Late Triassic to Earliest Eocene Magmatism in the North American Cordillera: Implications for the Western Interior Basin

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Abstract

Paleozoic and Late Triassic to Late Jurassic accretion of terranes added considerable dimension to western North America and thus protected the continental interior from continental-margin magmatism and its side-effects until late Mesozoic-early Cenozoic time. Late Triassic and Jurassic magmatism in exotic terranes and affecting the outer parts of the miogeosyncline was largely unrecorded in the continental interior. The Triassic and Jurassic magmatic arcs developed on the cratonic platform only in Mexico, southern California and Arizona. Separate Late Triassic and Middle to Late Jurassic magmatic culminations provided significant input of volcanic ash to basins on the craton only in southwestern North America.

The Middle to Late Jurassic magmatic culmination was accompanied by regional metamorphism and deformation in the area of the Mesocordilleran Geanticline, development of an incipient foredeep east of the Geanticline, on top of the Cordilleran miogeosyncline, the first Mesozoic marine incursion (Sundance Sea) into the Western Interior Basin, and the first of two major Mesozoic depositional cycles in the continental interior.

During the Cretaceous and early Cenozoic, only minor reshaping of the continental margin occurred. In Early Cretaceous time, following a widespread lull of magmatic activity, an Andean continental-margin magmatic belt, continuous from Mexico to Alaska, became established: a high temperature batholith belt existed in accreted terranes. High heat flow behind the arc thinned the lithosphere under miogeosynclinal areas. A-type subduction (a consequence of thermally thinned lithosphere and trench-continent convergence) formed fold and thrust belts with thickened crust. A second magmatic belt, most evident in Canada, parallel to the B-subduction-related arc, but chemically and isotopically distinct, was created by melting or bulk assimilation of that thickened crust. Coincident with a worldwide rise of sea level, tectonic loading of lithosphere on the continent side of the A-subduction belt created a broad seaway, ultimately connecting the Gulf of Mexico and the Arctic Ocean. This seaway received sediment from the active orogenic belt and volcanic ash, particularly during the mid- to Late Cretaceous culmination of magmatism.

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[1] R.L. Armstrong passed away in 1991, while this paper was in press.

For a brief time interval at the beginning of this second magmatic culmination, thermal uplift of the maturely eroded Mesocordilleran Geanticline shed coarse sediment across the future foredeep site. Soon thereafter, development of the foredeep sediment trap, close to thrust ramps, prevented further transport of coarse material far across the Western Interior Basin. The distinctive and widespread coarse-clastic Cadomin-Kootenai-Dakota deposits can thus be explained by the linkage of cause and effect in the reactivated orogenic belt. Heating and uplift must precede thrusting and foredeep development, so a sediment source is activated before the sediment trap is effective.

About 80 million years (m.y.) ago, a dramatic cessation of magmatic activity occurred between latitudes 32°N and 47°N, forming the Laramide magmatic gap. Soon thereafter, and at the same latitudes, thick-skinned Laramide tectonics disrupted the Western Interior Basin opposite the magmatic gap. A change to sub-horizontal subduction with absence of the mantle wedge has been inferred by others. At the same time, the earlier Cretaceous magmatic-tectonic patterns persisted to the north and south of the magmatic gap, although magmatism in those areas was somewhat reduced in volume and extent, and the thin-skinned thrust belt continued its eastward migration. The western edge of the Western Interior Basin underwent tectonic imbrication, while subsidence and sediment accumulation continued within the Basin.

Beginning 55 m.y. ago, approximately the beginning of the Eocene, the Mesozoic magmatic-tectonic patterns were suddenly extinguished and replaced by a new regime: magmatic quiescence and waning Laramide basement uplift and basin subsidence south of 42°N, and volcanism and crustal extension across the deformed belt north of 42°N (accompanying rapid subduction of the Vancouver Plate). At this time, convergence (A-subduction) in the northern Rocky Mountains ceased abruptly and consequently subsidence and filling of the Western Interior Basin ended.

Résumé

Les accrétions de terrains du Paléozoïque et de la période allant de la fin du Trias jusqu'à la fin du Jurassique ont considérablement accru les dimensions de l'ouest de l'Amérique du Nord et ont ainsi protégé l'intérieur du continent, jusqu'à une périod allant de la fin du Mésozoïc au début de l'ère Tertiaire, du magmatisme se produisant le long des continents ainsi que de ses effets secondaires. On a rarement détecté dans l'intérieur continental le magmatisme qui s'est produit au cours du Trias et du Jurassique dans les terraines exotiques, affectant aussi les bords du miogéosynclinal. Les arcs de magmatism du Trias et du Jurassique ne se sont formés sur le bouclier cratonique qu'au Mexique, dans le sud de la Californie et en Arizona. C'est seulement dans le sud-ouest de l'Amérique du Nord que des poussés distinctes de magma, à la fin du Trias et dans le Jurassique moyen et supérieur, ont apporté d'abondantes cendres volcaniques dans les bassins du bouclier.

La poussée de magma du Jurassique moyen et supérieur s'est accompangée de déformation et de métamorphisme locaux dans la région du Géanticlinal de la Méso-Cordillère, de la formation d'un début d'avant-fosse à l'est du géanticlinal, sur le miogéosynclinal de la cordillière, de la première pénétration de la mer au Mésozoïque (mer Sundance) dans le Bassin Occidental Interne et du premier des deux cycles sédimentaires majeurs du Mésozoïc.

Au cours du Crétace et du début de l'ère Tertiaire la bordure continental s'est peu transformée. Au début du Crétacé, à la suite d'une accalmie presque générale du magmatisme, une zone andine de magmatisme s'est établie le long du continnet, allant du Mexique à l'Alaska, une zone de batholite à haute température existant dans les terrains accrétés. Le flot de chaleur derrière l'arc a amemuisé la lithosphère sous les régions du miogéosynclinal. Une subduction de type A, due à l'amenuisement de la lithosphère créé par la chaleur et au rapprochment de la fosse et du continent, a formé des zones orogéniques et de charriage à l'écorce épaisse. Une seconde zone de magmatisme, qui se voit surtout au Canada, s'est créé parallélement à l'arc apparenté à la subduction de type B mais distincte par composition chimique et ses isotopes, quand se sont produites fonte ou assimilation en masse de cette écorce épaisse.

Au moment d'une hausse générale du niveau de la mer à travers le monde, le chargement tectonique de la lithosphère sur la partie continentale de la zone de subduction de type A a créé un large détroit qui a fini par relier le Golf du Mexique à l'Océan Arctique. Ce détroit a reçu, en particulier au cours de la poussée de magma du Crétacé moyen et supérieur, cendres volcaniques et sédiments venus de la zone orogénique active.

Dans un court espace de temps au début de cette deuxième poussée de magma, le soulèvement thermique du Géanticlinal de la Méso-Cordillère, arrivé à maturité par l'effect de l'érosion, a déversé des sédiments grossiers à l'emplacement de l'avant-fosse à venir. Peu aprés, la formation de la trappe à l'arrivée de la matière grossiere qui s'était avancée profondément à l'intérieur du Bassin Interne Occidental. Les sédiments clastiques grossiers (Cadomin-Kootenai-Dakota) très répandus et facilement reconnaissables peuvent donc s'expliquer par la relation de cause à effet dans la zone orogénique réactivée. Hautes températures et soulèvement doivent précéder charriage et formation de l'avant-fosse. La source de sédiments s'active donc avant que la trappe à sediments ne fonctionne.

Il y a quelque 80 m.a. un arrêt extraordinaire de l'activité du magma s'est produit entre les 32ᵉ et 47ᵉ degrés de latitude et représente la discontinuité de magmatisme laramienne. Peu après, aux mêmes latitudes, la tectonique laramienne agissant sur l'écorce épaisse a perturbé le Bassin Interne Occidental situé en face de la zone de discontinuité de magmatisme. On a parlé de subduction à angle faible où le coin du manteau terrestre serait absent. Les mouvements tectoniques et de magma de la période Crétacée précédente ont continué durant cette période au nord et au sud de la zone de discontinuité de magmatisme, quoique l'activité du magma dans ces régions ait été de moindre volume et de moindre étendue; la zone de charriage à écorce mince a poursuivi sa migration vers l'est. À l'ouest, le bord du Bassin Interne Occidental a été soumis à un chevauchement tectonique tandis que l'affaisement et l'accumulation de sédiments se poursuivaient à l'intérieur de bassin.

Il y a 55 m.a., à peu près au début de l'Éocène, l'activité tectonique et magmatique du Mésozoïque a soudain cessé et un nouveau régime a pris place: au sud du 42e degré, le magma s'est apaisé, le soulèvement du soubassement laramien et l'affaissement du bassin s'est affaibli; au nord du 42e degré, le volcanisme s'est accru et l'écorce s'est étendue dans la zone déformée (s'accompagnant d'une subduction rapide de la plaque de Vancouver). À ce moment le rapprochement (la subduction de type A) dans le nord des Montagnes Rocheuses s'est arrêté abruptement, mettant fin à l'affaissement et au remplissage du Bassin Interne Occidental.

INTRODUCTION

The coincidence of magmatism, orogenesis and high sea level in western North America (Fig. 1) has received considerable attention in recent years (*e.g.*, Kauffman, 1984, 1985). In this review, we take a fresh look at the Cordilleran magmatic story, starting from basic data to produce a description of the space and time distribution of magmatism from approximately the Mexican border to the Alaska-Yukon boundary (Fig. 2). The essence of this contribution is a series of maps (Figs. 3 to 8) showing areas of magmatic activity during specific time intervals that are more complete and accurate than any previous offerings. The time divisions used are, for the most part, distinct breaks between culminations of magmatic activity. They are natural turning points in the magmatic history derived from review of geochronometric and stratigraphic data.

What we present here is a development from previous regional syntheses. Damon and Mauger (1966) were among the first to identify distinct magmatic episodes in the Basin and Range Province. Evernden and Kistler (1970), Kistler *et al.* (1971) and Kistler (*e.g.*, 1978) defined multiple brief (10-15 m.y. long) episodes of Mesozoic magmatism in California and western Nevada, but the details of their chronology have changed somewhat as further work filled in some of the gaps they recognized. Gilluly (1973) claimed there was a continuum of magmatism in the western United States from about 200 Ma to the present, with an Oligocene maximum due to sampling bias; he felt that distinct magmatic episodes were only a local phenomenon. Lanphere and Reed (1973) noted the episodic character of magmatism in different regions and showed broad later Jurassic and mid-Cretaceous and early Cenozoic culminations of activity in areas scattered along western North America. Armstrong and Suppe (1973) and Armstrong *et al.* (1977) published maps and histograms showing the distribution of age determinations of Mesozoic plutons in the western United States, based on new data and reviews of literature cited in those papers. Snyder *et al.* (1976) and Cross and Pilger (1978a) reviewed Late Cretaceous and Cenozoic magmatic patterns in the U.S. and emphasized loci of persistent activity and time transgressive patterns in the Cenozoic. Armstrong (1988) reviewed the Mesozoic to early Cenozoic magmatic history of western Canada and cited earlier studies and reviews of that region. The Canadian part of this review is derived largely from that publication. Woodsworth *et al.* (1991) review the plutonic history of the Canadian Cordillera with more emphasis on plutonic suites and their chemistry.

For many years, the United States Geological Survey has been building RADB, a Radiometric Age Data Bank (Zartman *et al.*, 1976). Coverage has gradually accumulated state by state and, recently, Ward (1986, 1991) assembled those files for the entire western U.S. and produced a series of computer-plotted maps showing distribution of dated rocks during a sequence of time intervals, and discussed the observed magmatic history and possible plate tectonic explanations, with particular emphasis on the Cenozoic patterns in the western U.S.

