountains (Coe et al., 1985). Intrusive rocks of Middle and Late Jurassic age are voluminous in western Canada (Armstrong, 1988; van der Heyden, 1992; Armstrong and Ward, 1993), but work is still needed to define their extent.

A complex belt of magmatic activity extended from eastern Alaska through British Columbia to northern Washington between 115 Ma and 100 Ma. This belt includes the Nutzotin-Chichagof belt of Hudson (1983), the Muir-Chichagof belt of Brew and Morrell (1983), and most of the southern part of the Coast Plutonic Complex in British Columbia (Armstrong, 1988; van der Heyden, 1992). It includes the Klukwan-Duke mafic/ultramafic belt in southeast Alaska (Brew and Morrell, 1983).

APPENDIX 2: GEOLOGIC EVIDENCE FOR APPARENT POLAR WANDER OF THE NORTH AMERICAN PLATE

Changes in paleomagnetic poles listed in Table 3 and plotted in Figure 7A are interpreted as resulting from motion of the North American plate with respect to the time-averaged magnetic north pole, which is assumed to be the spin axis of the Earth. It is also possible that the spin axis moved relative to the North American plate. Thus the purpose of this appendix is to describe geologic data showing that at least part of apparent polar wander involved tectonism and motion along some boundaries of the North American plate.

Late Permian to Triassic motion

The North American plate moved rapidly northward approximately 1,000 km during Early Triassic time (245–241.1 Ma), perhaps related to the Sonoma orogeny. Morel and Irving (1981) argued that 3,500 km of right-lateral displacement took place between Laurasia and Gondwana along the rift that would become the central Atlantic Ocean in Late Permian to Triassic time (250–200 Ma) based on the differences in polar wander curves for Europe–northern Asia, North America, and Gondwana. Livermore et al. (1986) argued against this shift. This northward motion relates to the end of a Paleozoic subduction cycle and thus the details are beyond the scope of this chapter.

Jurassic motion

The largest and most rapid apparent northward motion of the North American plate occurred primarily during Tithonian time (152.1–145.6 Ma) at an average northward component of motion of at least 25 cm/yr. Since there are no reliable paleomagnetic reference poles between 145 Ma and 122 Ma, it is not clear whether this motion continued to 140 Ma as shown by the heavy dashed line in Figure 7A or continued as shown by the heavy solid line at a slower rate during the ensuing period of subduction. The Tithonian Stage and the Nevadan orogeny, as discussed above, were contemporaneous with major tectonism along the margins of North America. Hopson et al. (1986) proposed a similar rate of northward motion (30 ± 3 cm/yr) in the Late Jurassic for the Coast Range ophiolite based on paleomagnetic data. The Coast Range ophiolite is located today primarily along the west side of the Great Valley of California. They proposed that the ophiolite moved northward during rapid seafloor spreading as shown by an up-section change in radiolarian assemblages lying on top of the Coast Range ophiolite from central Tethyan to Boreal. But Pessagno et al. (1987) mapped a similar change in Radiolaria during Tithonian time in east-central Mexico, well inboard of North America. Their data are consistent with the paleomagnetic data, suggesting that it was the continent with the ophiolites attached that moved. Thus the primary plate boundary in western North America during Tithonian time was apparently the subduction zone. Northward motion of the North American plate relative to the oceanic plates most likely took place on this zone or on related, margin-parallel, strike-slip faults (Fig. 5). Inland, the last and most extensive Jurassic marine transgression ended and sedimentation in the Interior Basin changed rapidly from carbonate, evaporite, eolianite, and red beds to coarse siliciclastic materials derived from the west (Brenner, 1983; Tipper, 1984). The Tithonian Morrison Formation was deposited from a western tectonically uplifted source at rates of 6.2 m/m.y., an order of magnitude larger than the rate during the interval following Tithonian time (Kowallis and Heaton, 1987). The two paleomagnetic poles that show the most rapid northward motion are from the lower and upper parts of the Morrison Formation (Table 3).

The motion of oceanic plates to the west during the latest Jurassic and earliest Cretaceous is unclear except that some data suggest that the Pacific plate, which was separated from the North American plate by the Farallon plate, either remained fixed or moved rapidly southward (Cox and Gordon, 1984). Magnetic anomalies now located in the western Pacific show that during Late Jurassic time there were two mid-ocean ridges that had a combined spreading in the NNW–SSE direction of more than 2,200 km from 152 Ma to 140 Ma and 5,200 km from 160 Ma to 130 Ma (Hilde et al., 1976; Cande et al., 1978; Nakanishi et al., 1992). Spreading on these ridges was probably connected to spreading on the Proto-Caribbean ridge.

Rifting along the southern coast of North America had been underway since the J-1 cusp in Hettangian time (208–203.5 Ma) (Schmidt-Effing, 1980). By Callovian time (161.3–157.1 Ma) major salt deposits formed in the Gulf of Mexico (Imlay, 1984) during a major sea transgression. Opening of the Gulf of Mexico may have been underway by late Callovian time with abrupt termination of gulf-wide salt deposition, but the first clear evidence of open ocean between North and South America was in Kimmeridgian time (154.7 Ma to 152.1 Ma) (Anderson and Schmidt, 1983) when rapid spreading must have begun in the Proto-Caribbean. Motion in the Caribbean was connected at least in part to motion along the west coast via the Bisbee Basin rift and the Chihuahua Trough.

Along the east coast of North America the oldest recognizable magnetic anomalies in the central Atlantic Ocean are M-25 (156 Ma), and the highest total rate of spreading ever recorded in the Atlantic, 3.8 cm/yr, occurred between 156 Ma and 150 Ma (Klitgord and Schouten, 1986). But 500 km of ocean floor west of anomaly M-25 appears to have formed from spreading including a probable ridge jump. Extrapolation across this zone has been used to suggest spreading began at approximately 175 Ma (e.g., Klitgord and Schouten, 1986) or even 187 Ma (Jansa, 1986). The oldest ocean floor drilled is Callovian (161.3–157.1 Ma) in age (Sheridan and Gradstein, 1983). The North Atlantic had not opened during Jurassic time, and the paleomagnetic data for Eurasia imply that it also moved rapidly northward between 150 Ma and 130 Ma (Heller, 1978; Besse and Courtillot, 1991).

The end of the Jurassic Period appears to have been a time of significant plate change worldwide as Gondwanaland broke up, and the Gulf of Mexico, the central Atlantic, the Ligurian Tethys (Lemoine, 1984), and the Indian Ocean (Coffin and Rabinowitz, 1987) were formed. Collision of terranes occurred in Tibet (Coleman, 1989) and between the South China block and the North China block along the Qinling fold belt (Lin et al., 1985). From this summary it is clear that there appears to have been a major change in the tectonics of North America and associated plates during Tithonian time that is compatible with the sudden northward motion implied in Figure 7A.

Cenozoic motion

Geologic evidence for the southward movement of the North American plate between about 80 Ma and 40 Ma is quite clear. The oldest magnetic anomalies identified in the Arctic Ocean along the Nansen ridge are A24 (56 Ma) (Vogt et al., 1979). Spreading continued at a total rate of 2 cm/yr until sometime before anomaly 13 (35.5 Ma) when it slowed to less than half that rate. At anomaly 5 (10 Ma) the rate increased again. Prior to anomaly 24 (55 Ma), a 100-km to 200-km-wide section of reversely magnetized ocean floor formed most likely by very rapid spreading at the initiation of opening along this ridge. Spreading in the Labrador Sea shifted to a more north-south direction and spreading began in the Greenland-Norwegian Sea (Srivastava and Tapscott, 1986). Subduction was widespread in the northern Caribbean from middle to late Eocene time (50–36.6 Ma) under Puerto Rico (Cox et al., 1977), Cuba (Gealey, 1980), and probably near the current Motaqua-Polochic fault zones in Guatemala (Perfit and Heezen, 1978). Right-lateral strike-slip faulting was active along the western margin of North America in Eocene time (56.6–35.4 Ma) (Graham, 1978; Gabrielse, 1985; Kleinspehn, 1985; Blake, 1986). Deformation and volcanism were extensive in the northwestern United States and British Columbia at this time as the Kula plate suddenly rotated counterclockwise (Lonsdale, 1988) and more than 1,000 km of new ocean floor formed along a ridge perpendicular to the coast of Washington and Oregon (Duncan, 1982) (CR Ocean Floor in Fig. 5).

Neogene motion

The timing of 400 km of apparent northward motion of the North American plate between 15 Ma and the present is not well constrained by the paleomagnetic reference poles for the continent, but paleomagnetic reference poles from Hawaii (Fig. 7B) seem to constrain this motion to the last few million years, a time of major strike-slip faulting in California and Mexico and of rapid subduction under northeastern Asia and Alaska. As discussed previously, under true polar wander, some of this motion was apparently the spin axis moving toward North America.

REFERENCES CITED

Aldrich, M. J., Jr., Chapin, C. E., and Laughlin, A. W., 1986, Stress history and tectonic development of the Rio Grande rift, New Mexico: Journal of Geophysical Research, v. 91, p. 6199–6211.

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

Allmendinger, R. W., and Jordan, T. E., 1984, Mesozoic structure of the Newfoundland Mountains, Utah: Horizontal shortening and subsequent extension in the hinterland of the Sevier belt: Geological Society of America Bulletin, v. 95, p. 1280–1292.

Anderson, T. H., and Schmidt, V. A., 1983, The evolution of Middle America and the Gulf of Mexico-Caribbean Sea region during Mesozoic time: Geological Society of America Bulletin, v. 94, p. 941–966.

Andrew, A., and Godwin, C. I., 1989, Lead- and strontium-isotope geochemistry of the Karmutsen formation, Vancouver Island, British Columbia: Canadian Journal of Earth Science, v. 26, p. 908–919.

Applegate, J. D. R., Walker, J. D., and Hodges, K. V., 1992, Late Cretaceous extensional unroofing in the Funeral Mountains metamorphic core complex, California: Geology, v. 20, p. 519–522.

Argall, G. O., Jr., and Wyllie, R. J. M., eds., 1983, World mining porphyry copper map: San Francisco, Miller Freeman, scale 1:30,000,000.

Armstrong, R. L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458.

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., and Misch, P., 1987, Rb-Sr and K-Ar dating of mid-Mesozoic blueschist and late Paleozoic albite-epidote-amphibolite and blueschist metamorphism in the North Cascades, Washington and British Columbia, and Sr-isotope fingerprinting of eugeosynclinal rock assemblages: Washington Division of Geology and Earth Resources Bulletin, v. 77, p. 85–105.

Armstrong, R. L., and Ward, P. L., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 96, p. 13201–13224.

Armstrong, R. L., and Ward, P. L., 1993, Late Triassic to earliest Eocene magmatism in the North America Cordillera: Implications for the Western Interior Basin, *in* Caldwell, W. G. E., and Kauffman, E. G., eds., The evolution of the Western Interior Basin: Geological Association of Canada Special Paper, v. 39, p. 49–72.

Armstrong, R. L., Harakal, J. E., and Hollister, V. F., 1976, Age determination of late Caenozoic porphyry copper deposits of the North American Cordillera: Institute of Mining and Metallurgy Transactions, v. 85, p. B239–B244.

Armstrong, R. L., Harakal, J. E., Forbes, R. B., Evans, B. W., and Thurston, S. P., 1986, Rb-Sr and K-Ar study of metamorphic rocks of the Seward Peninsula and Southern Brooks Range, Alaska, *in* Evans, B. W., and Brown, E. H., eds., Blueschists and eclogites: Geological Society of America Memoir 164, p. 185–203.

Arth, J. G., Zen, E., Sellers, G., and Hammarstrom, J., 1986, High initial Sr isotopic ratios and evidence for magma mixing in the Pioneer batholith of southwest Montana: Journal of Geology, v. 94, p. 419–430.

Arth, J. G., Zmuda, C. C., Foley, N. K., Criss, R. E., Patton, W. W., Jr., and Miller, T. P., 1989, Isotopic and trace element variations in the Ruby batholith, Alaska, and the nature of deep crust beneath the Ruby and Angayucham terranes: Journal of Geophysical Research, v. 94, p. 15941–15955.

