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Mountain Building in the Central Andes

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The Central Andes is the middle part of the Andean chain between about 13°S and 27°S, characterized by the parallel running high mountain chains (the Western and Eastern Cordilleras) at the edges of high plateaus with a height of about 4000 m and a width of 200 to 450 km (the Altiplano-Puna). From the examination of geophysical and geological data in this area, including earthquakes, deformation, gravity anomaly, volcanism, uplift history, and plate motion, we conclude that the continued plate subduction with domination of compressive stress over the entire arc system is the main cause of the tectonic style of the Central Andes. We propose that the present cycle of mountain building has continued in the Cenozoic with the most active phase since the Miocene, and that the present subduction angle (30°) is not typical in that period but that subduction with more shallowly dipping oceanic lithosphere has prevailed at least since the Miocene, because of the young and buoyant slab involved. This situation is responsible for the production of a broad zone of partial melt in the mantle above the descending slab. Addition of volcanic materials was not restricted to the western edge (where active volcanoes of the Western Cordillera exist) but extended to the western and central portion of the Altiplano-Puna. The western half of the Central Andes is essentially isostatic because the heat transferred with the volcanic activities softened the crust there. In the eastern edge, the thermal effect is small, and the crust is strongly pushed by the westward moving South American plate. This caused the shortening of crustal blocks due to reverse faulting and folding in the Eastern Cordillera and Amazonian foreland. The magmatism and crustal accretion are dominant at the western end of the mountain system and decrease eastward, while the compression and consequent crustal shortening are strongest at the eastern end and wane toward west. These two processes are superposed between the two mountain chains and form high plateaus there: the Altiplano of Bolivia and Peru and the Puna of Argentina. This interpretation is supported by the observation that (1) Neogene sedimentary formations have been uplifted to high elevations without heavy distortion in the Altiplano and the Western Cordillera, (2) no significant reverse fault systems are observed on the Altiplano, (3) Neogene volcanic rocks and volcanic centers since the Miocene are not restricted to the Western Cordillera but are widely distributed over most of the Altiplano, (4) most of the Altiplano is in a zone of high heat flow values, (5) thick Paleozoic rocks are strongly folded and faulted in the Eastern Cordillera with little volcanism and no large-scale plutonism in the Cenozoic age, (6) crustal earthquakes with reverse fault mechanisms are concentrated on the eastern flank of the Eastern Cordillera and Amazonian foreland, and (7) the crustal thickness suddenly decreases at the junction of the Eastern Cordillera and the Amazon Basin, exactly at the place of reverse earthquakes.

INTRODUCTION

The formation of the Andes is an important and interesting problem in global tectonics as it is a very large mountain chain in length (more than 8000 km) and in width (sometimes more than 400 km), as well as in height (close to 7000 m). This large scale is unique to the Andes among the mountain chains of the world, if we exclude the ones in Central Asia such as the Himalaya, Hindu Kush, or Pamirs. Between about 13°S and 27°S, the mountain ranges are most well developed, forming parallel chains of highest mountains. The term "Central Andes" in this paper refers to this area of the Andean chain, which covers parts of Peru, Chile, Bolivia, and Argentina (Figure 1). In this paper, we shall use the terms the Eastern Cordillera and Western Cordillera to denote the eastern and western mountain chains, respectively. In contrast to the Himalaya, which is a continent-continent collision boundary, the Andes is a mountain chain associated with the subduction of an oceanic lithosphere below the continental plate, similar to the island arcs on the western edge of the Pacific. In this respect, the Andes is often called a continental arc. Both the island arcs and continental arcs are characterized by deep trenches, active volcanoes, and deep earthquakes. However, there are marked differences between the two arcs, which should be related to the different tectonic processes occurring in these arcs.

Many of the island arcs in the western Pacific are accompanied by back arc basins. For example, the Japan arc is composed of the Japan trench to the east, Honshu island at the center, and the Japan Sea to the west. The overall structure at an island arc is better defined as a trench–arc–back arc system. In contrast, back arc basins do not exist behind the Andes. There is no evidence that oceanic crust existed behind the continental arc in any part of the Cenozoic. Cretaceous marine sediments, especially limestones, are distributed abundantly in northern and central Peru, but all of them are shallow facies, indicating that the sea was formed due to transgression and not as a back arc basin [*Bellido*, 1979; *Reyes*, 1980; *Megard*, 1979, 1984]. This contrasts with the situation in Patagonia, where the early Cretaceous back arc basin was closed again in the middle and late Cretaceous, leaving ophiolites as evidence [*Dalziel et al.*, 1974].

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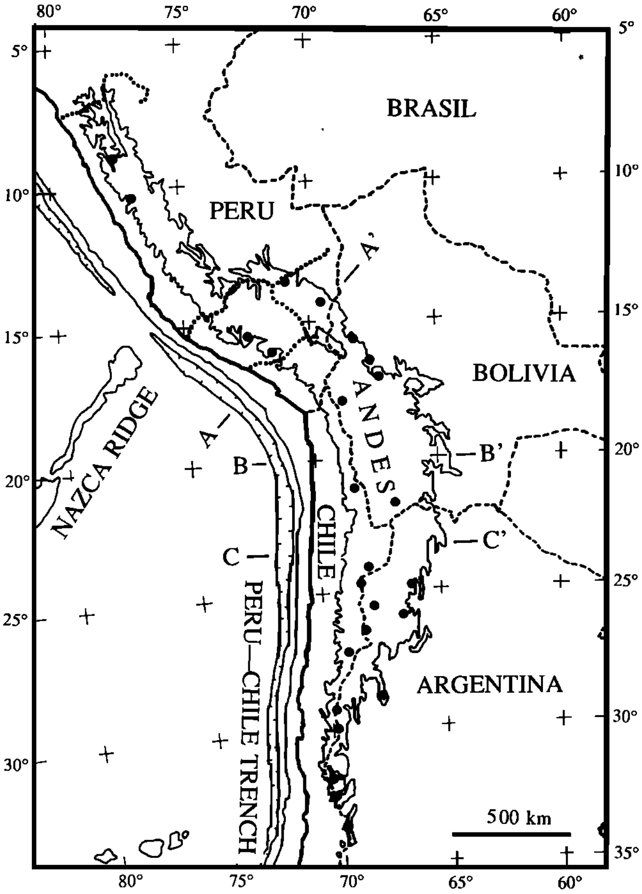

Fig. 1. Index map showing the Central Andes with its surroundings. Contours show 3000 m height on land, which roughly delineate the extent of the Altiplano, and 3000 m and 5000 m depths in the sea. Dotted lines show the gravity survey routes of *Fukao et al.* [1988]. Large solid circles are some of the major peaks with heights more than 6000 m.

The highest peaks in the Central Andes form distinct parallel chains several hundred kilometers apart: the Western and Eastern Cordilleras (Figure 1). The highest peaks in both chains attain heights of more than 6500 m. But the most prominent feature of the Central Andes is not the parallel mountain chains themselves but the very flat plateau between them: the Altiplano of Bolivia and southern Peru and the Puna of Argentina, which have a nearly constant height of about 4000 m (Figure 2). In other words, the most fundamental land shape in this area is the trapezoidal form of the Altiplano–Puna, while the Western and Eastern Cordilleras may be thought of as the volcano chain on the western edge of the plateau and dissected eastern edge of the plateau, respectively. The high peaks occupy only small areas in both cordilleras, and so the hypsometry is dominated by the altitude of the plateaus. Accordingly, if we project the topography along the trend of the mountain chain, the mountains themselves are not a very prominent feature (Figures 2 and 8). This can be compared with the similar situation in the Himalaya–Tibet section (e.g., [*Kono*, 1974]; also see Figure 2). The maximum width of the Altiplano–Puna is about 450 km and is not as large a feature as the Tibetan plateau, where the width is of the order of 1000 km and the mean height is 5000 m. However, it is a big question how this large-scale crustal feature is produced and supported.

The subduction angles of the slabs below the Andes are generally shallow, in the range of 10° to 30°, but there are alternating segments of steeper (about 30°) and shallower (between 10° and 20°) subduction [*Barazangi and Isacks*, 1976, 1979]. Active volcanoes exist above the more steeply dipping segments, but are absent above the shallower slabs. The nonexistence of volcanic activity is usually attributed to the absence of wedge mantle between the crust and shallow Wadati-Benioff zone, where shallowly dipping slabs are directly in contact with the bottom of thick continental lithosphere. In central Peru, the subducting slab is not going down into the mantle with a constant dip angle, but is 20°–30° near the trench, almost flat at 150–200 km depth below the Altiplano, and becomes steeper again to 20°–30° farther to the east [*Hasegawa and Sacks*, 1981]. This shallowing may be related to the collision of the Nazca Ridge from the southwestern direction, and there is a suggestion that some part of the Nazca Ridge is already subducting below the Andes [*Pilger*, 1981]. Another mechanism suggested for the cause of shallow subduction is the retardation of basalt-eclogite phase transformation in the slab due to the low temperature there [*Sacks*, 1983].

Mountain building in the Central Andes is undoubtedly a very complex process and its complete understanding is very difficult. However, a plausible scheme can be constructed based on geophysical data such as seismicity and earthquake source mechanisms [e.g. *Suarez et al.*, 1983], and a high-quality gravity profile in southern Peru [*Fukao et al.*; this issue] combined with other geological data. In the following, we present summary of various observations related to the process of formation of the Central Andes and then try to construct a tectonic model which is consistent with these observations.