The Canadian Isotopic Date Data File was converted to computer-readable form by Bentzen (1987), with support from the Geological Survey of Canada and British Columbia Ministry of Energy, Mines and Petroleum Resources, during the winter of 1986–87. We became aware of our complementary activities and arranged to merge the two data banks to provide reasonably comprehensive coverage for the entire North American Cordillera between Mexico and Alaska (Fig. 2).

The data presented in this paper represent a five-fold increase in the number of isotopic dates compiled over the last similar synthesis (Snyder *et al.*, 1976), but there are certain necessary disclaimers. The data are not complete for many reasons. The intent of the compilers of RADB was to include only the dates published in major journals with supporting details on techniques, decay constants used, and observed consistency. The Canadian file, in contrast, contains many unpublished, or grey literature, items. Large regions, such as central Idaho and southern California, where major resetting of dates has occurred, are not properly represented in this type of summary. In areas of extensive Cenozoic volcanic cover, such as the U.S. Pacific Northwest and parts of the Canadian Intermontane Belt, older rocks cannot be sampled for dating. Neither file is entirely up-to-date nor complete. For example, the Canadian file on magnetic tape has been updated only to late 1984, did not have unpublished data from universities other than the University of British Columbia or from the Geological Survey of Canada, and was known to be incomplete with respect to dates for ash layers in the Western Interior Basin. The RADB was last updated in 1986. There are unknown amounts of grey literature, unpublished data, and overlooked data that result in incomplete representation of all the information that exists at any time. Probably another 20-30% could be added today to the data collection. Both large files will contain errors and misleading dates. The Canadian file has been fairly heavily edited to flag any dubious result or results giving metamorphic or mixed ages. It is clear from study of the raw

plots that the U.S. file contains many questionable items. These have been assigned to the "ash layer or dubious" category, which are shown as small dots on the maps, when they were recognized during compilation of the figures herein. An effort to bring both files completely up-to-date and to edit them exhaustively would involve years of scholarly work and is beyond the limits of this study. This is thus only a progress report on an unending process of data generation, systematization and synthesis. There are 11,500 age determinations plotted on the maps we prepared spanning the last 230 m.y. of geologic time in the Cordillera. About 50% of those are within the 230-55 Ma time interval we focus on here. The later Cenozoic maps are the topic of another paper (Armstrong and Ward, 1991).

PROCEDURE

From the merged computer files (Ward, 1986; Armstrong, 1988), two series of maps were plotted using Albers equal area conic projections: one from 46°N to 67.5°N (western Canada and adjacent parts of Alaska and the western United States) and the other from 28°N to 50°N (western United States and adjacent parts of Canada and Mexico). One pair of maps was created for each 5 m.y. time interval from 225 Ma to 0 Ma. Only a few dates in the files lie between 225 Ma and 235 Ma and all are located in the shaded areas of Figure 3. On the original plots, distinction was made between dates for intrusive rocks and different types of extrusive rock (mafic, felsic, pyroclastic) and of dates that were no more
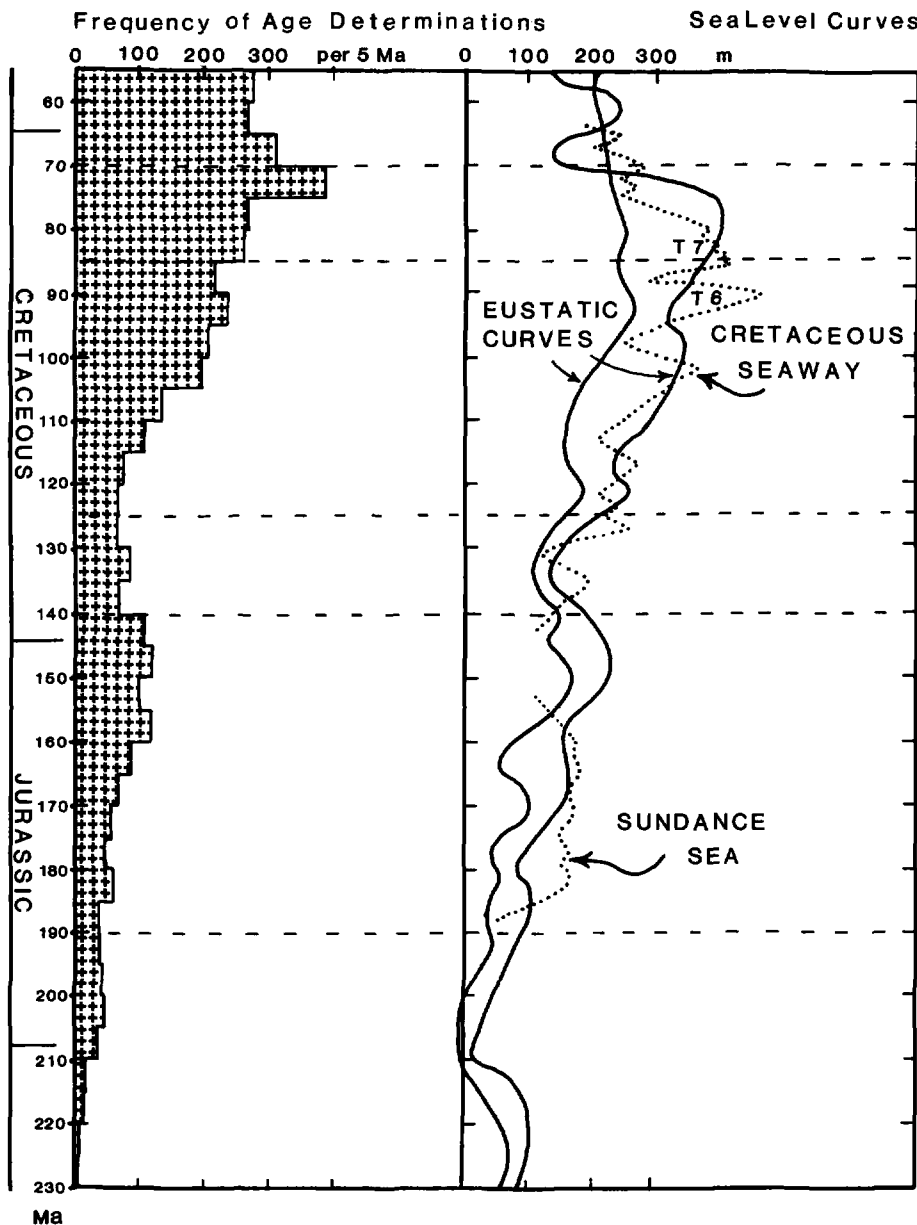

Figure 1. *Comparison of the frequency of isotopic dates between 230 Ma and 55 Ma for magmatic rocks in the North American Cordillera (from RADB and Canadian Cordilleran Isotopic Data File) between the northern border of Mexico and the western border of Yukon Territory, and sea-level curves from several sources. The worldwide eustatic sea-level curves are from Haq et al. (1987) and Hallam (1984) (who gives somewhat higher estimates of eustatic sea-level rise), and show the general agreement on broad trends, but the uncertainty of some details. The Cretaceous seaway transgression-regression curve is modified from Kauffman (1985) and the Sundance Sea curve derived from Imlay (1980).*
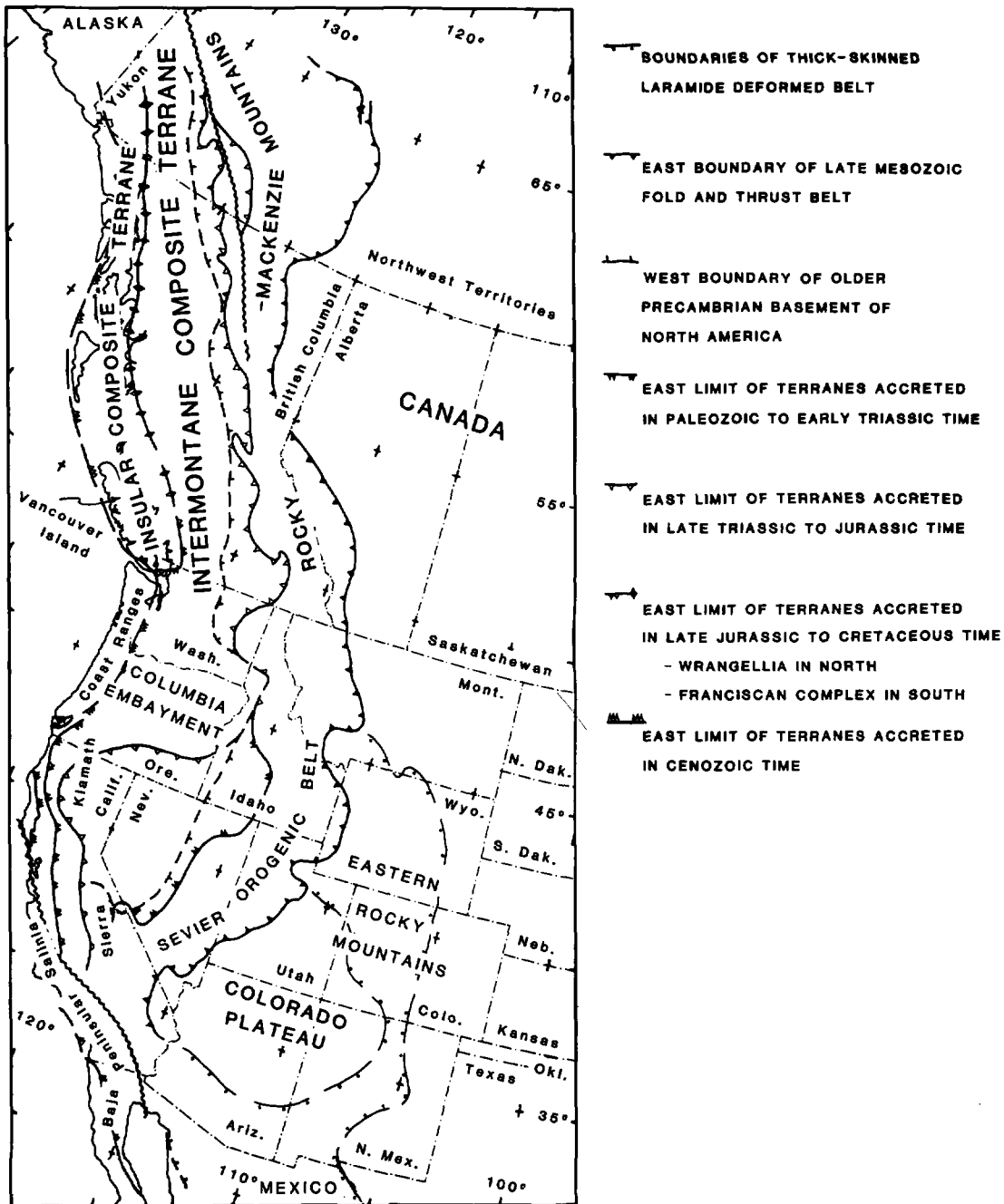
Figure 2. *Tectonic and geographic reference map which forms the base for Figures 3 to 8. The tectonic terrane boundaries are simplified from Monger and Berg (1987) and Silberling et al. (1987). The western boundary of Precambrian basement marks the steep gradient in initial $^{87}Sr/^{86}Sr$ ratios in Mesozoic granitic rocks from values of less than 0.704 (ensimatic Phanerozoic basement) to greater than 0.706 (Precambrian basement) (Armstrong et al., 1977; Kistler, 1983; Armstrong, 1988).*

than minimum or maximum values for the time of emplacement or of dubious significance.

These initial figures were then used to construct histograms and composite time-interval maps to decide what simplified time groupings were meaningful, with distinction based on magmatic lulls or minima and changes in geographic pattern. For the final choice of composite time intervals, a series of maps for the Cordillera between Mexico and Alaska were drafted (Figs. 3 to 8) showing the distribution of magmatism during each time interval. These maps are the basis for the following discussion.