Atwater, T., and Severinghaus, J., 1989, Tectonic maps of the northeast Pacific, *in* Winterer, E. L., Hussong, D. M., and Decker, R. W., eds., The Eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, The Geology of North America, v. N., p. 15–20.

Avé Lallemant, H. G., and Oldow, J. S., 1988, Early Mesozoic southward migration of Cordilleran transpressional terranes: Tectonics, v. 7, p. 1057–1075.

Babcock, R. S., Armstrong, R. L, and Misch, P., 1985, Isotopic constraints on the age and origin of the Skagit metamorphic suite and related rocks: Geological Society of America Abstracts with Programs, v. 17, no. 6, p. 339.

Backus, G., Park, J., and Garbasz, D., 1981, On the relative importance of the driving forces of plate motion: Geophysical Journal of the Royal Astronomical Society, v. 67, p. 415–435.

Baldwin, S. L., and Harrison, T. M., 1989, Geochronology of blueschists from west-central Baja California and the timing of uplift in subduction complexes: Journal of Geology, v. 97, p. 149–163.

Barker, F., Sutherland Brown, A., Budahn, J. R., and Plafker, G., 1989, Back-arc with frontal-arc component origin of Triassic Karmutsen basalt, British Columbia, Canada: Chemical Geology, v. 75, p. 81–102.

Bateman, P. C., 1992, Plutonism in the central part of the Sierra Nevada batholith, California: U.S. Geological Survey Professional Paper 1483, 186 p.

Bazard, D. R., and Butler, R. F., 1992a, Paleomagnetism of the Late Jurassic Morrison Formation, southeast Utah and southwest Colorado: Eos, Transactions of the American Geophysical Union, v. 73, no. 14, p. 95.

Bazard, D. R., and Butler, R. F., 1992b, Paleomagnetism of the Middle Jurassic Summerville Formation, east central Utah: Journal of Geophysical Research, v. 97, p. 4377–4385.

Beck, M. E., Jr., Burmester, R. F., Craig, D. E., Gromme, C. S., and Wells, R. E., 1986, Paleomagnetism of middle Tertiary volcanic rocks from the Western Cascade series, northern California: Journal of Geophysical Research, v. 91, p. 8219–8230.

Beets, D. J., Maresch, W. V., Klaver, G. T., Mottana, A., Bocchio, R., Beunk, F. F., and Monen, H. P., 1984, Magmatic rock series and high-pressure metamorphism as constraints on the tectonic history of the southern Caribbean, *in* Bonini, W. E., Hargraves, R. B., and Shagam, R., eds., The Caribbean–South American plate boundary and regional tectonics: Geological Society of America Memoir 162, p. 95–130.

Bellizzia, A., and Dengo, G., 1990, The Caribbean mountain system, northern South America: A summary, *in* Dengo, G., and Case, J. E., eds., The Caribbean region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. H, p. 167–175.

Berg, H. C., Jones, D. L., and Richter, D. H., 1972, Gravina-Nutzotin belt—Tectonic significance of an upper Mesozoic sedimentary and volcanic sequence in southern and southeastern Alaska: U.S. Geological Survey Professional Paper 800-D, p. D1–D24.

Besse, J., and Courtillot, V., 1991, Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma: Journal of Geophysical Research, v. 96, p. 4029–4050.

Bevier, M. L., 1983, Regional stratigraphy and age of Chilcotin basalts, south-central British Columbia: Canadian Journal of Earth Science, v. 20, p. 515–524.

Bird, P., 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84, p. 7561–7571.

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

Bishop, E. M., and Kays, M. A., 1989, Transect through the Baker and Wallowa–Seven Devils terranes, northeastern Oregon: Idaho Geological Survey Bulletin, v. 28, p. 65–84.

Bittenbender, P., and Walker, N., 1990, Constraints on timing of metamorphism, deformation, and plutonism in the Huckleberry Mountain area, North Cascades, Wa.: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 8.

Blackwelder, E., 1914, A summary of the orogenic epochs in the geologic history of North America: Journal of Geology, v. 22, p. 633–654.

Blake, M. C., 1986, Evidence for pre-San Andreas strike-slip faulting in northern California and southwest Oregon: Eos, Transactions of the American Geophysical Union, v. 67, p. 1219.

Blake, M. C., Jr., Howell, D. G., and Jayko, A. S., 1984, Tectonostratigraphic terranes of the San Francisco Bay region, *in* Blake, M. C., Jr., ed., Franciscan geology of northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 43, p. 5–22.

Blake, M. C., Jr., Jayko, A. S., and McLaughlin, R. J., 1985, Tectonostratigraphic terranes of the northern Coast Ranges, California, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, no. 1, p. 159–171.

Blake, M. C., Jr., Jayko, A. S., McLaughlin, R. J., and Underwood, M. B., 1988, Metamorphic and tectonic evolution of the Franciscan complex, Northern California, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 1035–1060.

Blythe, A. E., Wirth, K. R., and Bird, J. M., 1990, Fission-track and $^{40}Ar/^{39}Ar$ ages of metamorphism and uplift, Brooks Range, northern Alaska: Geological Association of Canada Program with Abstracts, v. 15, p. A12.

Bogen, N. L., 1984, Stratigraphy and sedimentary petrology of the Upper Jurassic Mariposa Formation, western Sierra Nevada, California, *in* Crouch, J. K., and Bachman, S. B., eds., Tectonics and sedimentation along the California margin: Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 119–134.

Bogen, N. L., Kent, D. V., and Schweickert, R. A., 1985, Paleomagnetism of Jurassic rocks in the western Sierra Nevada metamorphic belt and its bearing on the structural evolution of the Sierra Nevada block: Journal of Geophysical Research, v. 90, p. 4627–4638.

Bohlke, J. K., and Kistler, R. W., 1986, Rb-Sr, K-Ar, and stable isotope evidence for the ages and sources of fluid components as gold-bearing quartz veins in the northern Sierra Nevada foothills metamorphic belt, California: Economic Geology, v. 81, p. 296–322.

Branch, C. U., 1976, Development of porphyry copper and stratiform volcanogenic ore bodies during the life cycle of andesitic stratovolcanoes, *in* Johnson, R. W., ed., Volcanism in Australia: New York, Elsevier, p. 337–342.

Brandon, M. T., 1989, Deformational styles in a sequence of olistostromal mélanges, Pacific Rim Complex, western Vancouver Island, Canada: Geological Society of America Bulletin, v. 101, p. 1520–1542.

Brenner, R. L., 1983, Late Jurassic tectonic setting and paleogeography of western interior, North America, *in* Reynolds, M. W., and Dolly, E. D., eds., Mesozoic paleogeography of west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 119–132.

Brew, D. A., and Morrell, R. P., 1983, Intrusive rocks and plutonic belts of southeastern Alaska, U.S.A., *in* Roddick, J. A., ed., Circum-Pacific plutonic terranes: Geological Society of America Memoir 159, p. 171–193.

Brooks, H. C., and Vallier, T. L., 1978, Mesozoic rocks and tectonic evolution of eastern Oregon and western Idaho, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 133–145.

Brown, E. H., 1977, Ophiolite on Fidalgo Island, Washington, *in* Coleman, R. G., and Irwin, W. P., eds., North American ophiolites: Oregon Department of Geology and Mineral Deposits Bulletin, v. 95, p. 67–73.

Brown, E. H., Wilson, D. L., Armstrong, R. L., and Harakal, J. E., 1982, Petrologic, structural, and age relations of serpentinite, amphibolite, and blueschist in the Shuksan Suite of the Iron Mountain–Gee Point area, North Cascades, Washington: Geological Society of America Bulletin, v. 93, p. 1087–1098.

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 Science, v. 25, p. 292–300.

Brown, R. L, and Read, P. B., 1983, Shuswap terrane of British Columbia: A Mesozoic "core complex": Geology, v. 11, p. 164–168.

Brown, R. L., Journeay, J. M., Lane, L. S., Murphy, D. C., and Rees, C. J., 1986, Obduction, backfolding and piggyback thrusting in the metamorphic hinterland of the southeastern Canadian Cordillera: Journal of Structural Geology, v. 8, p. 255–268.

Bruns, T. R., 1983, Model for the origin of the Yakutat block, an accreting terrane in the northern Gulf of Alaska: Geology, v. 11, p. 718–721.

Bryan, P., and Gordon, R. G., 1990, Rotation of the Colorado Plateau: An updated analysis of paleomagnetic data: Geophysical Research Letters, v. 17, p. 1501–1504.

Buddington, A. F., 1969, Granite emplacement with special reference to North America: Geological Society of America Bulletin, v. 70, p. 671–747.

Busby-Spera, C. J., 1988, Speculative tectonic model for the early Mesozoic arc of the southwest Cordilleran United States: Geology, v. 16, p. 1121–1125.

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

Busby-Spera, C. J., Mattinson, J. M., Riggs, N. R., and Schermer, E. R., 1990, The Triassic-Jurassic magmatic arc in the Mojave-Sonoran Deserts and the Sierra-Klamath region: Similarities and differences in paleogeographic evolution, *in* Harwood, S. S., and Miller, M. M., eds., Paleozoic and early Mesozoic paleogeographic relations: Sierra Nevada, Klamath Mountains, and related terranes: Geological Society of America Special Paper 255, p. 325–337.

Butler, R. F., Dickinson, W. R., and Gehrels, G. E., 1991, Paleomagnetism of coastal California and Baja California: Alternatives to large-scale northward transport: Tectonics, v. 10, p. 561–576.

Campa, M. F., 1985, The Mexican thrust belt, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, no. 1, p. 299–313.

Cande, S. C., Larson, R. L., and LaBrecque, J. L., 1978, Magnetic lineations in the Pacific Jurassic quiet zone: Earth and Planetary Science Letters, v. 41, p. 434–440.

Carden, J. R., Connelly, W., Forbes, R. B., and Turner, D. L., 1977, Blueschists of the Kodiak Islands, Alaska: An extension of the Seldovia schist terrane: Geology, v. 5, p. 529–533.

Cashman, S. M., Cashman, P. H., and Longshore, J. D., 1986, Deformational history and regional tectonic significance of the Redwood Creek Schist, northwestern California: Geological Society of America Bulletin, v. 97, p. 35–47.

Caskey, S. J., and Schweickert, R. A., 1992, Mesozoic deformation in the Nevada test site and vicinity: Implications for the structural framework of the Cordilleran Fold and Thrust Belt and Tertiary extension north of Las Vegas Valley: Tectonics, v. 11, p. 1314–1331.

Centeno-Garcia, E., Ruiz, J., Coney, P. J., Patchett, P. J., and Ortega-Gutierrez, F., 1993, Guerrero terrane of Mexico: Its role in the southern Cordillera from new geochemical data: Geology, v. 21, p. 419–422.

Chapin, C. E., and Cather, S. M., 1981, Eocene tectonics and sedimentation in the Colorado Plateau–Rocky Mountain area: Arizona Geological Society Digest, v. 14, p. 173–198.

Chapple, W. M., and Tullis, T. E., 1977, Evaluation of the forces that drive the plates: Journal of Geophysical Research, v. 82, p. 1967–1984.

Chen, J. H., and Moore, J. G., 1979, Late Jurassic Independence dike swarm in eastern California: Geology, v. 7, p. 129–133.

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

Christiansen, R. L., and Yeats, R. S., 1992, Post-Laramide geology of the U.S. Cordillera 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, The Geology of North America, v. G-3, p. 261–406.

Clark, L. D., 1960, Foothills fault system, western Sierra Nevada, California: Geological Society of America Bulletin, v. 71, p. 483–496.

Cloetingh, S. A. P. L., Wortel, M. J. R., and Vlaar, N. J., 1984, Passive margin evolution, initiation of subduction and the Wilson cycle: Tectonophysics, 109, p. 147–163.

Cloos, M., 1982, Flow mélanges: Numerical modeling and geologic constraints on their origin in the Franciscan subduction complex, California: Geological Society of America Bulletin, v. 93, p. 330–345.

Coe, R. S., Globerman, B. R., Plumley, P. W., and Thrupp, G. A., 1985, Paleomagnetic results from Alaska and their tectonic implications, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, no. 1, p. 85–108.