PREVIOUS MODELS RELEVANT TO THE CENTRAL ANDES

Since the classic paper of *Dewey and Bird* [1970], many models incorpolating plate tectonic theory have been presented to explain the mountain building in the Andes. The addition of magmas to the crust and the crustal shortening due to reverse

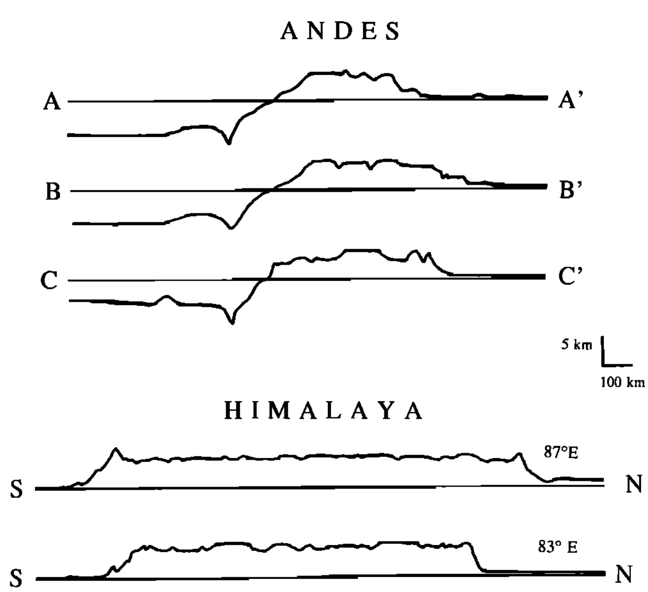

Fig. 2. Comparison of topography of the Central Andes and the Himalaya. Vertical exaggeration 20x. The locations of the Andean sections are shown in Figure 1. Himalaya-Tibet sections are along 87°E and 83°E meridians.

faults are generally recognized as the most important processes in building the thick crust which underlies the Andean chain. In addition, *Rutland* [1971] suggested that tectonic erosion by subduction of the crust at the western edge of South America and eventual addition of this material to the base of the crust may be important in the formation of the Central Andes. Models of different authors place various emphasis on these processes as the agent of crustal thickening. Besides these mechanisms, thermal expansion can cause significant uplift without thickening the crust if the underlying mantle (lithosphere) is hot enough [*Froidevaux and Isacks*, 1984]. In this paper, we wish to derive a model which can explain many of the observational data in the Central Andes. To better characterize our model, we shall briefly review three previous models which we think are most relevant to the Central Andes.

In the model of *James* [1971*b*, 1973], subduction of the oceanic plate from the Pacific side started in the Triassic or Jurassic and continued through the Cretaceous and Tertiary. An important assumption in his model is the migration of the magmatic activity to the east with time, because, with the continuation of subduction, the depth of the mantle melting point isotherm is lowered and the center of magma generation moves more to the continental side. The main process responsible for the formation of the morphology of the Central Andes is the magma accretion in the Western Cordillera, with the center of activity moving eastward with time. Formation of the Eastern Andes and of the Altiplano is of a subsidiary nature. The Eastern Cordillera was formed by folding and reverse faulting caused by the compressive stress exerted by the magma intruded in the crust below the Western Cordillera, and the Altiplano is an intermontane sediment fill formed by erosion of the high terrains to the east and west.

Recently, *Suarez et al.* [1983] proposed a new model of the formation of the Central Andes based mostly on the study of the source mechanisms of the earthquakes occurring at the foot of the Eastern Cordillera. In their model, reverse faults occur at the edge of the Altiplano under the compressional tectonic setting in the continental crust, and they serve to shorten (and to thicken) the crust to the west. When the thickness reaches some critical value, further deformation is hindered because of the crustal buoyancy, the fault positions jump to the east and a new reverse faulting regime starts. By repeating this process, the crust thickens starting near the trench and progressing to the east with time. *Suarez et al.* [1983] concluded that the crustal shortening by the repeated reverse faults is the main cause of the formation of the thick crust supporting the Altiplano. Present motion inferred from their model is also supported by gravity data. *Lyon-Caen et al.* [1985] analyzed an east-west section spanning from Chile to Bolivia and concluded that Bouguer anomalies near the Eastern Cordillera and Amazon Basin can be explained by the flexure of the continental lithosphere subducting below the Altiplano from the east.

Uyeda [1979, 1982] and *Uyeda and Kanamori* [1979] compared various properties of many subduction zones in the world and categorized them into two different types depending on the strength of interaction between the two plates: the Chilean type and Mariana type. Although their study is not meant for detailed description of a specific arc, the Chilean type is apparently based on the situation at the western coast of South America and therefore relevant to the formation of the Andes and the Altiplano. In a Chilean type subduction zone, a young oceanic lithosphere subducts below the continental lithosphere which advances toward the trench. As the plate is still hot from the formation at an oceanic ridge, average density of the plate is not so large, and consequently the plate is still buoyant. The continental lithosphere overrides and forces the oceanic lithosphere to subduct, but the buoyant slab only goes down into the mantle at a shallow angle. The interaction between the continental and oceanic lithospheres is very severe, and large thrust earthquakes occur at trenches. The compressive stress regime prevails in the overriding continent, causing folding and thickening of the crust. Back arc basin formation is prohibited by the strong compressive forces in the crust.

These models contain important ideas and are good in explaining some of the feature of the Central Andes, but have inconsistencies in other aspects. This can be seen by reviewing relevant geophysical and geological data obtained in recent years. We shall show this by going through various observations.

Seismicity and Earthquake Mechanisms

In the South American continent, most shallow earthquakes occur near the Pacific coast area. Hypocenters of earthquakes with focal depths shallower than or equal to 60 km are plotted in Figure 3. This depth may seem too large as a maximum depth for the crustal earthquakes especially in the Amazon Basin east of the Eastern Cordillera, but it was chosen to include all the interplate earthquakes occurring near the trench. If we take shallower boundaries, 50 km, say, the overall features do not change for the inland earthquakes. Intermediate and deep earthquakes also occur continuing from these shallow events eastward, delineating the Wadati-Benioff plane below the Andes.

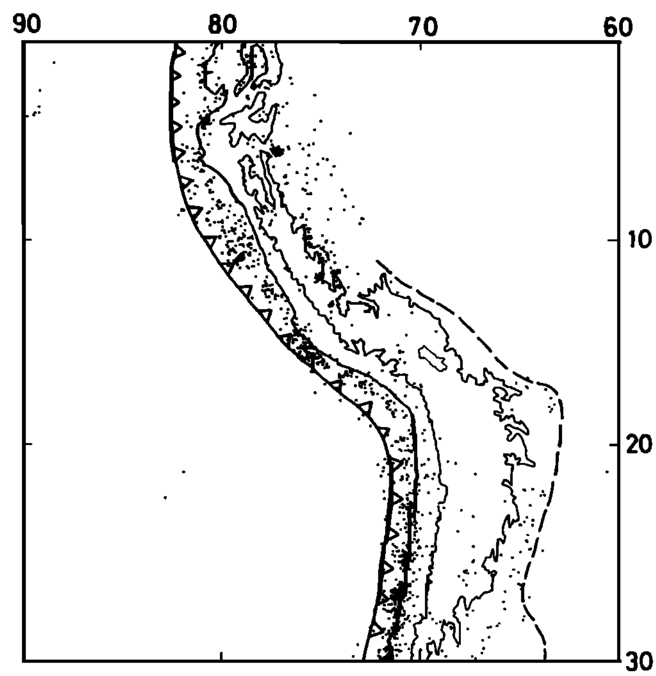

Fig. 3. Epicenters of earthquakes from the catalogue of the International Seismological Centre for 1964–1982. (Courtesy of T. Yoshii, University of Tokyo.) Numerals are latitudes (S) and longitudes (W) in degrees. Earthquakes with magnitude greater than or equal to 4.0 and depth shallower than 60 km are plotted. Trench axis and the contour of 3000 m altitude are shown. The dashed line indicates the eastern limit of Neogene deformation [after *Jordan et al.*, 1983].

In the Central Andes region, shallow earthquakes are most abundant between the coast and the Peru-Chile trench (Figure 3). This is certainly expected, as a strong coupling is suspected between the oceanic (Nazca) and continental (South American) lithospheres. Once in the continent, the number of shallow earthquakes gradually decreases to a low level. However, as pointed out by many authors [*Fukao*, 1982; *Suarez et al.*, 1983; *Chinn and Isacks*, 1983; *Jordan et al.*, 1983; *Froidevaux and Isacks*, 1984], a considerable number of earthquakes are again observed where the Eastern Cordillera ends and the Amazon Basin begins (Figure 3). The shallow earthquakes abruptly end here, and no more events are observed in the continental crust of the Amazon Basin in the Brazilian shield. In contrast, considerable activity is observed in central Peru even below the mountain area (Figure 3). The almost bimodal distribution of the shallow earthquakes is a peculiar characteristic of the Altiplano-Puna. In other arcs, for example, the Kuril-Kamchatka and Aleutian arcs, shallow earthquakes are distributed more or less continuously from the trench to landward except a narrow aseismic gap [e.g., *Yoshii*, 1979]. In the continent-continent collision zones such as the Himalaya, the distribution of the shallow events is more diffuse, and there is no indication of bimodality. This is an interesting feature when we consider the tectonic situation prevailing in the Central Andes.