As a general rule, distal ash layers in sedimentary basins have been excluded or reduced in symbol size on the figures. The magmatic belts shown are intended to be the areas where magmatism occurred, not the entire areas into which volcanic products were transported by earth surface processes.

The figures are designed to show not just the extent of magmatism within any time interval, but also the significant changes between and during time intervals. Single-shafted arrows facilitate the comparison of successive figures by showing the movement of magmatic belt boundaries from the previous interval to the one being illustrated. Filled symbols are used to show age determinations in the early part of time intervals and open symbols to show the age determinations in the later part (the last 5-10 m.y.). This allows changes within any interval to be observed directly. These within-interval changes are highlighted by larger outlined arrows. In some cases, the larger arrows are from literature discussions of the magmatic evolution of specific areas. Where open and closed age determination symbols mingle on the maps, magmatism persisted throughout the time interval for the map.

THE COMPOSITE TIME INTERVALS

The time intervals are chosen to encompass discrete episodes of magmatic activity, as far as that is possible (Fig. 1). Some compromise is required in defining times where one episode ends and another begins, particularly when so large an area is involved. Armstrong (1988) placed the times of lull or change in western Canada at 235, 215 (approximately the Triassic-Jurassic boundary), 192, 155, 130, 85, 64 (approximately the Cretaceous-Tertiary boundary) and 55 Ma. Ward (1986) independently chose subdivisions at 220, 185, 149, 120, 77 and 55 Ma for the western United States. In the present study, 230, 190, 140, 125, 85, 70 and 55 Ma are used as punctuation of the magmatic record. The detailed justifications for these breaks will emerge in the discussion of each time interval, but some brief comment is worthwhile at this point. Throughout the discussion, we accept the Decade of North American Geology (DNAG) time-scale calibration (Palmer, 1983) as most up-to-date, accurate and conventional. A revision of the Harland et al. (1982) time scale

(Harland et al., 1990) makes no significant departures from the DNAG Mesozoic scale, in spite of an enlarged data base.

It is interesting and significant that several times of change separating Cordilleran magmatic events coincide with the times of change in plate velocity and direction of plate motion in the Pacific Ocean at 135, 85 and 56 Ma, derived purely from sea-floor magnetic lineations and transform fault orientation data (Engebretson et al., 1984).

A histogram showing frequency of age determinations in 5 m.y. time intervals is shown in Figure 1 and a similar plot of frequency, in 1 m.y. intervals, is presented in Ward (1991), which includes a more detailed discussion of plate motions.

An organized pattern of widespread magmatism, parallel to the continental margin, began in Late Triassic time, at about 230 Ma. Previous magmatism is a separate story. Early Paleozoic orogenic magmatism occurred at various times in "eugeosynclinal" terranes. There was a culmination of magmatism throughout much of the Cordillera in exotic, accreted, pericratonic and miogeoclinal terranes in Devonian-Mississippian time (e.g., Okulitch et al., 1975; Okulitch, 1985; Pell, 1986; Brandon et al., 1986; Saleeby et al., 1987). Late Paleozoic through Middle Triassic magmatism was scattered in distribution, volumetrically modest and, in many cases, on exotic terranes. The coherent Mesozoic pattern began in Late Triassic time, coincident with rifting of North America from Pangea (Hamilton, 1969a; Armstrong and Suppe, 1973).

Late Triassic and Early Jurassic magmatic regions were largely co-extensive, although often differing in character. For our purposes, these times are combined on one map. After about 190 Ma (Toarcian time), major accretion of terranes had been achieved in western Canada (Monger et al., 1982; Monger, 1984) and, in both Canada and the western United States, magmatism spread eastward to engulf previously stable areas with clear long-term links to cratonic North America. Jurassic magmatism culminated at about 160-165 Ma (Chen and Moore, 1982; Wright and Miller, 1986; Armstrong, 1988) and then diminished dramatically, so that by 140 Ma most of the Cordilleran region was quiescent.

The interval 140-125 Ma encompasses a widely recognized magmatic (and tectonic) lull (Bateman, 1983; Armstrong, 1988). The Klamath arc was dead by about 135 Ma (Harper and Wright, 1984; Irwin, 1985); a greatly diminished Sierran arc is documented between 135 Ma and 125 Ma (Chen and Moore, 1982). In Canada-Alaska, the lull at about 140-130 Ma was ended with the beginning of a new Coast Plutonic arc linking the exotic Insular Composite Terrane and terranes attached to North America.

The Mesozoic Andean-type arc of western North America reached its zenith about 90-100 Ma, and significant changes in magmatic patterns began

circa 80 Ma (Coney, 1972; Armstrong and Suppe, 1973; Armstrong, 1974b). In this paper, we often refer to a "mid-Cretaceous" magmatic episode. Our use of mid-Cretaceous is informal and essentially refers to the middle third of Cretaceous time. There is no equivalent time scale or stratigraphic unit that would be a convenient designation for this time interval.

We show two maps between 85 Ma and 55 Ma to capture the transition from "Sierran" to "Laramide" magmatic patterns. Over this interval, there are no Cordillera-wide punctuations by magmatic lulls, but rather notable changes in geographic distribution of magmatism. Maps for several different breakdowns of Late Cretaceous time were prepared, with the ones presented here felt to be the most expressive of the geographic changes in magmatism.

Our review ends abruptly at 55 Ma. This was the beginning of a discrete and spectacular Challis-Absaroka-Kamloops magmatic episode north of 42°N (Armstrong, 1974a) and a sharp reversal from compressional to extensional tectonics in Canada and the northwestern United States (Ewing, 1980). Farther south in the United States, this time marked a reduction in the area affected by Laramide-style basement-cored uplifts and the end of Laramide magmatic patterns (Tweto, 1975; Dickinson *et al.*, 1988). After 55 Ma in the United States south of 42°N, a magmatic-tectonic lull preceded development of complicated Cenozoic time-transgressive magmatic patterns (Damon and Mauger, 1966; Shafiqullah *et al.*, 1980). 55 Ma marked the end of voluminous clastic accumulation in the Western Interior Basin (Spence Taylor *et al.*, 1964; Robinson, 1972). The post 55 Ma magmatism and extensional tectonic pattern north of 42°N is closely linked with an episode of rapid subduction of the Farallon plate (Jurdy, 1984) and particularly of a detached portion called the Vancouver plate (Menard, 1978).

In many recent papers, 40 Ma has been cited as the time of ending of Laramide magmatic-tectonic patterns (Coney, 1971, 1978; Dickinson and Snyder, 1978; Dickinson, 1979; Engebretson *et al.*, 1985), but this is not an accurate view. Plate tectonic events dated at 40-45 Ma correlate with the end of the Challis-Absaroka-Kamloops magmatic activity and conclusion of an extensional-tectonic episode and not with the end of Laramide tectonics, which came at 55 Ma in Canada, Montana and Wyoming, when the breakup of the Farallon plate and extinction or re-organization of the Kula-Pacific boundary occurred (Menard, 1978; Byrne, 1979; Engebretson *et al.*, 1984). South of Wyoming, Laramide-style tectonism appears to have persisted through most of Eocene time (Dickinson *et al.*, 1988) and a 40 Ma termination may have local validity. But by 40 Ma, in Canada and the northwestern United States, the post-Laramide magmatic episode was over and the southward volcanic transgression into Nevada and Utah had begun (Armstrong, 1974a).

THE ANATOMY OF A MAGMATIC EVENT

Mesozoic continental-margin magmatism in the Cordilleran region appears to have been largely of volcanic arc origin, with only minor complication by magmatism at plate edges, triple junctions and hot spots. Some regions appear to have been unusually persistent or vulnerable to magmatism. Snyder *et al.* (1976) referred to these as persistent magmatic loci. Other areas of similar dimension are notably non-magmatic; these will be referred to later as "cold spots".

Most enigmatic is near-trench magmatism such as occurred in the Gulf of Alaska at about 50-60 Ma (Marshak and Karig, 1977; Hudson *et al.*, 1979; Hill *et al.*, 1981; Moore *et al.*, 1983) and on Vancouver Island *circa* 50-55 Ma (Carson, 1973; Woodsworth *et al.*, 1991). This magmatism has been variously rationalized as subducted ridge (Hill *et al.*, 1981; Moore *et al.*, 1983; Forsythe and Nelson, 1985), end of subduction (Hudson *et al.*, 1979), plate-edge effect (Armstrong *et al.*, 1985), or triple junction effect (Dickinson and Snyder, 1979; Johnson and O'Neil, 1984), but no explanation seems completely satisfactory. But for discussion of Cordilleran North America during the Mesozoic, the ordinary steep-subduction Andean-arc model seems most applicable as an explanation for magmatism (Hamilton, 1969a,b; Burchfiel and Davis, 1975; Dickinson, 1981).

The review of Canadian magmatism by Armstrong (1988) showed that a typical arc-magmatic event could be subject to a number of generalizations. Many are general knowledge (Gill, 1981; Thorpe and Francis, 1979). Geographic distribution of arc magmatism is in elongate belts, parallel to the continent margin, with a sharp seaward front (not usually preserved for pre-Cretaceous arcs) and diffuse inland edge. The temporal distribution of isotopic ages is normally distributed or somewhat skewed toward younger ages. Magmatism begins in a narrow belt, close to the magmatic front, then spreads inland at rates on the order of centimetres per year. The magmatic front slowly regresses inland at rates on the order of millimetres per year, with successive arc episodes stepping inland. The end of an episode is often an abrupt event, virtually unresolvable within the conventional precision of isotopic dates.

Magma chemistry varies systematically in time and space: sodic magmas occur near the magmatic front, calc-alkaline magmas occur over much of the width of the magmatic belt, and alkaline or shoshonitic magmas may occur in distal inland areas (Miyashiro, 1974). Early stages tend to be more alkaline or show mixed alkaline and calc-alkaline character than later stages of the same episode or later parts of long multi-episodic histories in the same area. Magma chemistry and isotopic com-

position normally show some reflection of crust type and isotopic character, but mantle-derived magma is predominant (Thorpe and Francis, 1979; Coulon and Thorpe, 1981). Aluminous magmas (especially intrusive rocks with muscovite and garnet) occur in more cratonic areas where thick older basement is present, and generally in areas of thicker crust, and aluminous magmas are especially notable later in a magmatic episode when higher crustal temperatures presumably prevail (Keith, 1978, 1982). Muscovite may be a late-appearing phase, even in ensimatic terranes, after several plutonic-tectonic episodes have built up crustal thickness and temperature (Armstrong, 1988). Alkaline, less crust-contaminated magmas may appear further inland than aluminous magmas of the same age. The local tectonics within magmatic belts, in cases where sufficient volcanic and subvolcanic features are preserved, are commonly extensional (Pitcher, 1978; Sébrier *et al.*, 1985; Smith *et al.*, 1987).

THE CORRELATIONS

Magmatism does not occur in isolation from other geologic processes. One can see the immediate association with subduction and mountain building in modern volcanic arcs. A considerable literature examines the correlation of magmatism and sea level (Hallam, 1963, 1984; Damon and Mauger, 1966; Kistler *et al.*, 1971; Hays and Pitman, 1973; Turcotte and Burke, 1978). There is a direct link at ocean ridges: rapid spreading leads to greater ridge volume which leads to a rise in sea level, with respect to the continents. On a global scale, more rapid sea-floor spreading should be complemented by increased subduction and consequently accelerated magmatism. Magmatism brings heat to shallower levels, thus energizing regional metamorphism and thermally weakening the lithosphere. In the Cordilleran region, magmatism and regional metamorphism go hand in hand (Miyashiro, 1973; Armstrong, 1988; Barton *et al.*, 1988; Miller *et al.*, 1988). Magmatic events begin and accompany periods of crustal shortening or extension (Cross and Pilger 1978a; Davis, 1980), and the logical link is lithosphere weakening by heating, leading to deformation guided by boundary conditions of the weakened lithosphere, and whatever tectonic forces are active at the time.