Coffin, M. F., and Rabinowitz, P. D., 1987, Reconstruction of Madagascar and Africa; evidence from the Davie fracture zone and western Somali Basin: Journal of Geophysical Research, v. 92, p. 9385–9406.

Coleman, R. G., 1972, The Colebrooke Schist of southwestern Oregon and its relation to the tectonic evolution of the region: U.S. Geological Survey Bulletin 1339, 61 p.

Coleman, R. G., 1989, Continental growth of northwest China: Tectonics, v. 8, p. 621–635.

Coleman, R. G., and Lanphere, M. A., 1971, Distribution and age of high-grade blueschists, associated eclogites, and amphibolites from Oregon and California: Geological Society of America Bulletin, v. 82, p. 2397–2412.

Coleman, M. E., and Parrish, R. R., 1991, Eocene dextral strike-slip and extensional faulting in the Bridge River terrane, southwestern British Columbia: Tectonics, v. 10, p. 1222–1238.

Coney, P. J., and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406.

Connelly, W., 1978, Uyak complex, Kodiak Islands, Alaska: A Cretaceous subduction complex: Geological Society of America Bulletin, v. 89, p. 755–769.

Cooper, A. K., Marlow, M. S., and Scholl, D. W., 1976, Mesozoic magnetic lineations in the Bering Sea marginal basin: Journal of Geophysical Research, v. 81, p. 1916–1934.

Cordey, F., and Schiarizza, P., 1993, Long-lived Panthalassic remnant: The Bridge River accretionary complex, Canadian Cordillera: Geology, v. 21, p. 263–266.

Cowan, D. S., 1985, Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America: Geological Society of America Bulletin, v. 96, p. 451–462.

Cox, A., and Gordon, R. G., 1984, Paleolatitudes determined from paleomagnetic data from vertical cores: Reviews of Geophysics and Space Physics, v. 22, p. 47–72.

Cox, D. P., Marvin, R. F., M'Gonigle, J. W., McIntyre, D. H., and Rogers, C. L., 1977, Potassium-argon geochronology of some metamorphic, igneous, and hydrothermal events in Puerto Rico and the Virgin Islands: U.S. Geological Survey Journal of Research, v. 5, p. 689–703.

Crisp, J. A., 1984, Rates of magma emplacement and volcanic output: Journal of Volcanology and Geothermal Research, v. 20, p. 177–211.

Crouch, J. K., 1981, Northwest margin of California continental borderland: Marine geology and tectonic evolution: American Association of Petroleum Geologists Bulletin, v. 65, p. 191–218.

Crowell, J. C., 1987, Late Cenozoic basins of onshore southern California: Complexity is the hallmark of their tectonic history, *in* Ingersoll, R. V., and Ernst, W. G., eds, Cenozoic basin development of coastal California; Rubey Volume VI: Englewood Cliffs, New Jersey, Prentice-Hall, p. 207–241.

Currie, K. L., and Larochelle, A., 1969, A paleomagnetic study of volcanic rocks from Mistastin Lake, Labrador, Canada: Earth and Planetary Science Letters, v. 6, p. 309–319.

Dalrymple, G. B., 1979, Critical tables for conversion of K-Ar ages from old to new constants: Geology, v. 7, p. 558–560.

Dalrymple, G. B., Pringle, M. S., Vallier, T. L., and Roudnik, G. B., 1990, $^{40}Ar/^{39}Ar$ ages of volcanic rocks from southern Hess rise, north central Pacific Ocean: Eos, Transactions of the American Geophysical Union, v. 71, no. 43, p. 1668.

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 Science, v. 20, p. 1052–1071.

Davis, A., and Plafker, G., 1985, Comparative geochemistry and petrology of Triassic basaltic rocks from the Taku terrane on the Chilkat Peninsula and Wrangellia: Canadian Journal of Earth Science, v. 22, p. 183–194.

Day, H. D., Moores, E. M., and Tuminas, A. C., 1985, Structure and tectonics of the northern Sierra Nevada: Geological Society of America Bulletin, v. 96, p. 436–450.

Decker, J., Wilson, F. H., and Turner, D. L., 1980, Mid-Cretaceous subduction event in southeastern Alaska: Geological Society of America Abstracts with Programs, v. 12, p. 103.

Dengo, G., and Case, J. E., eds., 1990, The Caribbean region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. H, 529 p.

Dewey, J. F., 1988, Extensional collapse of orogens: Tectonics, v. 7, p. 1123–1139.

Dickinson, W. R., and Luth, W. C., 1971, A model for plate tectonic evolution of mantle layers: Science, v. 174, p. 400–404.

Dickinson, W. R., Klute, M. A., and Swift, P. N., 1986, The Bisbee Basin and its bearing on Late Mesozoic paleogeographic and paleotectonic relations between the cordilleran and Caribbean regions, *in* Abbott, P. L., ed., Cretaceous stratigraphy, western North America: Pacific Section, Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 46, p. 51–62.

Dickinson, W. R., and eight others, 1987, Geohistory analysis of rates of sediment accumulation and subsidence for selected California basins, *in* Ingersoll, R. V., and Ernst, W. G., eds., Cenozoic basin development of coastal California; Rubey Volume VI: Englewood Cliffs, New Jersey, Prentice-Hall, p. 1–23.

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.

Diehl, J. F., Beck, M. E., Jr., Beske-Diehl, S., Jacobson, D., and Hearn, B. C., Jr., 1983, Paleomagnetism of the Late Cretaceous-Early Tertiary north-central Montana alkalic province: Journal of Geophysical Research, v. 88, p. 10593–10609.

Diehl, J. F., McClannahan, K. M., and Bornhorst, T. J., 1988, Paleomagnetic results from the Mogollon-Datil volcanic field, southwestern New Mexico, and a refined mid-Tertiary reference pole for North America, Journal of Geophysical Research, v. 93, p. 4869–4879.

Dilles, J. H., and Wright, J. E., 1988, The chronology of early Mesozoic arc magmatism in the Yerington district of western Nevada and its regional implications: Geological Society of America Bulletin, v. 100, p. 644–652.

Dillon, J. T., 1986, Timing of thrusting and metamorphism along the Vincent-Chocolate Mountain thrust system, southern California: Geological Society of America Abstracts with Programs, v. 18, p. 101.

Doell, R. R., 1972a, Paleomagnetism of lava flows from Kauai, Hawaii: Journal of Geophysical Research, v. 77, p. 862–876.

Doell, R. R., 1972b, Paleomagnetism of volcanic rocks from Niihau, Nihoa, and Necker Islands, Hawaii: Journal of Geophysical Research, v. 77, p. 3725–3730.

Doell, R. R., and Dalrymple, G. B., 1973, Potassium-Argon ages and paleomagnetism of the Waianae and Koolau volcanic series, Oahu, Hawaii: Geological Society of America Bulletin, v. 84, p. 1217–1242.

Donato, M. M., 1987, Evolution of an ophiolitic tectonic mélange, Marble Mountains, northern California Klamath Mountains, Geological Society of America Bulletin, v. 98, p. 448–464.

Donato, M. M., 1992, A newly recognized ductile shear zone in the northern Klamath Mountains, Oregon—Implications for Nevadan accretion: U.S. Geological Survey Bulletin 2028, 10 p.

Donnelly, T. W., and 10 others, 1990, History and tectonic setting of Caribbean magmatism, *in* Dengo, G., and Case, J. E., eds., The Caribbean region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. H, p. 339–367.

Dott, R. H., Jr., 1965, Mesozoic-Cenozoic tectonic history of the southwestern Oregon coast in relation to Cordilleran orogenesis: Journal of Geophysical Research, v. 70, p. 4687–4707.

Drewes, H., 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geological Society of America Bulletin, v. 89, p. 641–657.

Duncan, R. A., 1982, A captured island chain in the Coast Range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 10827–10837.

Dunne, G. C., Gulliver, R. M., and Sylvester, A. G., 1978, Mesozoic evolution of the White, Inyo, Argus, and Slate Ranges, Eastern California, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 189–207.

Eaton, G. P., 1982, The Basin and Range Province: Origin and tectonic significance: Annual Reviews of Earth and Planetary Sciences, v. 10, p. 409–440.

Eby, G. N., 1984, Geochronology of the Monteregian Hills alkaline igneous province, Quebec: Geology, v. 12, p. 468–470.

Eddington, P. K., Smith, R. B., and Renggli, C., 1987, Kinematics of Basin and Range intraplate extension, *in* Coward, M. P., Dewey, J. F., and Hancock, P. L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 371–392.

Edelman, S. H., and Sharp, W. D., 1989, Terranes, early faults, and pre-Late Jurassic amalgamation of the western Sierra Nevada metamorphic belt, California: Geological Society of America Bulletin, v. 101, p. 1420–1433.

Eisbacher, G. H., Carrigy, M. A., and Campbell, R. B., 1974, Paleodrainage pattern and late-orogenic basins of the Canadian Cordillera, *in* Dickinson, W. R., ed., Tectonics and Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 143–166.

Ekstrand, E. J., and Butler, R. F., 1989, Paleomagnetism of the Moenave Formation: Implications for the North American apparent polar wander path: Geology, v. 17, p. 245–248.

Ellis, M., 1988, Lithospheric strength in compression: Initiation of subduction, flake tectonics, foreland migration of thrusting, and an origin of displaced terranes: Journal of Geology, v. 88, p. 91–100.

Engebretson, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.

England, P., and Holland, T. J. B., 1979, Archimedes and the Tauern eclogites, The role of buoyancy in the preservation of exotic tectonic blocks: Earth and Planetary Science Letters, v. 44, p. 287–294.

England, P., and Wortel, R., 1980, Some consequences of the subduction of young slabs: Earth and Planetary Science Letters, v. 47, p. 403–415.

Epp, D., Sager, W. W., and Theyer, F., 1983, Hotspot-spin axis motion or magnetic far-sided effect?: Nature, v. 303, p. 318–320.

Erickson, S. G., 1993, Sedimentary loading, lithospheric flexure, and subduction initiation at passive margins: Geology, v. 21, p. 125–128.

Ernst, W. G., 1975, Systematics of large-scale tectonics and age progressions, *in* Alpine and circum-Pacific blueschist belts: Tectonophysics, v. 26, p. 229–246.

Evenchick, C. A., 1991, Structural relationships of the Skeena Fold Belt west of the Bowser Basin, northwest British Columbia: Canadian Journal of Earth Science, v. 28, p. 973–983.

Evernden, J. F., and Kistler, R. W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geological Survey Professional Paper 623, 42 p.

Fisher, G. R., 1990, Middle Jurassic syntectonic conglomerate in the Mt. Tallac roof pendant, northern Sierra Nevada, California, *in* Harwood, S. S., and Miller, M. M., eds., Paleozoic and early Mesozoic paleogeographic relations; Sierra Nevada, Klamath Mountains, and related terranes: Geological Society of America Special Paper 255, p. 339–350.

Forsyth, D., and Uyeda, S., 1975, On the relative importance of the driving forces of plate motions: Geophysical Journal of the Royal Astronomical Society, v. 43, p. 163–200.

Foster, J., and Symons, D. T. A., 1979, Defining a paleomagnetic polarity pattern in the Monteregian intrusives: Canadian Journal of Earth Science, v. 16, p. 1716–1725.

Fox, K. F., Jr., and Beck, M. E., Jr., 1985, Paleomagnetic results from Eocene volcanic rocks from northeastern Washington and the Tertiary tectonics of the Pacific Northwest: Tetonics, v. 4, p. 323–341.

