Geof. Int. Vol. 25-1, 1986, pp. 61-84

LATE MESOZOIC-CENOZOIC EVOLUTION OF THE NORTHWESTERN MEXICO MAGMATIC ARC ZONE

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RESUMEN

Los datos radiométricos de rocas ígneas del Mesozoico tardío - Cenozoico de la provincia magmática del noroeste de México se emplean para estudiar la evolución tectónica del margen continental. Los resultados indican que la actividad magmática ha cambiado su posición con el tiempo, desde ~140 ma al presente. Entre los 140 y 60 ma, la distancia arco magmático - trinchera se incrementó desde 100 a 400 km, con una velocidad entre 1 y 12 cm/año. El área cubierta por el material ígneo se incrementó hasta ~540 km, lo que combinado con los cambios en la distancia arco - trinchera, resultó en un arco magmático espacial de ~1 200 km. Los magmas fueron predominantemente calco-alcalinos y la tectónica fue compresional. Entre ~60 y ~30 ma, la actividad magmática se desarrolló en localidades alejadas de la trinchera, con rocas calco-alcalinas de alto potasio y alcalinas. La tectónica cambió de compresiva (orogenia Laramide, ~80 a 45 ma) a extensiva (orogenia del Terciario medio, ~35 - 15 ma). Finalmente, entre 35 - 30 y 10 - 0 ma, la actividad magmática se desplazó rápidamente hacia la trinchera y la tectónica fue extensiva. El volcanismo fue bimodal e incluyó el emplazamiento de secuencias ignimbríticas.

En este intervalo ocurrió una reorganización en las relaciones de placas litosféricas que incluyó el encuentro de segmentos de la dorsal con la trinchera y la generación de fallas transformadas. El Golfo de California comenzó a desarrollarse y se incrementaron fases activas de esparcimiento del fondo oceánico en los últimos 4.5 m.a. Los cambios observados en la distancia arco-trinchera y en el ancho de la zona de manifestaciones magmáticas se interpretan con un modelo de ángulo de subducción variable y de profundidad y rango de generación de magma variable. Los factores principales involucrados fueron el cambio de edad de la placa oceánica (paulatinamente más joven), cocientes de convergencia de placa, abducción de corteza oceánica, subducción de altos batimétricos y extensión tectónica.

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ABSTRACT

Late Mesozoic - Cenozoic radiometric data on igneous rocks from the extensive magmatic province of northwestern Mexico are used to investigate on the evolution of the continental margin. Results show that magmatic activity changed systematically with time from about 140 my B.P. to the present. Between about 140 and 60 my B.P. the trench-arc gap increased from about 100 to 400 km with a velocity varying from 1 to 12 cm/yr. The area covered by magmatic products also increased up to ~540 km, which, combined with the trench-arc gap changes, resulted in a ~1 200 km wide spatial magmatic arc. Magmas were dominantly calc-alkaline and tectonism was predominantly compresional. Between about 60 and 35 - 30 my B.P., magmatic activity developed at points farthest from the trench, giving high-K calc-alkalic and alkaline rock suites. Tectonism changed from mainly compressional (Laramide orogeny, ~80-45 my B.P.) to mainly extensional (mid-Tertiary orogeny, ~35 - 15 my B.P. Finally, between about 35 - 30 and 10 - 0 my B.P., magmatic activity was rapidly displaced towards the trench and tectonism was mainly extensional. Bimodal volcanism developed including the emplacement of a thick ignimbritic sequence, and apparently continued long after cesation of active plate subduction. Major plate reorganization occurred during this interval, associated with the encounter of segments of the spreading center and trench, which resulted in replacement of plate subduction by transform motion. Major recent events include the development of the Gulf of California, about 15 my ago, with active spreading occurring mainly during the last 4.5 my. The changes observed in the trench-arc gap and in the width of the zone of magmatic manifestations are interpreted in terms of a model of variable subduction zone dips and variable depth and range of magma generation. Major factors involved were the change of age of the plate being subducted (progressively younger), rate of plate convergence, absolute motion of upper plate, sediment accretion, obduction, subduction of oceanic plateaus and tectonic extension. Relative importance of these factors, however, remains to be quantified.

INTRODUCTION

The Sierra Madre Occidental (SMO) of northwestern Mexico is a linear ~1 200 km long partly dissected volcanic-capped plateau which parallels the western coastline from the USA-Mexico political boundary to the Trans-Mexican volcanic belt (Fig. 1). Its width varies up to 200 - 300 km, and additional flanking volcanic manifestations extend up to 300 - 400 km from the main axis of the SMO. Further, plutonic (roots of a volcanic arc; Dickinson, 1970) and volcanic rocks are exposed in the Baja California peninsula and western margin of mainland Mexico (Fig. 1). In all, the entire region from the Baja California peninsula to more than 1 200 km to the east represents a wide magmatic province. Current plate tectonic models for western North America indicate that eastward dipping plate subduction was the predominant tectonic process during the Mesozoic and Cenozoic (Atwater, 1970; Atwater and Molnar, 1973). The extensive magmatic province of northwestern Mexico (together with that of southwestern USA) represents a subduction-related magmatic arc. The spatial characteristics of this magmatic arc differ however from those observed in presently active magmatic arcs which are narrow (Dickinson and Hatherton, 1967). The purposes of this work are: (1) to evaluate whether the widespread Late Mesozoic-Cenozoic magmatic activity is in general consistent with the plate subduction-magmatic arc model, and (2) to evaluate major tectonic processes which may have controlled the evolution of the continental margin.