In a given arc, the amount of magmatism is crudely related to the rate of convergence, but it is also greatly influenced by the angle of descent of the oceanic plate (Gill, 1981; Pilger, 1984; Verplanck and Duncan, 1987). Rapid, but shallow, descent may produce little magma so that rapid convergence is a necessary, but not total, condition for a magmatic episode. Over the last 230 m.y., the amount of magmatism has generally been proportional to the velocity of North America westward with respect to the hot spot reference frame (Engebretson *et al.*, 1985; Armstrong, 1988). Pardo-

Casas and Molnar (1987) have documented the coincidence of rapid convergence and tectonic pulses in the Andes.

A further tectonic linkage is important in the evolution of the Western Interior Basin. When crustal shortening results in tectonic loading of the craton edge with allochthonous masses of rock, the craton lithosphere is flexed elastically, and isostatically depressed, creating a foredeep in which clastic sediments, eroded from the advancing allochthons, may accumulate (Cross and Pilger, 1978b; Monger and Price, 1979; Jordan, 1981). Regional subsidence near foreland belts may be enhanced by the cold slab descending in the mantle beneath the thrust belt and its foredeep basin (Cross and Pilger, 1978b).

Through the linkage between magmatism, thermal weakening of the lithosphere, crustal shortening, tectonic loading and foredeep subsidence, a close correlation of magmatic history and foredeep development is plausible. To the extent that global tectonics links sea level and magmatism, then onset of magmatism, rising sea level, and foredeep subsidence may occur in rapid succession.

Magmatism gives one of the best records of past plate interaction. The usual inference is that subduction beneath continental margins is associated with magmatism (Gill, 1981). But there are qualifications: hot spots can produce magma anytime, anywhere (Burke and Wilson, 1976); sub-horizontal subduction may suppress magmatism; slab windows (Dickinson and Snyder, 1979) may produce uplift-extension and model-volume basaltic or bimodal volcanism (Christiansen and Lipman, 1972); transtension may likewise be associated with magma generation (Gill, 1981); melting of tectonically thickened crust may create aluminous magmas far from the responsible magmatic arc or without an associated arc (LeFort, 1975); and magmatism may occur above descending plate edges and related to triple junctions, as mentioned previously. But for the Mesozoic, more than the Cenozoic, these exceptions seem of minor importance.

If magmatic culminations are thus linked to crustal shortening, their onset will be predictive of foredeep subsidence events, and they will be recorded directly in the foredeep as volcanic ash or sediment from volcanic sources.

THE BUFFER OF
ACCRETED TERRANES

Mid-Paleozoic (Antler), Permo-Triassic (Sonoma) and Early Jurassic accretion added substantial continental crust to the Proterozoic-Paleozoic continental margin of North America (Burchfiel and Davis, 1975; Dickinson, 1981; Monger, 1984). These acquired rocks acted as a buffer, separating the Mesozoic Pacific Ocean from the continental interior, so that impingement of magmatism on indigenous

North American terranes was considerably reduced in extent or delayed. Only along the truncated southern California-Mexico margin (Hamilton, 1969a; Schweichert, 1976) was Triassic to Early Jurassic magmatism able to reach cratonic areas that lay across southernmost California to Arizona. Elsewhere, it was only the Middle to Late Jurassic and mid-Cretaceous magmatic culminations that had sufficient extent to spread beyond accreted terranes into indigenous North American rocks. During most of the Mesozoic, Cordilleran magmatism was confined to the accreted, eugeosynclinal areas, and some of this magmatism occurred before the terranes accreted. The development of a foredeep in the Western Interior Basin was thus delayed 50 m.y. while continental margin tectonic belts migrated cratonward and grew larger, and foredeep development reached its full extent only 100 m.y. after continent-margin subduction and westward drift of North America began.

Without the buffering effect of accreted terranes, foredeep development might have begun much sooner and a more complex, cannibalistic evolution of foredeep basins would have ensued. Moreover, the Mesozoic magmatic belts would have engulfed the stable craton to a much greater extent than actually did occur. Thus, accretion tectonics indirectly, but profoundly, affected the evolution of the Western Interior Basin.

REVIEW OF WESTERN INTERIOR BASIN AND MAGMATIC HISTORY

230 Ma to 190 Ma: Late Triassic and Early Jurassic Time

The data for this time interval was first plotted on two maps, but, upon inspection, it was evident that the magmatic belts were virtually identical and that a single map (Fig. 3) suffices. During this time interval, the Mesozoic Western Interior Basin had not yet begun its development. Deposition patterns of the Cordilleran Geosyncline persisted on the western edge of North America (McKee et al., 1959; Barss et al., 1964). In Canada, siltstone and shale were deposited in an open continental margin sea covering the future site of the Rocky Mountains. A shallow, shrinking, continental margin sea, connected westward with open ocean, likewise existed over Nevada and the future site of the Sevier Orogenic Belt. On the craton, volcanic ash and volcaniclastic muds and shales (Chinle Formation) of the southwestern United States were succeeded by widespread sands (Navajo, Aztec and Nugget formations). Further inland, only red mud and shale record these times (Stanley et al., 1971).

Magmatism occurred on indigenous North American terranes, even within the cratonic platform, only in the far southwest, and was the source for the volcanic sediment transported northeastward into the southern part of the Western Interior Basin.

From central California northward, the magmatic areas were entirely on terranes not yet completely attached to North America. Some, such as the Insular Composite Terrane of Canada-Alaska, may have been located far from their present position in Triassic-Early Jurassic time (Monger, 1984). Other Canadian terranes may have been only a marginal basin away from their eventual resting place (Klepacki, 1985; Klepacki and Wheeler, 1985).

In Canada, the Intermontane Composite Terrane was assembled during this time interval (Monger, 1984). Both Canadian composite terranes were sites of abundant magmatic activity. Much of the Insular Terrane was covered by thick Late Triassic tholeiitic rift/flood basalts with trace element affinities to mid-ocean ridge basalt (MORB) and by Early to Middle Jurassic calc-alkaline arc rocks (Muller, 1977). No chemical polarity has been documented to give any clue to the orientation of this arc. Between Insular and Intermontane terranes lay unknown arcs, platforms and ocean basins that continued to be accreted to the Intermontane Terrane through Jurassic time. The northwestern Intermontane Terrane accumulated a mixture of Late Triassic alkaline and calc-alkaline arc volcanic rocks and plutons succeeded by Jurassic calc-alkaline to alkaline arc rocks which are more alkaline and potassic eastward, toward the craton (which we will refer to as "normal" petrochemical polarity) (Woodsworth et al., 1991). In the southern to southeastern Intermontane Terrane, Triassic to Early Jurassic arc volcanic rocks show a mixed alkaline and calc-alkaline character, but clear normal chemical polarity and an eastward-younging trend (Mortimer, 1987). Similar volcanic and plutonic rocks occur in accreted belts of the Columbia Embayment, Klamath Mountains and Sierra Foothills, but their chemical polarity has not yet been recognized (Mortimer, 1986).

In general, the magmatism of these accreted terranes did not impinge on North America. The Triassic-Jurassic seas marginal to the craton remained largely free of volcanic input due to distance or to effective sediment traps or to transport barriers between magmatically active areas and cratonal North America. Only two granitic plutons intruding indigenous North American rocks in northern Washington and southern British Columbia are old enough to suggest that the magmatic belts lapped onto parts of North America north of southern California before 185 Ma (Miller and Engels, 1975; P. van der Heyden, pers. comm., 1987).