Frizzell, V. A., Jr., Tabor, R. W., Zartman, R. E., and Blome, C. D., 1987, Late Mesozoic or Early Tertiary melanges in the western Cascades of Washington: Washington Division of Geology and Earth Resources Bulletin,

v. 77, p. 129–148.
Fuis, G. S., Ambos, E. L., Mooney, W. D., Christensen, N. I., and Geist, E., 1991, Crustal structure of accreted terranes in southern Alaska, Chugach mountains, and Copper River basin, from seismic refraction results: Journal of Geophysical Research, v. 96, p. 4187–4227.
Gabrielse, H., 1985, Major dextral transcurrent displacements along the northern Rocky Mountain trench and related lineaments in north-central British Columbia: Geological Society of America Bulletin, v. 96, p. 1–14.
Gabrielse, H., Snyder, W. S., and Stewart, J. H., 1983, Sonoma orogeny and Permian to Triassic tectonism in western North America: Geology, v. 11, p. 484–486.
Gabrielse, H., Monger, J. W. H., Yorath, C. J., and Dodds, C. J., 1992, Part F. Transcurrent faults, *in* Structural styles, *in* Gabrielse, H., and Yorath, C. J., eds., Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, no. 4, p. 651–660 (*also* Geological Society of America, The Geology of North America, v. G-2).
Gary, M., McAfee, R., Jr., and Wolf, C. L., eds., 1974, Glossary of geology: Washington, D.C., American Geological Institute, 858 p.
Gealey, W. K., 1980, Ophiolite obduction mechanism, *in* Panayiotou, A., ed., Ophiolites: Proceedings of the International Ophiolite Symposium, Cyprus, 1979, Republic of Cyprus Geological Survey Department, p. 228–243.
Globerman, B. R., and Irving, E., 1988, Mid-Cretaceous paleomagnetic reference field for North America: Restudy of 100 Ma intrusive rocks from Arkansas: Journal of Geophysical Research, v. 93, p. 11721–11733.
Goldfarb, R. J., Snee, L. W., Miller, L. D., and Newberry, R. J., 1991, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits: Nature, 354, p. 296–298.
Goodge, J. W., 1990, Tectonic evolution of a coherent Late Triassic subduction complex, Stuart Fork terrane, Klamath Mountains, northern California: Geological Society of America Bulletin, v. 102, p. 86–101.
Goodge, J. W., and Renne, P. R., 1993, Mid-Paleozoic olistoliths in eastern Hayfork terrane mélange, Klamath mountains: Implications for Late Paleozoic–Early Mesozoic cordilleran forearc development: Tectonics, v. 12, p. 279–289.
Gordon, R. G., 1982, Paleomagnetic test of the Emperor fracture zone hypothesis: Geophysical Research Letters, v. 9, p. 1283–1286.
Gordon, R. G., 1983, Late Cretaceous apparent polar wander of the Pacific plate: Evidence for a rapid shift of the Pacific hotspots with respect to the spin axis: Geophysical Research Letters, v. 10, p. 709–712.
Gordon, R. G., 1990, Test for bias in paleomagnetically determined paleolatitudes from the Pacific plate Deep Sea Drilling Project Sediments: Journal of Geophysical Research, v. 95, p. 8397–8404.
Gordon, R. G., Cox, A., and O'Hare, S., 1984, Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America: Tectonics, v. 3, p. 499–537.
Graham, S. A., 1978, Role of Salinian Block in evolution of San Andreas fault system: American Association of Petroleum Geologists Bulletin, v. 62, p. 2214–2231.
Grand, S. P., 1987, Tomographic inversion for shear velocity beneath the North American plate: Journal of Geophysical Research, v. 92, p. 14065–14090.
Grand, S. P., and Engebretson, D. C., 1992, The relation between subduction history and lower mantle heterogeneity: Eos, Transactions of the American Geophysical Union, v. 73, no. 43, p. 385.
Gromme, S., and Vine, F. J., 1972, Paleomagnetism of Midway atoll lavas and northward movement of the Pacific plate: Earth and Planetary Science Letters, v. 17, p. 159–168.
Gromme, C. S., Beck, M. E., Jr., Wells, R. E., and Engebretson, D. C., 1986, Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific northwest: Journal of Geophysical Research, v. 91, p. 14089–14103.
Gunderson, J. A., and Sheriff, S. D., 1991, A new Cretaceous paleomagnetic pole from the Adel Mountains, west central Montana: Journal of Geophysical Research, v. 96, p. 317–326.
Gurnis, M., 1992, Rapid continental subsidence following the initiation and evolution of subduction: Science, v. 255, p. 1556–1558.
Hacker, B. R., 1993, Evolution of the northern Sierra Nevada metamorphic belt: Petrological, structural, and Ar/Ar constraints: Geological Society of America Bulletin, v. 105, p. 637–656.
Hacker, B. R., and Ernst, W. G., 1993, Jurassic orogeny in the Klamath Mountains: A geochronological analysis, *in* Dunne, G. C., and McDougall, K. A., eds., Mesozoic Paleogeography of the Western United States: II: Northridge, California, California State University, Department of Geological Sciences, Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Field Trip Guidebook, p. 37–59.
Haeussler, P. J., 1992, Structural evolution of an arc-basin: The Gravina belt in central southeastern Alaska: Tectonics, v. 11, p. 1245–1265.
Hagstrum, J. T., 1993, North American Jurassic APW: The current dilemma: Eos, Transactions of the American Geophysical Union, v. 74, no. 6, p. 65–69.
Hamilton, W., 1981, Plate-tectonic mechanism of Laramide deformation: Contributions to Geology, University of Wyoming, v. 19, p. 87–92.
Hannula, K. A., McWilliams, M. O., and Gans, P. B., 1991, Triassic or older blueschists facies metamorphism on the Seward Peninsula: results of $^{40}Ar/^{39}Ar$ dating of white micas from the Nome Group: Geological Society of America Abstracts with Programs, v. 23, no. 2, p. 33.
Hansen, V. L., 1990, Yukon-Tanana terrane: A partial acquittal: Geology, v. 18, p. 365–369.
Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G., and Smith, D. G., 1990, A geologic time scale 1989: Cambridge University Press, 263 p.
Harms, T. A., Jayko, A. S., and Blake, M. C., Jr., 1992, Kinematic evidence for extensional unroofing of the Franciscan Complex along the Coast Range fault, northern Diable Range, California: Tectonics, v. 11, p. 228–241.
Harper, G. D., and Wright, J. E., 1984, Middle to Late Jurassic tectonic evolution of the Klamath Mountains, California-Oregon: Tectonics, v. 3, p. 759–772.
Harper, G. D., Saleeby, J. B., and Norman, E. A. S., 1985, Geometry and tectonic setting for the Josephine ophiolite, and implications for Jurassic accretionary events along the California margin, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, no. 1, p. 239–257.
Haxel, G. B., and Dillon, J. T., 1978, The Pelona-Orocopia Schist and Vincent-Chocolate Mountain thrust system, southern California, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 453–469.
Heller, F., 1978, Rock magnetic studies of Upper Jurassic limestones from southern Germany: Journal of Geophysics, v. 46, p. 525–543.
Heller, P. L., Bowdler, S. S., Chambers, H. P., Coogan, J. C., Hagen, E. S., Shuster, M. W., and Winslow, N. S., 1986, Time of initial thrusting in the Sevier orogenic belt, Idaho-Wyoming and Utah: Geology, v. 14, p. 388–391.
Heller, P. L., Tabor, R. W., and Suczek, C. A., 1987, Paleogeographic evolution of the United States Pacific Northwest during Paleogene time: Canadian Journal of Earth Science, v. 24, p. 1652–1667.
Helper, M. A., 1986, Deformation and high P/T metamorphism in the central part of the Condrey Mountain window, north-central Klamath Mountains, California and Oregon, *in* Evans, B. W., and Brown, E. H., eds., Blueschists and eclogites: Geological Society of America Memoir 164, p. 125–141.
Henry, C. D., Price, J. G., and James, E. W., 1991, Mid-Cenozoic evolution and magmatism in the southern cordillera, Texas and Mexico: Transition

from continental arc to intraplate extension: Journal of Geophysical Research, v. 96, p. 13545–13560.

Herrero-Brevara, E., and Helsley, C. E., 1983, Paleomagnetism of a polarity transition in the Lower (?) Triassic Chugwater Formation, Wyoming: Journal of Geophysical Research, v. 88, p. 3506–3522.

Hilde, T. W. C., Isezaki, N., and Wageman, J. M., 1976, Mesozoic sea-floor spreading in the north Pacific: American Geophysical Union, Geophysical Monograph 19, p. 205–226.

Hildreth, W., 1981, Gradients in silicic magma chambers: Implications for lithospheric magmatism: Journal of Geophysical Research, v. 86, p. 10153–10192.

Hildreth, W., 1987, New perspectives on the eruption of 1912 in the Valley of Ten Thousand Smokes, Katmai National Park, Alaska: Bulletin Volcanologique, v. 49, p. 680–693.

Hodych, J. P., and Dunning, G. R., 1992, Did the Manicouagan impact trigger end-of-Triassic mass extinction?: Geology, v. 20, p. 51–54.

Hodych, J. P., and Hayatsu, A., 1988, Paleomagnetism and K-Ar isochron dates of Early Jurassic basaltic flows and dikes of Atlantic Canada: Canadian Journal of Earth Science, v. 25, p. 1972–1989.

Hollister, V. F., 1978, Geology of the porphyry copper deposits of the Western Hemisphere: New York, American Institute of Mining Metallurgical and Petroleum Engineers, 219 p.

Hopson, C. A., Mattinson, J. M., and Pessagno, E. A., Jr., 1981, Coast Range ophiolite, western California, *in* Ernst, W. G., ed., The geotectonic development of California; Rubey Volume I: Englewood Cliffs, New Jersey, Prentice-Hall, p. 418–510.

Hopson, C., Beebe, W., Mattinson, J., Pessagno, E., and Blome, C., 1986, California Coast Range ophiolite: Jurassic tectonics: Eos, Transactions of the American Geophysical Union, v. 67, p. 1232.

Hotz, P. E., Lanphere, M. A., and Swanson, D. A., 1977, Triassic blueschist from northern California and north-central Oregon: Geology, v. 5, p. 659–663.

Hsü, K. J., 1991, Exhumation of high-pressure metamorphic rocks: Geology, v. 19, p. 107–110.

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.

Hudson, T., 1983, Calc-alkaline plutonism along the Pacific rim of southern Alaska, *in* Roddick, J. A., ed., Circum-Pacific plutonic terranes: Geological Society of America Memoir 159, p. 159–169.

Humphreys, E., Clayton, R. W., and Hager, B. H., 1984, A tomographic image of mantle structure beneath southern California: Geophysical Research Letters, v. 11, p. 625–627.

Hutton, D. H. W., and Reavy, R. J., 1992, Strike-slip tectonics and granite petrogenesis: Tectonics, v. 11, p. 960–967.

Hutton, D. H. W., Dempster, T. J., Brown, P. E., and Becker, S. D., 1990, A new mechanism of granite emplacement: Intrusion in active extensional shear zones: Nature, 343, p. 452–455.

Imlay, R. W., 1984, Jurassic ammonite successions in North America and biogeographic implications, *in* Westermann, G. E. G., ed., Jurassic-Cretaceous biochronology and biogeography of North America: St. Johns, Newfoundland, Geological Society of Canada Special Paper 27, p. 1–12.

Ingersoll, R. V., 1983, Petrofacies and provenance of Late Mesozoic forearc basin, northern and central California: American Association of Petroleum Geologists Bulletin, v. 67, p. 1125–1142.

Irving, E., and Irving, G. A., 1982, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana: Geophysical Surveys, v. 5, p. 141–188.

Irving, E., and Park, J. K., 1972, Hairpins and superintervals: Canadian Journal of Earth Science, v. 9, p. 1318–1324.

Irwin, W. P., 1985, Age and tectonics of plutonic belts in accreted terranes of the Klamath mountains, California and Oregon, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, no. 1, p. 187–199.

Isaac, S., Rockwell, T. K., and Gastil, G., 1986, Plio-Pleistocene detachment faulting, Yuma Desert region, western Salton Trough, northern Baja California: Geological Society of America Abstracts with Programs, v. 18, p. 120.

Jacobson, C. E., 1990, The $^{40}Ar/^{39}$ geochronology of the Pelona Schist and related rocks, southern California: Journal of Geophysical Research, v. 95, p. 509–528.

Jacobson, C. E., Dawson, M. R., and Postlethwaite, C. E., 1988, Structure, metamorphism, and tectonic significance of the Pelona, Orocopia, and Rand Schists, southern California, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 976–977.

James, E. W., and Mattinson, J. M., 1988, Metamorphic history of the Salinian block: An isotopic reconnaissance, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 939–952.

Janecke, S. U., 1992, Kinematics and timing of three superposed extensional systems, east central Idaho: Evidence for an Eocene tectonic transition: Tectonics, v. 11, p. 1121–1138.