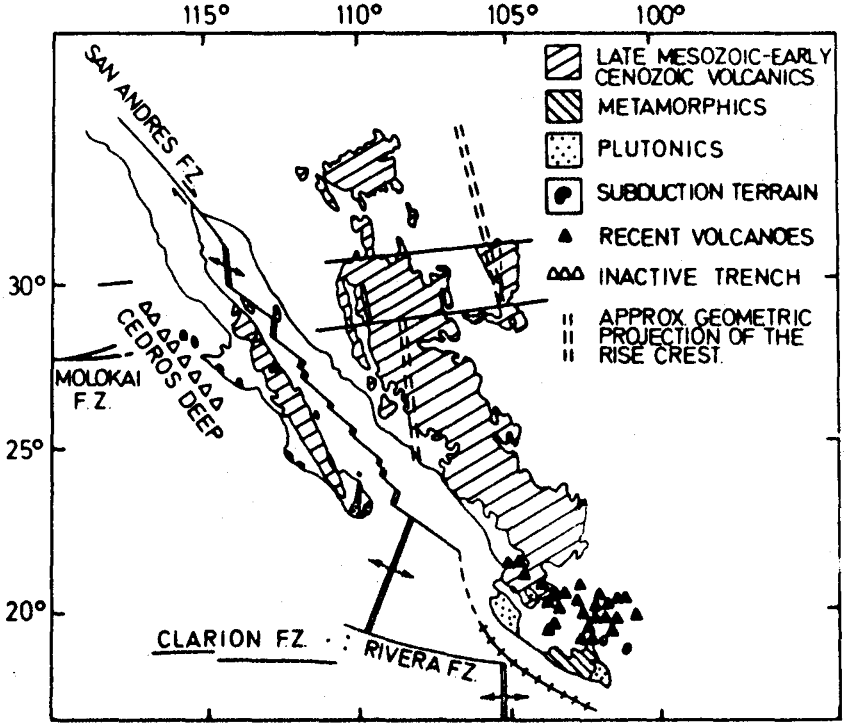

Fig. 1. Simplified tectonic map of northwestern Mexico showing the distribution and location of major Mesozoic - Cenozoic magmatic provinces and tectonic features. The main part of the Sierra Madre Occidental province is shown as SMO. The pattern superimposed represents possible geometric location of subducted ridge segments beneath the continent as estimated from the magnetic anomalies and major fracture zones.

SPATIAL MAGMATIC ARC OF NORTHWESTERN MEXICO

In order to investigate on the spatial-temporal evolution of magmatic activity, radiometric dates of subduction-related igneous rocks for northwestern Mexico were compiled. About 400 dates, mostly obtained by the K-Ar method and supplemented with some obtained by Rb/Sr and U/Pb methods, were used in the analysis. All data points were plotted according to their geographic locations (Fig. 2). Whenever possible, data were examined for geological setting, chemical composition and method used. Because of the relatively low number of radiometric dates available and the uneven geographic distribution, it was decided to integrate the results over the entire margin. The main objective was to estimate the possible lateral variation of magmatic activity with time, which apparently resulted in a wide area covered by magmatic

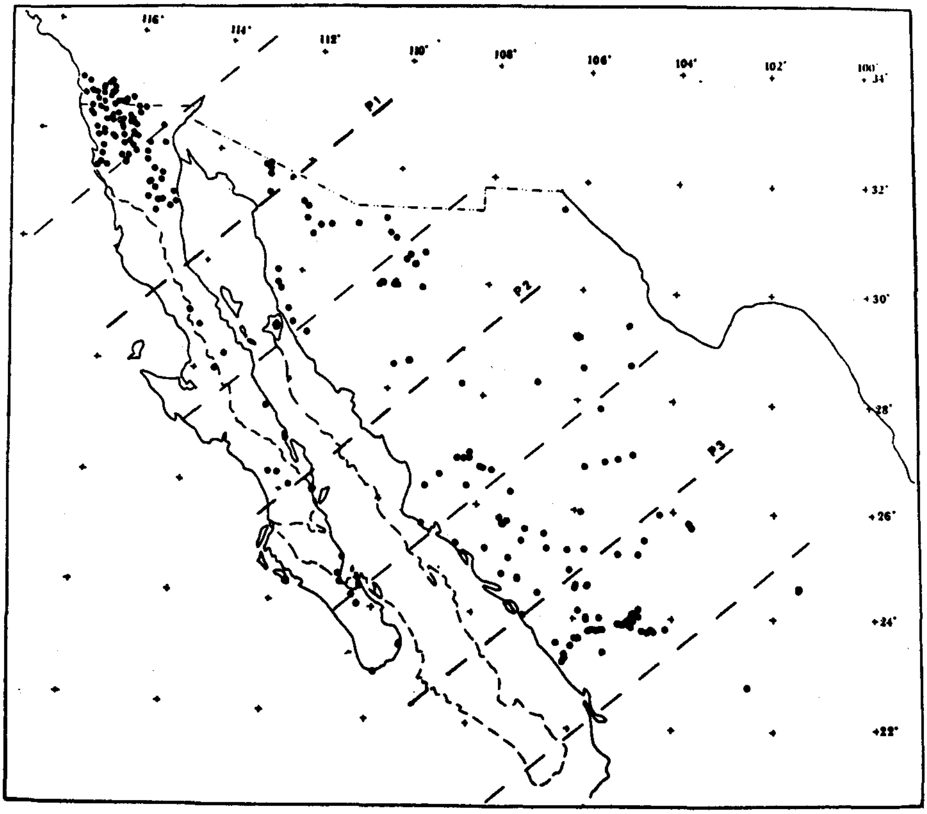

Fig. 2. Distribution of radiometrically dated igneous rocks in northwestern Mexico. Data are from Alba and Chavez (1974), Clark *et al.* (1980), Damon (1975), De Pablo (1973), Henry (1972, 1975), McDowell and Keizer (1977), Salas (1975) and Urrutia Fucugauchi (1982b). The profiles (P1, P2 and P3) are normal to the assumed palaeo-trench position, and all data points were projected normal to these profiles to form Fig. 3. The Baja California peninsula was restored to an assumed palaeo-drift position (discontinuous contour), close to the northwestern Mexico margin.

arc products. Therefore, any young feature such as the Gulf of California which modified the spatial arrangement should be restored to a position prior to the evolution of the arc. The Gulf was closed using the pattern of faults and basins (Moore, 1973). Then, the trench location (at least the last observable location) was estimated from the bathymetric and magnetic anomaly profiles and maps (Atwater and Menard, 1970; Chase *et al.*, 1970) and a series of profiles normal to the trench axis were marked (Fig. 2). Data points around these profiles were projected and the horizontal distances away from the trench were estimated. The patterns resulting for each of the profiles were combined into a single figure (Fig. 3), which shows the spatial-temporal variation of arc magmatism.

