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Long-term evolution of subduction zones and the development of wide magmatic arcs

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RESUMEN

Una gran parte de la superficie del sudoeste de Estados Unidos y del norte de México se encuentra cubierta por rocas ígneas de edad Mesozoica Tardía-Cenozoica. Estas se extienden a lo largo de varias provincias que muestran distintas características estructurales y petrotectónicas, además de tener estructura litosférica diferente. Resultados químicos y petrográficos muestran afinidades con arcos magmáticos, particularmente los complejos calcoalcalinos, apoyando un vínculo genético con los procesos de convergencia entre las placas Farallón y Kula con la placa Norteamericana. Sin embargo, el ancho del arco magmático (que llega a los 1100 km) y la distancia ente el arco y la trinchera (calculada a partir de reconstrucciones paleogeográficas) contrastan notoriamente cuando son comparadas con las rocas observadas en las zonas de subducción en sistemas de arcos magmáticos contemporáneos. Estudios geocronológicos y estratigráficos han fundamentado la aparente migración este-oeste de la actividad magmática que queda definida por el patrón espacio-tiempo a partir de los datos geocronológicos, es referido como un arco magmático espacial. Se analizan varios modelos considerando diferentes relaciones geométricas, cinemáticas y dinámicas: (1) ángulo de subducción variable-profundidad y rango de fusión constante (zona de generación de magma); (2) ángulo de subducción variable-profundidad y rango de fusión variable; (3) ángulo bajo de subducción y distancia variable entre la trinchera y el arco (migración lateral de la trinchera debido a la variación en el ángulo de subducción en la zona poco profunda y a los sedimentos de acreción); (4) tectónica de extensión, y (5) extensión de intra-arco y post-arco. El análisis de los modelos de espacio-tiempo muestran que el arco magmático espacial se alejó hasta 450 km de la trinchera entre los 120 y 55 millones de años, regresando nuevamente en dirección de la trinchera entre los 30 y 20-15 millones de años. El ancho del arco magmático se incrementa hasta 550 km entre 120 y 70 millones de años, manteniéndose casi constante hasta 20 millones de años. Las rocas de la Provincia Alcalina del Golfo representan la porción más oriental del arco magmático, cuyas características geoquímicas y petrográficas muestran una transición de magmatismo de subducción a magmatismo de extensión continental. Esta transición coincide con el modelo de subducción de ángulo bajo y la migración lateral de la actividad durante el Terciario.

PALABRAS CLAVE: Arcos magmáticos antiguos, subducción, geocronología, norte de México, suroeste de Estados Unidos.

ABSTRACT

Late Mesozoic-Cenozoic igneous rocks cover a large area in southwestern United States and northern Mexico, which extends over several provinces with contrasting structural and petrotectonic characteristics and lithospheric structure. Chemical and petrographic data show magmatic arc affinities, particularly for the calc-alkaline suites, supporting a genetic link with the plate convergence process between the North American and the Farallon and Kula plates. However, the width of the magmatic arc (in excess of 1100 km) and the trench-arc gap (estimated from paleogeographic reconstructions) are in marked contrast when compared to the ranges observed in contemporary subduction zone-magmatic arc systems. Geochronological and stratigraphic studies have documented apparent east-west migration patterns of activity, which support that the magmatic province is the result of a long-term evolution of the convergent continental margin. The wide magmatic province defined by the space-time pattern of geochronological data is referred to as a spatial magmatic arc. Several models with changing geometrical, kinematic and dynamic relationships are discussed: (1) variable subduction dip-constant depth and range of melting (magma generation zone); (2) variable dip-variable depth and range of melting; (3) low-angle subduction and variable trench-arc gap (lateral migration of trench due to variable dip in the shallow zone and sediment accretion); (4) extensional tectonism; and (5) intra-arc and back-arc extension. The space-time patterns show that the spatial magmatic arc was displaced away from the trench up to 450 km between 120 Myr to 55 Myr, and then back towards the trench between 30 Myr to 20-15 Myr. The width of the spatial magmatic arc increased up to 550 km from 120 Myr to 70 Myr and then remained fairly constant up to 20 Myr. Igneous rocks at the easternmost end of the magmatic arc occur in the Gulf alkaline province, whose geochemical and petrographic characteristics show a transition from subduction related to intraplate extension, in agreement with a model of low-angle subduction and lateral migration of activity during the Tertiary.

KEY WORDS: Ancient magmatic arcs, subduction, geochronology, northern Mexico, southwestern United States.

1. INTRODUCTION

Late Mesozoic-Cenozoic igneous rocks cover a large area in the southwestern United States and northern Mexico (Figure 1). This magmatic province has been related to plate subduction processes along the western North American margin (McKenzie and Morgan, 1969; Atwater, 1970; Lipman *et al.*, 1971). Most active magmatic arcs are elongated narrow belts (Table 1), with arc widths of < 300 km and trench-arc gaps between about 100 and 350 km

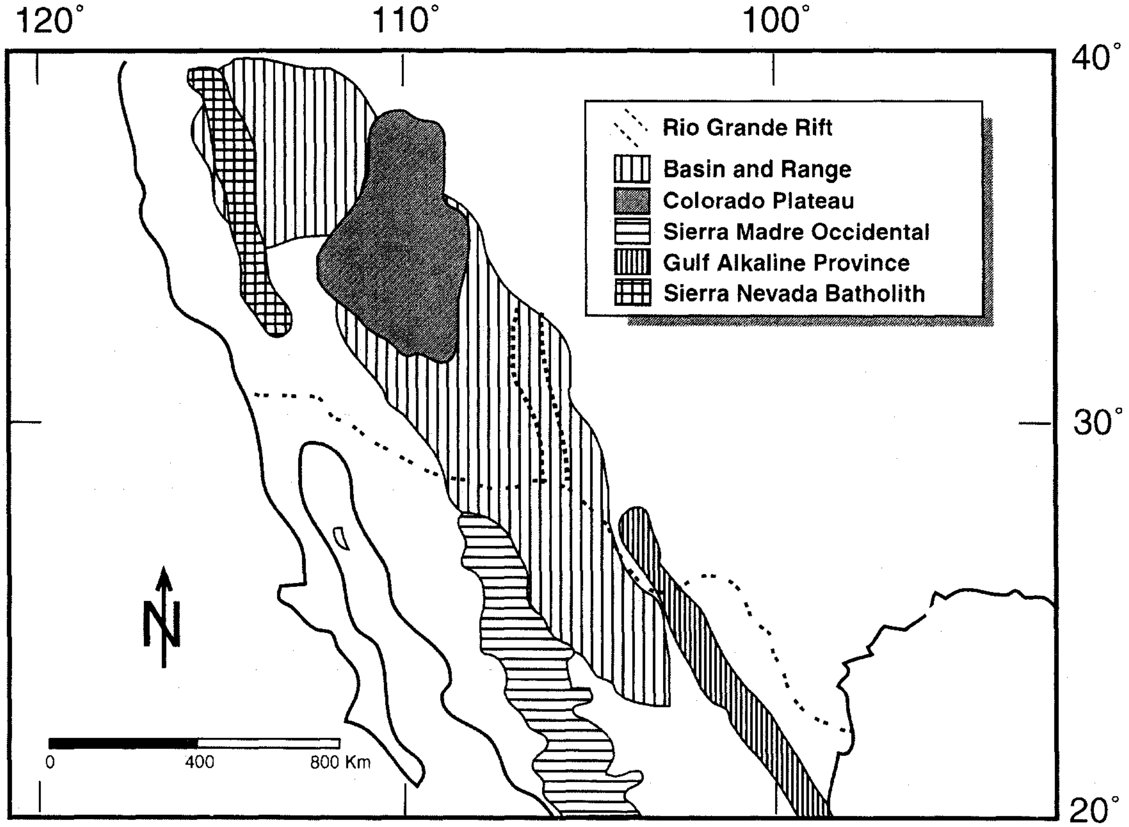

Fig. 1. Major physiographic and tectonic provinces of southwestern United States and northern Mexico.

(Hatherton and Dickinson, 1969; Dickinson, 1973; Jarrard, 1986). In contrast, the SW USA-NW Mexico magmatic province covers a width in excess of 1100 km normal to the continental margin. Contemporary subduction zone-magmatic arc models cannot be directly applied to this wide province, unless shifting space-time patterns of magmatic activity and extensional tectonism are considered.

Several contrasting models have been proposed. Studies of space-time distributions of magmatism have documented abundant volcanic activity, changing patterns and gaps (e.g., Lipman *et al.*, 1971, 1972; Snyder *et al.*, 1976; Coney and Reynolds, 1977; Urrutia-Fucugauchi, 1978; Cross and Pilger, 1978; Glazner and Supple, 1982; Spencer, 1996). The wide area covered by igneous rocks and the structural and tectonic patterns (Laramide orogeny and mid-Tertiary extensional tectonics) documented along the margin and in the continental interior have been related to various plate tectonic models that mainly involve low-angle plate subduction (e.g., Coney and Reynolds, 1977; Urrutia-Fucugauchi, 1978, 1986; Bird, 1984, 1988; Mitrovica *et al.*, 1989; Spencer, 1996). The composition of magmatic products also shows characteristic space-time patterns, which have been related to various petrogenetic models of arc magmatism. The abundant calc-alkaline magmatism of andesitic to rhyolitic composition has been genetically linked to plate subduction (e.g., Atwater, 1970, 1989; Snyder *et al.*, 1979; Cross and Pilger, 1978; Spencer, 1996). Basaltic and associated rhyolitic volcanism has been related to crustal extension in back-arc environments (e.g., Scholz *et al.*, 1971). Alkaline basalts of the Trans-Pecos province and the Gulf of Mexico province have been associated to plate subduction (Lipman *et al.*, 1971, 1972) or to intraplate rifting (Barker, 1977, 1979). Henry *et al.* (1991) proposed that magmatism in the Trans-Pecos province changed at around 31 Myr in response to a change from compressional (continental arc) to extensional intraplate tectonism.

In this paper we discuss a tectonic model which relates calc-alkaline and alkaline magmas to plate subduction. Changing space-time patterns and compositions relate to the geometric, thermal, kinematic and dynamic evolution of plate interactions along the continental margin. The result of these processes is the construction of a wide magmatic province.

Migration of volcanic activity has been documented in contemporary and old magmatic arcs (e.g., Lipman *et al.*, 1971; Dickinson, 1973; Jacob *et al.*, 1977; Coney and Reynolds, 1977; Urrutia-Fucugauchi, 1978; Cross and Pilger, 1978; Kay *et al.*, 1987; many others). Changing spatial-temporal patterns of activity have been linked to the geometry, kinematics and dynamics of the subduction processes. We examine processes related to a change in the

Table 1

Some parameters related to subduction zones

No.	Zone[a]	Width of arc-trench gap (km)[a]	Distance from trench axis to magmatic arc axis (km)[a]	Age of the oldest dated igneous activity (m.y.)[a]	dip angle (deg)[b]	Maximum depht (km)[b]	Subduction velocity (cm/y)[b]	Upperplate velocity (cm/y)[b]
1	Eastern Alaska (E of Shumagu island past Kodiak island)	225-250	300-325	> 175	40	250	5.6	0.1
2	Western Alaska (Shumagin to Bearing shelf edge)	175	225	75 ? (40)[e]	-	140[c]	5.9[c]	-
3	Eastern Aleutian (Andreanof and Fox islands)	125-150	175	~50	53	250	3.1	1.0
4	Kamchatka, Russia.	175	225	125-150	44	300	7.6	0.9
5	Kurile Islands	125-150	175-200	75-100	47 (42)	610 (500)	7.7 (7.8)	1.1 (1.2)
6	North Honohu, Japan	225	300	~125	40[d]	600[d]	-	-
7	Insland sea, Japan	250	300	> 175	-	-	-	-
8	Izu islands	125	175	25-50	54	530	8.6	-2.5
9	Ryukyu islands	100	150	~25	40 (36)	280 (290)	3.8 (4.0)	1.3 1.2
10	Mariana islands (central section)	150	200	~50	85	700	9.1	-5.5
11	Philippine islands (Luzan)	100	125	~25-50	-	-	-	-
12	Philippine islands (Mindanao)	125	175	~25-50	55[d]	600[d]	-	-
13	Java[f]	225	300	150-175 (150)[e]	-	650[c]	7.1[c]	-
14	Sumatra[f]	225	300	150-175 (80)[e]	-	200[c]	6.6[c]	-
15	New Britain	75	125	~50	65[d]	200[d] (600)	-	-
16	Solomon islands	50	100	~25	70[d]	150[d] (550 in NW segment)	-	-
17	New Hebrides	75	125	10-15	64 (50)	290 (700)	3.3 (8.2)	6.3 (0.8)
18	Tonga[f]	100-125	150-175	25-50	50	700	8.2	0.8
19	Kermadec[f]	100-125	150-175	25-50	60	500	7.0	-0.5
20	Peru[f]	250	300	175-200 (45)[e]	8[d]	200[c] (150)[d]	10.0[c]	-
21	Chile (central)[f]	250	300	175-200 (20)[e]	11[d]	160[c] (150)[d]	11.1[c]	-
22	Central America	125	175	~100	60	200	8.0	-0.1
23	Lesser Antilles	200	275	100?	65[d]	230[d]	-0.1	-

[a]Dickinson (1973); [b]Yokokura (1981); [c]Ruff and Kanamori (1980); [d]Uyeda and Kanamori (1979); [e]age of subducting oceanic lithosphere, mainly from Deep Sea Drilling data. Ruff and Kanamori (1980); [f]given as single zone in Dickinson (1973)

subduction dip angle and implications for long-term evolution of subduction zones-magmatic arcs that may result in particularly wide (> 1000 km) magmatic arcs.