Jansa, L. F., 1986, Paleoceanography and evolution of the North Atlantic Ocean basin during the Jurassic, *in* Vogt, P. R., and Tucholke, B. E., eds., The western North Atlantic region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. M, p. 603–616.

Jarrard, R. D., 1986, Relations among subduction parameters: Reviews of Geophysics and Space Physics, v. 24, p. 217–284.

Jones, D. L., Silberling, N. J., Coney, P. J., and Plafker, G., 1987, Lithotectonic terrane map of Alaska (west of the 141st meridian): U.S. Geological Survey Miscellaneous Field Studies Map MF-1874-A, scale 1:2,500,000.

Joseph, S. E., Davis, T. E., and Ehlig, P. L., 1982, Strontium isotopic correlation of the La Panza Range granitic rocks with similar rocks in the central and eastern Transverse Ranges, *in* Fife, D. L., and Minch, J. A., eds., Geology and mineral wealth of the California Transverse Ranges; Mason Hill Volume: Santa Ana, California, South Coast Geological Society Annual Symposium and Guidebook 10, p. 310–320.

Karig, D. E., 1982, Initiation of subduction zones: Implications for arc evolution and ophiolite development, *in* Leggett, J. K., ed., Trench-Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins: Geological Society of London Special Publication 10, p. 563–576.

Keith, S. B., and Wilt, J. C., 1986, Laramide orogeny in Arizona and adjacent regions: A stratotectonic synthesis, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 502–554.

Ketner, K. B., 1984, Recent studies indicate that major structures in northeastern Nevada and the Golconda thrust in north-central Nevada are of Jurassic or Cretaceous age: Geology, v. 12, p. 483–486.

King, P. B., 1969, Tectonic map of North America, U.S. Geological Survey, Reston, Virginia, scale 1:5,000,000.

Kistler, R. W., 1990, Two different lithosphere types in the Sierra Nevada, California, *in* Anderson, J. L., ed., The nature and origin of Cordilleran magmatism: Geological Society of America Memoir 174, p. 271–281.

Kleinspehn, K. L., 1985, Cretaceous sedimentation and tectonics, Tyaughton-Methow basin, southwestern British Columbia: Canadian Journal of Earth Science, v. 22, p. 154–174.

Klitgord, K. D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, *in* Vogt, P. R., and Tucholke, B. E., eds., The western North Atlantic region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. M, p. 351–378.

Kluth, C. F., Butler, R. F., Harding, L. E., Shafiqullah, M., and Damon, P. E., 1982, Paleomagnetism of the Late Jurassic rocks in the northern Canelo Hills, southeastern Arizona: Journal of Geophysical Research, v. 87, p. 7079–7086.

Kono, M., 1980, Paleomagnetism of DSDP leg 55 basalts and implications for the tectonics of the Pacific plate, *in* Shambach, J., and 14 others, Initial reports of the deep sea drilling project, v. 55, p. 737–752.

Kono, M., Kobayashi, K., Ozima, M., Kinoshita, H., Nagata, T., Larson, E. E., and Strangway, D., 1967, Paleomagnetism of Pliocene basalts from the southwestern U.S.A.: Journal of Geomagnetism and Geoelectricity, v. 19, p. 357–375.

Kowallis, B. J., and Heaton, J. S., 1987, Fission-track dating of bentonites and bentonitic mudstones from the Morrison Formation in central Utah: Geology, v. 15, p. 1138–1142.

Kriens, B., and Wernicke, B., 1990, Nature of the contact zone between the North Cascades crystalline core and the Methow sequence in the Ross Lake area, Washington: Implications for cordilleran tectonics, Tectonics, v. 9, p. 953–981.

Krummenacher, D., Gastil, R. G., Bushee, J., and Doupont, J., 1975, K-Ar apparent ages, Peninsular Ranges batholith, Southern California and Baja California: Geological Society of America Bulletin, v. 86, p. 760–768.

Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States and the thermal regime of the crust, *in* Heacock, J. G., Keller, G. V., Oliver, J. E., and Simmons, G., eds., The Earth's crust; its nature and physical properties: American Geophysical Union Geophysical Monograph 20, p. 626–675.

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

Lanphere, M. A., 1971, Age of the Mesozoic ocean crust in the California Coast Ranges: Geological Society of America Bulletin, v. 82, p. 3209–3212.

Lanphere, M. A., Blake, M. C., Jr., and Irwin, W. P., 1978, Early Cretaceous metamorphic age of the South Fork Mountain Schist in the northern Coast Ranges of California: American Journal of Science, v. 278, p. 798–815.

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.

Lawver, L. A., and Scotese, C. R., 1990, A review of tectonic models for the evolution of the Canada Basin, *in* Grantz, A., Johnson, L., and Sweeney, J. F., eds., The Arctic Ocean region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. L, p. 593–618.

Lemoine, M., 1984, Mesozoic evolution of the western Alps: Annales Geophysicae, v. 2, p. 171–172.

Lewis, P. D., Haggart, J. W., Anderson, R. G., Hickson, C. J., Thompson, R. I., Dietrich, J. R., and Rohr, K. M. M., 1991, Triassic to Neogene geologic evolution of the Queen Charlotte region: Canadian Journal of Earth Science, v. 28, p. 854–869.

Lin, J., Fuller, M., and Zhang, W., 1985, Preliminary Phanerozoic polar wander paths for the North and South China blocks: Nature, v. 313, p. 444–449.

Lipman, P. W., 1984, The roots of ash flow calderas in western North America: Windows into the tops of granite batholiths: Journal of Geophysical Research, v. 89, p. 8801–8841.

Lipman, P. W., and Hagstrum, J. T., 1992, Jurassic ash-flow sheets, calderas, and related intrusions of the Cordilleran volcanic arc in southeastern Arizona: Implications for regional tectonics and ore deposits: Geological Society of America Bulletin, v. 104, p. 32–39.

Livermore, R. A., Smith, A. G., and Vine, F. J., 1986, Late Paleozoic to early Mesozoic evolution of Pangea: Nature, 322, p. 162–165.

Longtine, M. W., and Walker, N., 1990, Evidence for Late Cretaceous N-S dextral shear in the west-central crystalline core, North Cascades, Washington: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 38.

Lonsdale, P., 1988, Paleogene history of the Kula plate: Offshore evidence and onshore implications: Geological Society of America Bulletin, v. 100, p. 733–754.

Lonsdale, P., 1989, Geology and tectonic history of the Gulf of California, *in* Winterer, E. L., Hussong, D. M., and Decker, R. W., eds., The eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, The Geology of North America, v. N, p. 499–521.

Lonsdale, P., 1991, Structural patterns of the Pacific floor offshore of Peninsular California, *in* Dauphin, J. P., and Simoneit, B. R. T., eds., The gulf and peninsula province of the Californias: American Association of Petroleum Geologists Memoir 47, p. 87–125.

Luyendyk, B. P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California: Geological Society of America Bulletin, v. 103, p. 1528–1536.

Mak, E. K., York, D., Grieve, R. A. F., and Dence, M. R., 1976, The age of the Mistastin Lake crater, Labrador, Canada: Earth and Planetary Science Letters, v. 31, p. 345–357.

Mammerickx, J., and Klitgord, K. D., 1982, Northern East Pacific rise: Evolution from 25 m.y. to the present: Journal of Geophysical Research, v. 87, p. 6751–6759.

Mammerickx, J., and Sharman, G. F., 1988, Tectonic evolution of the north Pacific during the Cretaceous Quiet Period: Journal of Geophysical Research, v. 93, p. 3009–3024.

Mangan, M. T., Wright, T. L., Swanson, D. A., and Byerly, G. R., 1986, Regional correlation of Grande Ronde Basalt flows, Columbia River Basalt Group, Washington, Oregon, and Idaho: Geological Society of America Bulletin, v. 97, p. 1300–1318.

Mankinen, E. A., Larson, E. E., Gromme, C. S., Prevot, M., and Coe, R. S., 1987, The Steens Mountain (Oregon) geomagnetic polarity transition, 3. Its regional significance: Journal of Geophysical Research, v. 92, p. 8057–8076.

Maresch, W. V., 1974, Plate tectonics origin of the Caribbean mountain system of northern South America: Discussion and proposal: Geological Society of America Bulletin, v. 85, p. 669–682.

Marsden, H., and Thorkelson, D. J., 1992, Geology of the Hazelton volcanic belt in British Columbia: Implications for the Early to Middle Jurassic evolution of Stikinia: Tectonics, v. 11, p. 1266–1287.

Marvin, R. F., Hearn, B. C., Jr., Mehnert, H. H., Naeser, C. W., Zartman, R. E., and Lindsey, D. A., 1980, Late Cretaceous–Paleocene-Eocene igneous activity in north-central Montana: Isochron/West, v. 29, p. 5–25.

Marzolf, J. E., 1990, Speculative tectonic model for the early Mesozoic arc of the southwest Cordilleran United States: Comment: Geology, v. 18, p. 285–286.

Marzolf, J. E., 1991, Lower Jurassic unconformity (J-0) from the Colorado Plateau to the eastern Mojave Desert: Evidence of a major tectonic event at the close of the Triassic: Geology, v. 19, p. 320–323.

Mattinson, J. M., 1986, Geochronology of high-pressure–low-temperature Franciscan metabasites—A new approach using the U-Pb system, *in* Evans, B. W., and Brown, E. H., eds., Blueschists and eclogites: Geological Society of America Memoir 164, p. 95–105.

Mattinson, J. M., and Echeverria, L. M., 1980, Ortigalita Peak gabbro, Franciscan Complex—U-Pb date of intrusion and high-pressure–low-temperature metamorphism: Geology, v. 8, p. 589–593.

Mattinson, J. M., and James, E. W., 1985, Salinian Block U/Pb age and isotopic variations: Implications for origin and emplacement of the Salinian terrane, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, no. 1, p. 215–226.

May, S. R., and Butler, R. F., 1986, North American Jurassic apparent polar wander: Implications for plate motion, paleogeography, and Cordilleran tectonics: Journal of Geophysical Research, v. 91, p. 11519–11544.

May, S. R., Butler, R. F., Shafiqullah, M., and Damon, P. E., 1986, Paleomagnetism of Jurassic volcanic rocks in the Patagonia Mountains, southeastern Arizona: Implications for the North American 170 Ma reference pole: Journal of Geophysical Research, v. 91, p. 11545–11555.

May, S. R., Beck, M. E., Jr., and Butler, R. F., 1989, North American apparent polar wander, plate motion, and left-oblique convergence: Late

Jurassic–Early Cretaceous orogenic consequences: Tectonics, v. 8, p. 443–451.

Mayfield, C. F., Tailleur, I. L., and Ellersieck, I., 1988, Stratigraphy, structure, and palinspastic synthesis of the western Brooks Range, northwestern Alaska: U.S. Geological Survey Professional Paper 1399, p. 143–186.

McDowell, F. W., Lehman, D. H., Gucwa, P. R., Fritz, D., and Maxwell, J. C., 1984, Glaucophane schists and ophiolites of the northern California Coast Ranges: Isotopic ages and their tectonic implications: Geological Society of America Bulletin, v. 95, p. 1373–1382.

McGroder, M. F., 1991, Reconciliation of two-sided thrusting, burial metamorphism, and diachronous uplift in the Cascades of Washington and British Columbia: Geological Society of America Bulletin, v. 103, p. 189–209.

McKenzie, D. P., 1977, The initiation of trenches: A finite amplitude instability, *in* Talwani, M., and Pitman, W. C., III, eds., Island arcs, deep sea trenches, and back-arc basins: American Geophysical Union Maurice Ewing Series, no. 1, p. 57–61.

McLaughlin, R. J., Sorg, D. H., Morton, J. L., Theodore, T. G., Meyer, C. E., and Delevaux, M. H., 1985, Paragenesis and tectonic significance of base and precious metal occurrences along the San Andreas fault at Pt. Delgada, California: Economic Geology, v. 80, p. 344–359.

McMechan, M. E., Thompson, R. I., Cook, D. G., Gabrielse, H., and Yorath, C. J., 1992, Part E. Foreland belt, *in* Structural styles, *in* Gabrielse, H., and Yorath, C. J., eds., Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, no. 4, p. 634–650 (*also* Geological Society of America, The Geology of North America, v. G-2).