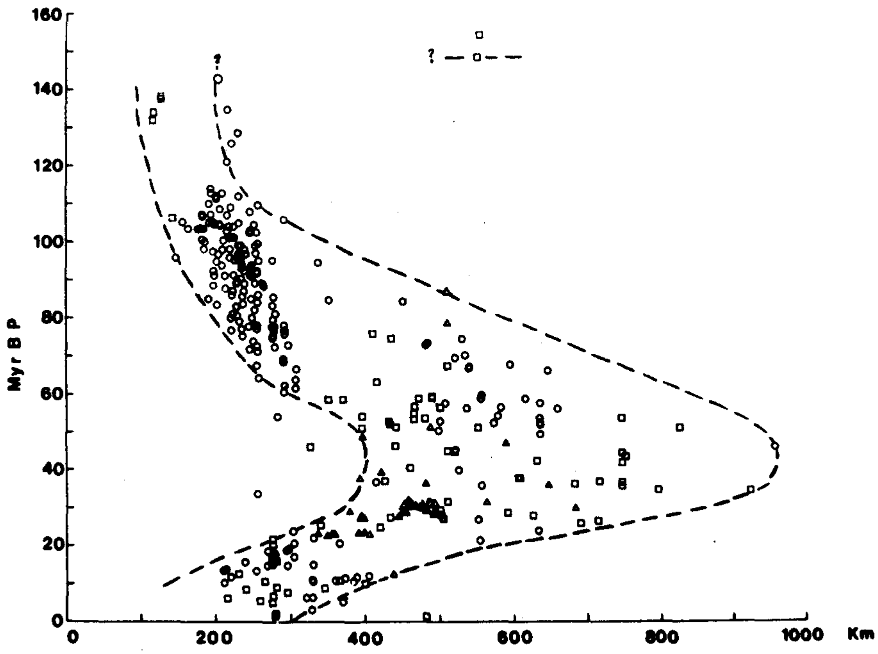

Fig. 3. Spatial-temporal variation of radiometric dates of magmatic arc rocks for northwestern Mexico. Symbols refer to three transects shown in Fig. 2 as follows: circles correspond to P3, squares correspond to P2, and triangles correspond to P3. Dashed curves represent approximate envelope of magmatic activity manifestations.

The pattern (Fig. 3) seems reasonably well defined, with an apparent agreement between the 3 transects; although there are less data points for profiles 2 and 3 than for profile 1 (Fig. 4). The distribution of radiometric dates suggests that magmatic activity was almost continuous since 140 my ago (Figs. 3 and 4). This apparent continuity does not necessarily mean that plate subduction was continuous during that interval, although it was certainly the dominant tectonic phenomenon. Location of magmatic activity varied with time, from close to the trench at 140 my to farther from the trench at 50 - 30 my, and close again to the trench at 10 - 0 my. Therefore, the area covered by the magmatic manifestations increased with time, resulting in a 1 000 km-wide magmatic arc.

During the evolution of the arc, the portion with active magmatism may have been similar to presently active arcs, but due to the lateral migration (relative to the trench) of the activity, the area covered by magmatic manifestations was wider, and it is here simply called spatial magmatic arc to distinguish it from active narrow arcs.

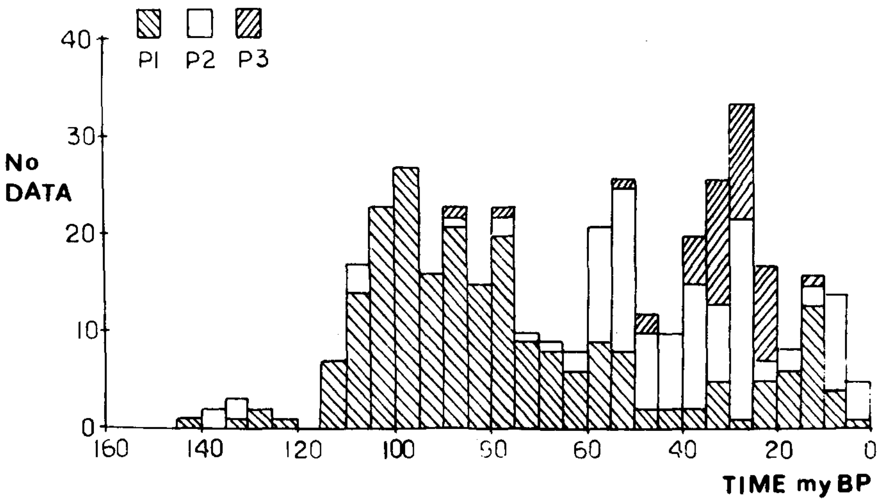

Fig. 4. Histogram of Late Mesozoic - Cenozoic isotopic dates used in Figs. 2 and 3.

DISCUSSION

Before analysing possible interpretations of the spatial-temporal pattern of magmatic arc activity (Fig. 3), there are several potential problems which should be mentioned. Among the factors affecting the pattern of Figure 3 we have: (1) systematic errors in some or all of the radiometric dates; (2) strong sampling bias in the overall pattern, where significant portions of the stratigraphic record in critical areas are miss-represented; (3) multiple intrusion events, particularly in the Peninsular batholith of Baja California which may have caused resetting of K/Ar dates; (4) transgressive regional cooling in the batholiths related to factors such as geothermal gradient movement independent of erosional level changes or due to progressive uplift and erosion; and (5) selective erosion of parts of the record.

Although it is difficult to assess the overall effect of the factors listed, it is believed that the approach adopted (see also discussion in interpretation of results) gives a valid regional view of the evolution of this continental margin. The radiometric dates used have been obtained by many researchers working in different laboratories, and there is apparent good agreement in the results which conform a coherent smooth pattern (Fig. 3), suggesting that large systematic errors are not serious. Obviously, further detailed radiometric studies will result in a modification and improvement of the results and conclusions of this work. In particular, studies are needed for Chihuahua, southern Sonora and central and southern Baja California (Fig. 2). Integration of results over the entire margin may have helped in averaging out potential problems (Fig. 3).

Most dates of transect 1 which are close to the trench are from the Peninsular Ranges batholith and have been discussed by Krummenacher *et al.* (1975) and Gastil *et al.* (1975). Krummenacher *et al.* (1975) found an apparent pattern of variation with K/Ar dates decreasing from about 120 my in the southwestern (coastal) portion of the batholith to less than 70 my in the northeastern (inland) portion. It was suggested that concordant K/Ar dates may not necessarily approximate the time of emplacement but give younger ages. If so, this factor may explain the apparent spread of data points between 120 and 60 my and between 150 and 300 km (Fig. 3). The magmatic or volcanic front (dashed line in Fig. 3) may have then been displaced away from the trench more rapidly than it is indicated in the diagram. Farther inland in Sonora and Sinaloa, Silver and Anderson (1974) and Henry (1975) respectively, had documented eastward shifts of magmatic activity. If some of the ages of the plutons examined by these authors are younger than the time of emplacement then this affects the extent of magmatic manifestations observed. However, for these areas the ages are consistent with some K/Ar dates obtained from volcanic rocks. Farther inland ($\gtrsim$500 km) the radiometric pattern is based on volcanic rocks of calc-alkalic (high-K) character of the SMO and easterly flanking manifestations. Rock units of the SMO are separated by a major unconformity into the Lower Volcanic Complex (100 to 45 my) and the Upper Volcanic Supergroup (34 to 27 my) (Mc Dowell and Clabaugh, 1979). Details of the geochemistry and isotopic composition for some areas (roughly between profiles 2 and 3; Fig. 2) have been reported by several workers (Cameron *et al.*, 1980; Lanphere *et al.*, 1980; McDowell *et al.*, 1978). The results indicate a fundamental change in the character of arc magmatism and tectonics in the margin (this aspect is discussed in next section). This portion of the radiometric pattern (Fig. 3) is fairly well documented by detailed K/Ar dating on whole-rock and mineral separates (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979 for details). Farther to the east, there are very few radiometric studies reported for Chihuahua and Coahuila, and this portion of the curve (>700 km) is not well defined. Radiometric dates for areas in Texas have not been included in the analysis. Dates for areas such as the Trans-Pecos field (McDowell, 1978) cluster at about 40 to 31 my, and if included, the extension of magmatism increases some 100 km to the east (Fig. 3). Also, alkaline magmas in west Texas (Barker *et al.*, 1977), Tamaulipas (Bloomfield and Cepeda, 1973) and Tamaulipas and Veracruz (Cantagrel and Robin, 1979), if related to the lateral migration of arc magmatism, will modify the pattern of Figure 3. Dates are younger than 30 my, and apparently become younger southward, then falling outside of the envelope in Figure 3. Results for Tamaulipas and Veracruz should have been left out of the analysis anyway because these areas are well outside of the southernmost traverse considered in the analysis.