As noted by many authors [e.g., *Isacks and Barazangi*, 1977; *Uyeda and Kanamori*, 1979], the dip angle of the Wadati-Benioff plane is mostly shallow (between 10° and 30°) below the Pacific side of South America. Figure 4 illustrates the shape of the Wadati-Benioff plane under Peru and northern Chile. There are places where discontinuities or gradual changes take place in the dip angle of the descending slab below the Andes [*Isacks and Barazangi*, 1977; *Hasegawa and Sacks*, 1981; *Yamaoka et al.*, 1986]. These are closely related to the existence or absence of the active volcanoes.

[*Stauder*, 1973, 1975], *Suarez et al.* [1983], and *Chinn and Isacks* [1983] obtained source mechanisms of shallow earthquakes in this area. The earthquakes near the trench are of shallow-angle reverse fault type with slip direction of east by northeast, which is nearly parallel to the present direction of the movement of the Nazca plate relative to the South American plate. These mechanisms undoubtedly represent the relative motion between the oceanic and continental lithospheres at present. As their coupling is very strong [*Uyeda and Kanamori*, 1979], very big earthquakes such as the Chilean earthquake of 1960 take place. On the other hand, most of the shallow earthquakes below the Eastern Cordillera show source mechanisms of reverse fault type with compressive axis in east-west direction. The fault planes associated with these earthquakes are considered to be the fault plane which dips to the west, as such faults actually occur abundantly in surface outcrops in this region [e.g., *Bellido*, 1979; *Suarez et al.*, 1983]. They form a conspicuous zone of reverse faults in the foreland basin to the east of the Eastern Cordillera.

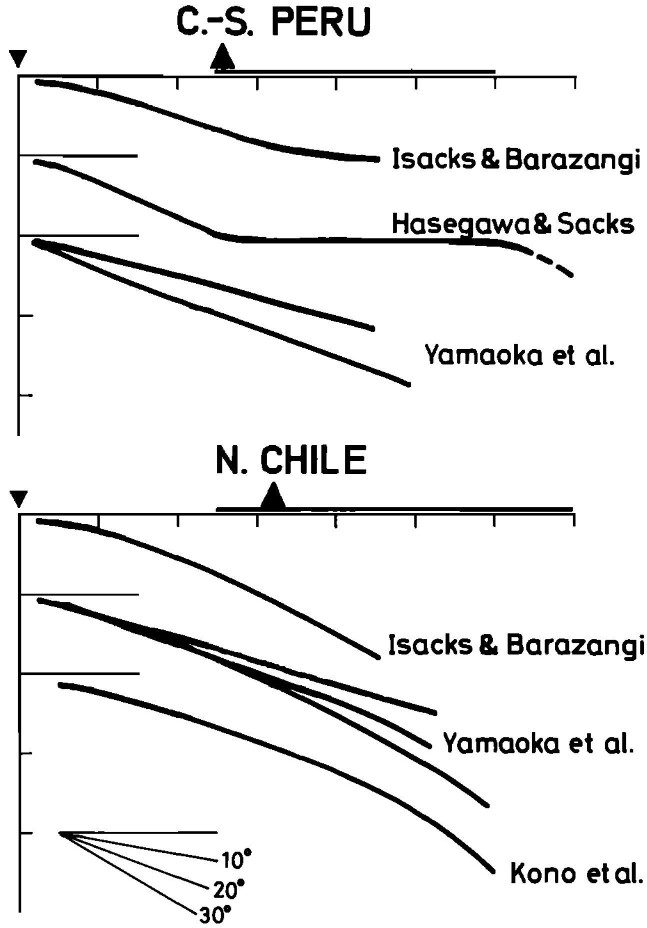

Fig. 4. Shapes of Wadati-Benioff plane below central to southern Peru and northern Chile. Tick marks at every 100 km horizontally and vertically. Horizontal lines indicate the approximate extent of the Altiplano. Triangles and inverted triangles show the positions of volcanic lines (volcanic fronts) and trenches, respectively. After *Isacks and Barazangi* [1977] (8°–16°S, 19°–26°S), *Hasegawa and Sacks* [1981] (10°–16°S), *Yamaoka et al.* [1986] (18°–23°S), and *Kono et al.* [1985*b*] (22°–25°S).

DEFORMATION OF LAYERS ON THE ALTIPLANO

In southern Peru, where we measured gravity values (Figure 1), the Altiplano is formed by rocks of the Barroso, Sencca, and Tacaza Groups [*Gutierrez*, 1981]. Tacaza Group is composed of basal conglomerate, sandstones and mudstones, and tuffs and other pyroclastic deposits at the top. A K-Ar age of 27.2 ± 2.8 Ma is reported for the volcanic rock sample in the upper members [*Gutierrez*, 1981], which is concordant with the assigned age of middle Tertiary. Sencca Group is assigned an age of upper Tertiary and is composed mostly of volcanic rocks, andesites and rhyolites. Barroso Group is the youngest volcanic rock in this area and was formerly assigned to the Quaternary. However, recent K-Ar dating by *Kaneoka and Guevara* [1984] showed that the activity spans a far wider age range of 0 to 7 Ma.

A remarkable fact about the Altiplano, especially in the central and western part, is that, despite its high altitude and vast horizontal extent, a significant amount of deformation cannot be found for geologic formations producing the Altiplano. Figures 5*a* and 5*b* show examples of Miocene sedimentary layers belonging to Tacaza Group, which is exposed near the northern edge of the Altiplano, about 15 km east of Nazca. Where sections of geological strata are exposed due to cutting by rivers or by the cliffs at the central and western parts of the Altiplano, the strata are astonishingly flat, and deformations (faulting and folding) are minimal. Figure 5*c* shows an outcrop of a pillow lava belonging to either Tacaza or Sencca Group, about 10 km further east. This lava flow is probably of Miocene age but is remarkably fresh with a well-preserved pillow structure. In

Fig. 5a

Fig. 5b

Fig. 5c

Fig. 5. (*a*) Flat sandstone layers of Miocene age (Tacaza formation) observed on the Altiplano about 15 km east of Nazca (14.7°S, 74.5°W). (*b*) Surface of the Altiplano capped by flat lying lava flows seen about 17 km east of Nazca. (*c*) Miocene pillow lava on Altiplano between Puquio and Nazca (14.6°S, 74.4°W).

these photographs, absence of deformation is quite remarkable and suggests that these layers were raised without severe deformation from the original level to the present height in the Neogene.

The lack of deformation is not restricted to the southern Peru portion, but seems to be a peculiar characteristic of the Altiplano. *Noble et al.* [1979] reported that although the Mesozoic Yura formation is moderately deformed, the Nazca tuffs with K-Ar age of 18–22 Ma capping the altiplano were completely undeformed. *Rutland* [1971] noted that folding became less intense in the Tertiary and folds have large wavelength in the Altiplano of northern Chile. The lack of severe deformation can be appreciated by the inspection of small-scale geologic maps of this area; the distribution of formations is quite simple in the Altiplano-Puna compared to the Eastern Cordillera, where many formations with different ages are exposed, sometimes with significant amount of deformations [*Instituto Geologico Minero y Metalurgico* (INGEMMET), 1975; *Servicio Geologia de Bolivia* (GEOBOL), 1975; *Instituto de Investigaciones Geologicas* (IIG), 1968; *Direccion Nacional de Geologia y Mineria* (DNGY), 1964; *Circum-Pacific Map Project*, 1981]. Thus the surface layers, at least in the center and west of the Altiplano, seem to have been elevated to the present height without much distortion affecting the layers. The situation may be slightly different between the northern and southern Central Andes. *Allmendinger* [1986] pointed out that the Altiplano and the northern Puna generally show little neotectonic activity, while the southern Puna is neotectonically active and a few crustal earthquakes are observed there.

Figure 5 and other geomorphological evidences suggest that at least the surface layers of the Altiplano have not experienced heavy deformation since their formation. In conjunction with this, it is interesting to note that the mountains of the Western Cordillera are not under compression. Extensional deformation such as normal faults was reported from this area [*Katz*, 1970; *Megard and Philip*, 1976; *Yonekura et al.*, 1979; *Dalmayrac and Molnar*, 1981; *Sebrier et al.*, 1985]. *Froidevaux and Isacks* [1984] concluded that a neutral to extensional stress regime prevails within the high plateau. However, normal faults are few in number and restricted in distribution compared to the reverse faults in the Eastern Cordillera and Amazonian foreland. Some of the extensional features may correspond not exactly to the present stress state but to that of an earlier period. Also, the tensional stress in the high mountain range of the Western Cordillera may only indicate local stress condition produced by the presence of high mountains themselves [e.g., *Froidevaux and Isacks*, 1984]. We conclude that the stress regime in the western part of the Altiplano and the Western Cordillera is almost neutral, with local tensional patches as indicated by normal faults.

The mountain ranges are also well developed in the Eastern Cordillera, but the stress state seems to be completely different; abundant reverse faults are observed while normal faults do not exist in this area. This is confirmed by surface observations as well as from the study of seismicity (Figure 3) and earthquake source mechanisms [*Stauder*, 1973, 1975; *Suarez et al.*, 1983; *Chinn and Isacks*, 1983]. Therefore, the compressional regime seems to play an essential role in the Eastern Cordillera. We note, in passing, that the fault system is most developed in the foreland basin (e.g., *Circum-Pacific Map Project* [1981]; see also Figure 3). Few faults exist on the western side of the Eastern Cordillera.