Metcalfe, P., and Clark, G. S., 1983, Rb-Sr whole-rock age of the Klondike Schist, Yukon Territory: Canadian Journal of Earth Science, v. 20, p. 886–891.

Metz, P. A., 1976, Occurrences of sodic amphibole-bearing rocks in the Valdez C-2 quadrangle: Alaska Division of Geology and Geophysical Surveys Geology Report 51, p. 27–29.

Miller, C. F., 1978, An Early Mesozoic alkalic magmatic belt in western North America, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 163–173.

Miller, D. M., and Allmendinger, R. W., 1991, Jurassic normal and strike-slip faults at Crater Island, northwestern Utah: Geological Society of America Bulletin, v. 103, p. 1239–1251.

Miller, D. M., and Hoisch, T. D., 1992, Mesozoic structure, metamorphism, and magmatism in the Pilot and Toano Ranges, *in* Wilson, J. R., ed., Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publications 92-3, p. 79–92.

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.

Miller, F. K., and Engels, J. C., 1975, Distribution and trends of discordant ages of the plutonic rocks of northeastern Washington and northern Idaho: Geological Society of America Bulletin, v. 86, p. 517–528.

Miller, M. G., 1988, Possible pre-Cenozoic left-lateral slip on the Yalakom fault, southwestern British Columbia: Geology, v. 16, p. 584–587.

Miller, M. M., and Harwood, D. S., 1989, Paleozoic and early Mesozoic paleogeographic relations between the Klamath Mountains, northern Sierra Nevada, and western North America: Geology, v. 17, p. 369–372.

Misch, P., 1966, Tectonic evolution of the northern Cascades of Washington—A west-Cordilleran case history, *in* A symposium on the tectonic history and mineral deposits of the western Cordillera: Canadian Institute of Mining and Metallurgy Special Volume 8, p. 101–148.

Molenaar, C. M., 1983, Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, p. 1066–1080.

Molina-Garza, R. S., Geissman, J. W., Van der Voo, R., Lucas, S. G., and Hayden, S. N., 1991, Paleomagnetism of the Moenkopi and Chinle Formations in central New Mexico: Implications for the North America apparent polar wander and Triassic magnetostratigraphy: Journal of Geophysical Research, v. 96, p. 14239–14262.

Monger, J. W. H., 1991, Correlation of Settler Schist with Darrington phyllite and Shuksan greenschist and its tectonic implications, Coast and Cascade mountains, British Columbia and Washington: Canadian Journal of Earth Science, v. 28, p. 447–458.

Monger, J. W. H., and nine others, 1992, Part B. Cordilleran terranes, *in* Upper Devonian to middle Jurassic assemblages, *in* Gabrielse, H., and Yorath, C. J., eds., Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, no. 4, p. 281–329 (*also* Geological Society of America, The Geology of North America, v. G-2).

Moore, J. C., Byrne, T., Plumley, P. W., Reid, M., Gibbons, H., and Coe, R. S., 1983, Paleogene evolution of the Kodiak Islands, Alaska: Consequences of ridge-trench interaction in a more southerly latitude: Tectonics, v. 2, p. 265–293.

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., 1986, Petrology and tectonic implications of the blueschist-bearing Puerto Nuevo mélange complex, Vizcaino Peninsula, Baja California Sur, Mexico, *in* Evans, B. W., and Brown, E. H., eds., Blueschists and eclogites: Geological Society of America Memoir 164, p. 43–58.

Mooser, F., Nairn, A. E. M., and Negendank, J. F. W., 1974, Paleomagnetic investigations of the Tertiary and Quaternary igneous rocks: VIII, A paleomagnetic and petrologic study of volcanics of the valley of Mexico: Geologische Rundschau, 63, p. 451–483.

Morel, P., and Irving, E., 1981, Paleomagnetism and the evolution of Pangea: Journal of Geophysical Research, v. 86, p. 1858–1872.

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

Mortimer, N., 1986, Late Triassic, arc-related, potassic igneous rocks in the North American Cordillera: Geology, v. 14, p. 1035–1038.

Mortimer, N., 1987, The Nicola group: Late Triassic and Early Jurassic subduction-related volcanism in British Columbia: Canadian Journal of Earth Science, v. 24, p. 2521–2536.

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

Mukasa, S. B., Dillon, J. T., and Tosdal, R. M., 1984, A Late Jurassic minimum age for the Pelona-Orocopia Schist protolith, southern California: Geological Society of America Abstracts with Programs, v. 16, no. 5, p. 323.

Muller, J. E., 1977, Evolution of the Pacific margin, Vancouver Island, and adjacent regions: Canadian Journal of Earth Science, v. 14, p. 2062–2085.

Nakanishi, M., Tamaki, K., and Kobayashi, K., 1992, Magnetic anomaly lineations from Late Jurassic to Early Cretaceous in the west-central Pacific Ocean: Geophysical Journal International, v. 109, p. 701–719.

Nelson, B. K., and DePaolo, D. J., 1985, Isotopic investigation of metasomatism in subduction zones: The Franciscan complex, California: Geological Society of America Abstracts with Programs, v. 17, no. 7, p. 674.

Nelson, K. D., 1992, Are crustal thickness variations in old mountain belts like the Appalachians a consequence of lithospheric delamination?: Geology, v. 20, p. 498–502.

Nilsen, T. H., 1986, Cretaceous paleogeography of western North America, *in* Abbott, P. L., ed., Cretaceous stratigraphy, western North America: Pacific Section, Society of Economic Paleontologists and Mineralogists Field Trip Guidebook 46, p. 1–39.

Nokleberg, W. J., 1983, Wallrocks of the central Sierra Nevada batholith, California: A collage of accreted tectono-stratigraphic terranes, U.S. Geological Survey Professional Paper 1255, 28 p.

ODP Leg 143 Shipboard Scientific Party, 1993, Examining guyots in the mid-Pacific mountains: Eos, Transactions of the American Geophysical Union, v. 74, p. 201–206.

Okamura, Y., 1991, Large-scale mélange formation due to seamount subduction: An example from the Mesozoic accretionary complex in central

Japan: Journal of Geology, v. 99, p. 661–674.
Oldow, J. S., 1984, Evolution of a late Mesozoic back-arc fold and thrust belt, northwestern Great Basin, U.S.A.: Tectonophysics, v. 102, p. 245–274.
Oldow, J. S., and Bartel, R. L., 1987, Early to Middle (?) Jurassic extensional tectonism in the western Great Basin: Growth faulting and synorogenic deposition of the Dunlap Formation: Geology, v. 15, p. 740–743.
Oldow, J. S., Avé Lallemant, H. G., and Schmidt, W. J., 1984, Kinematics of plate convergence deduced from Mesozoic structures in the western Cordillera: Tectonics, v. 3, p. 201–277.
Parrish, R. 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.
Paterson, I. A., and Harakal, J. E., 1974, Potassium-Argon dating of blueschists from the Pinchi Lake, central British Columbia: Canadian Journal of Earth Science, v. 11, p. 1007–1011.
Paterson, S. R., and Sample, J. C., 1988, The development of folds and cleavage in slate belts by underplating in accretionary complexes: A comparison of the Kodiak Formation, Alaska and the Calavaras Complex, California: Tectonics, v. 7, p. 859–874.
Patton, W. W., Jr., and Box, S. E., 1989, Tectonic setting of the Yukon-Koyukuk basin and its borderlands, western Alaska: Journal of Geophysical Research, v. 94, p. 15807–15820.
Peacock, S. M., 1988, Inverted metamorphic gradients in the westernmost cordillera, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 953–975.
Perfit, M. R., and Heezen, B. C., 1978, The geology and evolution of the Cayman Trench: Geological Society of America Bulletin, v. 89, p. 1155–1174.
Pessagno, E. A., Jr., and Blome, C. D., 1990, Implications of new Jurassic stratigraphic, geochronometric, and paleolatitudinal data from the western Klamath terrane (Smith River and Roque Valley subterranes), Geology, v. 18, p. 665–668.
Pessagno, E. A., Jr., Longoria, J. F., Macleod, N., and Six, W. M., 1987, Upper Jurassic (Kimmeridgian–Upper Tithonian) Pantanellidae from the Taman Formation, east-central Mexico: Tectonostratigraphic, chronostratigraphic, and phylogenetic implications: Cushman Foundation for Foraminiferal Research Special Publication 23, Part 1, p. 1–51.
Peterman, Z. E., Hedge, C. E., Coleman, R. G., and Snavely, P. D., Jr., 1967, $^{87}Sr/^{86}Sr$ ratios in some eugeosynclinal sedimentary rocks and their bearing on the origin of granitic magma in orogenic belts: Earth and Planetary Science Letters, v. 2, p. 433–439.
Philippot, P., and van Roermund, H. L. M., 1992, Deformation processes in eclogitic rocks: Evidence for the rheological delamination of the oceanic crust in deeper levels of subduction zones: Journal of Structural Geology, v. 14, p. 1059–1077.
Pindell, J. L., and Barrett, S. F., 1990, Geological evolution of the Caribbean region; A plate-tectonic perspective, *in* Dengo, G., and Case, J. E., eds., The Caribbean region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. H, p. 405–432.
Pitcher, W. S., 1979, The nature, ascent and emplacement of granitic magmas: Journal of the Geological Society of London, v. 136, p. 627–662.
Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., 1985, Magmatism at a plate edge: The Peruvian Andes: London, Blackie, 328 p.
Plafker, G., 1987, Regional geology and petroleum potential of the northern Gulf of Alaska continental margin, *in* Scholl, D. W., Grantz, A., and Vedder, J. G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins: American Association of Petroleum Geologists Circum-Pacific Earth Science Series, no. 6, p. 229–268.
Plafker, G., Nokleberg, W. J., and Lull, J. S., 1989, Bedrock geology and tectonic evolution of the Wrangellia, Peninsular, and Chugach terranes along the trans-Alaska crustal transect in the Chugach Mountain and southern Copper River Basin, Alaska: Journal of Geophysical Research, v. 94, p. 4255–4295.
Platt, J. P. 1975, Metamorphic and deformational processes in the Franciscan Complex, California—Some insights from the Catalina schist terrane: Geological Society of America Bulletin, v. 86, p. 1337–1347.
Platt, J. P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037–1053.
Potter, C. J., 1985, Significance of Mesozoic and Eocene deformation in the Bridge River terrane, SW British Columbia: Geological Society of America Abstracts with Programs, v. 17, no. 6, p. 401.
Powell, R. E., 1993, Balanced palinspastic reconstruction of pre-late Cenozoic paleogeology, southern California: Geologic and kinematic constraints on evolution of the San Andreas fault system, *in* Powell, R. E., Weldon, R. J., II, and Matti, J. C., eds., The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution: Geological Society of America Memoir 178, p. 1–106.
Price, R. A., 1981, The Cordilleran foreland thrust and fold belt in the southern Rocky Mountains, *in* McClay, K. R., and Price, N. J., eds., Thrust and nappe tectonics: Geological Society of London Special Publication 9, p. 427–448.
Price, R. A., and Carmichael, D. M., 1986, Geometric test for Late Cretaceous–Paleogene intracontinental transform faulting in the Canadian Cordillera: Geology, v. 14, p. 468–471.
Rangin, C., Girard, D., and Maury, R., 1983, Geodynamic significance of Late Triassic to Early Cretaceous volcanic sequences of Vizcaino Peninsula and Cedros Island, Baja California, Mexico: Geology, v. 11, p. 552–556.
Rea, D. K., and Duncan, R. A., 1986, North Pacific plate convergence: A quantitative record of the past 140 m.y.: Geology, v. 14, p. 373–376.
Reeve, S. C., and Helsley, C. E., 1972, Magnetic reversal sequence in the upper portion of the Chinle Formation, Montoya, New Mexico: Geological Society of America Bulletin, v. 83, p. 3795–3812.
Reyners, M., and Coles, K. S., 1982, Fine structure of the dipping seismic zone and subduction mechanics in the Schumagin Islands, Alaska: Journal of Geophysical Research, v. 87, p. 356–366.
Reynolds, S. J., Florence, F. P., and Trapp, R. A., 1986, Migration patterns of post-40–Ma magmatism in Arizona: Arizona Bureau of Geology and Mineral Technology Open-File Report 86-6, 23 p.
Reynolds, S. J., Spencer, J. E., Asmerom, Y., DeWitt, E., and Laubach, S. E., 1989, Early Mesozoic uplift in west-central Arizona and southeastern California: Geology, v. 17, p. 207–211.
Richards, M. A., and Engebretson, D. C., 1992, Large-scale mantle convection and the history of subduction: Nature, 355, p. 437–440.
Richardson, R. M., Solomon, S. C., and Sleep, N. H., 1979, Tectonic stress in the plates: Reviews of Geophysics and Space Physics, v. 17, p. 981–1019.
Richardson, R. M., and Cox, B. L., 1984, Evolution of oceanic lithosphere: A driving force study of the Nazca plate: Journal of Geophysical Research, v. 89, p. 10043–10052.
Ricketts, B. D., Evenchick, C. A., Anderson, R. G., and Murphy, D. C., 1992, Bowser basin, northern British Columbia: Constraints on the time of initial subsidence and Stikinia-North America terrane interactions: Geology, v. 20, p. 1119–1122.
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, Arizona: Journal of Geophysical Research, v. 102, p. 1114–1135.
Robertson, W. A., 1967, Manicouagan, P. Q., paleomagnetic results: Canadian Journal of Earth Science, v. 4, p. 641–649.
Rodgers, D. W., Hackett, W. R., and Ore, H. T., 1990, Extension of the Yellowstone plateau, eastern Snake River plain, and Owyhee plateau: Geology, v. 18, p. 1138–1141.
Roeske, S. M., Mattinson, J. M., and Armstrong, R. L., 1989, Isotopic ages of glaucophane schists on the Kodiak Islands, southern Alaska, and their implications for the Mesozoic tectonic history of the Border Ranges fault system: Geological Society of America Bulletin, v. 101, p. 1021–1037.
Ross, T. M., Luyendyk, B. P., and Haston, R. B., 1989, Paleomagnetic evidence