In summary, a lateral migration of magmatic activity with time seems well documented by the radiometric dates, and although the absolute limits (envelope in Fig. 3) are subject to modification, the general pattern seems reasonably defined. This pattern of migrating activity is similar to that documented and discussed by Coney and Reynolds (1977) and Urrutia-Fucugauchi (1978) for southwestern USA. It is also similar to that reported recently by Clark *et al.* (1982) for the same area of northwestern Mexico, and published while this work was being reviewed. Clark *et al.* (1982) considered a single profile and projected all data points into it, regardless of the apparent curvature of the trench-arc system and possible breaks in the downgoing plate. Nevertheless, the general shape is very similar, except for the most recent portion (<my). In general, the evolution of the magmatic arc, as seen in this study, can be divided into three stages of evolution (Fig. 3): (1) early stage, which starts about 140 my B.P. and covers the longer interval up to about 60 my B.P. It is characterized by a progressive increase of the trench-arc gap with an average velocity in the order of 1 - 2 cm/yr, but varying from 1 to 12 cm/yr (Fig. 5), and an apparent increase of the width of the magmatic arc. Magmas are calc-alkaline and tectonism is predominantly compressional. (2) Intermediate or mature stage, which extends from about 60 my to 30 my and is characterized by development of magmatic activity at .points farthest from the trench and little relative changes of the trench-arc gap. Chemical composition changes to high-K calc-alkalic and alkaline magmas, volume of material decreases, and tectonism becomes predominantly extensional. (3) Late stage, which perhaps extends to the present, and which is characterized by drastic changes in the plate tectonic configuration, including ridge subduction, termination of plate subduction and plate boundary transformation. It is characterized by rapid migration on the magmatic front back to the trench, extensional tectonism and bimodal magmatic activity occurring long after cesation of active subduction.

PLATE SUBDUCTION - ARC MAGMATISM

The radiometric dates of subduction-related igneous rocks (Fig. 3) provide a means to study the evolution of the continental margin and the relationships through time of plate subduction and arc magmatism. Prior to about 140 my ago, there is a 'jump' in the pattern (Fig. 3) which indicates changes in the plate configuration and plate subduction process, or tectonic motions affecting the earlier record of arc magmatism, or both. Several studies have indicated large-scale left-lateral tectonic translation of parts of northern Mexico along major faults. Tectonic models such as those of Silver and Anderson (1974) and de Cserna (1976) which involve 800 km along the Sonora-Mojave megashear, and 400 km along the Monterrey fault, respectively, may explain the apparent jump in the radiometric pattern.

McKenzie (1969) has indicated that old cold oceanic lithosphere is gravitationally unstable and likely to sink under its own weight. However, comparison of the location of subduction zones with the distribution of old and young oceanic lithosphere shows that old lithosphere is neither a necessary nor a sufficient condition for having plate subduction. For instance, at the margins of the Atlantic ocean the lithosphere is older than 100 my and yet an active trench-arc system has not been developed. In contrast, active subduction involving very young oceanic lithosphere is occurring at many places such as in southern Mexico where the young Cocos plate is being subducted. The length of the active ridge system (~80 000 km) is considerable greater than that of the trench-arc system (~40 000 km), which suggests that plate subduction may be more difficult to start and sustain. That is, the factors needed to initiate and mantain plate subduction are not easy to have together.

At the initial stage, plate subduction may be initiated through increasing compressive stress and plate convergence rate (McKenzie, 1977), or in response to a gravitational instability due to old lithosphere and thick sedimentary load (Worzel, 1976). Molnar and Atwater (1978) have indicated based on assumptions and equations reported by McKenzie (1969) that a gravitational instability may develop when the plate thickness is greater than 50 km (±15 km), which then corresponds to a lithosphere about 30 my old (Parker and Oldenburgh, 1973). Since lithosphere can reach older ages without initiation of plate subduction, then factors such as increasing plate convergence rate and thick sedimentary load may increase above certain critical levels to result in plate subduction. If plate convergence rate is a major controlling factor, then during the initial stage the rate should show a general trend from low values to higher values (across a critical level). Low plate convergence rates have been found to correlate with steep angles of subduction (Luyendyk, 1970), and although other factors in certain cases may affect this relationship (e.g. Tovish and Schubert, 1978), in general, this inverse correlation seems to be important (Cross and Pilger, 1982; Yokokura, 1981). Initial steep angle subduction may be facilitated if the lithosphere being subducted is much older than 30 my. Magmatic activity will develop close to the trench for steep angle subduction. The characteristics of the upper plate may also affect the geometry of the system; and old continental plate may be thick (Kono and Amano, 1978) and may effectively resist the push of an oceanic plate giving a steep initial subduction dip. This initial subduction zone geometry is consistent with a narrow trench-arc gap (Figs. 3 and 5), and may change with time. For northwestern Mexico, the trench arc gap steadily increased for the next 80 - 90 my, from about 90 km to 400 km, with a rate of change also increasing from about 1 cm/yr up to a peak value of 12 cm/yr at 55 - 60 my (Fig. 5). Studies of presently active trench-arc systems show that most active volcanoes are usually