Wide magmatic provinces exist in the Late Paleozoic province of Peru (>1000 km), the Jurassic-early Tertiary province of central Chile (>1000 km), the Mesozoic-Cenozoic zone of eastern Asia (>3000 km), and the western North America province (>1000 km). They represent old, long-term convergent plate margins. Patterns of migration of activity reflect changes in plate interactions and in the kinematics and dynamics of the plate subduction processes.

2. MAGMA GENERATION-SUBDUCTION ZONE DEPTH MODEL

Calc-alkaline igneous rocks characterize island arcs and continental margin arcs, where they display a close relationship with plate subduction (Gill, 1981; Aramaki and Kushiro, 1983). Activity in magmatic arcs generally occurs along elongated belts roughly parallel to oceanic trenches. Across the magmatic arc, in the direction of the dip of the subducted plate, there is a change in composition and a decrease in the volume of erupted magma (Coats, 1962; Kuno, 1966). The volcanic front, which is commonly located some 100-300 km away from the trench, is probably related to the onset of melting in or above the subducted plate. Volcanic fronts commonly occur some 100 km above the subducted plate (Figure 2). Andesites constitute the most common rocks in evolved island arcs and continental margin arcs. The core of the arcs is formed by batholiths with compositions ranging from diorite to granite (e.g., Dickinson, 1970). The magma volume decreases behind the volcanic fronts reflecting changes in pressure-temperature conditions, water content in the plate and sediments, or conditions for magma ascent. Across the arc there is an increase in strontium isotope ratios and in highly incompatible elements such as Rb, Th, K, Ba and rare-earth elements, and a depletion of Ta and Nb in relation to the large-ion lithophile elements. This Ta-Nb anomaly is referred to as the subduction zone component, and is has been related to increasing depth in the subduction zone (Dickinson, 1975; Sakuyama and Nesbitt, 1986). However, this compositional polarity is absent in some arcs (e.g., Arculus and Johnson, 1978), and there is also a comparable along-arc variation in chemical composition (e.g., Wheeler *et al.*, 1987).

The geometry of a subduction zone may be determined from an analysis of the seismicity (e.g., Figures 2 and 3). From the oceanic side, there is a zone of shallow, diffuse seismicity at 0-40 km depth, followed by intermediate-depth seismicity on an inclined plane (e.g., Figure 3). Dip angles in the upper zone are smaller than in the deeper zone (Figure 2) and at the surface there is a corresponding change in the gap between the trench and the volcanic front.

Some of the major features of contemporary subduction zone-magmatic arc systems may be incorporated in a simple geometric model, which may be used to infer the evolution of older arcs on the strength of the geologic record. Figure 4, the magmatic arc is assumed to be formed above the intersection of the oceanic plate with the low- velocity layer in the upper mantle (Hatherton and Dickinson, 1969; Dickinson, 1973, 1975; Spencer, 1996). This layer, which approximately corresponds to the asthenosphere, is found between about 100 km and 300 km depth and will be referred to as the magma-generation zone (Figure 4). Activity in the magmatic arc usually begins less than 5 my after initiation of subduction (Gill, 1981; Jarrard, 1986). The lithosphere up to 100 km depth corresponds to the shallow-earthquake zone (Figure 4). The properties of materials in the upper zone result in different subduction angles (Benioff, 1954; Isacks and Barazangi, 1977). The zone below the asthenosphere is the mesosphere which extends to about 660-700 km depth. This depth may represent a phase boundary that marks the deeper limit at which earthquakes occur: beyond this limit the plates cannot continue their descent or are assimilated into the mantle (e.g., Giardini and Woodhouse, 1986; Okino *et al.*, 1989). Tomographic inversion studies of mantle shear structure suggest, however, that a plate can descend deeper into the lower mantle (Grand, 1994). The interactions with these deeper layers may result in complex geometrical configurations (e.g., Isacks and Molnar, 1971; Okino *et al.*, 1989; Van der Hilst *et al.*, 1991, 1993).

During the earlier stages of development, the magmatic zone width is a function mainly of the subduction angle, subduction rate, and depth reached by the plate within the magma-generation zone. After the plate reaches the 300 km limit, the width becomes only a function of the subduction angle in the magma-generation zone (Figure 5). If the subduction angle does not change, the magmatic arc width remains constant. On the other hand, the position of the magmatic zone is a function mainly of the subduction angle in the shallow earthquake zone and of lateral migration of the subduction zone. Changes in these parameters result in overlapping magmatism due to shifting of the magmatic activity (Figure 5).

It is useful to distinguish the magmatic province defined by the total area covered by magmatic rocks, from the zone resulting from across-arc migration of igneous activity (within the temporal resolution of geochronological methods and from the active magmatic zone. The total area will be called the spatial magmatic arc. Thus when the activity ends the result is a spatial magmatic arc zone. If the front does not shift, both zones coincide in space until the activity ends. Figure 6 shows the magmatic displacement from the trench plotted as a function of the dip of the shallow earthquake zone. Figure 7 shows two examples of magmatic arc width versus dip. Figure 7 (a) assumes the same dip in the shallow earthquake and the magma generation zones and Figure 7 (b) considers different dips and dip variation. Other cases can be derived easily from Figures 5 and 6. When these processes are present during the evolu-

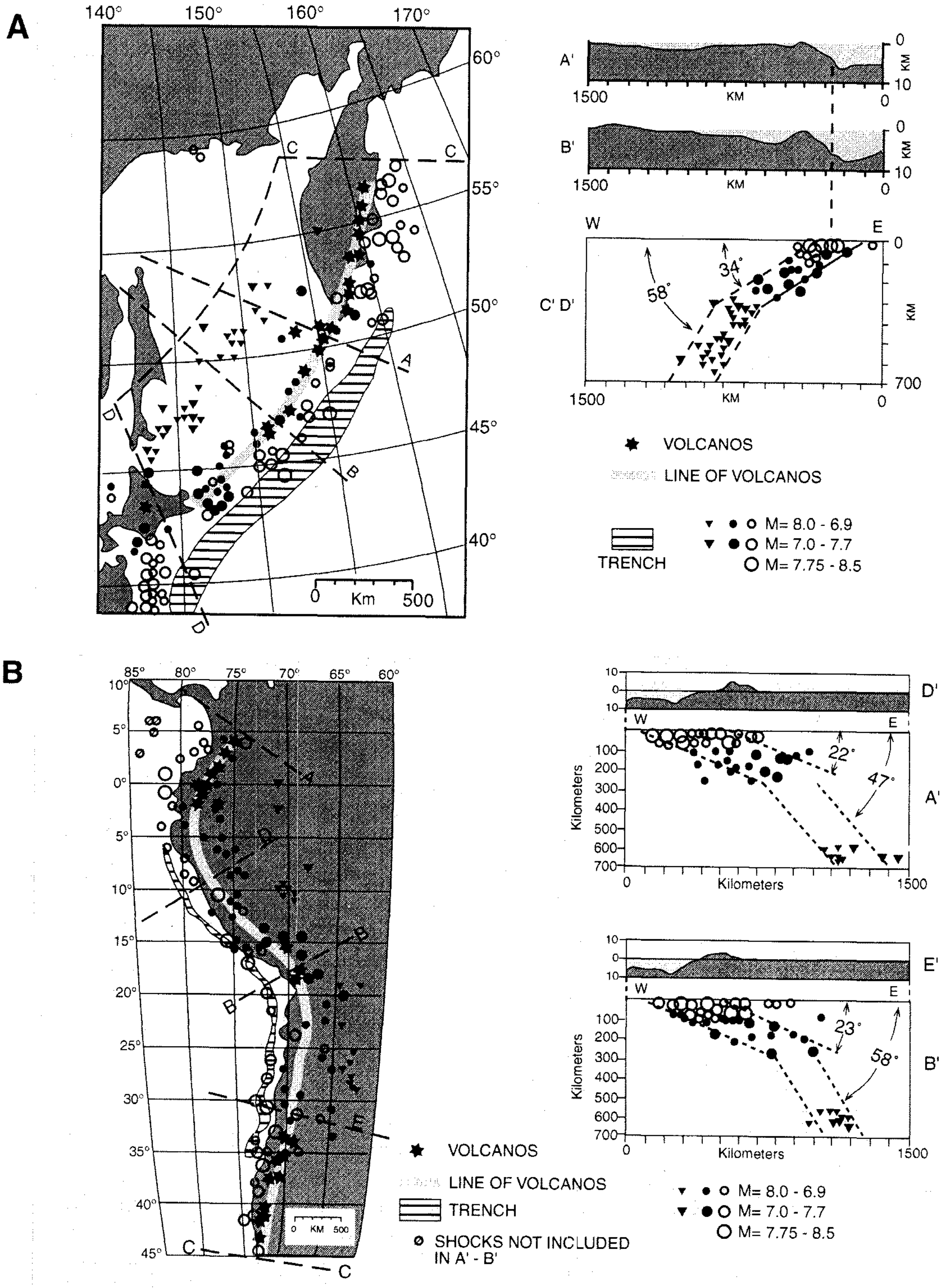

Fig. 2. Plan view and composite earthquake hypocenter profiles for (A) Kurile-Kamchatka and (B) South America subduction zones-magmatic arc zones (from Benioff, 1955). Observe shallow zones and deep seismicity zones, with different dip angles.

tion of a magmatic arc, the result is a wide composite magmatic arc zone.

Subduction angles range from 0° to 90°, with an average near 45° (Isacks and Molnar, 1971; Karig *et al.*, 1976; Isacks and Barazangi, 1977; Jarrard, 1986). However, old magmatic arc zones are often much wider than those of today. If subduction processes in the past were similar as in the present and the depth range of magma generation has not significantly changed, old magmatic arcs must repre–

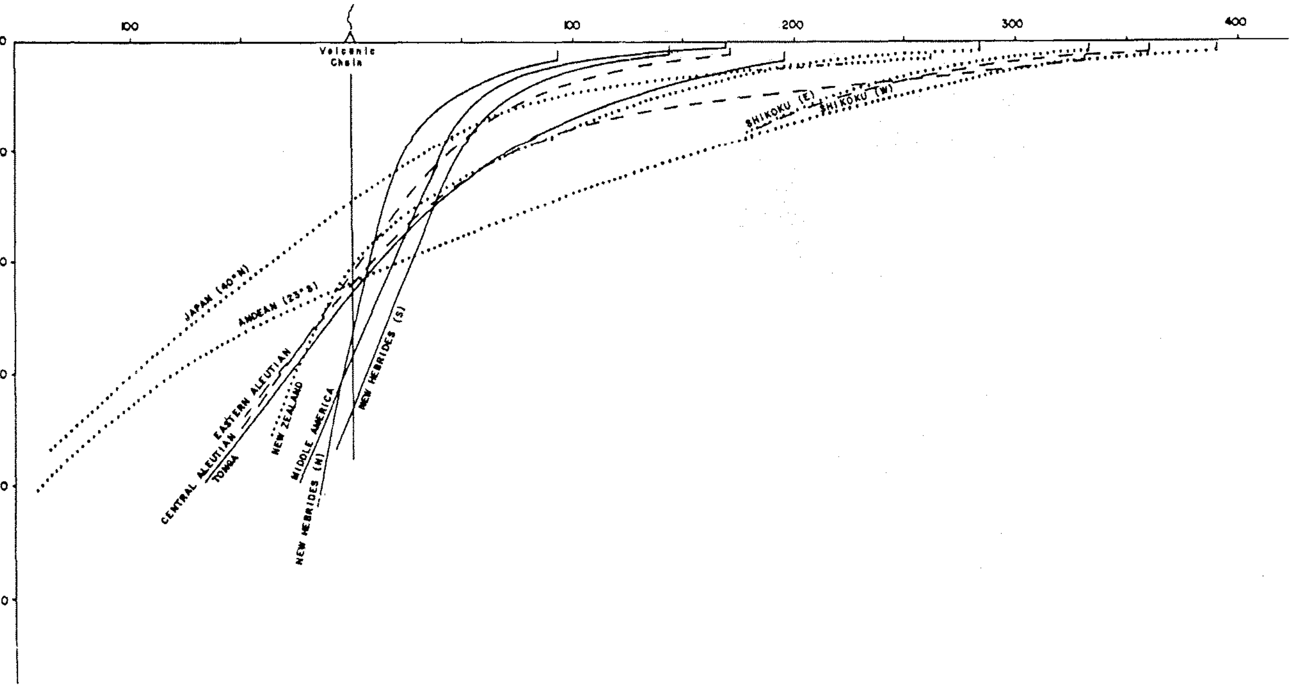

Fig. 3. Cross-sections of seismic zones from island and continental arcs with location of the volcanic front in the magmatic arc (from Karig *et al.*, 1978; Molnar and Atwater, 1981). Observe the shallow dip angles at shallow depths and the position of the subducted plate marked by the Wadati-Benioff seismicity zone beneath the volcanic front (depth beneath volcanic front roughly between 75 and 175 km).

sent spatial magmatic arcs. There is evidence of magmatic arc displacements with these zones which supports the simple geometric model even if some of the geometrical parameters may have been different.