for Neogene clockwise tectonic rotations in the central Mojave Desert, California: Geology, v. 17, p. 470–473.

Rubie, D. C., 1984, A thermal-tectonic model for high-pressure metamorphism and deformation in the Sesia zone, Western Alps: Journal of Geology, v. 92, p. 21–36.

Rubin, C. M., Saleeby, J. B., Cowan, D. S., Brandon, M. T., and McGroder, M. F., 1990, Regionally extensive mid-Cretaceous west-vergent thrust system in the northwestern Cordillera: Implications for continent-margin tectonism: Geology, v. 18, p. 276–280.

Sacks, P. E., and Secor, D. T., Jr., 1990, Delamination in collisional orogens: Geology, v. 18, p. 999–1002.

Sager, W. W., 1984, Paleomagnetism of Abbott Seamount and implications for the latitudinal drift of the Hawaiian hot spot: Journal of Geophysical Research, v. 89, p. 6271–6284.

Sager, W. W., 1987, Late Eocene and Maastrichtian paleomagnetic poles for the Pacific plate: Implications for the validity of seamount paleomagnetic data: Tectonophysics, 144, p. 301–314.

Sager, W. W., and Bleil, U., 1987, Latitudinal shift of Pacific hotspots during the late Cretaceous and early Tertiary: Nature, 326, p. 488–490.

Sager, W. W., and Keating, B. H., 1984, Paleomagnetism of Line Islands seamounts: Evidence for Late Cretaceous and early Tertiary volcanism: Journal of Geophysical Research, v. 89, p. 11135–11151.

Sager, W. W., and Pringle, M. S., 1988, Mid-Cretaceous to early Tertiary apparent polar wander path of the Pacific plate: Journal of Geophysical Research, v. 93, p. 11753–11771.

Saleeby, J. B., 1981, Ocean floor accretion and volcanoplutonic arc evolution of the Mesozoic Sierra Nevada, *in* Ernst, W. G., ed., The geotectonic development of California; Rubey Volume I: Englewood Cliffs, New Jersey, Prentice-Hall, p. 132–181.

Saleeby, J. B., 1982, Polygenetic ophiolite belt of the California Sierra Nevada: Geochronological and tectonostratigraphic development: Journal of Geophysical Research, v. 87, p. 1803–1824.

Saleeby, J., 1990, Geochronological and tectonostratigraphic framework of Sierran-Klamath ophiolitic assemblages, *in* Harwood, S. S., and Miller, M. M., eds., Paleozoic and early Mesozoic paleogeographic relations; Sierra Nevada, Klamath Mountains, and related terranes: Geological Society of America Special Paper 255, p. 93–114.

Saleeby, J., 1991, The Cretaceous Sierra Nevada—A transtitching batholitic belt: Geological Society of America Abstracts with Programs, v. 23, p. 94

Saleeby, J., Harper, G. D., Snoke, A. W., and Sharp, W. D., 1982, Time relations and structural-stratigraphic patterns in ophiolite accretion, west central Klamath Mountains, California: Journal of Geophysical Research, v. 87, p. 3831–3848.

Sandiford, M., Martin, N., Zhou, S., and Fraser, G., 1991, Mechanical consequences of granite emplacement during high-T, low-P metamorphism and the origin of "anticlockwise" PT paths: Earth and Planetary Science Letters, v. 107, p. 164–172.

Savostin, L. A., Sibuet, J.-C., Zonenshain, L. P., LePichon, X., and Roulet, M.-J., 1986, Kinematic evolution of the Tethys belt from the Atlantic Ocean to the Pamirs since the Triassic: Tectonophysics, 123, p. 1–23.

Sawlan, M. G., and Smith, J. G., 1984, Petrologic characteristics, age and tectonic setting of Neogene volcanic rocks in northern Baja California Sur, Mexico, *in* Frizzell, V. A., ed., Geology of the Baja California Peninsula: Pacific Section, Society of Economic Paleontologists and Mineralogists 39, p. 237–251.

Schlanger, S. O., Garcia, M. O., Keating, B. H., Naughton, J. J., Sager, W. W., Haggerty, J. A., and Philpotts, J. A., 1984, Geology and geochronology of the Line Islands: Journal of Geophysical Research, v. 89, p. 11261–11272.

Schmidt-Effing, R., 1980, The Huayacocotla aulacogen in Mexico (Lower Jurassic) and the origin of the Gulf of Mexico, *in* Pilger, R. H., Jr., ed., The origin of the Gulf of Mexico and the early opening of the central North Atlantic Ocean: Baton Rouge, School of Geoscience, Louisiana State University, p. 79–86.

Scholl, D. W., Marlow, M. S., MacLeod, N. S., and Buffington, E. C., 1976, Episodic Aleutian ridge igneous activity: Implications of Miocene and younger submarine volcanism west of Buildir Island: Geological Society of America Bulletin, v. 87, p. 547–554.

Scholl, D. W., Vallier, T. L., and Stevenson, A. J., 1983, Geologic evolution of the Aleutian ridge—Implications for petroleum resources: Alaskan Geological Society Journal, v. 3, p. 33–46.

Scholl, D. W., Vallier, T. L., and Stevenson, A. J., 1986, Terrane accretion, production, and continental growth: A perspective based on the origin and tectonic fate of the Aleutian–Bering Sea region: Geology, v. 14, p. 43–47.

Schweickert, R. A., 1978, Triassic and Jurassic paleogeography of the Sierra Nevada and adjacent regions, California and western Nevada, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 361–384.

Schweickert, R. A., and Lahren, M. M., 1987, Continuation of Antler and Sonoma orogenic belts to the eastern Sierra Nevada, California, and Late Triassic thrusting in a compressional arc: Geology, v. 15, p. 270–273.

Schweickert, R. A., Armstrong, R. L., and Harakal, J. E., 1980, Lawsonite blueschist in the northern Sierra Nevada, California: Geology, v. 8, p. 27–31.

Schweickert, R. A., Bogen, N. L., Girty, G. H., Hanson, R. E., and Merguerian, C., 1984, Timing and structural expression of the Nevadan orogeny, Sierra Nevada, California: Geological Society of America Bulletin, v. 95, p. 967–979.

Schweig, E. S., 1989, Basin-range tectonics in the Darwin Plateau, southwestern Great Basin, California: Geological Society of America Bulletin, v. 101, p. 652–662.

Severinghaus, J., and Atwater, T., 1990, Cenozoic geometry and thermal state of the subducting slabs beneath western North America, *in* Wernicke, B. P., ed., Basin and range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 1–22.

Sheridan, R. E., and Gradstein, F. M., eds., 1983, Initial reports of the Deep Sea Drilling Project, Volume 76: Newark Delaware, University of Delaware Department of Geology, 947 p.

Sheriff, S. D., and Shive, P. N., 1980, The Rattlesnake Hills of central Wyoming revisited: Further paleomagnetic results: Geophysical Research Letters, v. 7, p. 589–592.

Shive, P. N., and Frerichs, W. E., 1974, Paleomagnetism of the Niobrara Formation in Wyoming, Colorado, and Kansas: Journal of Geophysical Research, v. 79, p. 3001–3007.

Shive, P. N., and Pruss, E. F., 1977, A paleomagnetic study of basalt flows from the Absaroka Mountains, Wyoming: Journal of Geophysical Research, v. 82, p. 3039–3048.

Shive, P. N., Steiner, M. B., and Huycke, D. T., 1984, Manetostratigraphy, paleomagnetism, and remanence acquisition in the Triassic Chugwater Formation of Wyoming: Journal of Geophysical Research, v. 89, p. 1801–1815.

Silberling, N. J., and Roberts, R. J., 1962, Pre-Tertiary stratigraphy and structure of northwestern Nevada: Geological Society of America Special Paper 72, p. 1–58.

Sillitoe, R. H., 1973, The tops and bottoms of porphyry copper deposits: Economic Geology, v. 68, p. 799–815.

Silver, L. T., Taylor, H. P., Jr., and Chappell, B., 1979, Some petrological, geochemical observations of the Peninsular Ranges batholith near the international border of the U.S.A. and Mexico, *in* Abbott, P. L., and Todd, V. R., eds., Mesozoic crystalline rocks; Peninsular Ranges batholith and pegmatites, Point Sal ophiolite: Geological Society of America Annual Meeting Guidebook: San Diego, California, San Diego State University Department of Geological Sciences, p. 83–110.

Sisson, V. B., and Onstott, T. C., 1986, Dating blueschist metamorphism: A combined $^{40}Ar/^{39}Ar$ and electron microprobe approach: Geochimica et