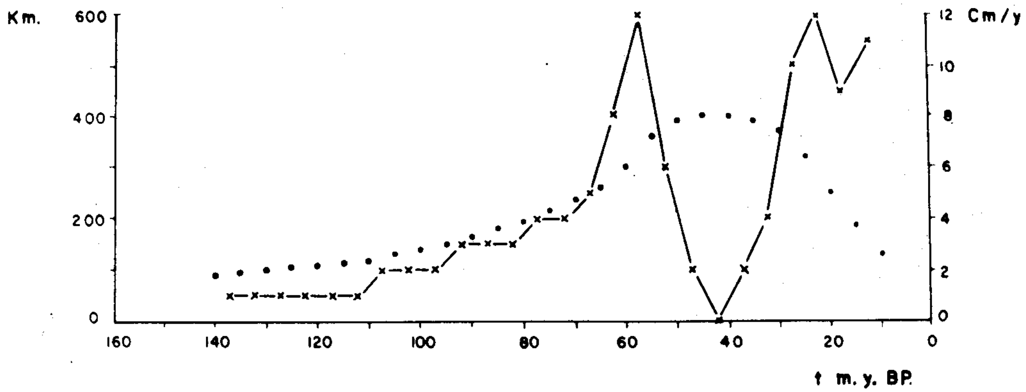

Fig. 5. Variation of trench-arc gap (dots) in kilometers, and rate of change with time (crosses) in cm/yr for the trench-arc system of northwestern Mexico. Figure constructed from data shown in Fig. 3.

located above the zone where the top of the seismic plane intersects the 100 km depth-plane (Isacks and Barazangi, 1977). Deviations in this pattern do occur, however, and 'volcanic lines' can be located from about 75 km to about 180 km above the top of the seismic plane (Karig *et al.*, 1976; Isacks and Barazangi, 1977). Then, differences in the dip angle of the plane of intermediate seismicity result in different trench arc gaps. In general, steep angles correspond to narrow trench-arc gaps and shallow angles correspond to wide trench-arc gaps. A variable subduction zone dip angle with time (Fig. 6) may then explain the migration of the magmatic front (Fig. 5). This model of variable dip angle has been used to explain a similar pattern of migration of magmatic activity for the southwestern United States (Coney and Reynolds, 1977). The model used by Coney and Reynolds (1977) assumed a simplified geometry in terms of a single flat inclined plane for the top of the subducted plate,

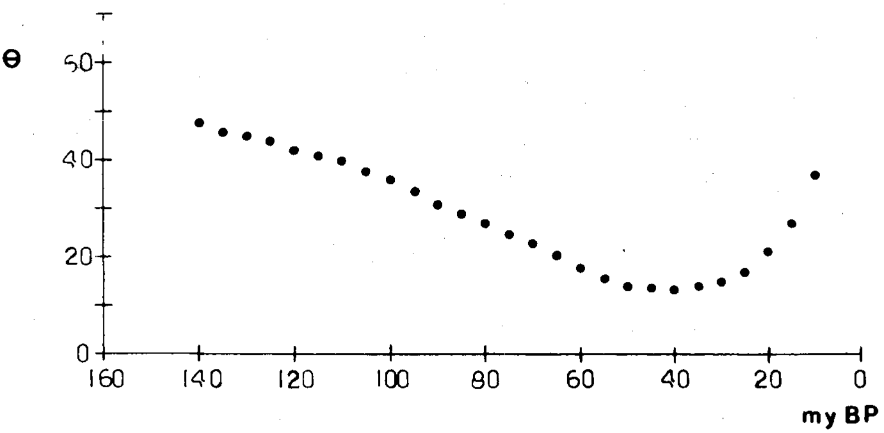

Fig. 6. Apparent variation of subduction zone dip angle for the northwestern Mexico Trench-arc system, which can explain variation on trench-arc gap (Fig. 5). Assumed depth of magma generation is 100 km (see text).

and no changes in the thermal conditions of the system with time (Urrutia Fucugauchi, 1978). Composite cross-sections of earthquake hypocenters for given segments of active trench-arc systems have long shown that the dip at which the plate subducts changes from generally shallow dips at shallow depths to steeper dips at intermediate depths (Karig *et al.*, 1976; Isacks and Barazangi, 1977). The effects of subduction with time have been also studied, and theoretical models indicate that the arrangement of isotherms changes with time, generally given deeper isotherms due to the cold oceanic lithosphere being subducted. This, then displaces the zone of partial melting downwards along the inclined plate, resulting in lateral displacement of the magmatic front at the surface. This change in the depth of partial melting is supported by the observed changes in chemical and mineralogical composition of magmas along magmatic arcs (Kuno, 1966; Hatherton and Dickinson, 1969; Green and Ringwood, 1968; Gill, 1981). A schematic representation of this model of variable subduction zone dips and variable depth and range of partial melting is shown in Fig. 9. Although not clear from the diagram, this model can take into account changes in the position of the trench. Several studies (Dickinson, 1973; Jacob *et al.*, 1977; Karig *et al.*, 1978) have shown that the trench location can vary in response to a number of processes, such as sediment accretion, obduction, tectonic erosion, margin truncation, and even (accretion) collision of small blocks and bathymetric highs. These changes are recorded by variations in the trench-arc gap. Furthermore, the extent of the zone of magma manifestations (magmatic arc) can be affected by tectonic extension, in addition to the lateral migration of the magmatic front and changes in the depth of magma generation. In the simplified geometry of Figure 7, such changes are only reflected in the width of the magmatic arc zone (Fig. 8) and the apparent subduction zone dip angle θ_2 (i.e. angle required to explain the extent of the arc of an assumed geometry). Tectonic extension may be controlled by the location of arc magmatism giving a zone of weakness, which may in certain cases result in formation of back-arc basins (Karig, 1970; Molnar and Atwater, 1978).