3. SPATIAL MAGMATIC ARC OF SOUTHWESTERN NORTH AMERICA

The magmatic activity of southwestern North America is among the best documented in space and time. The Late Mesozoic to Cenozoic period is of almost continuous magmatism (Lipman, 1980; Lipman *et al.*, 1971, 1972). This activity was associated with an active spreading and subduction system along the western North America continental margin (McKenzie and Morgan, 1969; Atwater, 1970, 1989). The magmatism covers a zone more than 1000 km wide. An eastward shift of igneous activity (Lindgren, 1915) took place during Late Mesozoic to Early Cenozoic times (Lipman *et al.*, 1971; Snyder *et al.*, 1976). These features were interpreted in terms of two subparallel subduction zones and dip flattening (e.g., Lipman *et al.*, 1971), or a single subduction zone and dip changes (e.g., Coney and Reynolds, 1977; Urrutia-Fucugauchi, 1978, 1980, 1986; Keith, 1978; Cross and Pilger, 1978; Bird, 1984, 1988; Mitrovica *et al.*, 1989; Spencer, 1996).

The magmatic province extends over several tectonic and physiographic provinces along the continental margin and towards the continental interior (Figure 1). The Basin and Range province is characterized by intense magmatism, Mesozoic crustal compression, and Cenozoic extension resulting in a pattern of mountain ranges and valleys. In contrast, the Colorado plateau was little affected by Mesozoic and Cenozoic deformation or magmatism. The plateau is formed by thick Paleozoic and Mesozoic sequences over an early to middle Proterozoic basement. The Rocky Mountains province is characterized by basement uplifts commonly attributed to crustal shortening during the Laramide orogeny. The easternmost igneous manifestations associated with the magmatic arc are those of the Trans-Pecos field of southwestern Texas, within the southeastern Basin and Range province.

Plate convergence has been the dominant tectonic process along the western North America margin during the Mesozoic and Cenozoic. Reconstruction of space-time patterns for earlier periods is problematic because of large-scale displacements and deformation of portions of the margin (e.g., Beck, 1980; Urrutia-Fucugauchi, 1981; Hudson and Geissman, 1987; Sager *et al.*, 1992; King *et al.*, 1994). Paleogeographic reconstructions of space-time patterns of igneous activity (Figure 8) document the migration across and along the margin, with loci of intense activity and gaps (McKee *et al.*, 1970; Lipman *et al.*, 1971, 1972; Snyder *et al.*, 1976; Lipman, 1980). Activity in the Late Mesozoic appears to have been confined near the mar–

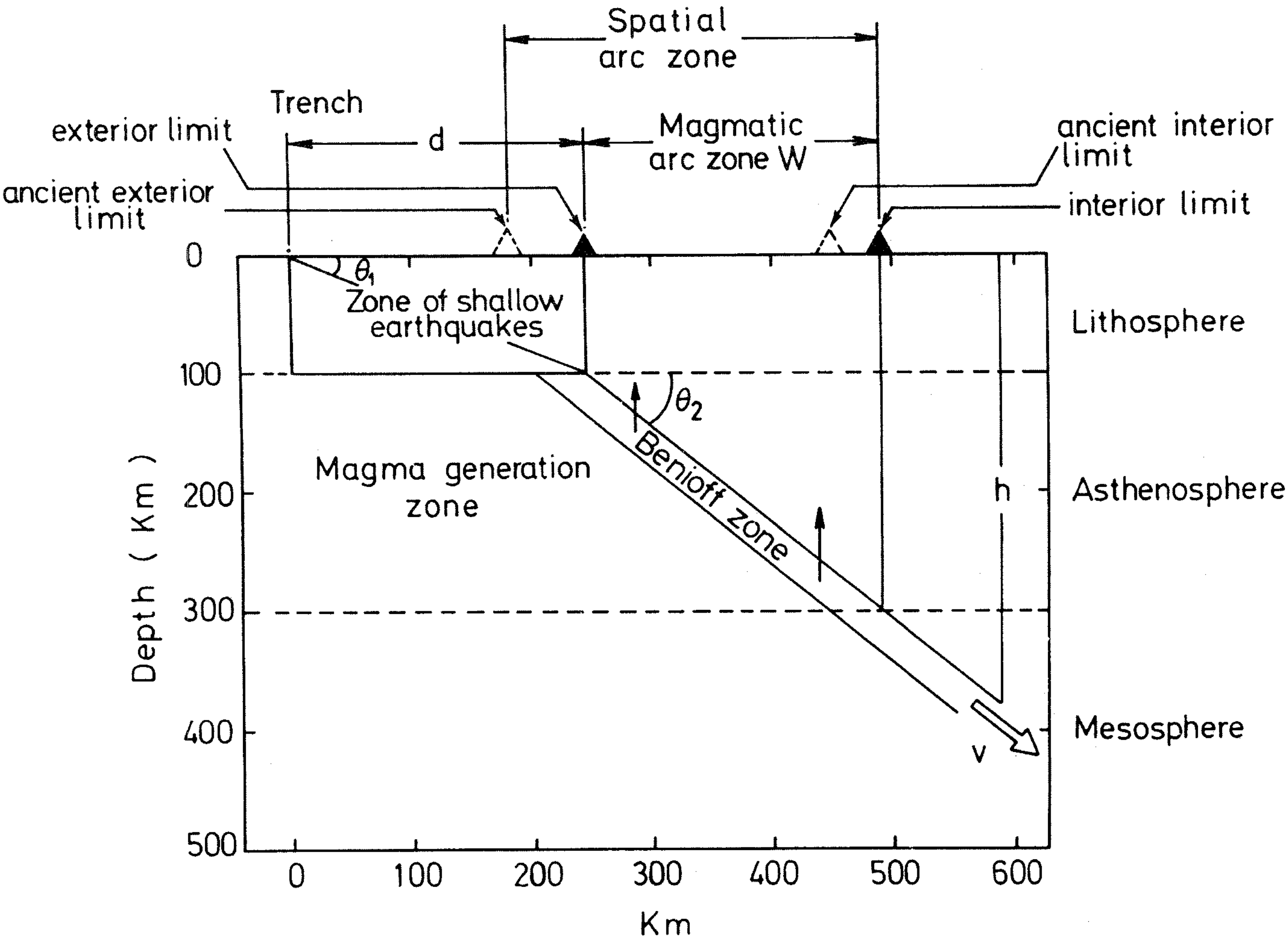

Fig. 4. Schematic subduction zone-magmatic arc model. Note the distinction between the widths of the magmatic arc zone and the spatial magmatic arc zone (Urrutia-Fucugauchi, 1978).

gin, as in the Peninsular Ranges batholith, Sierra Nevada batholith, western Nevada, Oregon and Washington. For the period 120-80 Myr before present, activity concentrated along the margin extending from Canada to Mexico (Figure 8a). During the Late Cretaceous, about 80 Myr ago, activity migrated eastward across the margin into Nevada and Arizona and northwestern USA (Figure 8b). Between 70 and 60 Myr ago, igneous activity covered a wide area, but appears discontinuous and probably asynchronous (Figure 8c). Activity in the Boulder batholith area of western Montana vanished abruptly at about 70 Myr, while intense activity occurred in southern Arizona and southwestern New Mexico and in the southern Rocky Mountain region. Between 60 and 50 Myr ago, activity was displaced eastwards, with loci of intense activity in the northern Rocky Mountains, in the northwestern Pacific and in Arizona and New Mexico (Figure 8d). The regional pattern of activity continued over the next 10 Myr (Figure 8e).

In the northwestern sector, activity in the Absaroka and Challis fields of Idaho and Wyoming decreased around 45 Myr ago and moved southwards into northern Nevada and northern Utah (Stewart *et al.*, 1977; Bromfield *et al.*, 1977). Magmatic activity began in the Trans-Pecos area around 48 Myr ago, coinciding with the end of Laramide deformation. The apparent gap in the Colorado plateau and adjacent regions remained, with activity occurring further south in southern New Mexico, Arizona and northern Mexico. The regional pattern of activity changed relatively rapidly over the next period between 40 and 30 Myr ago, ending in the eastern sectors and moving westwards (Figure 8F). Activity vanished east of Wyoming and Idaho, but andesitic volcanism occurred in the Cascades of western Washington and Oregon. Eocene submarine activity also occurred in the Coast Ranges (Snavely *et al.*, 1986) and subaerial activity took place farther south in Nevada and Utah (Stewart *et al.*, 1977). By 35 Myr, intense activity occurred in the southern Rocky Mountains in Colorado and New Mexico and along a major area southwards extending into the Sierra Madre Occidental of northwestern Mexico. Basaltic volcanism developed between 48 and 31 Myr in

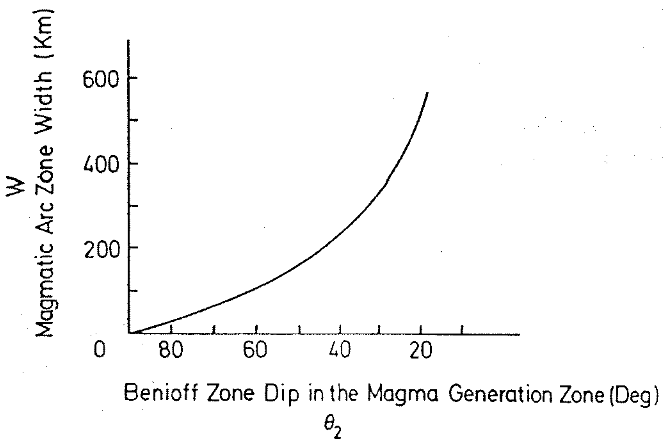

Fig. 5. Width of the magmatic arc zone as a function of the dip angle in the deep magma-generation zone

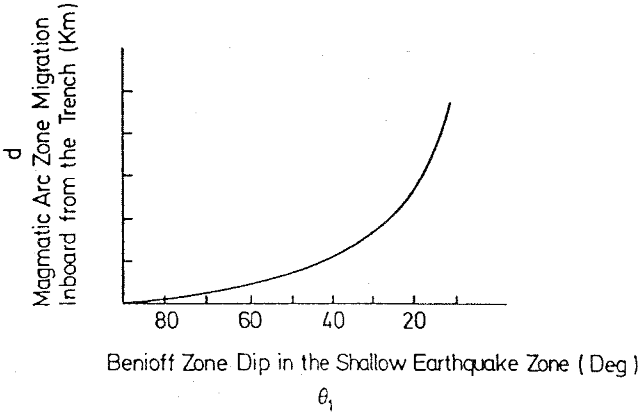

Fig. 6. Variation of the arc-trench gap as a function of dip angle in the shallow zone. The arc-trench gap variation can be viewed as the migration of the magmatic arc away from the trench, considered as the reference point in the arc-trench system.

the Trans-Pecos field. This volcanism featured subduction-related calc-alkaline suites low in Ta and Nb (although higher than near-trench volcanic suites), but highly alkalic with higher concentrations of incompatible elements. This suggests melts from deep sources (McDowell and Clabaugh, 1979; James and Henry, 1991). Over the next 10 Myr (30 to 20 Myr ago), the spatial pattern of volcanism was preserved but there were significant changes in the tectonics and the character of the magmatism (Figure 8g). The tectonic events included plate interactions along the margin with subduction of segments of the spreading ridge and transform faulting. The development of triple junctions of trench-transform-ridge type and their subsequent displacement along the margin resulted in rapidly evolving magmatism.