190 Ma to 140 Ma: A Bit More Than Middle and Late Jurassic Time

The second largest of the two Mesozoic magmatic culminations, the second Mesozoic sea-level maximum (Hallam, 1984), and the first development of an interior seaway on North America occurred during the latter part of Jurassic time (McKee et al., 1956; Springer et al., 1964; Peterson, 1972; Imlay, 1984)(Fig. 4). During this time, an elevated sedi-
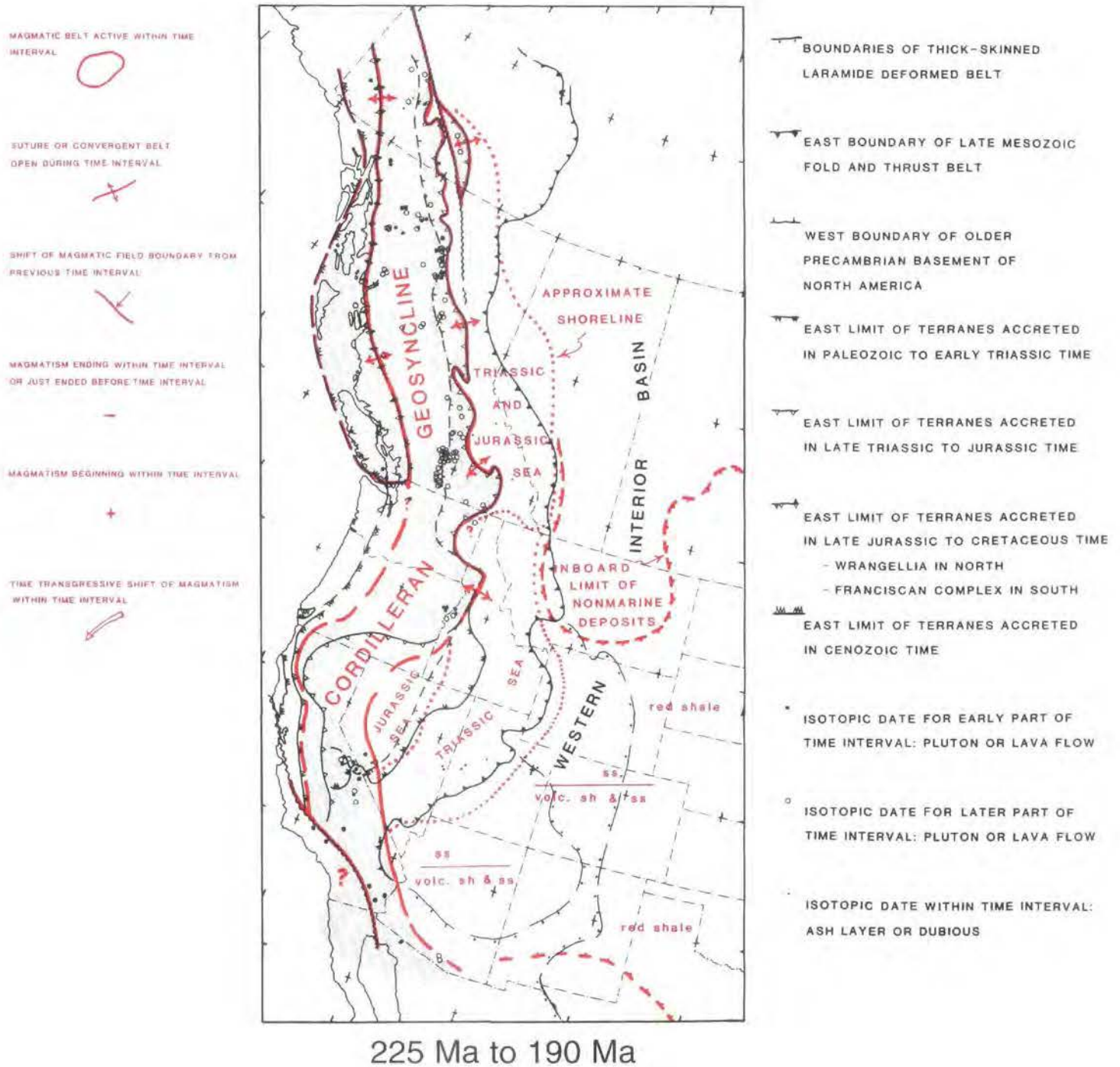
Figure 3. *Magmatic belts and paleogeography at 225 Ma to 190 Ma (Late Triassic and Early Jurassic time: Carnian to Toarcian). Paleogeography derived from McKee et al. (1956, 1959), Barss et al. (1964), Imlay (1980, 1984), Peterson (1972), and Springer et al. (1964).*
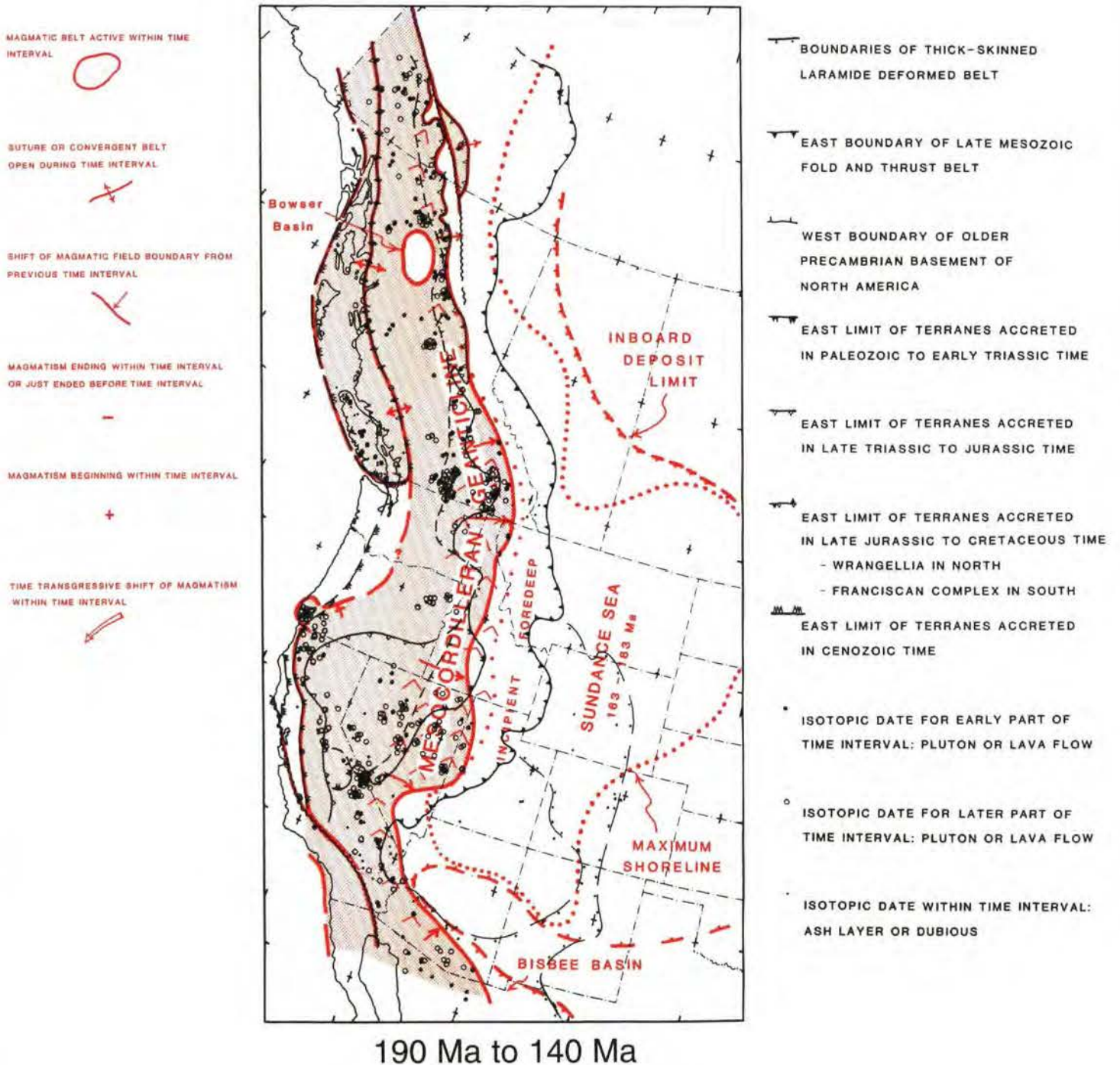
Figure 4. *Magmatic belts and paleogeography at 190 Ma to 140 Ma (slightly more than Middle to Late Jurassic time:* **Toarcian to Berriasian**). *Paleogeography derived from McKee* et al. *(1956), Imlay (1980, 1984), Peterson (1972), Springer* et al. *(1964), and Dickinson* et al. *(1986).*
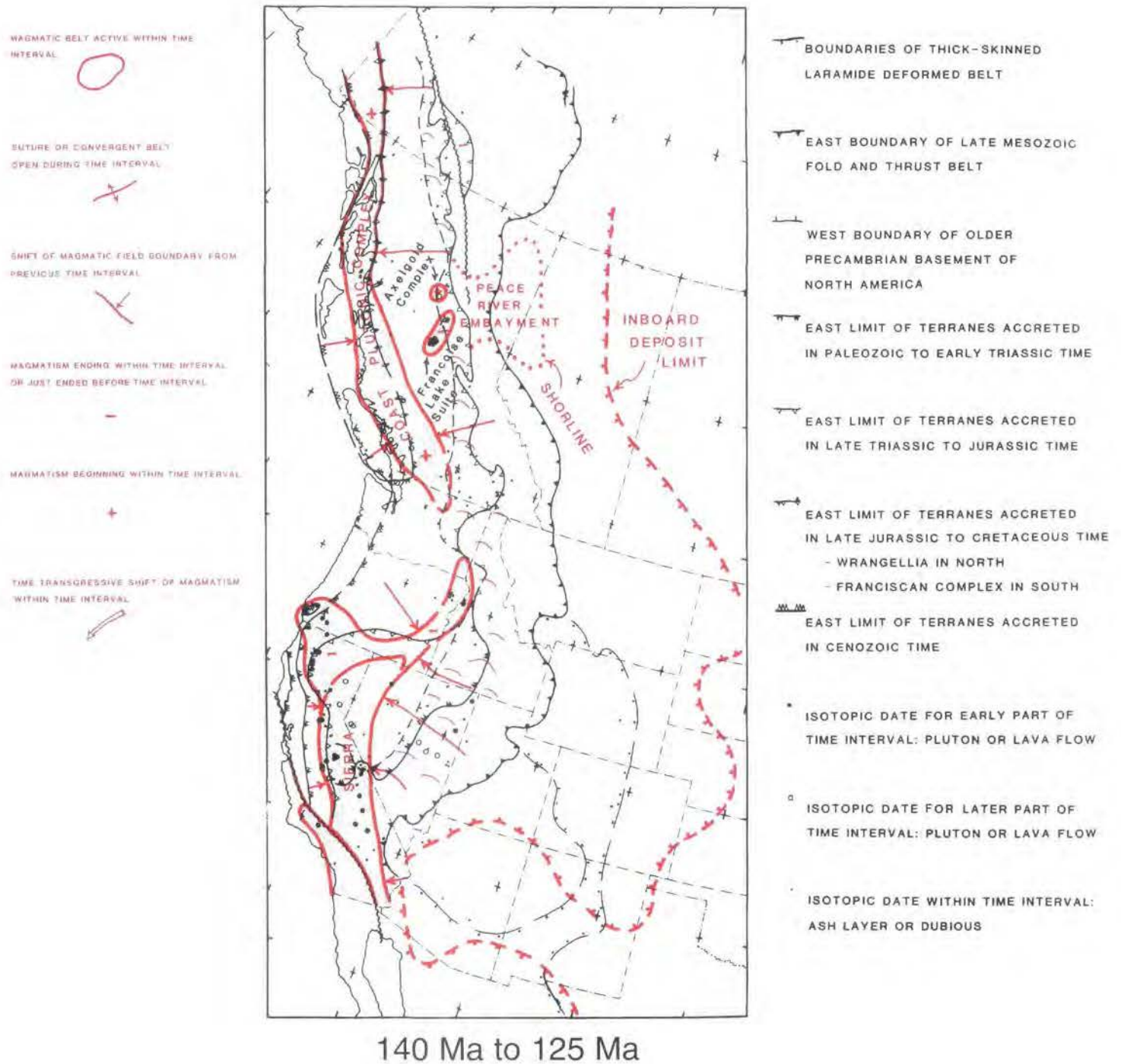
140 Ma to 125 Ma

Figure 5. *Magmatic belts and paleogeography 140 Ma to 125 Ma (Early Cretaceous time:* **Berriasian to Hauterivian**). *Paleogeography derived from McGookey et al. (1972), Williams and Stelck (1975), and Kauffman (1984).*

ment source, the Mesocordilleran Geanticline, extended from southeastern Arizona through central and eastern Nevada, western Idaho and along the Omineca Belt in British Columbia. Sediment shed eastward accumulated in an incipient foredeep, later to be tectonically incorporated into the Cretaceous fold and thrust belt structures. The Sundance Sea, connected only to the Arctic Ocean, expanded over a large part of the craton. Later during this time interval, culmination of uplift and volcanism in the magmatic belt, shown in Figure 4, resulted in deposition of a fluvial clastic unit (Morrison-Kootenay-Minas formations) over the earlier shale, limestone and evaporite of the Sundance Sea. In the United States, this non-marine unit is rich in volcanic ash and reworked volcanic debris. In the Yukon and Northwest Territories, this same stratigraphic interval is occupied by the Ellesmerian sediment cycle with a southerly source (Norris and Yorath, 1981). The first deposition cycle of the Mesozoic Western Interior Basin was comprised of Jurassic to earliest Cretaceous deposits.

Middle Jurassic magmatism expanded from its Early Jurassic distribution eastward into indigenous North American terranes from Arizona to southern Canada. The Insular Composite Terrane may still have lain offshore of North America (Monger, 1984; Tipper, 1984); its eastern and northern parts continued to be magmatically active into Late Jurassic time. Magmatism was calc-alkaline. Complex and extensive Jurassic calc-alkaline arc volcanic fields covered a broad belt along the continental margin from Alaska to Mexico.

Suturing of the Intermontane Composite Terrane to North America occurred at the beginning of this time interval. Middle Jurassic plutons stitch the terranes together in southeastern British Columbia (Parrish and Wheeler, 1983). Tectonic burial and magmatic heat resulted in extensive regional metamorphism and complex histories of overprinted deformation along the length of the Mesocordilleran Geanticline. Late plutons of this episode show the muscovite-garnet signature of crustal melting.

In the Sierra-Klamath region, the culmination of deformation, precisely bracketed by pluton emplacement, is the traditional Nevadan Orogeny, just one episode in a complicated Jurassic history of tectonism and magmatism along the continental margin (Hamilton, 1969a; Harper and Wright, 1984; Irwin, 1985; Ingersoll and Schweickert, 1986).

The accretion of the Insular Composite Terrane to the Intermontane Composite Terrane occurred either at the end of this time interval or during the succeeding magmatic-tectonic lull. This is a controversial point, however. Accretion dates ranging from Middle to Late Jurassic (Tipper, 1984; Potter, 1986) to mid-Cretaceous (Monger et al., 1982) have been proposed by different authorities. But it seems most plausible that this major accretion event would have plugged the Jurassic subduction zone, and been the reason this magmatic-tectonic episode came to an

end. The youngest rocks caught between Insular and Intermontane terranes are Middle Jurassic. The suture is overprinted by the magmatic episode that began in Early Cretaceous time. The end of the Jurassic, possibly earliest Cretaceous time, is also the last possible time for imbrication of the Yukon allochthons onto North American rocks (Tempelman-Kluit, 1979). The imbricate stack is clearly stitched together by mid-Cretaceous plutons. There are hints in transported clasts that the Yukon allochthons were close to North America in Late Triassic time (Tempelman-Kluit, 1979), so the amount of final closure on these structures may have been modest.