GRAVITY ANOMALIES AND THE CRUSTAL STRUCTURE

Several seismic refraction experiments have been performed in the Central Andes, especially in the southern Peru (for a review, see *Ocola* [1983]). However, crustal structures beneath the Central Andes are not well constrained by these studies, because of the high attenuation and noisy record associated with the Altiplano. Though various authors proposed crustal models based on these studies, the evidences are still far from decisive. *James* [1971*a*] studied dispersions of surface waves traveling across and along the Andes chain and estimated the depths to the Moho. His contours show that the crustal thickness is over 70 km beneath the Western Cordillera and gradually diminishes to the east to a value of 55 to 60 km below the Eastern Cordillera.

In 1980 and 1984, we performed traverses crossing the Central Andes in Peru, measuring gravity values at bench marks with precise altitude information at a separation of 1 to 3 km. Details of gravity measurements, calibration, and gravity corrections are described in the accompanying paper [*Fukao et al.*, this issue]. The longest of these profiles is the one connecting Nazca on the Pacific coast with Puerto Maldonado on the Amazon Basin, passing through Puquio, Chalhuanca, Abancay, Cuzco, and Mazuco (Figure 6*a*). This route crosses the entire section of the coast–Western Cordillera–Altiplano–Eastern Cordillera–Amazon Basin. The station height as well as the topography in a band 100 km wide centered on the Nazca–Puerto Maldonado line is shown in Figure 6*b*. The Bouguer anomalies obtained are shown in Figure 6*c*. In the oceanic area, free-air anomaly of *Hayes* [1966] is plotted. Although this route is close to the northern edge of the Altiplano, it was shown that the effect of topographic cutoff is much smaller than the amplitude of observed gravity anomalies [*Fukao et al.*, this issue]. As no such precise data are available from the central portion of the Altiplano-Puna, and as the topography is essentially two-dimensional to the southeast of this route, we may take this as a gravity profile characteristic to the Central Andes.

The prominent features of the gravity anomalies obtained by *Fukao et al.* [this issue] from the traverse crossing the Altiplano, from west to east, can be summarized as follows (Figure 6*c*). After crossing the –150 mGal low associated with the Peru-Chile trench, the Bouguer anomaly returns to a normal value of about 0 mGal near the Pacific coast. From the coast inland, the Bouguer anomaly decreases steeply, and the minimum value of about –400 mGal is reached just below the mountains of the Western Cordillera. Although the surface topography is almost symmetric and suggests a similar structure below the Eastern Cordillera (Figure 6*b*), gravity data show that that is not the case. The magnitude of the negative Bouguer anomaly gradually decreases from west to east and reaches a value of about –280 mGal below the Eastern Cordillera. The crustal model consistent with the gravity anomalies has a Moho depth of 65 km below sea level under the Western Cordillera and 55 km under the Eastern Cordillera [*Fukao et al.*, this issue]. The thinning of the crust from west to east suggested from the Bouguer anomaly profile is in good agreement with the structure obtained by dispersion of surface waves [*James*, 1971*a*]. A discontinuous jump of Bouguer anomaly occurs where the Eastern Cordillera rapidly loses height to reach the flat lands of the Amazon Basin. This step is nearly 150 mGal in magnitude and suggests a sudden change in the crustal thickness at the junction of the Andes and the stable continent. In the Amazon Basin, the Bouguer anomaly gradually approaches the zero level. As shown by *Fukao et al.* [this issue], the Western Cordillera appears to be essentially in isostatic equilibrium. As the mean height of the Eastern and Western Cordillera is about the same, the decrease of the magnitude of negative Bouguer anomaly observed in traversing the Andes from west to east indicates that the Eastern Cordillera is not in isostatic equilibrium.

Because the gravity data obtained by *Fukao et al.* [this issue] are of very high quality, they impose an important constraint to the models of the Central Andes. Although gravity values are not uniquely related to the subsurface structure, the models should at least conform with the observed data. The asymmetry of the Bouguer anomaly in spite of the apparent symmetry of the topography is a fundamental feature of the Central Andes and suggests that the formation process may also be asymmetrical.

DISTRIBUTION OF VOLCANOES AND RECENT VOLCANIC ROCKS

An enormous amount of Cenozoic volcanic rocks are distributed in the Central Andes of Peru, Bolivia, Chile, and Argentina. Unfortunately, geological exploration in this area is not so dense as to allow a detailed division into different age intervals. We have compiled the distribution of Quaternary and upper Tertiary volcanic rocks in this area (Figure 7a) based on 1:1,000,000 scale geological maps of Peru, Bolivia, and Chile [*INGEMMET*, 1975; *GEOBOL*, 1975; *IIG*, 1968]. For Argentina, we used a 1:2,500,000 scale map [*DNGY*, 1964], which was the only one available to us. In central and northern Peru, the volcanic rocks are distributed in a narrow zone and intermittently. Active volcanoes are absent in this segment nowadays [*Barazangi and Isacks*, 1979]. The narrow belt of the volcanic rocks probably corresponds to the volcanic front in the Pliocene or late Miocene. The amount of surface outcrops of young volcanics shows an abrupt increase in southern Peru, coincident with the start of the Altiplano. In the Altiplano-Puna ranging from Peru through Bolivia to Chile and Argentina, young volcanic rocks are found very abundantly and in a wide spatial extent.

James [1971*b*] argued that the center of volcanic activity migrated from the west from the Jurassic to Cenozoic. In his model, the migration of the center of volcanic activity is one reason why the Central Andes attained such width. *Rutland*

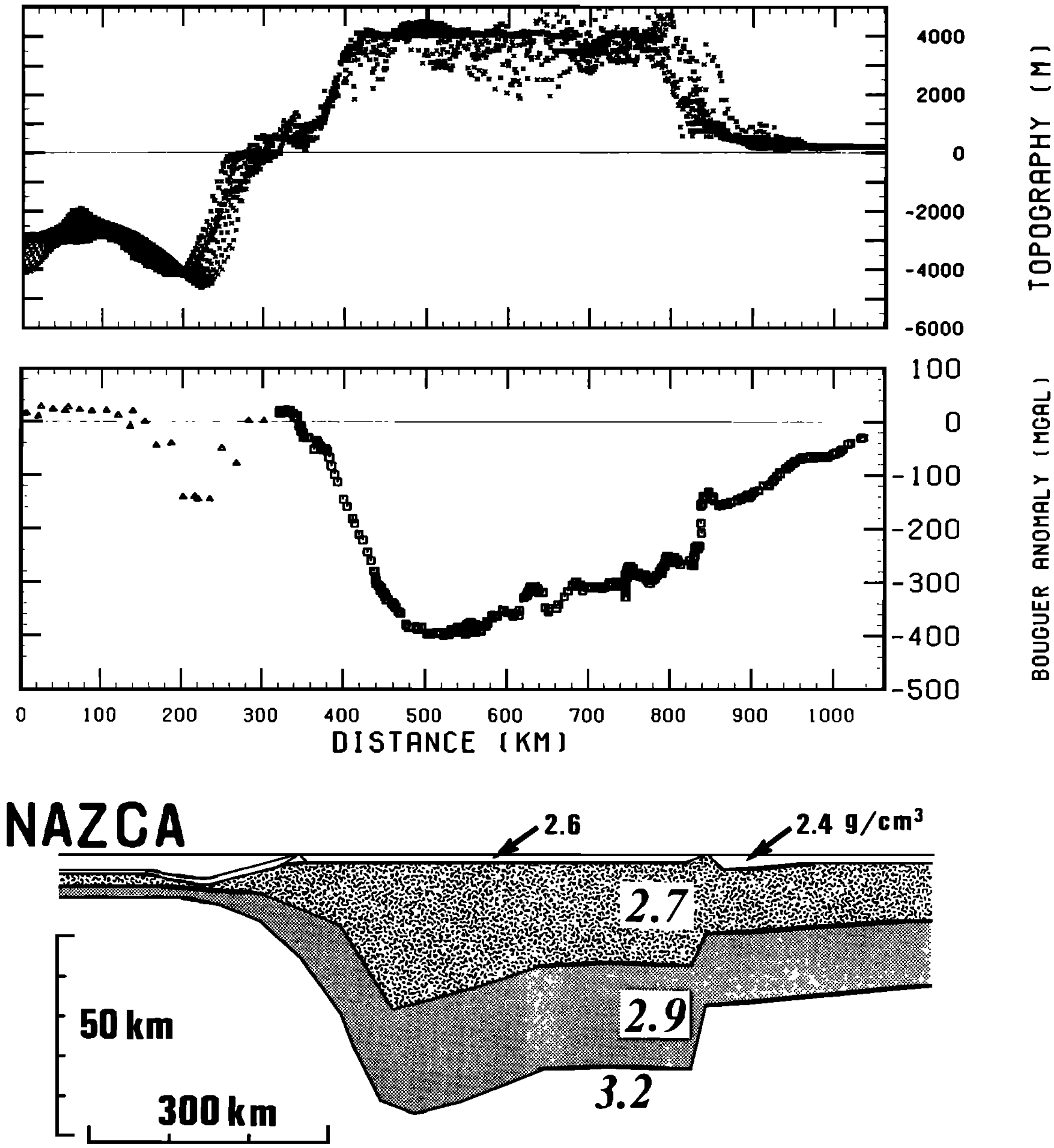

Fig. 6. Gravity anomalies obtained for the route Nazca–Puerto Maldonado, which spans from the Pacific coast through the Western and Eastern Cordillera and the Altiplano and continues to the flat land of the Amazon river, where the height is only about 200 m [*Fukao et al.*, this issue]. From top to bottom, station height (dots) and heights of grid points in a 100-km belt containing the traverse route, Bouguer gravity anomaly on land [*Fukao et al.*, this issue] and free air anomaly on the sea [*Hayes*, 1966], and the crustal structure model.