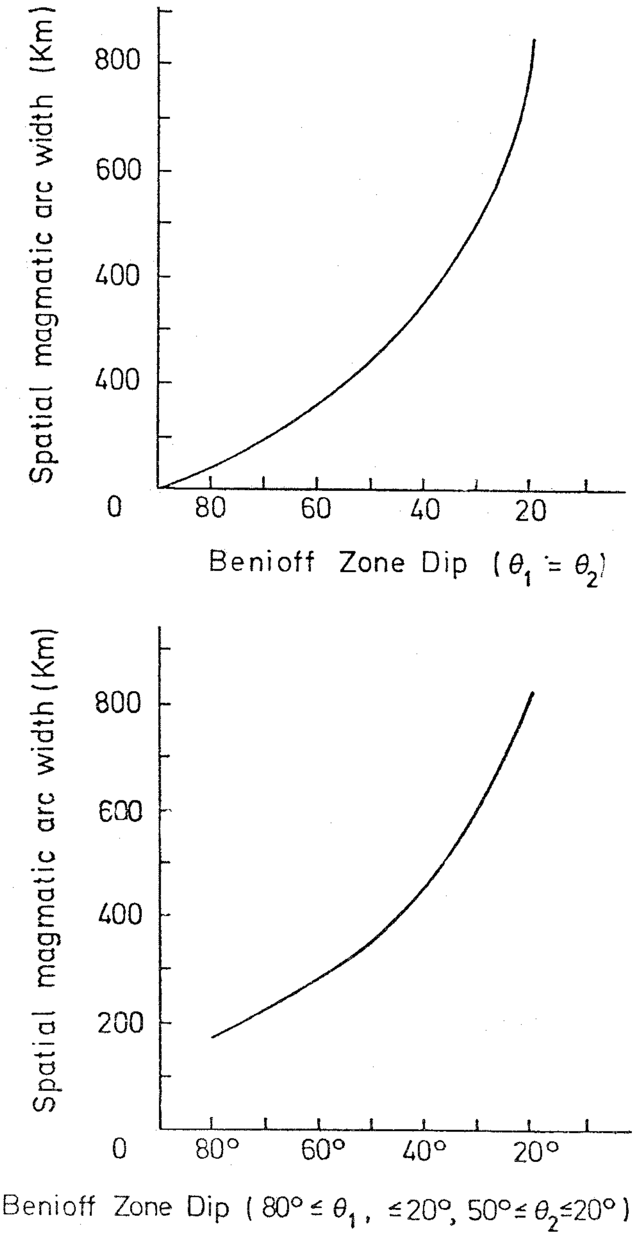

Fig. 7. Two examples of variation of the width of the spatial magmatic arc (see Fig. 4 for reference to geometric model), as a function of the dip angles in the shallow and deep zones. (a) No change in the dip angles in the two zones. (b) Different dip angles in the two zones.

Widespread extensional tectonism in the Basin and Range (particularly towards the period around 20 Myr) and other. regions such as the Rio Grande rift (around 29-26 Myr) and the Trans-Pecos field also developed during this period (Christiansen and Lipman, 1972; Chapin and Seager, 1975; Snyder *et al.*, 1976). The extensional tectonism was associated with widespread basaltic volcanism. Alkaline magmatism occurred in New Mexico, Arizona and Colorado between about 29 and 21 Myr ago (Christiansen and Lipman, 1972). Potassic volcanism peaked around 25 Myr, beginning around 30 Myr ago, in the Colorado plateau and neighboring areas such as Chino Valley, Arizona (Roden *et al.*, 1979). The character of magmatism

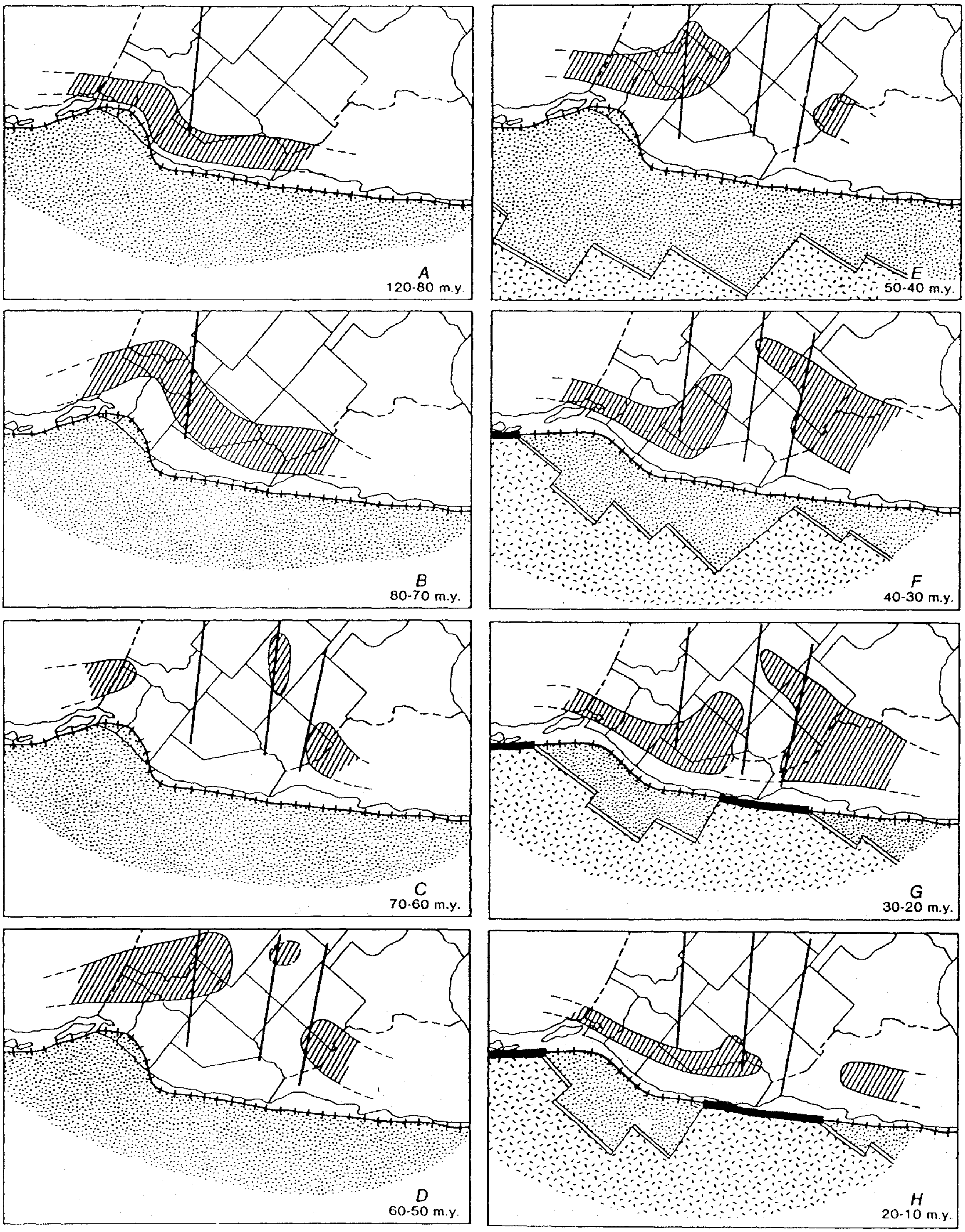

Fig. 8. Volcanic-tectonic patterns of evolution in southwestern North America (from Lipman, 1980).

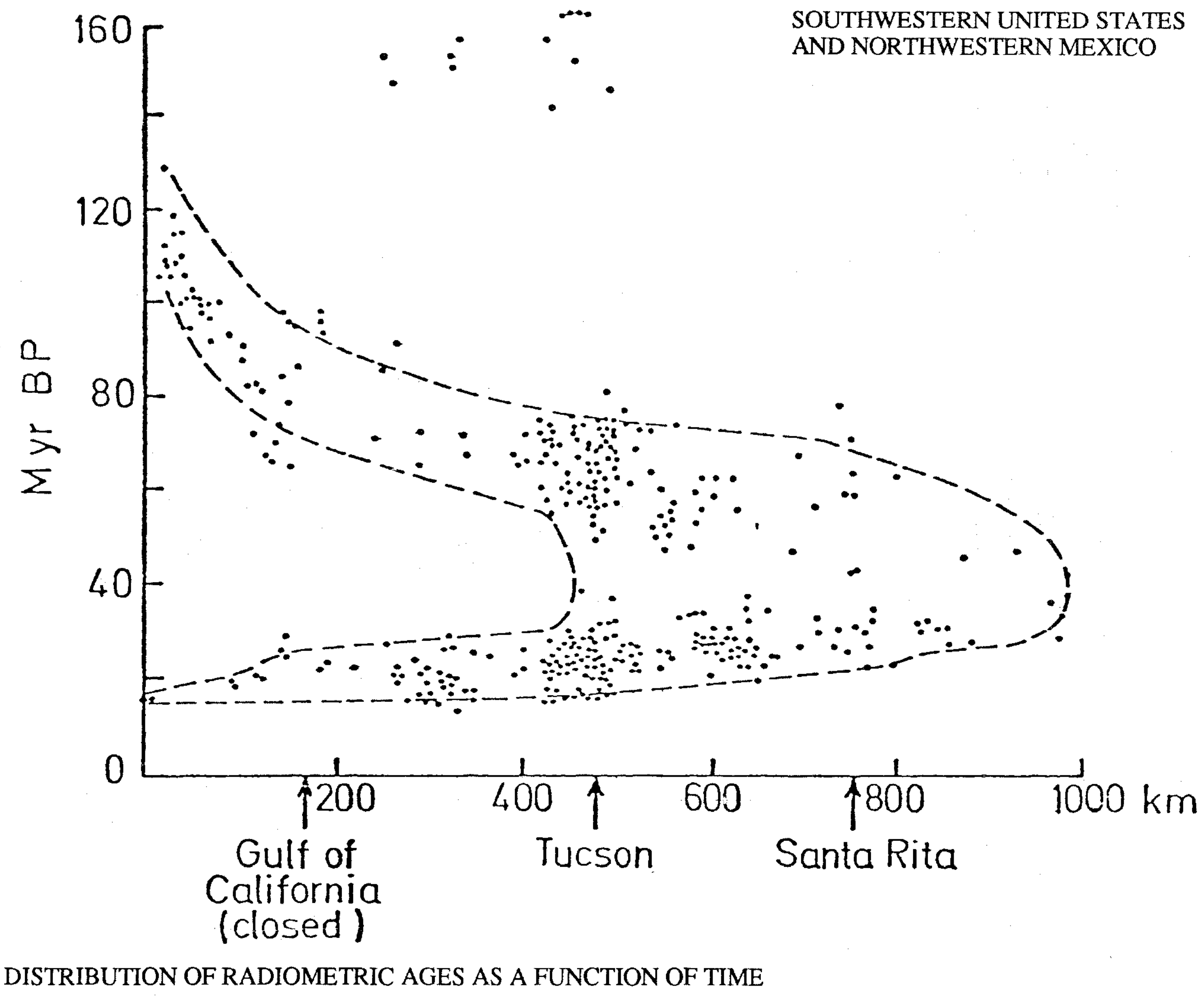

Fig. 9. Space-time pattern of geochronological data for magmatic-related igneous rocks in southwestern North America. Dates are plotted as a funcion of horizontal distance from the continental margin (paleo-trench). The Gulf of California has been closed for the reconstruction of the profile (modified from Coney and Reynolds, 1977).

in the Trans-Pecos area shows a marked change between 31 and 29 Myr, with the emplacement of bimodal suites. Volcanic rocks were either alkali basalts and rhyolites or basalts (James and Henry, 1991). Youngest rocks in the Trans-Pecos area are represented by alkali basalts emplaced between 24 and 17 Myr, contemporaneous with Basin and Range faulting. Activity continued to migrate further west during the next 10 Myr (between 20 and 10 Myr ago), and concentrated mainly along a narrow belt parallel to the margin (Figure 8h). The San Andreas fault system developed with northward or southward displacement of active plate subduction to the Juan de Fuca and Cocos plate areas. This resulted in changing patterns of tectonism along the margin. Activity in the Cascades volcanic arc continues to the present day as a narrow elongated andesitic arc which extends into California and western Nevada. Extensional tectonism over the Great Basin and Columbia plateau was associated with basaltic volcanism. Volcanic activity also occurred along the Yellowstone and Snake river area.