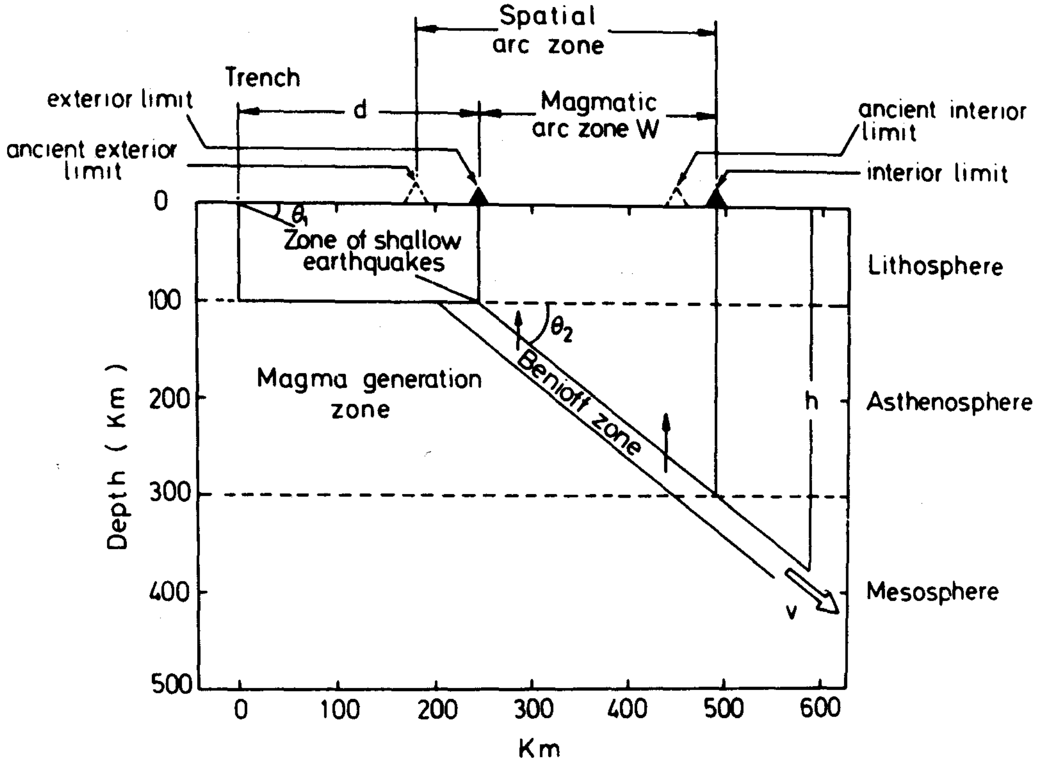

Fig. 7. Schematic representation of plate subduction model showing major details discussed in text. Note difference in magmatic arc zone and spatial magmatic arc zone.

The width of the magmatic arc zone seems to have varied in a systematic manner (Fig. 8), similar to the migration of the magmatic front (Fig. 5). Figure 9 shows three extreme examples of the models examined to explain the observed pattern in terms of the above discussion. Model 1 corresponds to a variable dip-constant range of magma generation. The dip angle varies from about 60^{o} at 140 my to about 20^{o} at 60 - 35 my and to about 40^{o} at 10 my (Fig. 9a). The range of partial melting

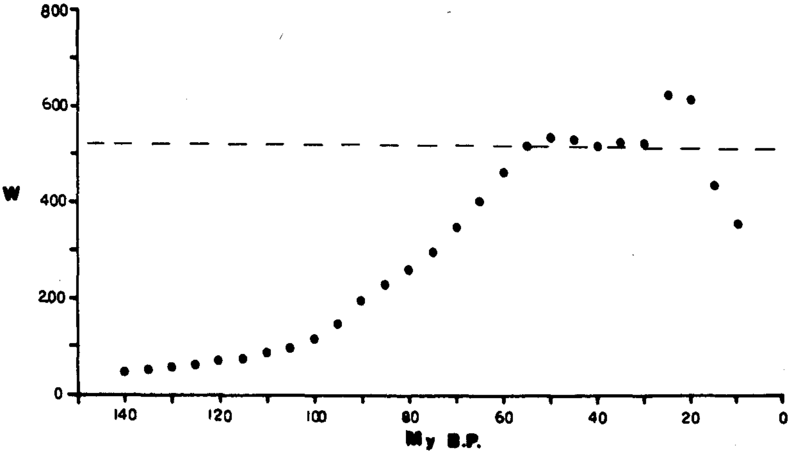

Fig. 8. Apparent variation of the extent of zone covered by magmatic arc rocks with time. Diagram constructed from data shown in Fig. 3.

used is 200 km (Fig. 7), which may result in an overestimate of the subduction dip angle, particularly during the formation and cessation of subduction activity, when the zone of magmatic manifestations may be expected to be narrower than during a 'stable' subduction regime. Studies have indicated that the range of partial melting can vary with time (James, 1971; Dickinson, 1973). Furthermore, data from magmatic arcs of Japan and western Indonesia apparently support that magmas of different composition are being generated almost simultaneously at different depths along the subducted plate (Kuno, 1966; Hatherton and Dickinson, 1969). Models 2 and 3 show two cases of variable depth and range of melting. Steeper angles seem to require too high depths of partial melting (Fig. 9b), whereas shallower dip angles require more reasonable values for the depth of partial melting (Fig. 9c). In order to evaluate the possible alternatives, estimates of the depth to the top of the descending plate on the K_2O (at given SiO_2 level) depth of seismic plane relationship (Dickinson, 1970, 1975) are compared with the geometries based on the analysis of variable dip-variable depth and range of partial melting (Fig. 10). Most studies place the zone of magma generation at the top of the seismic zone (Isacks and Barazangi, 1977), but in other studies, the zone is placed at the middle of the seismic zone (James, 1978). The apparent agreement between the results supports the model of variable depth and range of melting. The nature of the data does not permit however to conclude that magmas of different composition were emplaced simultaneously along the arc. The definition of the radiometric date pattern is in general in the order of millions of years ($\lesssim$5 my) and the geometries defined do not refer to instantaneous situations. Results for the magmatic arc of Chiapas, southern Mexico (Fig. 3) (Urrutia-Fucugauchi, 1982a) show that the location of magmatic activity varies across the arc in intervals of a few million years. The general trend and scatter