[1971] suggested tectonic erosion as an important element of his model of the Central Andes partly because of this apparent age progression from west to east. However, most of the volcanic rocks associated with the Altiplano are of Cenozoic age. Recent radiometric age determinations show no definite trend in the ages of the Cenozoic volcanic rocks in the Altiplano [e.g., *Baker and Francis*, 1978; *Thorpe and Francis*, 1979; *Kaneoka and Guevara*, 1984]. Even a reverse trend in age progression (west to east) was found in the volcanic rocks of southwestern Bolivia [*Kussmaul et al.*, 1977]. With the addition of newer age data, it now appears that the important thing about the distribution of volcanic rocks in the Central Andes is not the regular age progression but the wide occurrence as noted by *James* [1971*b*]. Ignimbrites of Miocene age show especially wide distribution and are the evidence of the very strong volcanic activity in the late Tertiary [*Rutland et al.*, 1965; *Guest*, 1969; *Francis and Rundle*, 1976; *Kussmaul et al.*, 1977; *Baker and Francis*, 1978; *Baker*, 1981; *Lahsen*, 1982; *Francis et al.*, 1983]. Some center of volcanic activity may have lasted several million years [e.g., *Kaneoka and Guevara*, 1984]. The locations of volcanic centers seem to have moved not in a systematic but in a random manner with age.

Figure 8 shows the distribution of active volcanoes and volcanic centers younger than Miocene [*International Association of Volcanology and Chemistry of the Earth's Interior*, (IAVCEI), 1979]. For Argentina, Figure 8*b* was supplemented by the volcanic centers younger than 10 Ma reported by *Froidevaux and Isacks* [1984] using Landsat imagery, because that

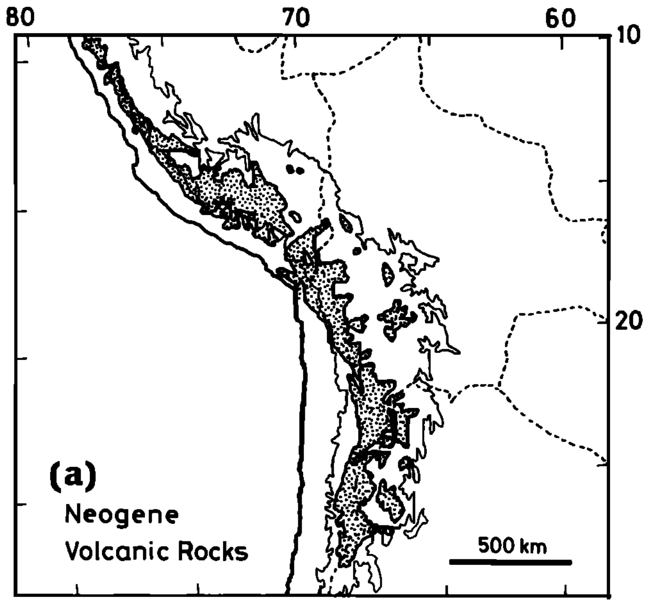

Fig. 7. Distributions of Neogene volcanic rocks in (*a*) the Central Andes (compiled from 1:1,000,000 geologic maps of Peru, Bolivia, and Chile, and 1:2,500,000 map of Argentina), and in (*b*) northeastern Japan [after *Geological Survey of Japan* 1982].

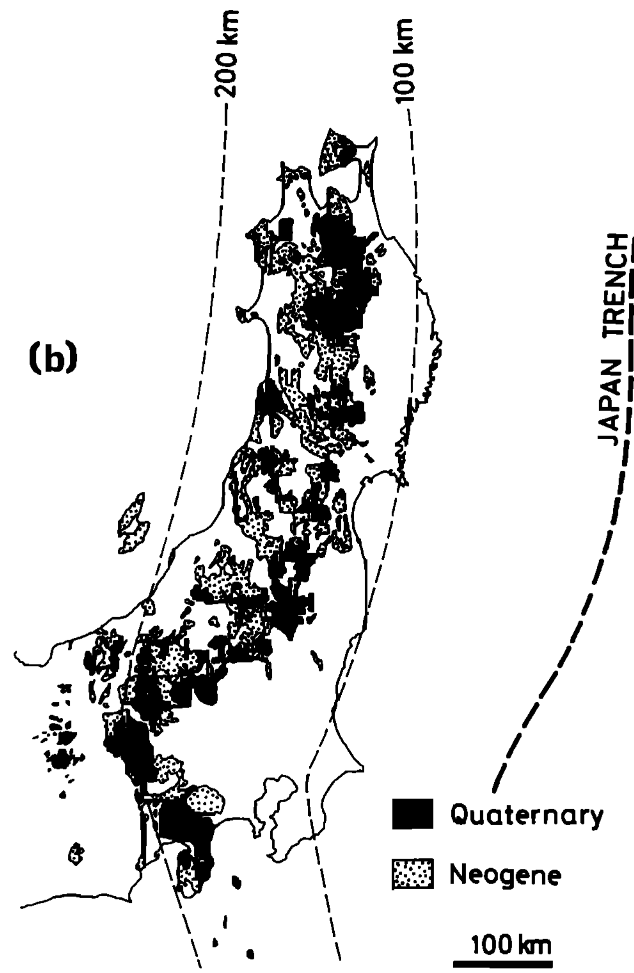

Fig. 7. (continued)

region was not described in the IAVCEI catalog. The active volcanoes align in a single line forming a distinct volcanic front in southern Peru and northern Chile. However, if we look back for the entire Neogene period, the volcanic centers are not restricted to a narrow zone as the present-day volcanic centers are. The post-Miocene volcanoes are distributed almost all over the Altiplano, especially in Bolivia (Figure 8*b*). One of the largest ignimbrite field (Frailes Plateau with an area of 13,000 km^2) is displaced from the present-day volcanic front by almost 300 km toward the continental side [*Baker*, 1981]. We suggest that the concentration of the active volcanoes at the volcanic front today is an exception rather than a rule for the distribution of the volcanic activity in the Central Andes. A much wider region has been under the influence of the volcanic activity, and a considerable amount of magmatic material should have been supplied to the crust beneath the Western Cordillera as well as the Altiplano. A wide distribution of volcanism is also consistent with high heat flow values observed not only near the Western Cordillera but in most parts of the Altiplano [*Uyeda and Watanabe*, 1982].

Combining the distributions of young volcanic rocks (Figure 7*a*) and active and post-Miocene volcanic centers (Figure 8), we suggest that the volcanic activity in the Central Andes is perhaps distributed over a wide geographical extent covering most of the Altiplano, and that the Altiplano corresponds roughly to the area of magma generation associated with the subduction of the Nazca plate beneath the South American continent.

TIMING OF THE UPLIFT OF THE PLATEAU

James [1971b] suggested that the formation of the Central Andes started in the late Paleozoic, when the subduction initiated from the Pacific side, and continued into the entire Mesozoic and Cenozoic. An orogenic cycle of such long duration seems to be popular in many standard texts [e.g., *Miyashiro et al.*, 1982]. *Coira et al.* [1982] divided the orogeny of the Central Andes into two separate phases: the Hercynian orogeny of the Paleozoic and the recent one which started in the Jurassic and has continued to the present in a more or less continuous manner. The long time interval of the mountain building is suggested by examining the geology of the Central Andes area. Although the Western Cordillera is formed mostly by Cenozoic formations with some Mesozoic rocks, Paleozoic rocks are very abundant in the Eastern Cordillera. If these rocks represent a certain phase of a single event of orogeny, such an event must have spanned quite a long time.

However, we may take a viewpoint that the main part of the mountain building in the Central Andes coincides with the period when the topography (high mountains and plateaus) was formed and maintained. Such a consideration is permissible because of the isostatic adjustment which operates with a typical time constant of about 5000 years [e.g., *Turcotte and Schubert*, 1982]. If active mountain building process is not operating, topographic features with a considerable horizontal dimension will be lost in a geologically negligible time. The ages of formations involved in the mountains themselves may not have causal relations with the mountain building. They may have been "prepared" in a more tranquil environment before any of the orogenic process was operative. This concept applies to the Nepal Himalaya, where the folded and uplifted formations (e.g., the Everest limestone of Carboniferous age) originated in the continental margin of the Tethys Sea long before India and