Bowser "Cold Spot". A peculiar feature of the magmatic distribution maps for Jurassic and Cretaceous magmatic culminations is the oval-shaped area in northern British Columbia where magmatism did not occur, but Jurassic and Cretaceous sedimentation was fairly continuous. This feature, the Bowser Basin (Eisbacher, 1974, 1977; Tipper and Richards, 1976), persisted from Middle Jurassic to late Cenozoic time as a non-magmatic region. This is in spite of magmatic flareups on all sides at several times. It deserves note as the antithesis of a hot spot. This "cold spot" appears fixed in position in the crust. We observe its presence, but do not venture to explain it here.

140 Ma to 125 Ma: The Early Cretaceous Magmatic Lull

It is rather difficult to find either magmatic or sedimentary rocks of pre-Aptian Early Cretaceous age anywhere in the Cordillera (or throughout the world for that matter) because this was a time of relative magmatic and tectonic quiescence (McGookey et al., 1972; Kauffman, 1984). Sea level was, at the same time, relatively low (Fig. 2) so that, within continental areas, this interval is usually an erosional hiatus. The Western Interior Basin is no exception in that it lay mostly high and dry, with the exception of a Peace River Embayment (Fig. 5), shown connected to the Pacific Ocean on some paleogeographic maps for this time (e.g., Williams and Stelck, 1975). Marine deposition did occur at this time, as well, in deep basins along the continental margin, such as the Great Valley of California.

At the beginning of the Cretaceous, the Mesocordilleran Geanticline remained a subdued sediment source, supplying material to the Lower Gannett-Kootenai-Kootenay-Nikanassin basin.

The Early Cretaceous magmatic lull has been recognized by many authors (Evernden and Kistler, 1970; Lanphere and Reed, 1973; Armstrong and Suppe, 1973; Bateman, 1983; Page and Engebretson, 1984; Ernst, 1984), as beginning in Late Jurassic time, 155-147 Ma, and ending in the Early Cretaceous, about 125-120 Ma, in most discussions. In Canada, few, if any, Jurassic plutons are younger
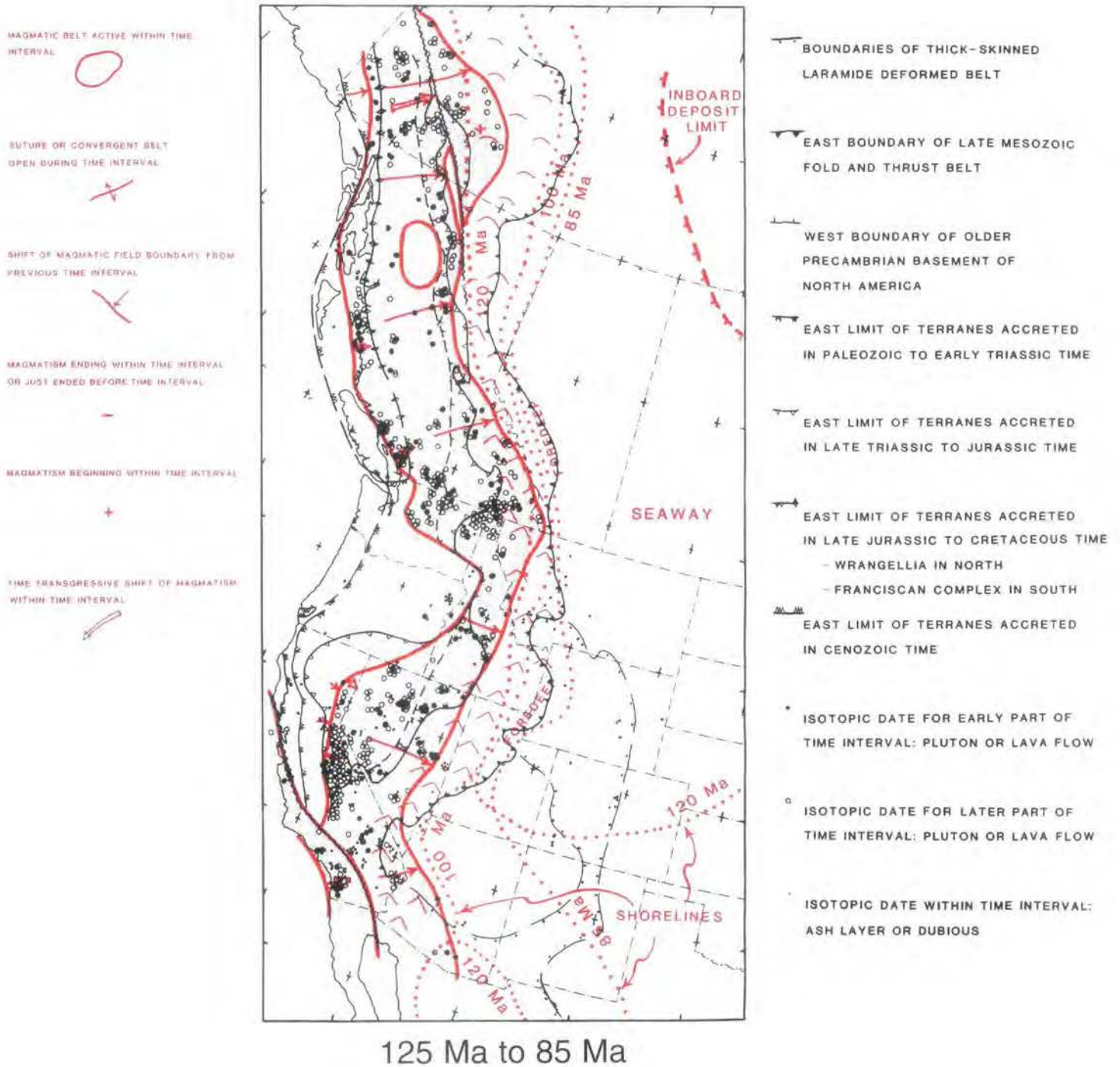
Figure 6. *Magmatic belts and paleogeography 125 Ma to 85 Ma (mid-Cretaceous time:* **Barremian to Santonian***). Paleogeography derived from McGookey et al. (1972), Williams and Stelck (1975), and Kauffman (1984).*

than 155 Ma. The only important exceptions being plutons dated as 140-150 Ma in northwestern British Columbia-Alaska-Yukon region (and possibly in the Coast Plutonic Complex further south) and the Francoise Lake suite at almost exactly 140 Ma in one small area of central British Columbia. In general, Coast Plutonic Complex magmatism began with a distinct resurgence of plutonism at about 130 Ma (oldest zircon dates), and expanded to the culmination of activity at about 100 Ma. The Gravina-Nutzotin and Gambier groups of the Coast Plutonic Complex and Insular Belt contain volcanic rocks that may span the time interval of the magmatic lull, but these groups are not well dated and coeval plutons are not known. The beginning of the mid-Cretaceous magmatic episode in central British Columbia is represented on the map (Fig. 5) by symbols for the Axelgold Complex (130-125 Ma) which is probably related to mafic lavas of the Early Cretaceous Skeena Group (Tipper and Richards, 1976).

In the Klamath Mountains, magmatism died out by approximately 135 Ma, and was extinct for the remainder of the Mesozoic. The Sierra Nevada batholith has few plutons in the 147 Ma to 120 Ma time range (Chen and Moore, 1982; Bateman, 1983). As observed in British Columbia, the rate of magmatism in the Sierra accelerated at about 120-130 Ma, to begin the next major episode. Much of the Jurassic magmatic belt in both Canada and the United States lay quiescent, undergoing erosion over the entire time interval 140 Ma to 125 Ma. Some magmatic debris was transported across the drainage divide of the Mesocordilleran Geanticline to reach the craton (Mudge and Sheppard, 1968).

125 Ma to 85 Ma: The mid-Cretaceous Magmatic Culmination

The greatest Cordilleran magmatic episode, spectacular crustal shortening, and culmination of seaway expansion in the Western Interior Basin occurred in mid-Cretaceous time (Fig. 6). From the Peace River region to central Utah, the subsiding foredeep received sediment from a tectonically active source made up of the Sevier Orogenic Belt, western part of the Canadian Rocky Mountains, and Mackenzie Mountains in the Yukon. Even farther north in Alaska, the Brooks Range appeared as a sediment source about 125 m.y. ago (Molenaar, 1983). The seaway expanded as worldwide sea level rose (Fig. 1)(Hallam, 1984; Haq et al., 1987) and foredeep subsidence increased. Tongues of shallow sea advanced inland from both Arctic and Gulf oceans, eventually merging onto a through-going Western Interior Seaway about 100 m.y. ago, with maximum extent achieved about 90-100 m.y. ago (McGookey et al., 1972; Williams and Stelck, 1975; Kauffman, 1984). Subsequently, tectonism along the western margin and foredeep filling by synorogenic sediment progressively narrowed the seaway. The western

shore migrated irregularly eastward. World sea level remained high from 95 Ma to the end of the Cretaceous (Hancock and Kauffman, 1979; Hallam, 1984).

In Canada and Alaska, magmatism spread from the magmatic front, established about 130 m.y. ago, eastward across the interior into the Omineca Belt. Dual culminations — the Coast Plutonic Belt on the west and Omineca Belt-Selwyn Plutonic Belt to the east — are evident in Canada. The greatest extent of magmatism was reached at about 95-90 Ma, exactly coincident with the maximum Cretaceous sea transgression (T6 of Kauffman, 1984, 1985). Chemical variety was fully developed: sodic to normal calc-alkaline to aluminous to exceptionally alkaline across the magmatic belt at its full development. The extremely radiogenic Sr of the aluminous plutons in the eastern culmination establishes that melting and bulk assimilation of old, tectonically thickened, and magmatically warmed crust was involved in their genesis. The western magmatic front in the Coast Plutonic Complex slowly regressed eastward over this time interval.

The bulk of Peninsular-Salinian-Sierran magmatism occurred during this time interval (Chen and Moore, 1982; Bateman, 1983; Gastil, 1983; Mattinson, 1985). By 120 Ma, the batholith belt was continuous through Idaho, although curiously narrow there. Plutonic rocks of this time interval are abundant across northern Washington and Idaho (Miller and Engels, 1975; Armstrong et al., 1977). Mid-Cretaceous plutons occur scattered across Nevada (Smith et al., 1971), with later plutons distinctive in occurrence of magmatic muscovite (Best et al., 1974; Miller and Bradfish, 1980; Lee et al., 1981, 1986; Kistler et al., 1981; Barton, 1990). A second regional metamorphic and tectonic episode is recognized coincident with this magmatic culmination in California (Labotka et al., 1985), and in eastern Nevada (Miller et al., 1988) and northeastern Nevada-southern Idaho (Snoke and Miller, 1988).

The Sierran magmatic front slowly regressed eastward, as noted for the Coast Plutonic Complex in Canada. The Cretaceous chemical gradient from sodic to more normal calc-alkaline magmas across the Sierra is well documented (Bateman, 1983). The magmatic belt at 40°N was wide, but dual culminations are not evident there, in contrast to the Canadian observations. The difference is not an important one and, in most respects, the two segments of the mid-Cretaceous magmatic belt are quite similar in character.