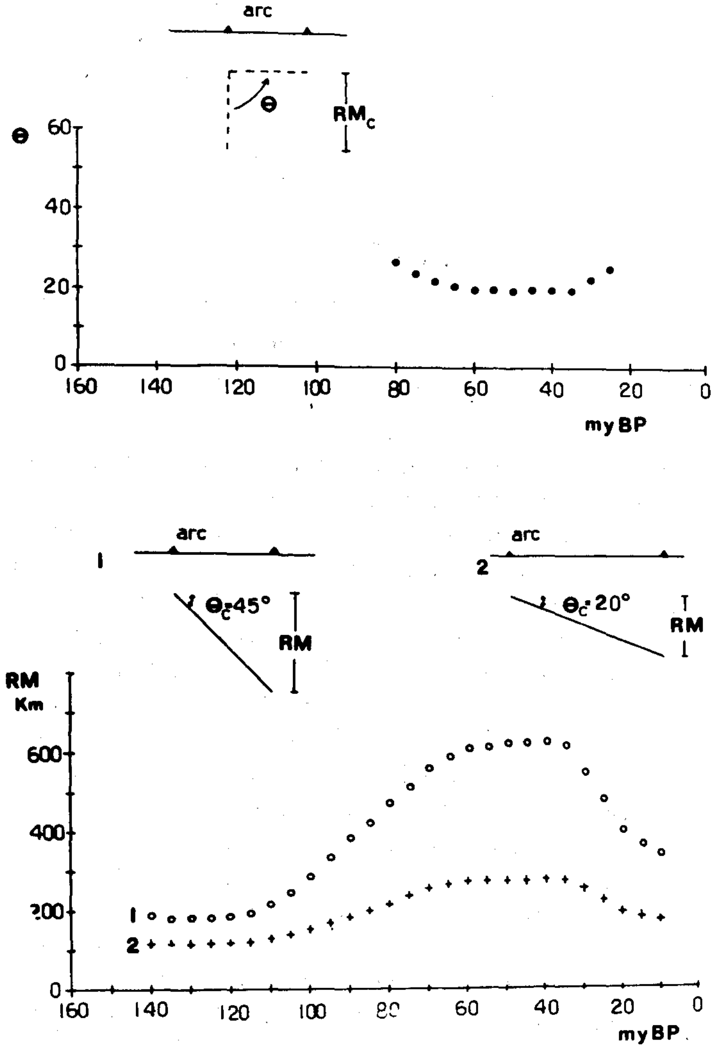

Fig. 9. Schematic representation of three models of evolution of trench-arc system. (a) Variable subduction zone dip angle (intermediate seismicity zone; Fig. 8) with range and depth of partial melting kept constant. The angle required for fitting the data of Figs. 3, 5 and 8 is shallow, 20°. (b) Variable depth and range of partial melting with constant 45° dip angle. Note that maximum depths of partial melting required to fit the patterns observed can be greater than 600 km. (c) Variable depth and range of partial melting with constant 20° dip angle. Note that maximum depths of partial melting required for fitting the data are in reasonable range as expected from modern examples of trench-arc systems.

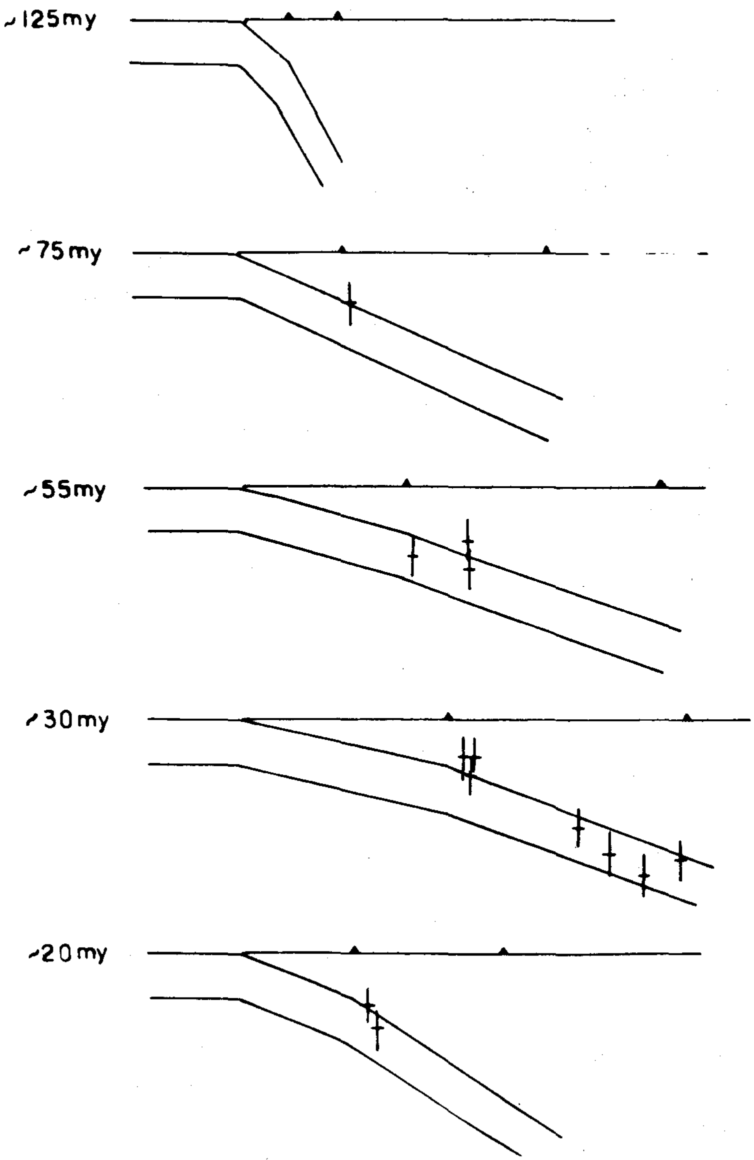

Fig. 10. Schematic cross-sections which illustrate inferred evolution of trench - arc system of northwestern Mexico. Estimates of depth of magma generation from K_2O - SiO_2 - depth are added for comparison (see text).

of data points agree well with the pattern observed for the northwestern magmatic arc. Available information does not fully permit to discriminate between the alternative configurations. However, it is possible to provide constraints to the most likely configurations. For instance: (a) usually the subduction zone dip in the shallow zone is shallower than that observed for the deeper zone (Karig *et al.*, 1976; Isacks and Barazangi, 1977); (b) the magmatic front (given by the line of active volcanoes) is located about 75 to 180 km above the top of the seismic planes, and very often, about 100-120 km; (c) too shallow dips of subduction ($<20^o$) seem to result in no active volcanism (*e.g.* Peru ($\sim 9^o$) and Central Chile ($\sim 12^o$) subduction zones); (d) depths of partial melting observed for high-K calc-alkaline and alkaline suites are up to 280 km (Dickinson, 1975); (e) initial subduction zone dips should be steep, and subsequently, dips should get shallower in agreement with increasing convergence rate and subduction of progressively younger oceanic lithosphere; (f) proposed geometries and changes must correlate with major tectonic events (compressional and extensional orogenies); (g) consumption of the spreading center during the late stage of evolution should be reflected in the geometry of system; (h) proposed geometries must correlate with the geochemical and petrographic character of magmas; and (i) proposed geometries and evolution should produce the patterns of magmatic activity as shown in Figures 3, 5 and 8. A preferred tentative model of evolution is schematically shown in Fig. 10.