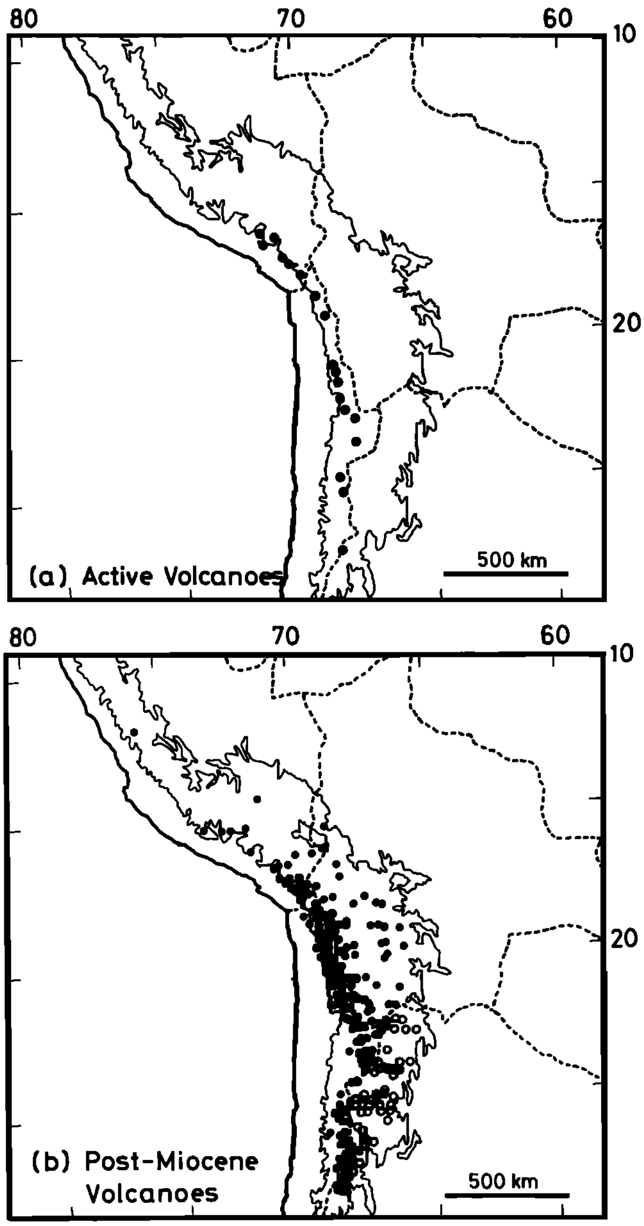

Fig. 8. Distribution of (*a*) active volcanoes and (*b*) post-Miocene volcanoes in the Central Andes. Solid circles are data from *IAVCEI* [1979]. Open circles are post-10-Ma volcanic centers obtained from Landsat imagery [after *Froidevaux and Isacks*, 1984].

Eurasia collided [e.g., *Gansser*, 1964]. It is therefore important to study the timing of the uplift.

Recently, more and more data have been reported which suggest that the uplift was a very recent phenomenon. From a study of the ages of the ignimbrites in northern Chile, *Rutland et al.*, [1965] concluded that the main phase of the uplift took place in the 6-Ma period between 4 and 10 Ma. They further suggested that the average rate of uplift is less than 0.5 mm/yr based on the assumption that the Puna surface attained 4000 m in the 10-Ma period, and that this rate is similar to the other Tertiary mountain chains, such as the Himalaya or the Alps. A similar conclusion was reached by many others working on the Miocene and Pliocene ignimbrites in the Central Andes. *Guest* [1969] concluded that the uplift occurred mostly in the Pliocene, forming the Puna surface which is covered by ignimbrites with ages between 19 and 3 Ma. *Allmendinger* [1986] places the most active period of uplift in the southern Puna at 10 Ma to present. The ignimbrite activity must have been a spectacular one. After a relatively quiet period in the Oligocene [*Lahsen*, 1982], the volcanic activity has continued almost continuously between 24 Ma and the present [*Kussmaul et al.*, 1977]. The Miocene and Pliocene ignimbrites are distributed in the entire north-south extension of the Central Andes [*Baker*, 1981], and some of the ignimbrite plateaus cover an area of as much as 13,000 km^2 [*Francis et al.*, 1983]. The total thickness of these ignimbrites are generally unknown [*Kussmaul et al.*, 1977], but one estimate places it at about 1 km [*Francis et al.*, 1983].

As the Miocene volcanic activity is very extensive, it is quite natural to assume that it is a part of the most active phase of the mountain building. The difficulty with this approach is in the estimate of the altitude of certain places in the past. *Rutland et al.* [1965] assumed that the Puna surface was nearly at sea level before the uplift started in the Miocene. However, such assumptions may not be validated by studying the rock formations of earlier ages. For example, existence of pillow lavas on the surface of the Altiplano (Figure 5*c*) is evidence that it was under water at that time, but not that it was below sea level. It may have formed under an inland lake, such as is possible in the present-day drainage system [e.g., *Froidevaux and Isacks*, 1984].

That the uplift in the Central Andes is a very recent phenomenon is supported from other directions. *Sebrier et al.* [1985] showed from neotectonic studies of active faults that the mountain building process is going on at a high speed in the Quaternary. An even more direct estimate of the uplift rate was obtained by the fission-track dating method. *Crough* [1983] and *Benjamin et al.* [1987] dated Triassic plutonic rocks in Zongo valley of Cordillera Real in Bolivia and obtained the apatite ages of 5–15 Ma and zircon ages of 25–45 Ma for rocks with K-Ar ages of about 210 Ma [*McBride et al.*, 1983]. Since the tracks in apatite and zircon are annealed at about 100°C and 200°C, it is possible to estimate the uplift or erosion rate by assuming an appropriate geothermal gradient. From the detailed study of rocks at various altitudes in Zongo valley, *Benjamin et al.* [1987] concluded that the uplift rate was small in the 20- to 40-Ma period (0.1–0.2 mm/yr), but sharply increased between 10 and 15 Ma and attained a high rate of 0.7 mm/yr at 3 Ma.

It is therefore reasonable to conclude that the main phase of the mountain building was within the Cenozoic and that the uplift was most severe since the Miocene. However, this refers only to the most recent cycle of mountain building in the Central Andes. For instance, the Peruvian plutons to the west of the Western Cordillera [*Pitcher and Bussell*, 1977] represent a former cycle of mountain building. The fact that they are already eroded to a low altitude indicates that the orogenic cycle related to these plutons ceased a long time ago. It is also possible that the Andes was the site of repeated orogeny in the geological history [*Coira et al.*, 1982]. What we dealt with in the last sections is concerned with this last cycle of the Andean orogeny. We will therefore confine our discussions to this last cycle, which started in the Cenozoic and became very vigorous since the Miocene.

A MODEL OF MOUNTAIN BUILDING IN THE CENTRAL ANDES

The key element in considering the mountain building in the Central Andes is why and how the high plateau of the

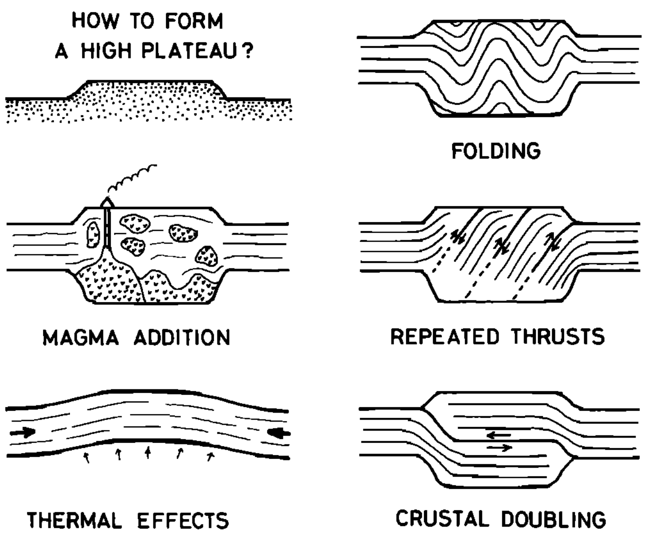

Fig. 9. Processes which can form an extended plateau of high altitude (compare with a similar figure in *Allmendinger* [1986]. The three on the right involve some sort of crustal shortening, while the two on the left rely on the supply of volcanic material or heat from below.

Altiplano-Puna was formed there. The absence of a back arc basin behind the Andes is another important feature, but we think that the latter problem is closely related to the former. It is well known that geologic features with sizes of about 200 km or larger cannot be supported completely by the elastic stress in the surficial layers. Yet, a substantial part of the Central Andes is not in the equilibrium state now. Our gravity study showed that the Moho lies about 65 km below the Western Cordillera and 55 km below the Eastern Cordillera, and the crustal thickness changes smoothly between these two values below the Altiplano [*Fukao et al.*, this issue]. Since this indicates that only the Western Cordillera and the western part of the Altiplano is compensated by the crust, some sort of support is needed for the eastern half of the Altiplano and the Eastern Cordillera.

The problem of formation of high plateaus is a problem of how to thicken the crust and how to support the excess load if compensation is not complete. In either way, excess mass should be supplied for the topography. A number of ways can be conceived for this purpose (Figure 9). The three cartoons on the right side of Figure 9 show thickening of crust due to shortening. The folding model is what is inferred for the Chilean type subduction by *Uyeda and Kanamori* [1979]. However, this model is not consistent with the fact that the observed deformation is very small in the Altiplano (Figure 5) and the east-west asymmetry shown by the gravity data. The crustal thickening by repeated underthrusting of the continental crust was the mechanism suggested by *Suarez et al.* [1983]. However, such motions are unlikely in the western half of the Central Andes. The compressive stress regime only prevails in the Eastern Cordillera and the Amazonian foreland. Addition of subducted crustal material was proposed by *Rutland* [1971], but this proposal was based on the assumption of constant migration of the volcanic centers to the east with time. As this assumption was denied, we may discard this process from the possible crustal shortening mechanisms.

The two cartoons on the left side of Figure 9 show ways to thicken the crust or at least to make the surface topography without shortening the crust. Volcanism is certainly a decisive factor in the Western Cordillera, but does not appear so in the east, where the crust appears to consist of Paleozoic to Mesozoic sedimentary and metamorphic rocks. Thermal expansion was studied by *Froidevaux and Isacks* [1984] by assuming that the Central Andes is essentially in equilibrium state. The idea is that the topography should be compensated either by the crust or by the lithosphere, because of the size of the Central Andes. However, we think this rather unlikely because of the east-west asymmetry; if the eastern part is supported by hot and lighter lithosphere underneath, similarly hot or even hotter lithosphere should exist under the Western Cordillera, leading to an overcompensation of the surface load there.