Volcanic and plutonic clasts, perhaps mostly recycled from Jurassic sources, appear in the southern Canada foredeep in Early Cretaceous time (Norris et al., 1965), but remain largely excluded from the foredeep in the United States at the same time. On the other hand, volcanic ash appeared abundantly in Cretaceous seaway deposits with culminations at 100-90 Ma and at about 85 Ma (Kauffman, 1985).

The mid-Cretaceous magmatic arc was built on North America. The only accretion events during, or after, this episode involve Franciscan, Oregon-
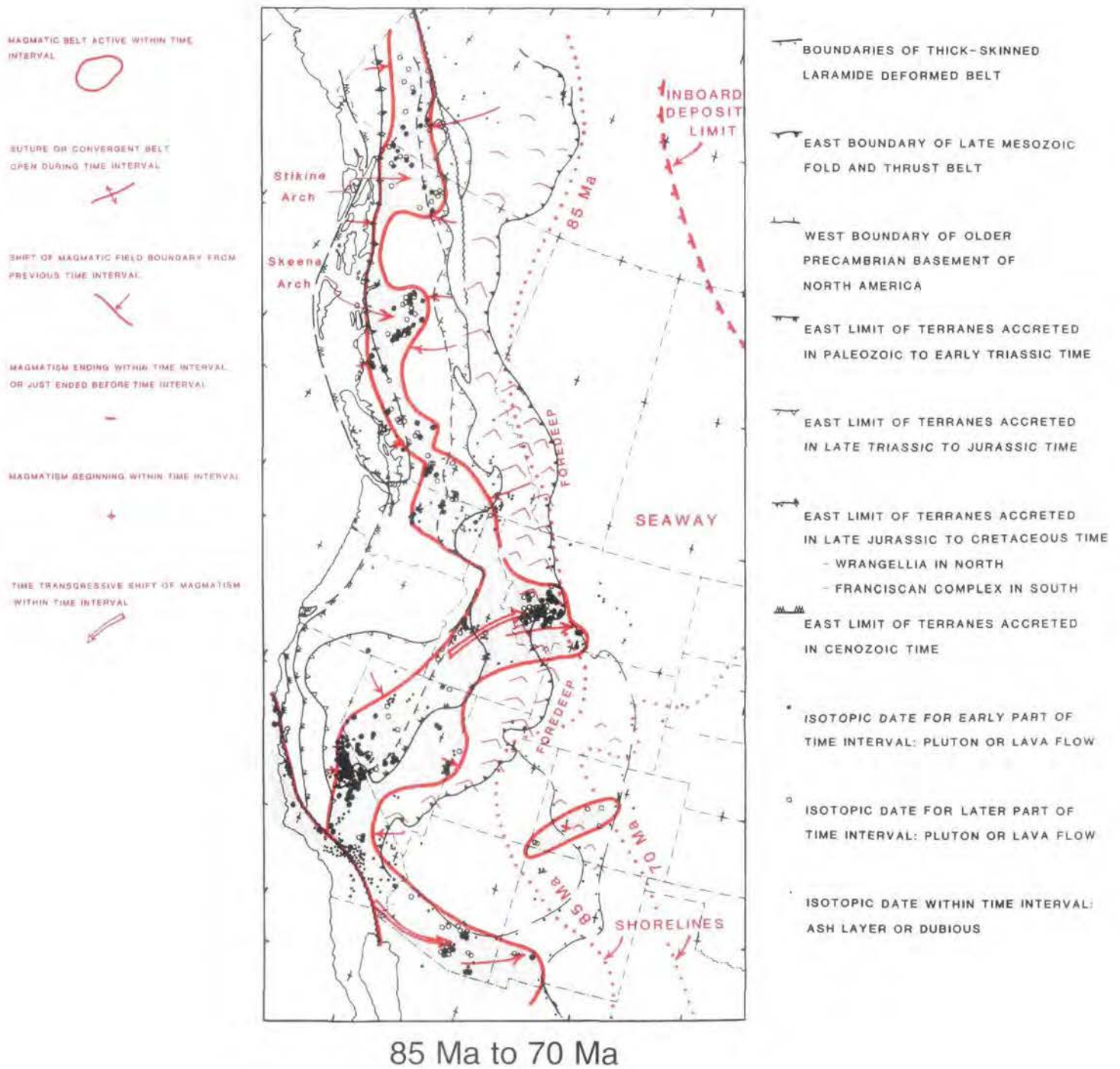
MAGMATIC BELT ACTIVE WITHIN TIME
INTERVAL

SUTURE OR CONVERGENT BELT
OPEN DURING TIME INTERVAL

SHIFT OF MAGMATIC FIELD BOUNDARY FROM
PREVIOUS TIME INTERVAL

MAGMATISM ENDING WITHIN TIME INTERVAL.
OR JUST ENDED BEFORE TIME INTERVAL

MAGMATISM BEGINNING WITHIN TIME INTERVAL

TIME TRANSGRESSIVE SHIFT OF MAGMATISM
WITHIN TIME INTERVAL

Stikine
Arch

Skeena
Arch

85 Ma

INBOARD
DEPOSIT
LIMIT

FOREDEEP

SEAWAY

FOREDEEP

70 Ma

85 Ma

SHORELINES

BOUNDARIES OF THICK–SKINNED
LARAMIDE DEFORMED BELT

EAST BOUNDARY OF LATE MESOZOIC
FOLD AND THRUST BELT

WEST BOUNDARY OF OLDER
PRECAMBRIAN BASEMENT OF
NORTH AMERICA

EAST LIMIT OF TERRANES ACCRETED
IN PALEOZOIC TO EARLY TRIASSIC TIME

EAST LIMIT OF TERRANES ACCRETED
IN LATE TRIASSIC TO JURASSIC TIME

EAST LIMIT OF TERRANES ACCRETED
IN LATE JURASSIC TO CRETACEOUS TIME
   – WRANGELLIA IN NORTH
   – FRANCISCAN COMPLEX IN SOUTH

EAST LIMIT OF TERRANES ACCRETED
IN CENOZOIC TIME

ISOTOPIC DATE FOR EARLY PART OF
TIME INTERVAL: PLUTON OR LAVA FLOW

ISOTOPIC DATE FOR LATER PART OF
TIME INTERVAL: PLUTON OR LAVA FLOW

ISOTOPIC DATE WITHIN TIME INTERVAL:
ASH LAYER OR DUBIOUS

85 Ma to 70 Ma

Figure 7. *Magmatic belts and paleogeography 85 Ma to 70 Ma (Late Cretaceous time:* **Santonian to Maastrichtian**). *Paleogeography derived from McGookey et al. (1972), Williams and Stelck (1975), and Kauffman (1984).*

Washington Coast Range, Metchosin-Leech River, and Baranoff-Chugach areas along the continental margin, all west of the magmatic front. The slow eastern migration of the magmatic front persisted more or less in spite of these additions to the continental margin.

Cretaceous-Paleocene sediments make up the second great cycle of filling of the Mesozoic Western Interior Basin (Kauffman, 1984, 1985). In the far north, the flyschoid Brookian sequence accumulated in a broad foredeep fed from Mackenzie-Brooks Range fold and thrust belt structures from about 110 Ma to 70 Ma (Norris and Yorath, 1981). Sedimentation here lasted to the end of the next time interval discussed in this paper. Overall, there was remarkable tectonic unity through the Cordillera and Western Interior Basin. This argues against Cordilleran tectonic history being a direct consequence of accretion-collision of exotic terranes during this time interval (as proposed by Monger et al., 1982). The continuity of magmatic, tectonic and subsidence history over thousands of kilometres cannot be explained by accretion of particular terranes that affect only a fraction of the continental margin. Dalziel and Forsythe (1985) reaffirm this conclusion in their studies of the southern Andes.

A major unresolved contradiction exists for mid-Cretaceous rocks. Examination of paleomagnetic data suggests that much of British Columbia and panhandle Alaska was at a position south of the Sierra Nevada in mid-Cretaceous time, and interpretation of the data suggests assembly of the Canadian Cordillera from disparate pieces after the middle of the Cretaceous (Irving et al., 1985; Coe et al., 1985; Umhoefer, 1987). Examination of geologic data, however, indicates the existence of a coherent magmatic belt, firmly attached to North America in Yukon and Purcell-Selkirk areas (southeastern British Columbia), at the same time. The magmatic belt appears whole, not duplicated or truncated, with complete and normal chemical polarity, and no identified sutures to separate parts of it from North America, or along which to assemble it from far travelled and in situ pieces. Models that favour the more extreme paleomagnetic inferences (e.g., Umhoefer, 1987) do not appear to be reconcilable with the wealth of geologic data on which most current syntheses are based. Examination of geologic data indicates that hundreds of kilometres of post mid-Cretaceous were translated northward piecemeal or on a grand scale on major strike slip faults (Tipper, 1981; Monger, 1984; Gabrielse, 1985) and intra-arc transcurrent shear zones (Woodsworth et al., 1985, van der Heyden, 1985; Jarrard, 1986). However, leapfrog movements, bringing much of British Columbia thousands of kilometres northward, past the western margin of California after Early Cretaceous time, seem untenable. The paleomagnetic evidence for large displacements of the Composite Intermontane Terrane itself is disputed (May and Butler, 1986). Explanations not involving extreme latitudinal displacements are preferable for the mid-Cretaceous paleomagnetic data.

85 Ma to 70 Ma: An Interval of Transition to Laramide Tectonics

The Arctic and Gulf seaway in the Western Interior Basin gradually narrowed from its second greatest expansion (T7 at about 85 Ma; Kauffman, 1984, 1985), and was pinched off by filling with orogenic clastic rocks and, to a lesser degree, by worldwide sea-level fall between Santonian and Maastrichtian time (Fig. 7). By the Maastrichtian, Laramide-style basement uplifts had begun segmenting the previously continuous foredeep into local basins that received non-marine clastic rocks from mixed sources. These include the erosion products of the fold and thrust belt at all latitudes, abundant volcanic debris at 43°-47°N and south of 40°N, and debris from unroofed basement between 35°N and 47°N (McGookey et al., 1972).

Magmatism in Canada was much reduced in extent from the mid-Cretaceous culmination, but reached a minor culmination of its own at about 75 Ma to 80 Ma. A narrow, but continuous, belt of activity, typically sodic to normal calc-alkaline in chemistry, lay along the eastern edge of the mid-Cretaceous batholith belt, and numerous small high-level calc-alkaline plutons were scattered across Skeena and Stikine arches in central and northern British Columbia, respectively, and across southern British Columbia and northern Washington. Vikre and McKee (1985) note a similar resolution of Cretaceous magmatic activity in northwestern Nevada into mid-Cretaceous (85-105 Ma) and Late Cretaceous (70-80 Ma) epochs.

The last Sierran magmatism occurred about 80 m.y. ago. At the same time, a spectacular shift of magmatic activity to Laramide patterns began (Armstrong, 1974b; Burchfiel and Davis, 1975; Coney, 1976). As mentioned before, the last plutons in eastern Nevada were distinctive in bearing abundant muscovite (Lee et al., 1981, 1986; Miller et al., 1988; Barton et al., 1988; Barton, 1990). One prominent prong of magmatic activity spread into southwestern Montana, the Boulder batholith region, where an interplay of fold and thrust belt structures, Laramide basement uplifts, foredeep and yoked basins, and magmatism occurred (McMannis, 1965; Robinson et al., 1968; Hyndman et al., 1975; Hyndman, 1983). In this area, large volumes of volcanic rock entered the Cretaceous seaway.