The space-time pattern of igneous activity across the margin was reconstructed from the distribution of available dates (Coney and Reynolds, 1977; Urrutia-Fucugauchi, 1978; Cross and Pilger, 1978; Henry *et al.*, 1991; Spencer, 1996). A composite profile oriented perpendicular to the margin in the southern United States and northern Mexico (Figure 1) shows a pattern of changes with time across the magmatic province (Figure 9). The spatial-temporal pattern of magmatism as delineated by the distribution of geochronological data has been analyzed before and several potential problems have been discussed (Krummenacher *et al.*, 1975; Coney and Reynolds, 1977; Cross and Pilger, 1978; Glazner and Supple, 1982; Urrutia-Fucugauchi, 1986). Factors that affect the spatial-temporal pattern of geochronological data include: (1) systematic errors (instrumental, human, etc) in some or all of the dates; (2) sampling bias, with portions of the volcanic sequence in critical areas misrepresented; (3) multiple intrusion events that reset the isotope systems, e.g., magmatic activity in the

Peninsular Ranges batholith of Baja California; (4) transgressive regional cooling in the batholiths associated with geothermal gradient motion independent of erosional level changes or due to progressive uplift and erosion; and (5) selective erosion or lack of outcrops in parts of the record.

From the space-time pattern of geochronological data on igneous rocks, Coney and Reynolds, (1977) found that the width of the magmatic arc increases from about 120-115 Myr to about 70 Myr (early stage) and then remains nearly constant between 70 Myr and 20 Myr ago (intermediate stage) with some changes mainly between 30 Myr and 20 Myr (Figure 10). During the intermediate stage the subduction angle in the magma generation zone remained nearly constant (Figure 11). The late stage extends from about 30-20 Myr to 15-10 Myr and perhaps continues into the present. During the intermediate and late stages the plate boundary evolved from a convergent boundary marked by dominant compressional tectonism to a transform boundary marked by dominant extensional tectonism. The spatial magmatic arc width increased as a result of arc migration inboard from 120-115 Myr to 50-40 Myr with progressive flattening of the shallow earthquake dip angle (Figure 12). The rate of plate convergence during the early development stage can also be estimated from the space-time pattern of geochronological data which increased by a simple linear relationship as a result of a 'constant' plate convergence acceleration (Figure 13).

4. EVOLUTIONARY MODELS

Several models have been proposed to explain the wide lateral extent of the magmatic province of southwestern North America. Lipman *et al.* (1971) initially proposed that the magmatic arc was the result of two eastwardly dipping subduction zones. Later studies proposed a single subduction zone, whose geometry and kinematics evolved with time. Here the following models are discussed: (1) variable subduction zone dip-constant depth of partial melting (magma generation zone) (Coney and Reynolds, 1977); (2) variable subduction zone dip-variable depth of magma generation zone (Keith, 1978); (3) low-angle subduction and variable trench-arc gap (sediment accretion and variable shallow-zone subduction dip) (Urrutia-Fucugauchi, 1978); (4) extensional tectonism (Basin and Range extension); and (5) back-arc spreading, rifting and subduction-related diapirs (including magmatism associated with continental rifting; Barker, 1977, 1979).

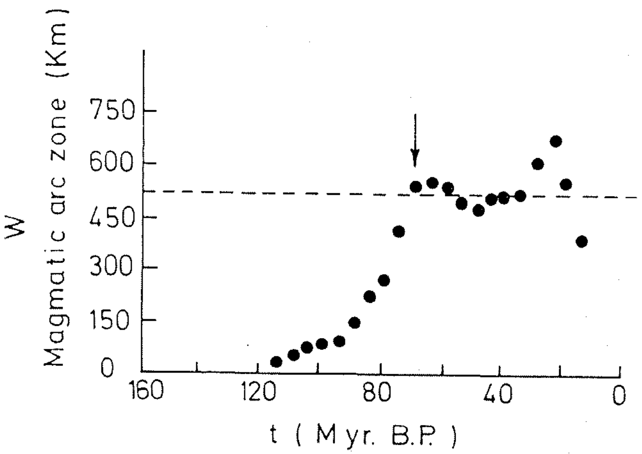

Fig. 10. Variation of the width of the magmatic arc zone (spatial arc) plotted as a function of age. The width has been derived from the spatial-temporal pattern of radiometric dates (Fig. 9). The arrow indicates the approximate time when the descending plate reaches the 300 km depth limit (referred to the geometric model of Fig. 4). Note that the width of the magmatic arc zone increases from 120 Myr to 70 Myr, and that the pattern changes at 70 Myr. The width of the zone does not increase after 70 Myr.

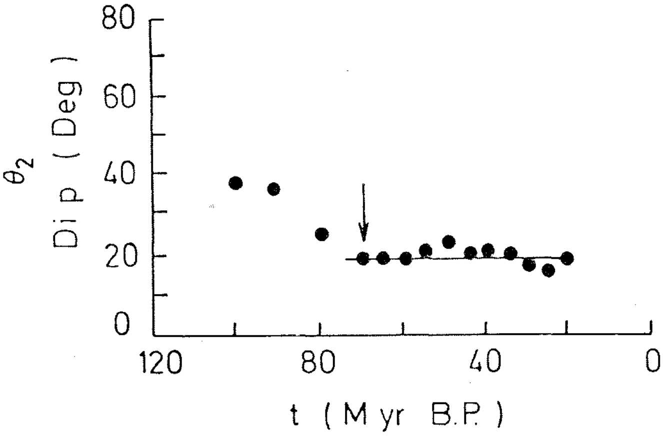

Fig. 11. Variation of subduction angles in the deep zone plotted as a function of time. Note that the dip remains fairly stable around 20 degrees from 70 Myr to 20 Myr. This pattern supports the occurrence of low-angle subduction beneath southwestern North America.

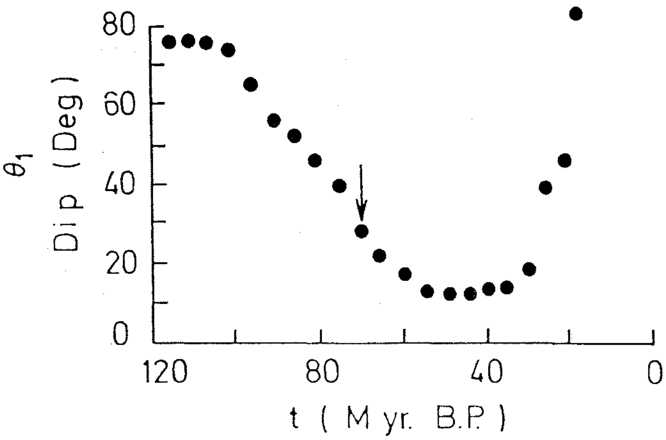

Fig. 12. Variation of subduction angles in the shallow earthquake zone plotted as a function of time. Note that this dip represents an apparent angle that geometrically gives the variation of the trench-arc gap with time when referred to the geometric model of Fig. 4. The trench-arc gap may increase as a result of shallowing of the subduction angle or trenchward migration of trench due to e. g., accretion in the sedimentary prism. See text for discussion.

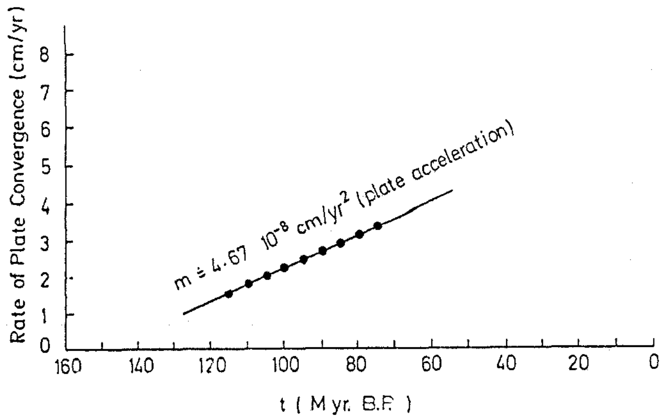

Fig. 13. Estimate of variation of plate convergence in terms of the second derivative of the spatial-temporal pattern defined by the geochronological data (Figure 9). Plate convergence increases linearly for the interval 120 Myr to 75 Myr, with a plate acceleration rate of 4.67 10^{-8} cm/yr^2.

In the variable subduction zone dip model, the lateral migration of magmatic activity across the arc is modeled as due to dip changes and a fixed zone of magma generation (Coney and Reynolds, 1977). The subduction zone dip (Θ) is related to the convergence rate by

$$\Theta = \sin^{-1} v_g/v_p \qquad (1)$$

where v_g is the vertical component due to gravitational sinking of the subducted plate (around 5 cm/yr) and v_p is the plate convergence rate in the direction of plate subduction (Luyendyk, 1970).

Coney and Reynolds (1977) assumed a Farallon-North America convergence rate of about 12-14 cm/yr for the interval 80 to 40-45 Myr, which results in a subduction angle of 20-25 degrees. From the spatial temporal diagram of radiometric dates (Figure 9), they concluded that the subduction angle changed from around 70 degrees at 100 Myr to shallow values of around 10 degrees at 45 Myr (Figure 14). This shallowing of the subduction angle resulted in landward migration of the magmatic arc. A decrease of the convergence rate after the Hawaiian-Emperor bend at about 42 Myr to 6-8 cm/yr (as the Pacific plate motion changed from north to northwest) resulted in steepening of the subduction angle to 40-60 degrees. The rapid post-25 Myr steepening of the subduction dip (Figure 14), after a period of very shallow subduction, resulted in a trenchward migration of magmatic activity. This model does not consider the effects of crustal structure and tectonics, nor does it address the mechanics of large changes in the subduction angle. Also, the assumption of homogenous parent magmas contrasts with the observed lateral changes in geochemistry and petrography, and particularly with the eastward increase in alkalinity across the magmatic province.

In the model of variable subduction angle with variable depth of magma generation, the variation in arc magmatism with eastward increase in alkalinity is considered and translated into greater depths of partial melting. Keith (1978) used the relation between K_2O content at a given SiO_2 content and the depth to the seismic zone as given by Dickinson (1975) to estimate the angle of subduction (Θ):

$$\Theta = \tan^{-1} (h/d) \qquad (2)$$

where h is the depth and d is the arc-trench gap.

The change of subduction angle estimated from the K_2O-h relation (Keith, 1978) is similar to that derived from the constant dip model (Coney and Reynolds, 1977). The two models are compared in Figure 14. For variable depth of magma generation, the interval of very shallow angles (about 10°) is brief and occurs earlier, at 65 Myr (Figure 14). Very shallow subduction angles, on the order of 10°, have been observed beneath contemporary subduction zones and have been linked to gaps in magmatic activity (e.g., in the Peru trench). The problem of explaining the mechanics of large long-term changes in subduction angle as required for the shallowing and rapid steepening of the slab remains to be addressed in detail.

In the model of low-angle subduction and variable trench-arc gap (Urrutia-Fucugauchi, 1978), it is assumed that the lateral migration of magmatic activity is mainly related to changes in the trench-arc gap. The changes are related to several processes (Table 2), mainly sediment accretion, seaward migration of the trench and change of subduction zone dip in the shallow zone (Dickinson, 1973; Jacobs *et al.*, 1977). Absolute motion with overriding of the subducted plate produces trenchward advance and shallower subduction angles. This leads to an evolutionary classification of subduction zones, from compressional Andean-type tectonics to back-arc spreading and marginal basin tectonics (Uyeda and Kanamori, 1979). The net effect of all these processes may be modeled in terms of an 'equivalent' subduction angle in the shallow zone (Figure 4). In addition, other processes may contribute to modify the trench-arc gap (Table 2), including extension (Basin and Range province), obduction, margin-transport of slivers and terrane accretion.