Major factors involved in the evolution of the system are difficult to quantify. A number of parameters can produce the changes observed. The age of the plate being subducted changed systematically with time (Atwater, 1970; Atwater and Molnar, 1973). Old oceanic lithosphere of the Farallon plate was subducted during the early stage of evolution of the margin of northwestern Mexico, and became progressively younger with time until segments of the Pacific-Farallon spreading center reached the trench. During the early stage, this may have resulted in a steep angle of subduction, and as the relatively old cold oceanic lithosphere ($\gtrsim 50$ my) interacted with the mantle, isotherms were progressively displaced downward and inward along the plate (Dickinson, 1973). As the age of the plate being subducted decreased ($\lesssim 50$ my), the effective density contrast between the plate and mantle and thermal characteristics of the plate may have resulted in shallower angle of subduction. The plate convergence rate may have also changed with time from relatively low values to higher values. Coney (1978) has estimated the North American - Farallon plate convergence rate during the Late Mesozoic - Cenozoic, where the rate increased from ~8 cm/yr to 15 cm/yr during the Laramide orogeny (~80 - 40 my) and decreased to ~7 cm/yr during the mid-Tertiary orogeny. These high convergence rates may have resulted in shallow dip angle of subduction, particularly during the Laramide orogeny, which agrees with the ~20° dip estimated in this study (Fig. 10). Furthermore, high convergence rates result in depression of isotherms and lengthening of the Benioff zone, which increases the trench-arc gap. Changes in absolute plate motion may have also affected the evolution of the system. Wilson and Burke (1972) initially pointed out the effects in deformation style of absolute upper plate motion where increase in the component of motion normal to and towards the trench results in effective overriding of upper plate, seaward migration of trench, shallower subduction zone dip, and landward migration of the magmatic arc (Cross and Pilger, 1982). The effects of sediments in the subduction process may have been also important. A thick sedimentary load may help in initiating plate subduction by effectively depressing the oceanic plate (Worzel, 1976). Incorporation of a thick sedimentary layer by a young oceanic plate may help in reducing the density contrast, increasing the buoyancy of the plate and giving shallower angle of subduction. This will result in increase of the trench-arc gap. Increase of the trench-arc gap will also result by accretion of trench sediments. Dickinson (1973) found an empirical correlation between the width of trench-arc gap and duration of magmatic activity for several active systems. Karig and Sharman (1975) also reported that the trench-arc gap approximately correlates with the amount of accreted sediments and obducted oceanic crust slices, in some Pacific trench-arc systems. The magnitude of addition of material to the system may be important. Jacob *et al.* (1977) showed that the trench-arc gap along the Alaska-Aleutian arc increases from about 170 km in the central Aleutians to about 570 km in the Gulf of Alaska/Cook Inlet/Mt. McKinley region, which correlated with the amount of sediments at the subduction zone. Jacob *et al.* (1977) concluded that during the evolution of the system, the trench migrated 200 km seaward due to accretion, and the arc front migrated some 300 - 400 km inland due to shallowing of the dip angle. Seaward migration of trench will also result from obduction. Ophiolitic complexes in Baja California peninsula (Fig. 1) indicate the effects of these processes. Subduction of oceanic plateaus (Ben-Avraham *et al.*, 1981) may have also produce profound effects in the evolution of the system. The effective density of the plate is reduced by the increased thickness of oceanic crust (Kelleher and McCann, 1977; Detrick and Watts, 1979), and this buoyancy effect may result in shallowing of the subduction dip, and increased deformation.

Alternatively, following the collision with the trench, part or most of the oceanic plateau may be accreted to the margin, and a new subduction zone may develop outboard of the oceanic plateau. Modification of the arc-trench system by addition of new material may also result from lateral displacement of parts of the margin along transform fault systems. Palaeomagnetic studies of several localities along the western margin of North America have been showing that most of the margin is composed of displaced terrains and that northward motion and clockwise rotations have affected many of the terranes (Beck, 1980). Karig *et al.* (1978) proposed that the Baja California peninsula moved northward from an initial position along the coast of southern Mexico during the Cretaceous - Early Tertiary to its present relative position in northwestern Mexico. Beck and Plumley (1979) reported palaeomagnetic evidence in support of a northward displacement of the Peninsular Ranges batholith of northern Baja California. Timing of events is not well constrained, and the occurrence of such a major movement of the peninsula requires further support, and alternative models involving left lateral motion for southern Mexico have also been proposed (Malfait and Dinkelman, 1982). One may also mention that removal of the peninsula results in major changes of the pattern defined in Figure 3, but still, an apparent lateral migration of magmatic activity across the margin will be recognized. This apparent continuity of the radiometric dates also argues against major tectonic deformation of the western margin. Local rotation of small blocks, possibly associated with regional compression or shear along large lateral faults is supported by palaeomagnetic results obtained in areas within the Sierra Madre Occidental (Urrutia-Fucugauchi, 1981).

These local rotations may have contributed to the apparent scatter observed in the pattern of magmatic activity. Tectonic deformation affected the area of the Sierra during the Late Cretaceous - Early Tertiary (during the Laramide orogeny) and later after the emplacement of the thick ignimbritic sequence of the Upper Volcanic Supergroup in the mid-Tertiary (during the mid-Tertiary extensional orogeny). The effects and amount of tectonic extension in northwestern Mexico are poorly documented. Eaton (1979) has reviewed the Cenozoic extensional deformation in western North America, and has recognized three major episodes: (1) 30 to 20 my BP, taking place in the Rio Grande rift and the Sonoran desert to the south of the Basin and Range province; (2) 20 to 10 my BP, occurring throughout most of the Basin and Range and Columbia plateau provinces; and (3) 10 my BP to Present, occurring mainly in the Rio Grande rift, Gulf of California and Great Basin section of the Basin and Range province. Extension between 30 and 20 my BP occurred within the magmatic arc, and is partly coincident with the emplacement of the ignimbritic sequence of the Upper Volcanic Supergroup. The eruption of bimodal suites in the southwestern United States has been interpreted as reflecting extensional tectonics

(Noble, 1972; Snyder *et al.*, 1976). A proto-Gulf of California may have been also formed during the Miocene as an interarc basin (Karig and Jensky, 1972). Evidence for southward continuation of the Rio Grande rift (Reiter *et al.*, 1978) is largely lacking. Smith and Jones (1979) have proposed its southern continuation, based on heat flow measurements, high mantle temperatures and crustal thinning beneath the northern Mexican Altiplano, but the density of heat flow results does not permit a clear demonstration of the continuity of the Rio Grande rift into Mexico. Crustal thickness varies across the margin of northwestern Mexico, increasing from about 10 km off the Baja California peninsula up to about 35 km beneath the northern part of the Altiplano (Urrutia-Fucugauchi, 1982b).

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(Received: April 11, 1984)
(Accepted: October 10, 1984).