The second magmatic transgression advanced across California and southern Arizona into New Mexico (Coney and Reynolds, 1977). The southwestern part of the Colorado Laramide magmatic belt appeared synchronously with the symmetrical shifts of magmatism out of California-Nevada. The popular explanation for these changing patterns is a change in configuration of the subducting plate to rapid shallow subduction, as is now occurring beneath non-volcanic sectors of the Andes (Dickinson and Snyder, 1978; Cross and Pilger, 1978b; Jordan et
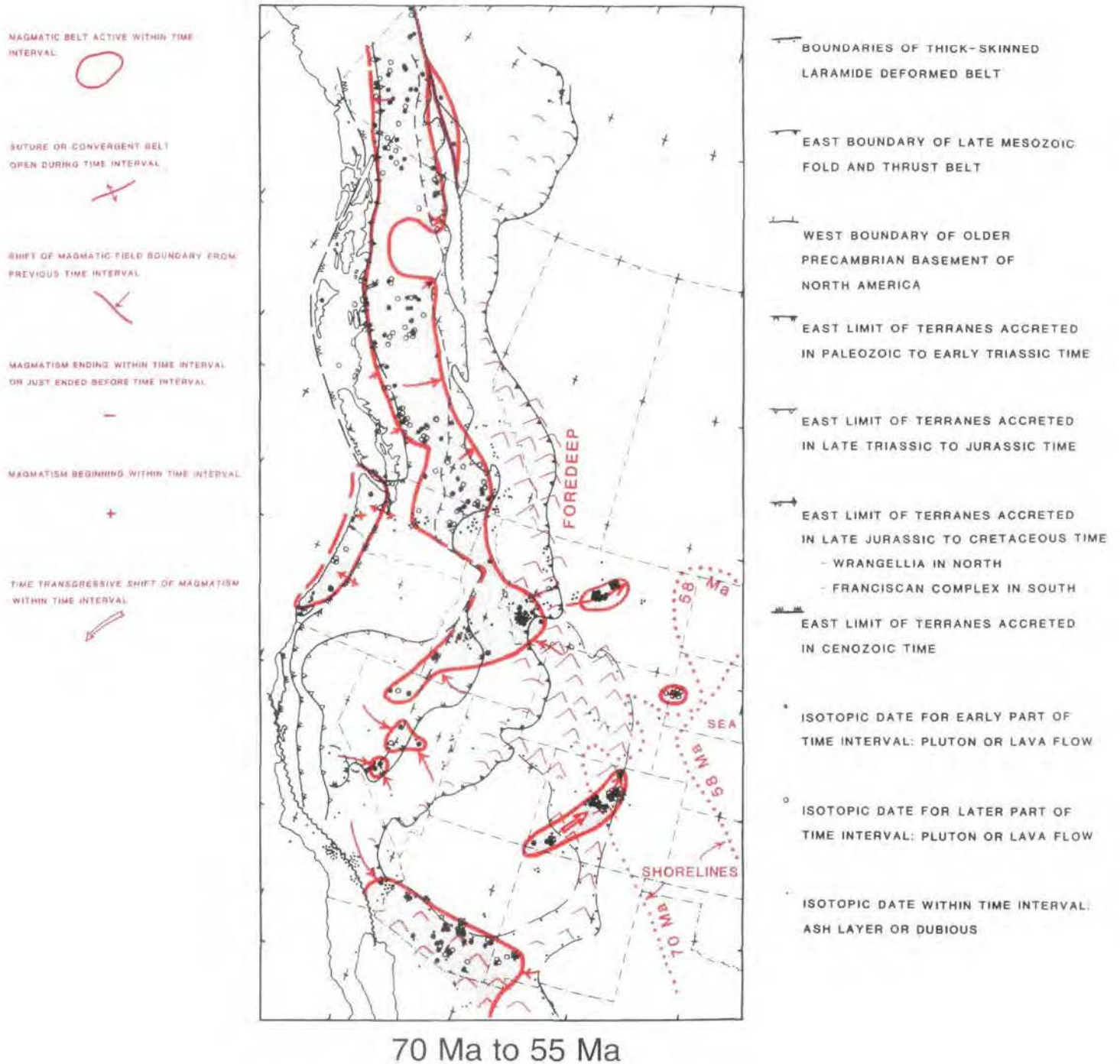
Figure 8. *Magmatic belts and paleogeography 70 Ma to 55 Ma (Late Cretaceous to earliest Eocene time:* **Maastrichtian to Ypresian***). Paleogeography derived from Spence Taylor* et al. *(1964), McDonald (1972), McGookey* et al. *(1972), Williams and Stelck (1975), and Kauffman (1984).*

al., 1983; Jordan and Allmendinger, 1986). In larger perspective, the Western Interior Basin showed little response to these changes in subduction style, only the direct and local interaction with new uplifts and proximal sources of basement and volcanic debris. In northern Montana and into Canada, thrust-belt and foredeep development continued as if nothing had changed. Convergence in Montana-Alberta may have even accelerated into the latest Cretaceous (Monger and Price, 1979; Price, 1981). In the Idaho-Wyoming to California Sevier Orogenic Belt, deformation declined at the same time as crustal shortening was transformed eastward, changed drastically in style, and was reduced in magnitude (Armstrong, 1968).

70 Ma to 55 Ma: Laramide Culmination and End

From 70 Ma to 55 Ma, the last seas connected to the Gulf of Mexico retreated from the Western Interior Basin as sea level fell (Hallam, 1984) and sediment from tectonic uplifts continued to overflow foredeep and yoked basins, culminating in deformation of the northern Montana-Canadian Rocky Mountains, Eastern or Laramide Rocky Mountains, and southern Basin and Range (Haxel *et al.*, 1984). Development of the Western Interior Basin was largely finished by the end of this time interval. What followed was a topping out of sedimentary basins, post-tectonic overlap by Early Eocene to Oligocene and Miocene sediments (some very rich in volcanic material between 38°N and 47°N), and epeirogenic uplift and erosion (Tweto, 1975; Epis and Chapin, 1975).

In western Canada, a weak volcanic arc persisted through this time interval. The map (Fig. 8) is somewhat misleading, in that the magmatic belt shown is exaggerated, mostly due to overlap of the time interval with the beginning of the next magmatic episode, which in Eocene time reached a culmination as extensive as the mid-Cretaceous episode. From 70 Ma to 60 Ma, western Canada experienced a pronounced lull; only scattered plutons in the Coast and Intermontane belts in magmatically persistent areas (such as the southwestern Yukon, Skeena Arch of central British Columbia, and southern Intermontane Belt) are known to be of this age. At least some must be responsible for the ash layers close to the Cretaceous-Tertiary boundary (Baadsgaard and Lerbekmo, 1983).

The magmatic belt in the Oregon-Washington Coast Ranges and southern Vancouver Island (Duncan, 1982; Massey, 1986) is a seamount chain accreted later in Cenozoic time and not directly related to events on the North American continent. From Nevada through Montana, scattered remnants of the northern Laramide magmatic belt are seen. Again, as in other examples, the late magmatism is distinctive in the occurrence of muscovite-bearing plutons (Marvin *et al.*, 1983; Snee and Zen, 1983). This area was magmatically quiescent for much of Paleocene time. The predominantly Early to Middle Eocene magmatic culmination north of 42°N in the United States began about 55-60 m.y. ago (Armstrong, 1974a).

Through Colorado, the Laramide magmatic belt expanded northeastward, reached its maximum development, and waned during this time interval (Marvin *et al.*, 1974). Almost as a sequel or precursor to the next episode, the 60-55 Ma magmatic episode of the Black Hills occurred in isolation close to the projected trace of the Colorado Laramide magmatic belt. These distinctive geographic patterns of magmatism suggest a hot spot origin, but the magmatic chemistry, sodic alkaline to calc-alkaline, generally intermediate rock types, is not typical of within-plate magmatism.

From southern California across Arizona to New Mexico, a Laramide magmatic culmination occurred during this time interval (Damon and Mauger, 1966; Shafiqullah *et al.*, 1980). By 55 Ma, an Early Cenozoic magmatic lull was beginning in the southwestern United States. It is notable that the Laramide igneous activity southeast of the magmatic gap through Nevada-Utah-Wyoming was virtually out of phase with magmatism north of the gap. Waning activity in the north, characterized by muscovite-bearing plutons, coincided with the climax of calc-alkaline magmatism in the south. At this time interval, the magmatic episode maps do not properly represent the complexities of Cordilleran magmatic patterns, but with only two dimensions on paper all representations must be some sort of compromise.

The ensuing Cenozoic magmatic history throughout the Cordillera adopted this new style of complexly shifting magmatic fields and time transgressive movements. For most of Mesozoic time, and including the early Cenozoic in Canada and nearby parts of the United States, the apparent pattern was of episodic magmatism in continuous belts parallel to the continental margin. The Andean analog with relatively steep subduction seems appropriate.

CONCLUSION

The Mesozoic Western Interior Basin developed while the western margin of North America was the site of an Andean magmatic arc. Crustal thickening between the Basin and the continental margin occurred by both tectonic and magmatic processes. At shallow crustal depths within the arc, extension appears to have been common, but on peripheral belts, as in the Andes, where the topographic surface sloped away from the area of thickened and heated crust, thrust belts formed. On the west, ocean-facing side, subduction and tectonic erosion and terrane accretion occurred (west-vergent B-subduction and predominantly west-vergent thrust faults). On the east side, thin- and thick-skinned fold and thrust belts were formed (east-vergent A-subduction of Bally, 1981). The geophysical compatibility of these contrasting tectonic styles has been explained by Súarez *et al.* (1983) and Jordan *et al.* (1983).

Overall, there are two major culminations of magmatism and convergence, one Middle to Late Jurassic, the other mid- to Late Cretaceous (Fig. 1). Each corresponds to one of the two major depositional cycles of the Mesozoic Western Interior Basin and to eustatic sea-level maxima. The Early Cretaceous lull, perhaps related to accretion of the Insular Composite Terrane and the tectonic adjustments that followed it, is represented in the Western Interior Basin by a regional hiatus, and extensive erosion. The beginning of the next episode was marked by a unique, short-lived episode of shedding of coarse clastic debris far across the Interior Basin from the maturely eroded source region (Mesocordilleran Geanticline, second incarnation) as it was thermally uplifted *before* thrust loading created foredeep basins to trap coarse sediment in the immediate vicinity of thrust ramps. These far-travelled resistite gravels of the late Early Cretaceous Cadomin-Kootenai-Dakota formations (Rudkin, 1964; Jansa, 1972; McGookey *et al.*, 1972; McLean, 1977; Schultheis and Mountjoy, 1978; DeCelles, 1986) have been an enigma to paleogeographers, but perhaps can be understood in terms of the detailed linkage of cause and effect in orogenic belts. Heating and uplift, and lithosphere weakening, must precede lithosphere failure, consequent development of thrust ramps, and the accumulation of lithosphere loads that create foredeep sediment traps. Only for a brief moment, as orogeny begins anew, is the sediment trap missing and coarse resistite fragments are able to travel large distances across the future foredeep site.

EPILOGUE

This paper is more review and selective citation of useful ideas in geologic literature than a startling new vision of Cordilleran geology. However, the exercise has derived from the largest compilation yet done of magmatic geochronometry for the North American Cordillera. This is only a pause to reflect on the implications of a large data collection that grows steadily. Such reviews will be redone again, each building on past knowledge, ideas and experience. These reviews serve to communicate the current status of knowledge, to subject published ideas to scrutiny, and highlight gaps to be filled and areas due for more refined modern study. Every accurate dating of a rock is a welcome contribution. One compilation that needs to be done is a three-dimensional quantification of the distribution of volcanic ash and volcaniclastic components in the Western Interior Basin. Kauffman (1985) presents a step in that direction, but much more could be done. It would be exciting to compare the results with magmatic activity distribution maps. In many respects, the sedimentary basin may contain a better record of explosive volcanism than randomly distributed dating projects on the roots and eroded remains of volcanoes. The two data sets would be complementary and advance our knowledge of paleogeography and

transport of materials into the evolving Western Interior Basin.

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