Jarrard (1986) noted that the gravitational component of sinking in the relationship suggested by Luyendyk (1970) increases with increasing age of the subducted plate, and that there is a moderate correlation between the maximum depth of the Benioff zone and age of the subducted plate, and between the horizontal extent of the Benioff zone and the convergence rate. The relationship in terms of age of the subducting plate at the trench (A_s) and convergence rate (CR) is

$$\Theta = 0.17\, A_s - 0.23\, CR + 41.7 \qquad (3)$$

which yields a subduction angle similar to that derived by Keith (1978). However, Jarrard (1986) concluded that the agreement is coincidental since there is a considerable difference between the average subduction angle in contempo–

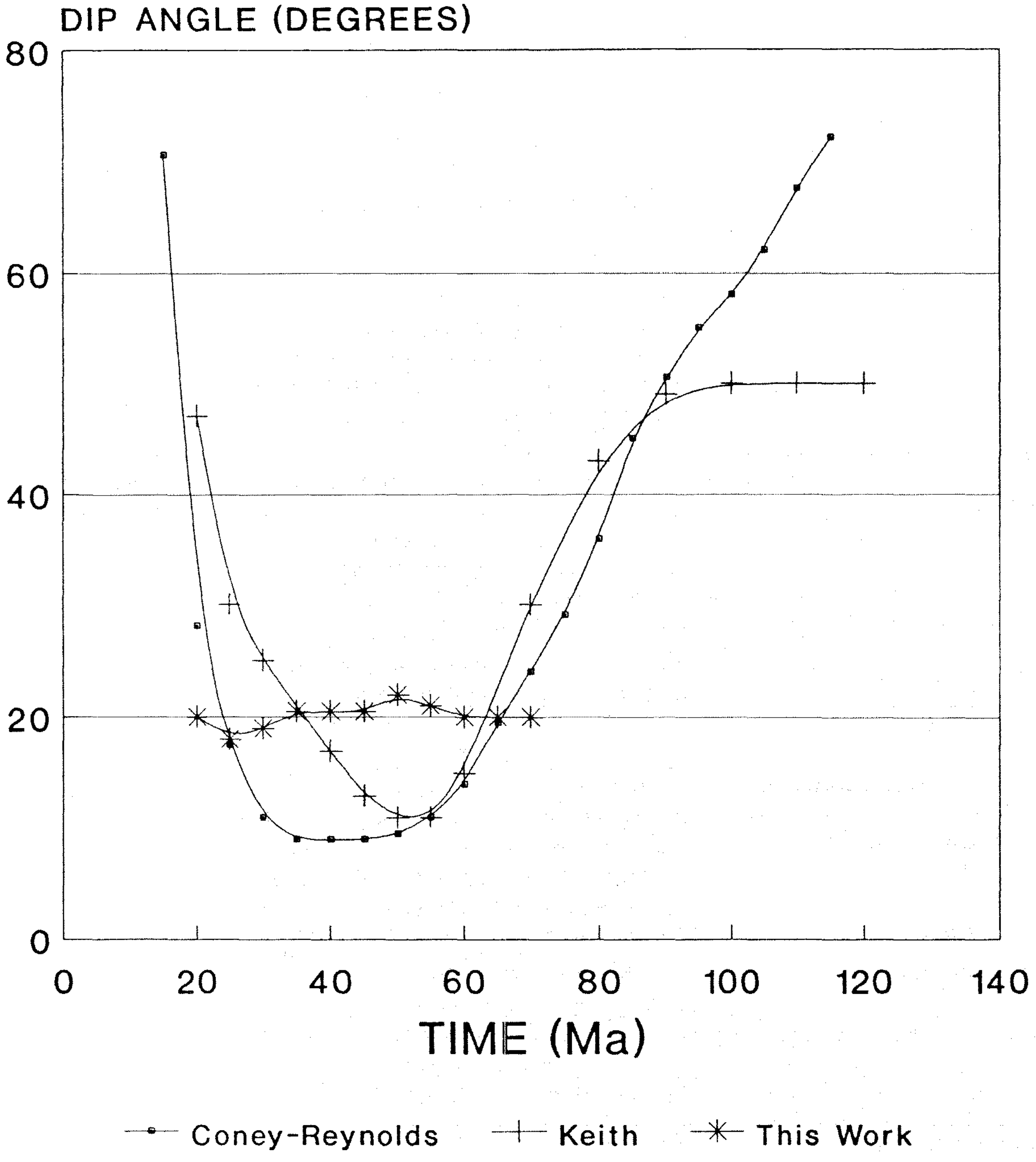

Fig. 14. Subduction angles plotted as a function of time, estimated from the models of Coney and Reynolds (1977), Keith (1978), and this study. In the first two models the subduction dip angle decreases steeply in the interval 120 Myr to 60 Myr. These models require that the subducted plate move upwards against the sinking component of the slab through the mantle wedge, or alternatively that the slab breaks as new plate is being subducted at progressively shallower dip angles.

rary subduction zones (e.g., Figures 2 and 3) and the angle at about 100 km depth in the zone of magma generation. Jarrard (1986) also mentioned the along-arc migration of magmatism associated with migration of the Mendocino triple junction as proposed by Glazner and Supple (1982). Along-arc migration is discussed in the next section. Cross and Pilger (1982) proposed that besides the age of subducted plate and convergence rate the subduction angle is a function of the absolute motion of the overriding plate and subduction of aseismic ridges. The shallow dip angle is also affected by accretion (Table 2).

The continental lithosphere and crust in southwestern North America has been modified and thinned during the Cenozoic, and large amounts of extension ranging from 10% to 300% have been proposed for the Basin and Range province (Hamilton and Myers, 1966; Wernicke *et al.*, 1982). Bogen and Schweickert (1985) estimated that exten-

Table 2

Some factors affecting width of trench-arc gap

Factor	Possible effects and associated phenomena	Comments
1. Age of plate being subducted	Younger lithosphere elevates isotherms and magmatic front gets closer to the trench. Lenght of Benioff zone also decreases.	This factor combines with convergence rate variations and produce lateral migration of trench
2. Benioff zone dip	Decrease in dip increases width of magmatic arc gap: increase decreases gap.	
3. Convergence rate	Faster rates depresse isotherms and increases width of trench-arc gap. Lenght of Benioff zone also increases.	
4. Absolute motion of upper plate	Decrease in component normal to trench axis may produce seaward migration of trench. (Also increase of component against plate margin). Increase in component normal to and towards trench reduces Benioff zone dip. Direction towards plate margin produces overriding and seawards migration of trench; against plate margin produces landward migration and back arc extention (3).	Fast rates in thrust faulting, absence of volcanic activity (2)
5. Hydrodynamic forces	Subducted plate sticks to upper plate volcanic activity decreases or becomes absent (2).	
6. Accretion of trench sediments	Increase of trench-arc gap sediment load may depress oceanic plate prior to subduction (4).	
7. Age of trench-arc system	(No subduction of young lithosphere). Additive effects of accretion and depression of isotherms which increase trench-arc gap. Upper plate (lithosphere and crust) thickens.	
8. Ridge subduction	Benioff zone dip decreases. Depth of melting decreases.	
9. Subduction of bathymetric highs	Benioff zone dip decreases and so does the width of the trench-arc gap	
10. Obduction	Increase of width of the trench-arc gap.	
11. Tectonic erosion	Decrease of width of the trench-arc gap	
12. Continental margin truncation	Decrease of width of the trench-arc gap	

(1) Ruff and Kanamori (1980); (2) Barazagni and Isacks (1976); (3) Wilson and Burke (1972); Worzel (1976).

sion in the northern sector of the Basin and Range province is in the order of 39 ± 12%, with maximum values of about 50%. Extension of 39% translates into some 188 ± 43 km of crustal extension. Extension in the Basin and Range province may thus account for part of the apparent large extent of the magmatic arc.

Processes afecting the width of the magmatic arc zone include changes in subduction zone dip within the deep zone, position of partial melting zone, and tectonic extension (Table 3).

5. DISCUSSION

Lateral migration of magmatic activity across the continental margin and into the continental interior was followed by an opposite migration during the final stages as suggested by the space-time distribution of geochronological data in the southwestern United States and northern Mexico. The characteristics and limits of the spatial-temporal pattern of changing magmatic activity are still subject to modification. The geometry of the subduction system and the kinematics and dynamics of plate interactions

Table 3

Some factors affecting the width of the magmatic arc zone*

Factor	Possible effects and associated phenomena	Comments
1. Benioff zone dip	Decrease in dip increases of magmatic arc. Magma geochemical belts are displaced with the arc, they are affected by the dip changes resulting in cessation or initiation of given belts.	Very low dips may result in absence of volcanic activity (1).
2. Depth and limits of zone of partial melting	Increased depth of partial melting may result in increasing alkalic magma geochemical belts and increase of the magmatic arc width.	
3. Back-arc extention	This may result in an increase of width of the magmatic arc, which could be eventually broken appart.	Break up of the arc may take place along the zone of active volcanism (2).

(1) Barazangi and Isacks (1976); (2) Molnar and Atwater (1978).
Note: * See also factors listed in Table 2

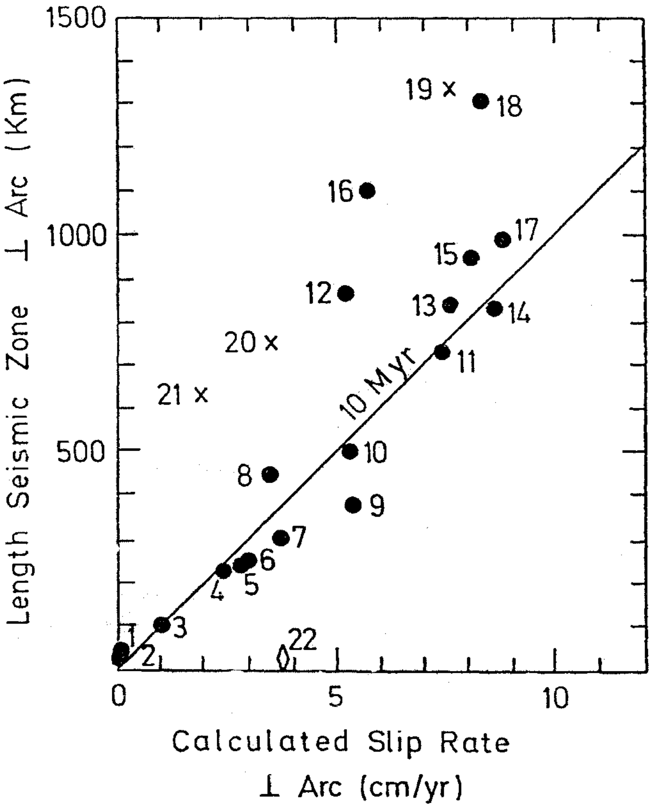

Fig. 15. Length of seismic zones perpendicular to the arc as a function of estimated slip rates for different subduction zones. The regression line has a slope of 10 Myr.

are not known with sufficient detail to incorporate constraints on the position of the trench, oblique volcanic front, lateral changes along the system (along and across changes in the magmatic arc), etc. Our pattern thus gives at best a regional simplified picture of the evolution of the magmatic arc. The long-term evolution of the continental magmatic arc suggests three stages, with an early stage characterized by dominant eastward migration of igneous activity away from the trench and into the continental interior. Landward migration of activity lasts for about 45-50 Myr. Magmas are mainly calc-alkaline and tectonism is predominantly compressional. The intermediate stage lasts for about 50 Myr and is characterized by development of magmatic activity far away from the trench. Activity in the Trans-Pecos field begins around 48 Myr and lasts about 17 Myr. The character of the magmatism changes between about 31 and 29 Myr, coinciding with the change in tectonism from dominantly compressional to extensional (Henry *et al.*, 1991; James and Henry, 1991). The late stage lasting some 10-20 Myr is characterized by trenchward migration of the magmatic activity at relatively rapid rates.