We conclude that a single mechanism cannot create and support the topographic features of the Central Andes. Instead, we propose that two different mechanisms operate simultaneously at the western and eastern halves: magma addition and crustal shortening (Figure 10). A combination of these two is the main agent which contributed to make the Central Andes a unique mountain chain associated with a subduction zone; e.g., existence of high plateaus of wide extent and absence of backarc basins.

In the western half of the Central Andes, a substantial amount of magma has been added to the crust from below, thickening the crust and raising the plateau without severely distorting the geologic formations. The reason for this is the shallow (10°–30°) and fast (about 10 cm/yr) subduction of the young Nazca plate, a situation which must have continued since the Miocene (Figure 10). The subduction angle must have changed in the past, reflecting the stress state of that time, but it stayed in the shallow range because of the hot and buoyant nature of the Nazca plate, and the trenchward advance of South America [*Uyeda and Kanamori*, 1979]. When the slab descends shallowly, magma may be generated in a wider zone across the arc (see Figure 7*b*), because the generation of magma is controlled by the supply of water to the hot mantle by dehydration of hydrous minerals and thus dependent on depth of the slab [*Tatsumi*, 1986]. The strong coupling between the downgoing slab and the overlying mantle induces secondary convection in the mantle wedge [*Toksoz and Bird*, 1977], which helps magma generation to occur in a wide zone by dragging the water-bearing mantle material toward continental interiors [*Tatsumi*, 1986].

The continued shallow and fast subduction below the Central Andes since the Miocene is consistent with the opening of the Atlantic Ocean and the ages of the seafloor inferred from the magnetic anomaly pattern analysis of the Nazca plate [*Couch and Whitsett*, 1981; *Couch et al.*, 1981].

When magma or mantle diapir ascends from the surface of the slab, only a small part of the magma would reach the surface. The rest is hindered form ascending to the surface by the compressive crust above and will either intrude in the crust or attach to the base of the lower crust and thicken it. This is because most of the Andean crust has continuously been under compressive stress regime since the Miocene. In the present Western Cordillera, a tensional field locally occurs, and magma can reach the surface, forming active volcanoes. Thus a clear volcanic front is formed parallel to the Pacific coast of South America. However, magma generation related to the formation of the Central Andes must have been more widely distributed. A hot or at least warm mantle must extend further eastward as suggested by the high heat flow observed there [*Uyeda and Watanabe*, 1982]. Because of shallow subduction, magma will be produced considerably inland behind the volcanic front,

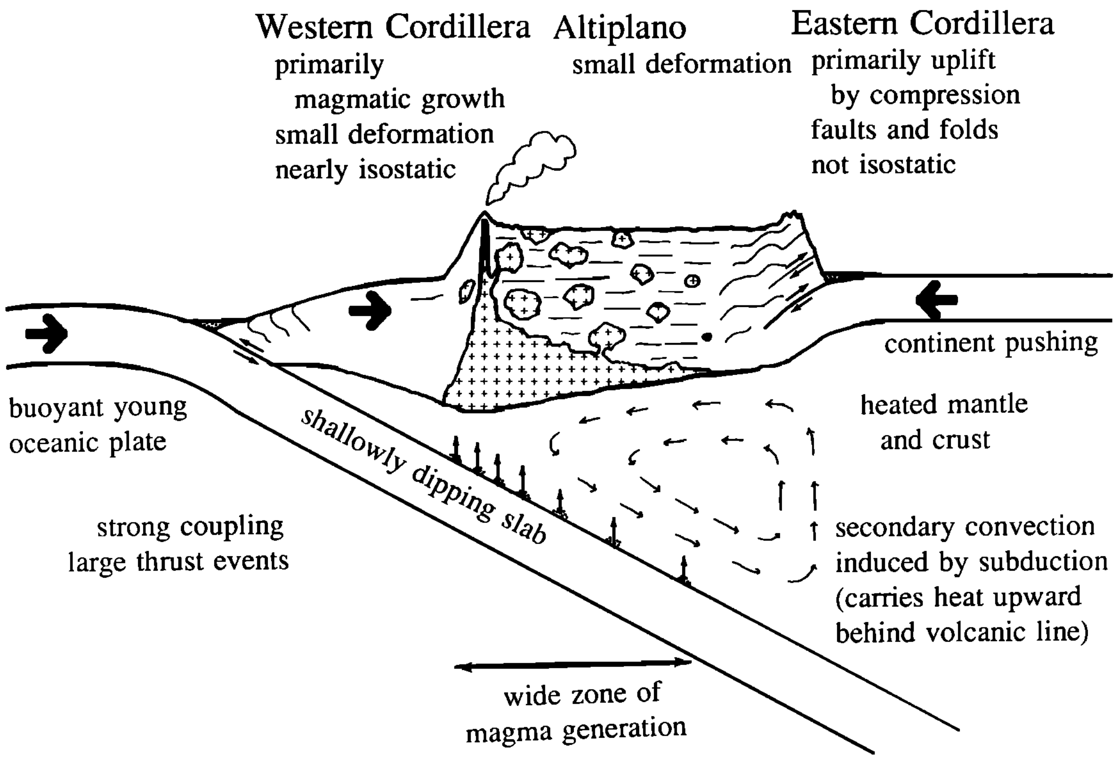

Fig. 10. A cartoon showing the processes operating in the formation of the Central Andes. Not to scale.

although it does not appear on the surface due to the overlying compressive crust. Accretion of such volcanic materials is the main reason for the thickening of the crust observed in the Central Andes, especially in the Altiplano and the Western Cordillera.

In the Eastern Cordillera and Andean foreland basin, there is little evidence for extensive magma intrusion during the Cenozoic age. Instead, thick Paleozoic rocks have been extensively folded and faulted. Crustal seismic activity shows horizontal compression almost perpendicular to the mountain axis. The sub-Andes foreland basin is formed by a series of folds and west dipping reverse faults active from at least Pliocene time to the present [*Suarez et al.*, 1983; *Allmendinger*, 1986]. Such evidence suggests that crustal shortening due to westward compression from the Brazilian shield is a major agent of the mountain building in the Eastern Cordillera. Perhaps the Andean crustal block is heated from below even in its eastern part and it is on the whole hotter and softer than the Brazilian shield block. When the soft Andes block is pushed by the hard block of the Brazilian shield, intense deformation would occur in the Andes block but is concentrated in the region near the colliding boundary. A similar situation occurs in the Himalaya where deformation is concentrated near the boundary between hard and soft blocks [*Molnar and Tapponnier*, 1979]. We consider that the resultant crustal shortening and thickening with possible underthrusting of the Brazilian shield block are the main reason for the uplifting of the Eastern Cordillera.

The two processes are strongest at both ends, but extend to the east or west, losing their strengths gradually. The superposition of the two different processes is responsible for the creation and maintenance of the intermediate plateau, the Altiplano-Puna. Sediment fill from both eastern and western mountain ranges must have been substantial [*James*, 1971*b*], but this is a secondary effect compared with the former two processes.

Thus our model of the mountain uplifting can be summarized as follows. Because of the relatively shallow subduction of the young oceanic plate, magma is generated in an extensive area above the descending slab. Accretion of magmatic material into the crust is most extensive at the volcanic front and progressively decreases eastward. The Andes block, even at its eastern end, is heated and softened by the extensive volcanism and is pushed westward by the hard block of the Brazilian shield. The deformation due to this push is severest at the Amazonian foreland basin and the Eastern Cordillera, but also extends to the west with decreasing magnitude. These two mountain ranges thus represent two extreme cases in the process of mountain uplifting. The superposition of asymmetric processes to form a relatively symmetric feature, the Altiplano-Puna, is the essential property of the Central Andes.

DISCUSSION

[*James*, 1971*b*] considered that the intrusion of melt into the crust beneath the Western Cordillera and the resultant crustal dilatation produced continentward compression to form thrust and fold mountains in the Eastern Cordillera. It is not evident why the volcanic materials intruding under the Western Cordillera can apply a compressive force to such a remote place as the Eastern Cordillera. Besides its physical implausibility, this mechanism is inconsistent with the fact that intense folding and reverse faulting occur on the eastern flank and not on the western flank of the Western Cordillera. The concept of the Altiplano as an intermontane valley filled by eroded materials from both mountains is also not convincing, since the topographic shape of the Altiplano is essentially trapezoidal (Figure 2) and not a "valley" between two high mountain chains. His model assumes the continuation of subduction from the Triassic to present, which is not supported by more recent models of plate motions [e.g., *Pilger*, 1981; *Couch et al.*, 1981]. The migration of the center of volcanic activity from west to east is also an important element of this model, which is inconsistent when the Cenozoic orogenic cycle is considered.

The model of [*Suarez et al.*, 1983] overestimates the importance of reverse fault motion under the Eastern Cordillera and attributes the entire crustal thickening to the repeated jump of the location of reverse faulting to the east. This model is apparently inconsistent with the near absence of deformation of layers in the Altiplano and the Western Cordillera. As we are mostly concerned with the deformation of surface layers of mostly Miocene age, it may be argued that deformation was severe in older layers which underly the Neogene formations at the surface of the Altiplano (Figure 5). In that case, the importance of crustal shortening may be underestimated due to the lack of relevant exposures. However, such discussions can be rejected because the main part of the uplift of the Central Andes occurred since the Miocene. Even if earlier strata may have been deformed, that cannot be associated with the most recent phase of the mountain building of the Central Andes.