Cosmochimica Acta, v. 50, p. 2111–2117.
Smedes, H. W., Klepper, M. R., and Tilling, R., I., 1988, Preliminary map of plutonic units of the Boulder batholith, southwestern Montana: U.S. Geological Survey Open-File Report 88-283, scale 1:200,000.
Smith, D. P., 1977, San Juan–St. Francis fault—hypothesized major middle Tertiary right-lateral fault in central and southern California: California Division of Mines and Geology Special Report 129, p. 41–50.
Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems, U.S. Geological Survey Circular 726, p. 58–83.
Smith, T. E., and Noltimier, H. C., 1979, Paleomagnetism of the Newark trend igneous rocks of the north central Appalachians and the opening of the central Atlantic Ocean: American Journal of Science, v. 279, p. 778–807.
Snow, J. K., Asmerom, Y., and Lux, D. R., 1991, Permian-Triassic plutonism and tectonics, Death Valley region, California and Nevada: Geology, v. 19, p. 629–632.
Sobolev, N. V., and Shatskii, V. S., 1987, Inclusions of carbon minerals in garnets of metasomatic rocks: Geologiya i Geofizika, v. 28, p. 77–80.
Souther, J. G., and Symons, D. T. A., 1973, Stratigraphy and paleomagnetism of Mount Edziza volcanic complex, north western British Columbia: Geological Survey of Canada Paper 73-32, p. 1–48.
Speed, R., Elison, M. W., and Heck, F. R., 1988, Phanerozoic tectonic evolution of the Great Basin, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 572–605.
Spencer, J. E., and Normark, W. R., 1979, Tosco-Abreojos fault zone: A Neogene transform plate boundary within the Pacific margin of southern Baja California, Mexico: Geology, v. 7, p. 554–557.
Srivastava, S. P., and Tapscott, C. R., 1986, Plate kinematics of the North Atlantic, *in* Vogt, P. R., and Tucholke, B. E., eds., The western North Atlantic region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. M, p. 379–404.
Steele, W. K., 1971, Paleomagnetic directions from the Iztaccihuatl volcano, Mexico: Earth and Planetary Science Letters, v. 11, p. 211–218.
Steiner, M. B., and Helsley, C. E., 1975, Reversal pattern and apparent polar wander for the Late Jurassic: Geological Society of America Bulletin, v. 86, p. 1537–1543.
Stern, T. W., Bateman, P. C., Morgan, B. A., Newell, M. F., and Peck, D. L., 1981, Isotopic U-Pb ages of zircon from the granitoids of the central Sierra Nevada, California: U.S. Geological Survey Professional Paper 1185, 17 p.
Stewart, J. H., 1988, Tectonics of the Walker Lane Belt, Western Great Basin: Mesozoic and Cenozoic deformation in a zone of shear, *in* Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States; Rubey Volume VII: Englewood Cliffs, New Jersey, Prentice-Hall, p. 683–713.
Stewart, J. H., and Crowell, J. C., 1992, Strike-slip tectonics in the Cordilleran region, western United States, *in* Burchfiel, B. C., Lipman, P. W., and Zoback, M. L., eds., The Cordilleran orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, p. 609–628.
Stock, J., and Hodges, K. V., 1989, Pre-Pliocene extension around the Gulf of California, and the transfer of Baja California to the Pacific plate, Tectonics, v. 8, p. 99–115.
Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates: Tectonics, v. 7, p. 1339–1384.
Stone, D. B., 1989, Paleogeography and rotations of Arctic Alaska—An unresolved problem, *in* Kissel, C., and Laj, C., eds., Paleomagnetic rotations and continental deformation: Boston, Kluwer Academic Publishers, p. 343–364.
Stone, D. B., and McWilliams, M. O., 1989, Paleomagnetic evidence for relative terrane motion in western North America, *in* Ben-Avraham, Z., ed., The evolution of the Pacific Ocean margin: New York, Oxford University Press, p. 53–72.
Stowell, H. H., and Hooper, R. J., 1990, Structural development of the western metamorphic belt adjacent to the Coast Plutonic Complex, southeastern Alaska: Evidence from Holkham Bay: Tectonics, v. 9, p. 391–407.
Struik, L. C., 1988, Crustal evolution of the eastern Canadian Cordillera: Tectonics, v. 7, p. 727–747.
Suppe, J., and Armstrong, R. L., 1972, Potassium-Argon dating of Franciscan metamorphic rocks: American Journal of Science, v. 272, p. 217–233.
Suppe, J., and Foland, K. A., 1978, The Goat Mountain Schists and Pacific Ridge Complex: A redeformed but still-intact Late Mesozoic Franciscan schuppen complex, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 431–451.
Suter, M., 1984, Cordilleran deformation along the eastern edge of the Valles–San Luis Potosi carbonate platform, Sierra Madre Oriental fold-thrust belt, east-central Mexico: Geological Society of America Bulletin, v. 95, p. 1387–1397.
Sutherland Brown, A., ed., 1976, Porphyry deposits of the Canadian Cordillera: Canadian Institute of Mining and Metallurgy, Special Volume 15, 510 p.
Swanson, E. R., and McDowell, F. W., 1984, Calderas of the Sierra Madre Occidental volcanic field western Mexico: Journal of Geophysical Research, v. 89, p. 8787–8799.
Sweeney, J. F., 1985, Comments about the age of the Canada Basin: Tectonophysics, 114, p. 1–10.
Symons, D. T. A., 1969, Paleomagnetism of the late Miocene plateau basalts in the Cariboo region of British Columbia: Geological Survey of Canada Paper 69-43, p. 1–16.
Thorkelson, D. J., Marsden, H., and Mortensen, J. K., 1991, Early Jurassic volcanism north of the Bowser Basin and its role in paired subduction beneath Stikinia: Geological Society of America Abstracts with Programs, v. 23, p. 191.
Till, A. B., 1992, Detrital blueschist-facies metamorphic mineral assemblages in early Cretaceous sediments of the foreland basin of the Brooks Range, Alaska, and implications for orogenic evolution: Tectonics, v. 11, p. 1207–1223.
Tipper, H. W., 1984, The allochthonous Jurassic–Lower Cretaceous terranes of the Canadian Cordillera and their relation to correlative strata of the North American craton, *in* Westermann, G. E. G., ed., Jurassic-Cretaceous biochronology and biogeography of North America: Geological Society of Canada Special Paper 27, p. 113–120.
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 North America: Tucson, Arizona, University of Arizona Press, p. 37–58.
Tobisch, O. T., Saleeby, J. B., and Fiske, R. S., 1986, Structural history of continental volcanic arc rocks, eastern Sierra Nevada, California: A case for extensional tectonics: Tectonics, v. 5, p. 65–94.
Tobisch, O. T., Paterson, S. R., Saleeby, J. B., and Geary, E. E., 1989, Nature and timing of deformation in the Foothills terrane, central Sierra Nevada, California: Its bearing on orogenesis: Geological Society of America Bulletin, v. 101, p. 401–413.
Tosdal, R. M., Haxel, G. B., and Wright, J. E., 1989, Jurassic geology of the Sonoran Desert region, southern Arizona, southeastern California, and northernmost Sonora: Construction of a continental-margin magmatic arc: Arizona Geological Society Digest, v. 17, p. 397–434.
Vallier, T. L., and Brooks, H. C., eds., 1987, Geology of the Blue Mountains region of Oregon, Idaho, and Washington: The Idaho batholith and its border zone: U.S. Geological Survey Professional Paper 1436, 196 p.
Vallier, T. L., Rea, D. K., Dean, W. E., Thiede, J., and Adelseck, C. G., 1981, The geology of the Hess Rise, central North Pacific Ocean, *in* Thiede, J., et al., Initial reports of the Deep Sea Drilling Project, Volume 62, Washington, D.C., U.S. Government Printing Office, p. 1031–1072.
Vandall, T. A., and Palmer, H. C., 1990, Canadian Cordilleran displacement: Paleomagnetic results from the Early Jurassic Hazelton Group, Ter-

rane I, British Columbia, Canada: Geophysical Journal International, v. 103, p. 609–619.

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.

Van Fossen, M. C., and Kent, D. V., 1992, Paleomagnetism of 122 Ma plutons in New England and the mid-Cretaceous paleomagnetic field in North America: True polar wander of large-scale differential mantle motion?: Journal of Geophysical Research, v. 97, p. 19651–19661.

Verma, S. P., and Nelson, S. A., 1989, Isotopic and trace element constraints on the origin and evolution of alkaline and calc-alkaline magmas in the northwestern Mexican volcanic belt, Journal of Geophysical Research, v. 94, p. 4531–4544.

Villien, A., and Kligfield, R. M., 1986, Thrusting and synorogenic sedimentation in central Utah, *in* Peterson, J. A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 281–307.

Vogt, P. R., Taylor, P. T., Kovacs, L. C., and Johnson, G. L., 1979, Detailed aeromagnetic investigation of the Arctic Basin: Journal of Geophysical Research, v. 84, p. 1071–1089.

Vugteveen, R. W., Barnes, A. E., and Butler, R. F., 1981, Paleomagnetism of the Roskruge and Gringo Gulch volcanics, southeast Arizona: Journal of Geophysical Research, v. 86, p. 4021–4028.

Wakabayashi, J., and Deino, A., 1989, Laser probe $^{40}Ar/^{39}Ar$ ages from high grade blocks and coherent blueschists, Franciscan Complex, California: Preliminary results and implications for Franciscan tectonics: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A267.

Walker, J. D., Martin, M. W., Bartley, J. M., and Coleman, D. S., 1990, Timing and kinematics of deformation in the Cronese Hills, California, and implications for Mesozoic structure of the southwestern Cordillera: Geology, v. 18, p. 554–557.

Wallace, W. K., and Engebretson, D. C., 1984, Relationships between plate motions and Late Cretaceous to Paleogene magmatism in southwestern Alaska: Tectonics, v. 3, p. 295–315.

Wang, X., Lion, L. G., and Mao, H. K., 1989, Coesite-bearing eclogite from the Dabie Mountains in central China: Geology, v. 17, p. 1085–1088.

Ward, P. L., 1991, On plate tectonics and the geologic evolution of southwestern North America: Journal of Geophysical Research, v. 96, p. 12479–12496.

Watkins, N. D., Gunn, B. M., Baksi, A. K., York, D., and Ade-Hall, J., 1971, Paleomagnetism, geochemistry, and potassium-argon ages of the Rio Grande de Santiago volcanics, central Mexico: Geological Society of America Bulletin, v. 82, p. 1955–1968.

Wells, R. A., and Coe, R. S., 1985, Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington, implications for mechanisms of tectonic rotation: Journal of Geophysical Research, v. 90, p. 1925–1947.

Wells, R. A., Engebretson, D. C., Snavely, P. D., Jr., and Coe, R. S., 1984, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington: Tectonics, v. 3, p. 275–294.

Wilson, D. S., 1988, Tectonic history of the Juan de Fuca ridge over the last 40 million years: Journal of Geophysical Research, v. 93, p. 11863–11876.

Windom, K. E., Seifert, K. E., and Vallier, T. L, 1981, Igneous evolution of Hess rise: Petrologic evidence from DSDP Leg 62: Journal of Geophysical Research, v. 86, p. 6311–6322.

Winterer, E. L, and Metzler, C. V., 1984, Origin and subsidence of guyots in the Mid-Pacific Mountains: Journal of Geophysical Research, v. 89, p. 9969–9979.

Wirth, K. R., and Bird, J. M., 1992, Chronology of ophiolite crystallization, detachment, and emplacement: Evidence from the Brooks Range, Alaska: Geology, v. 20, p. 75–78.

Witte, W. K., and Kent, D. V., 1989, A middle Carnian to early Norian (~225 Ma) paleopole from sediments of the Newark Basin, Pennsylvania: Geological Society of America Bulletin, v. 101, p. 1118–1126.

Woodsworth, G. J., and Monger, J. W. H., 1992, The coastal belt, *in* Gabrielse, H., and Yorath, C. J., eds., Upper Jurassic to Paleogene assemblages, *in* Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, no. 4, p. 352–354 (*also* Geological Society of America, The Geology of North America, v. G-2).

Woodsworth. G. J., Anderson, R. G., and Armstrong, R. L., 1992, Plutonic regimes, *in* Gabrielse, H., and Yorath, C. J., eds., Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, no. 4, p. 491–532 (*also* Geological Society of America, The Geology of North America, v. G-2).

Worral, D. M., 1981, Imbricate low-angle faulting in uppermost Franciscan rocks, South Yolla Bolly area, northern California: Geological Society of America Bulletin, v. 92, p. 703–729.

Wust, S. L., 1986, Regional correlation of extension directions in Cordilleran metamorphic core complexes: Geology, v. 14, p. 828–830.

Wyld, S. J., 1991, Permo-Triassic tectonism in volcanic arc sequences of the western U.S. Cordillera and implications for the Sonoma orogeny: Tectonics, v. 10, p. 1007–1017.

Yates, R. G., 1968, The Trans-Idaho Discontinuity: Proceedings, Section 1, International Geological Congress, 23rd, Prague: Prague, Academia, p. 117–123.

Yorath, C. J., Sutherland Brown, A., Campbell, R. B., and Dodds, C. J., 1992, The insular belt, *in* Upper Jurassic to Paleogene assemblages, *in* Gabrielse, H., and Yorath, C. J., eds., Geology of the Cordilleran Orogen in Canada: Geological Survey of Canada, no. 4, p. 354–360 (*also* Geological Society of America, The Geology of North America, v. G-2).

Zoback, M. L., Anderson, R. E., and Thompson, G. A., 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range Province of the western United States: Philosophical Transactions of the Royal Society of London, Series A, v. 300, p. 407–434.

Zoback, M. L., McKee, E. H., Blakely, R. J., and Thompson, G. A., 1994, The northern Nevada rift: Regional tectono-magmatic relations and middle Miocene stress direction: Geological Society of America Bulletin, v. 106, p. 371–382.

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