The model implies that the descending plate reaches increasing depths as the subduction zone evolves, until the lower limit of the mesosphere is reached or the plate geometries are changed. Isacks *et al* (1968) suggested that the maximum depth reached by the plates correlates with the rate of convergence and that the correlation is better between the subducted plate length, which depends on the maximum depth and the subduction angle, and the convergence rate (Figure 15). The relationship is linear with a slope of 10 Myr. They advanced two possible explanations. One assumes that the present subduction zones were created 10 Myr ago (Oliver and Isacks, 1968) and the other, that 10 Myr is the thermal time constant of the plate to be assimilated by the mantle. The first explanation has been ruled out (Le Pichon *et al.*, 1973), whilst the second has been considered as possible within certain constraints (McKenzie, 1969; Le Pichon *et al.*, 1973). These correlations have also been found for individual plate boundaries, e. g. the series of arcs from Tonga to Macquarie Island

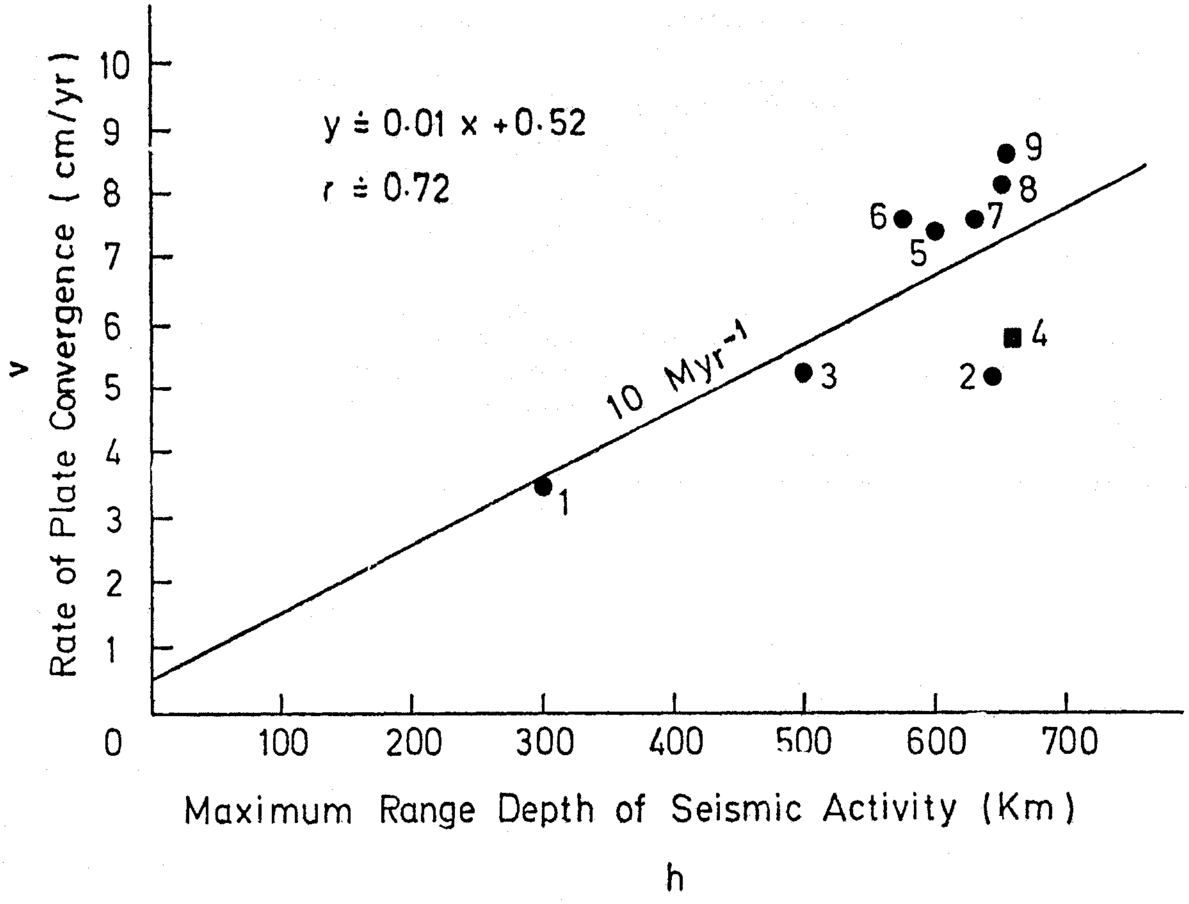

Fig. 16. Rate of plate convergence plotted as a function of maximum range of seismic activity or deepest earthquakes for various subduction zones.

(Isacks *et al.*, 1968; McKenzie, 1969), the Palau-Yap arcs to the Izu-Bonin arc (Isacks *et al.*, 1968), the New Zealand arc, and the Aleutian arc to the Kurile and Japanese islands (Isacks *et al.*, 1968).

The depth of the deepest earthquakes is related to the convergence rate in some subduction zones (Isacks *et al.*, 1968; Isacks and Molnar, 1971). This is shown in Figure 16 (Urrutia-Fucugauchi, 1980). The inverse slope of the regression line is about 10 Myr which agrees with the finding of Isacks *et al.* (1968). Note that the intercept is about 0.52 cm/yr. This suggests that the rate of plate convergence required to start a subduction process is of this order. The rates at 100 km and 300 km depth (limits of the magma generation zone) are about 1.5 and 3.6 cm/yr.

For southwestern North America (Figure 13), and assuming that the relationship can be extrapolated back in time, the period at which the rate of plate convergence is 0.52 cm/yr can be estimated at around 137 Myr. This age may represent an estimate for the initiation of plate subduction. The rate of plate convergence at the margin has changed with time. This variation can be estimated from the space-time plots (Figure 13). The inverse slope, which gives the plate convergence acceleration, is about 4.67 x 10^{-8} cm/yr^2. By extrapolating further back, the time required to increase the rate of plate convergence from 0 to 0.52 cm/yr, i. e. the initiation of active subduction, is about 11 Myr.

The changes between 30 Myr and 15 Myr ago (Figure 10) may be related with the subduction of the rise and the subsequent evolution of the Kula-Farallon-North America triple junction (Atwater, 1970, 1989; Stock and Molnar, 1988). Subduction of segments of a spreading system and subsequent subduction angle flattening could result in higher thermal effects and in lithospheric and subcrustal erosion and back-arc extension, thus explaining the origin of the Gulf of California and the Basin and Range province. These features are associated with dominant widespread extensional tectonism and high heat flow related to continental breakup.

During the earlier stages of increased subcrustal thermal effects, before the initiation of active extensional tectonism and rifting, regional uplift caused the elevation of the Basin and Range province. As the thermal effects increased, they resulted in subcrustal erosion which has been causing a progressive thinning and extension with lateral growth of the province. Heating of the crust resulted in the generation of an upward and lateral flow of decreasing density and viscosity. The molten material may have produced the upward force still acting under the Colorado plateau and causing the uplift. Concurrently, extensive and severe subaereal erosion was acting in the Basin and Range province. This process produced widespread extensional tectonism and rifting in the Basin and Range province (Urrutia-Fucugauchi, 1978).

During magmatic arc development between 115 Myr and 70 Myr ago, as the subduction rate was progressively increasing, the Kula-Pacific spreading system was being modified. Atwater (1970, 1989) concluded, from the offset of the Mendocino fracture zone, that this marks major changes between 115 Myr and 77 Myr ago. From variable spacing of magnetic anomalies, "until about 72 Myr ago, the Kula-Pacific (ridge) spreading system was still getting adjusted to a large change or to its original formation".

These results constrain the hypotheses about driving forces, suggesting that the source is more likely related to deep processes (McKenzie, 1969; LePichon *et al.*, 1973). At least this is true for the earlier stages, when neither a spreading center nor a trench were formed. The driving forces arising from rise push or trench pull (McKenzie, 1969; LePichon *et al.*, 1973) developed as the spreading center-trench system evolved.

It should be noted that a change in the trench-arc gap may result either from lateral migration of the trench or from migration of the magmatic front (Table 2). Thus the term "apparent" rate of migration is being used. This apparent rate of migration of the magmatic front can be estimated from Figure 10. The apparent rate of migration inboard from the trench (100 to 50 Myr) is about half the apparent rate observed towards the trench (40 to 15 Myr). The changes in the rate are not linear, with average rates of about 0.9 cm/yr and 1.8 cm/yr, respectively. The maximum displacement is about 450 km and the distance from the present coastline is about 475 km. Thus the trench-arc gap reached values of about 450 km.

Luyendyk (1970) suggested that the subduction angle correlates with the rate of plate convergence, higher dips corresponding to lower convergence rates. He used average subduction angles for his calculations instead of the two dip angles considered here. On the other hand, Tovish and Schubert (1978) have argued that the subduction angle does not correlate with the plate convergence rate in certain arcs. As the subduction zone dips are difficult to estimate there are different estimates in the literature for some arcs. Tovish and Schubert (1978) also considered a single dip estimation and pointed out some discrepancies between their values and values given elsewhere. The rate of convergence was only estimated during the early development stage, and this appears to agree with Luyendyk's correlation, with the rate (Figure 7) higher as the subduction angle gets shallower (Figures 11 and 12). Using Luyendyk's correlation, the rate should be higher during the earlier stages. This implies that the rate variation was different from that of the early stage (Figure 13), perphaps as a result of plate interaction with the mesosphere. This change in subduction angle and plate convergence rate correlates with the Laramide orogeny which occurred between about 80 Myr and 45 Myr ago (Coney, 1978). During the late stage, the dip increased again and the rate of convergence probably also decreased. This correlates with the mid-Tertiary orogeny which is associated with a change in magmatic activity and in type of tectonism (Figure 17). Roeder (1975) discussed some tectonic effects related to subduction angle changes and suggested that flattening was accompanied by compressional tectonism or steepening by tensional tectonism, which agrees with the above interpretation. In this case, dip changes are related to changes in convergence rate (Roeder, 1975). However, dip changes may also result from lateral variations in the age of the subducted lithosphere or the occurrence of anomalously busyant lithosphere (e.g., oceanic plateaux). In those cases, dip changes may occur locally within segments of the subduction zone. This situation has been documented for a portion of the subduction zone in South America (e.g., Wortel and Vlaar, 1978).

Livaccari *et al.* (1981) proposed that the Laramide orogeny was triggered by low-angle subduction of a large oceanic plateau (with anomalously high buoyancy). Subduction of this thick buoyant oceanic crust resulted in uplift of the fore-arc region, cessation of arc magmatism (hiatuses present in the southwestern United States) and widespread deformation. Subduction of young lithosphere (< 50 Myr) has been associated with Cordilleran tectonics (high mountain ranges, extensive deformation zones, thrust faulting and crustal shortening normal to trench-arc system). Molnar and Atwater (1978) have suggested that deformation in western North America may be related to long-term subduction of young Farallon and Kula lithosphere.

In Figure 18 the results corresponding to the temporal correlations of the width of the magmatic arc, the depth reached by the descending plate, the subduction angle in the magma generation zone, the length of the plate subducted, and the subduction rate are summarized. Additionally, in Figure 19, the main features of the plate tectonic evolution for the southwestern continental margin of North America are summarized. To get a three-dimensional picture, the lateral variations must be considered; this aspect will be examined elsewhere, as we consider the margin from Canada, where part of the ridge system is still active, to Mexico, where the active ridge portion is represented by the East Pacific rise.

Some studies have examined the potential effects of subducting the spreading ridge system beneath the continental margin. Using the Pacific plate marine magnetic

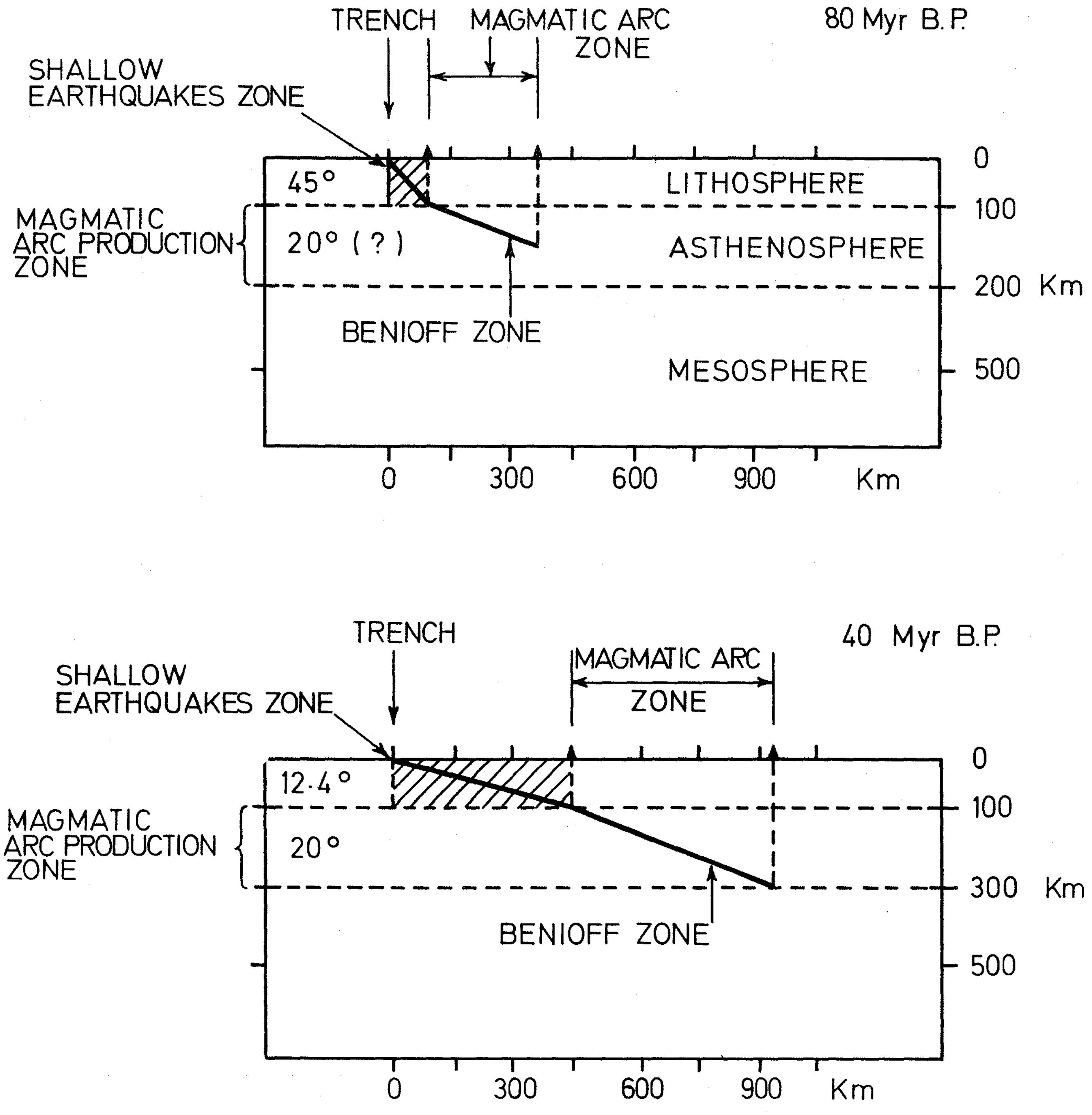

Fig. 17. Schematic representations of the geometry of the subduction zone-magmatic arc for two different time intervals. (a) 80 Myr, (b) 40 Myr.

anomaly and the fracture zone patterns (Dickinson and Snyder, 1979; Urrutia-Fucugauchi, 1986; Atwater, 1989), the position of the 'subducted' ridge segments can be estimated beneath North America. It is interesting to note the apparent correlation with one portion of the ancient spreading center located just beneath the Colorado plateau, another below the Rio Grande rift (Farrar and Dixon, 1993) and others beneath the Sierra Madre Occidental in northern Mexico (Urrutia-Fucugauchi, 1986). Studies of ridge-trench interactions have documented several potential effects of subduction of young buoyant lithosphere and segments of the spreading system beneath a continental margin (e.g., DeLong *et al.*, 1978; Farrar and Dixon, 1993). The resulting deformation of the margin and the change in stress regimes and magmatism produce uplift and tectonic erosion in the foreacrc as well as uplift in the arc and back-arc regions with high heat flow and extensional tectonism. Rift or plume-type magmatism develops, apparently related to active asthenospheric upwelling (e.g., Wilson, 1988; Farrar and Dixon, 1993). An important aspect of subduc–

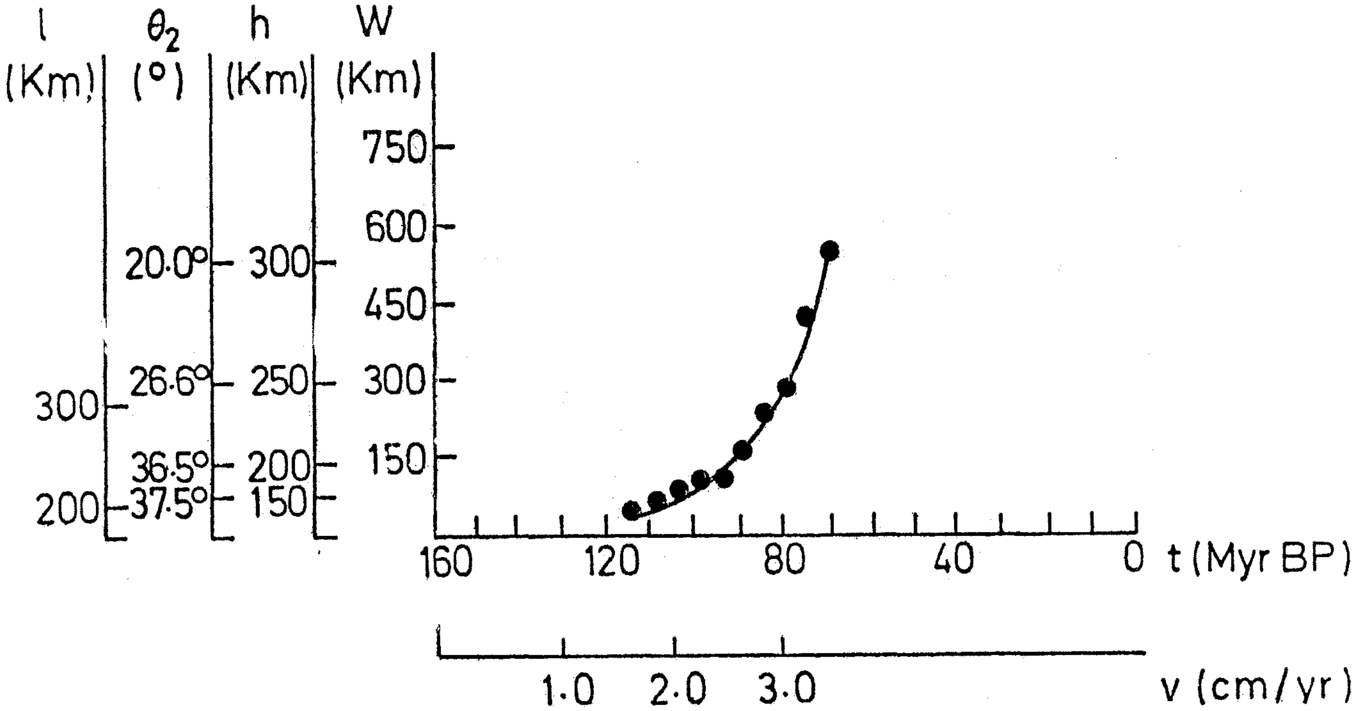

Fig. 18. Summary of spatial-temporal variation of the width of magmatic arc (W), maximum depth of subducted plate (h), apparent subduction dip angle in the deep zone (0_2), and (l) plotted as a function of time or subduction velocity for the interval 120 Myr to 70 Myr.

tion of ridge segments relates to the subsequent evolution of the ridge system after it interacts with the trench (Atwater, 1970, 1989). Spreading terminates with the trench interaction and eventually forms a slab window (Dickinson and Snyder, 1979).

A westward migration of magmatic activity during the Late Tertiary (< 40 Myr) has been questioned by Glazner and Supple (1982). They argued that the spatial-temporal pattern in the western United States defines a northward migration of magmatic activity that closely followed subduction of the Mendocino fracture zone. The estimated rate of northward migration is about 3.1 km/Myr. In the eastern or Gulf alkaline province of Mexico that extends from the Trans-Pecos area to the Tuxtlas volcanic field, Cantagrel and Robin (1979) documented a southward migration of activity. K-Ar dates for the Sierra de Tamaulipas to the Tuxtlas in northeastern Mexico get younger from Late Oligocene to Recent. It is, however, difficult to establish any relationship with the plate interactions along the western margin. The alkaline magmatism in the north which includes the older activity in the Trans-Pecos-Texas field and the complexes of Monclova-Candela and Sierra de San Carlos, has been related to low-angle subduction (Henry *et al.*, 1991; Morton-Bermea, 1995). Younger activity along the Gulf province has been related to extensional tectonism (James and Henry, 1991; Morton-Bermea, 1995; Ramírez-Fernández and Keller, 1997). Ramírez-Fernández and Keller (1997) recently examined the geochemistry of the intrusives in the Sierra de Tamaulipas complex and identified two distinct groups. One group composed of diorites to syenites with low Ta and Nb contents is related to Farallon plate subduction. The other group composed of high-level A-type granites and syenites formed by crystal fractionation from alkali basalt parental magmas is associated with extensional tectonism. Cross and Pilger (1978) analyzed both north-south and east-west cross sections approximately oriented normal and parallel to the western continental margin. The north-south cross-section shows a weak regional trend of northward migration. However, the geochronology of volcanic fields in Nevada displays a long-lived locus of activity spanning the past 40 Myr. The section normal to the margin displays a westward migration of activity in the form of a broad band which is disrupted in the Nevada area. Spencer (1996) has recently analyzed the space-time patterns of activity and its relation to crustal structure for a WSW-ENE cross-section that documents a westward migration of activity. His is tectonic model involves low-angle subduction. The pattern defines a westward migration from southwest New Mexico at around 35-30 Myr to central Mojave at about 20 Myr (Spencer, 1996).

Similar work in other spatial magmatic arcs, e.g., the Permian magmatic province of Peru, the Early Jurassic-Early Tertiary magmatic province in the Coast Range of Central Chile and the magmatic zone in eastern Asia and Japan, is in progress. Future results may reveal the presence of a long-term evolutionary pattern of spatial magmatic arcs in general.

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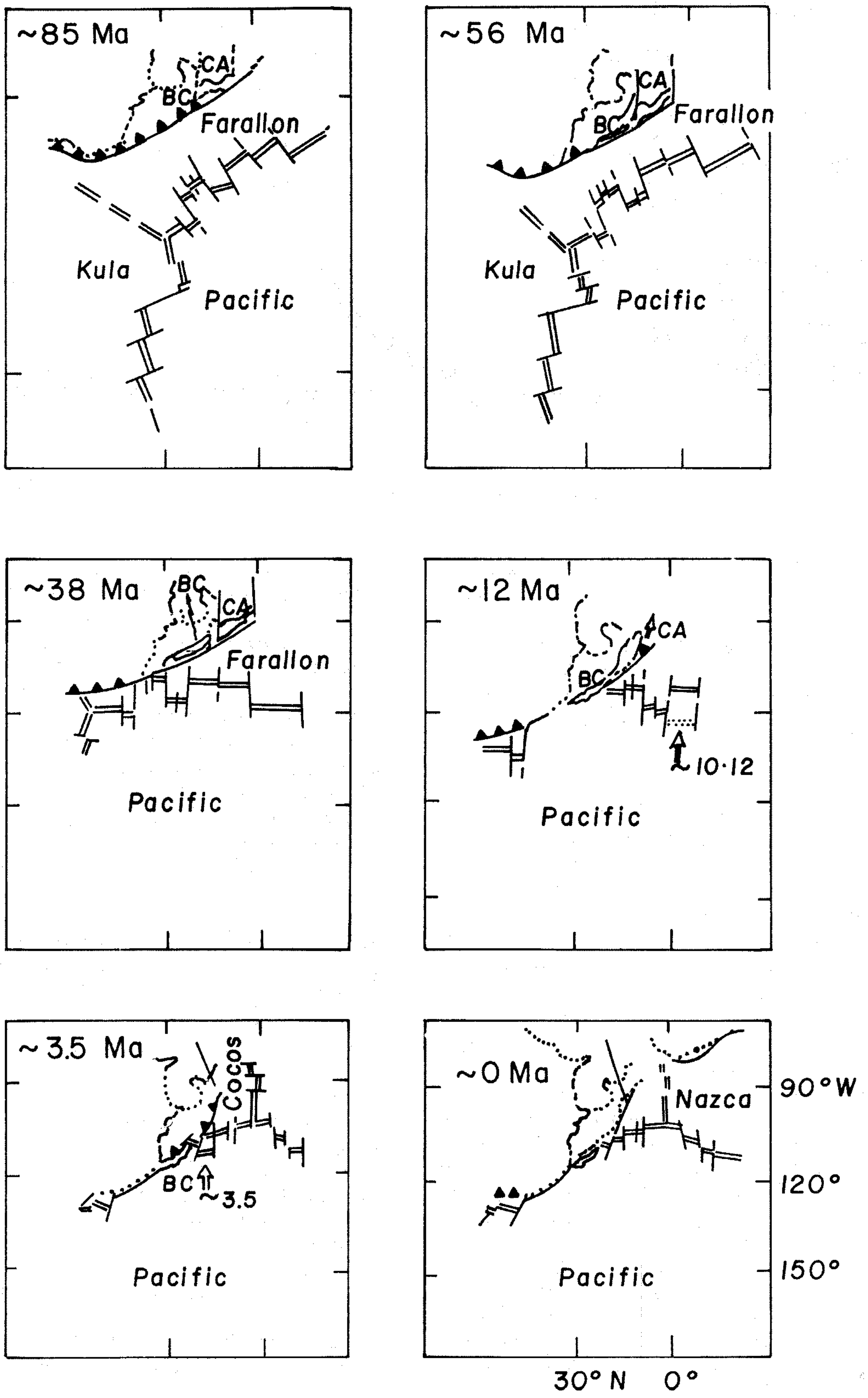

Fig. 19. Plate motions in the northeastern paleo-Pacific between about 85 Myr to present. The approximate configuration of the trench system is indicated by the saw-tooth pattern along the paleomargin.

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