The Chilean type subduction of *Uyeda and Kanamori* [1979] explains the essential feature of subduction of the young oceanic plate in the Central Andes area. However, their conclusion that the high plateau was formed because of the contraction due to the prevailing compressive stress in the continental crust is not adequate, as discussed earlier.

Previous models constructed to explain the mountain building in the Central Andes show inconsistencies with some of the observed data summarized above. Our new model contains elements derived from these three models but is consistent with most of the geophysical and geological data discussed before. Some consideration, however, is needed to assess the plausibility of this model.

The first of these is the profound difference between the Central Andes (continental arc) and the island arcs of the western Pacific, such as Japan. The subduction angle beneath northeast Japan is now about 30°, which is similar to the one in the Central Andes. The prevailing stress in northeast Japan is E-W compression, again similar to the Central Andes. Nevertheless, the distribution of volcanic rocks in northeast Japan is confined to a narrow zone of about 100 km starting at the well-defined volcanic front, both for the Quaternary and Neogene (Figure 7*b*). This contrasts with the situation in the Central Andes, where the upper Cenozoic volcanic rocks show a wide distribution (Figure 7*a*). Indeed the situation is quite similar, as shown by the similarity of the distribution of the active volcanoes today; they are confined to the volcanic front in both areas. The difference must be concerned with the past history.

Several authors have already suggested the possibility of the change in the subduction angles in the Central Andes [e.g., *Barazangi and Isacks*, 1976; *Baker and Francis*, 1978; *McBride et al.*, 1983; *Wortel*, 1984]. The suggestion is mainly based on the discrepancy in the distributions of the present active volcanoes (Figure 8*a*) and Neogene volcanic rocks (Figure 8*b*). We propose that the subduction angles changed in the past in both the Central Andes and northeast Japan in an opposite sense: 30° or shallower in the Andes, while 30° or steeper in Japan.

There is some evidence that the subduction angle was steeper in Japan in the past. At the present time, E-W compression prevails in northeast Japan to an extent that initiation of subduction from the Japan Sea side is suspected [*Nakamura*, 1983]. In the Miocene time, however, the backarc of the northeastern Japan was under tensional regime [*Nakamura and Uyeda*, 1980; *Tsunakawa*, 1986], and the Japan Sea opened under the tensional field [*Otofuji et al.*, 1985; *Hirooka and Torii*, 1986]. In this case, the Honshu arc seems to have changed from Mariana type in the Miocene to Chilean type in the Quaternary. Evidence is less decisive in the Central Andes, but the absence of back arc basins and the wide spread of Neogene volcanic rocks are in accord with a subduction angle shallower than now.

On the Pacific side of South America now, the subduction angle alternates between shallow (10°–20°) and steep (about 30°) portions, and they correspond to absence or existence of active volcanoes. It is usually considered that magma generation is not possible if the subducting slab is directly in contact with the continental crust so that asthenosphere (wedge mantle) does not exist between these two [*Barazangi and Isacks*, 1976]. However, magma generation near the subducting slab may still operate in the segments with shallower angles. Since generation of arc magma is primarily due to the lowering of solidus temperature by the supply of water from the subducting plate to the wedge mantle, and since the dehydration of hydrous minerals is mainly controlled by pressure (depth) [*Tatsumi*, 1986], magma generation may only be postponed when sufficient wedge mantle material is not available because of too shallow an angle of subduction. Such magma may come up from places considerably inland from the "volcanic front," which corresponds to a depth of about 110 km of the Wadati-Benioff plane [*Tatsumi*, 1986]. In the past, either because the subduction angle was shallower or because of a stress situation which was not so severely compressive as it is today, magma could come out rather far from the Pacific coast (Figures 8*a* and 8*b*). If magmatism is active on the shallowly dipping segment of today, the volcanic material generated there cannot reach the surface because of prevailing compression and is either intruding the crust or accreting to the underside of the crust, making the crust thicker.

The same argument can be applied to central Peru north of the Altiplano. Magma may be generated now above the shallowly dipping slab but cannot rise to the surface because of the highly compressive stress regime in the crust, which is shown by earthquake mechanisms and surface faults [*Suarez et al.*, 1983; *Megard and Philip*, 1976]. It may be that crustal thickening has already matured in the Central Andes with magma addition and crustal shortening which resulted in the formation of the Bolivian orocline [*Carey*, 1955; *Kono et al.*, 1985a], and that central Peru is now undergoing a similar process.

The other concern is how much volcanic material and how much crustal shortening are needed for this model and if such values are plausible. Consider that the crust is 65 km thick under the Western Cordillera and 55 km thick under the Eastern Cordillera, that normal crustal thickness is 35 km, and that the proportion due to magmatic material (crustal shortening) in the residual crust changes linearly from 100 (0)% at the western end to 0 (100)% at the eastern end. If the width of the plateau is taken to be 300 km, the volcanics account for 4500 km^2, and shortening accounts for 3000 km^2 of the crustal section. The needed crustal shortening is about 86 km, which is smaller than the estimates of most people (*Suarez et al.*, [1983] suggested 190 km shortening in 90–135 Ma).

The volume of volcanic material needed is similar to that obtained by [*James*, 1971*b*], though he argued that such a large amount is improbable, as melting of a substantial part of mantle material is needed so that the melt composition must be basaltic rather than intermediate or silicic. If the mantle wedge concerned with the magma generation is approximated by a trapezoid with bases of 50 km and 150 km and height of 300 km, the available source material is 30,000 km^3 for a 1-km segment; this means that about 15% of the mantle wedge should be melted to form the arc magma. This estimate is very similar to the one given by [*James*, 1971*b*] and almost the same as that put forward by *Thorpe et al.* [1981]. Thorpe et al. suggested the importance of the secondary convection in the mantle wedge [*Toksoz and Bird*, 1977], by which the asthenospheric material in the mantle wedge is replaced and the vast amount of intermediate to silicic melt can be produced. The secondary convection is also included in our model (Figure 10) for replacing the source material of magma as well as for carrying heat to the crust.

Thorpe et al. considered that the mountain building continued for about 180 Ma, since the time of the onset of magmatism, while we consider that Jurassic and Cretaceous volcanic events perhaps belong to an earlier cycle of orogeny and that the present cycle lasted at most 50 million years. Therefore, as the rate of magma production we obtain 9×10^{-5} km^3/yr per 1 km of subducting segment against their value of 2×10^{-5} km^3/yr/km. Taking the length of the Central Andes as 1500 km, we expect a very high rate of magma generation of 0.14 km^3/yr for the whole area. *Francis and Rundle* [1976] and *Baker and Francis* [1978] estimated the supply of volcanic material in northern Chile to be about 4×10^{-6} km^3/yr/km. The estimate of *Francis and Rundle* [1976] is based on the distribution of ignimbrites and (hidden) batholiths 10 Ma or younger between 21°S and 22°S. *Baker and Francis* [1978] suggested a similar figure on the assumption that about 24 km thickness increase was achieved in a crust of 50 km width. In place of these figures, our estimate of magma generation appears very large. The important question is if such an intensive volcanism is really possible or not.

This sort of estimate is always very difficult and contains much ambiguity. In the case of the Central Andes, the difficulty is enhanced because of the lack of intensive field descriptions. Even the amount of surface exposures of volcanic rocks cannot be adequately estimated without the help of Landsat imagery (see, for example, [*Baker*, 1981]). The amount of intrusives is more ambiguous because of the low rate of erosion and consequently bad exposures in the Central Andes. One way to make a reasonable estimate is to compare with the different arcs. Cenozoic volcanic rocks are quite well mapped in Japan (Figure 7*b*), and the amount of volcanic materials belonging to various ages can be estimated. According to *Sugimura* [1974], volcanism in the northeast Honshu arc was most active in the 10-Ma interval between 23 and 13 Ma with a total volume of about 1.5×10^5 km^3. If we take the length of the arc as 1300 km, the rate of magma generation for this volcanic activity is 1.2×10^{-5} km^3/yr/km. In this case, the rocks included are almost entirely effusive ones because Neogene granites are not exposed in the northeast Honshu arc. In the case of the Central Andes, *Francis and Rundle* [1976], *Baker and Francis* [1978], and *Thorpe et al.* [1981] estimate that the rate of plutonic activity is about 10 times that of the volcanic activity. The smaller figures they obtained may be attributable to the lack of visible outcrops of Cenozoic plutons because of low erosion rate.

As seen above, the estimate of volcanic activity includes much ambiguity. However, we suggest that the needed high activity is possible and it actually took place in the formation of the Central Andes. This conclusion is certainly tentative, and whether our model is successful or not depends heavily on this assumption.

CONCLUSIONS

The mountain building process in the Central Andes is characterized by the formation of high plateaus (the Altiplano and Puna) and by the absence of the marginal basins common to the subduction zones in the western Pacific. These features are related to the subduction of the young and buoyant lithosphere below the western coast of South America and continued advance of the South American plate to the west, which must have persisted at least since the Miocene, when subduction in the present direction started. The uplift of the Altiplano-Puna also became intensive since about the Miocene as a consequence of this subduction. As shown by the detailed gravity measurements [*Fukao et al.*, this issue], the Western Cordillera is essentially in isostatic equilibrium, whereas the Eastern Cordillera has heights of about 1000 m larger than its equilibrium values. Together with the paucity of evidence of faulting and folding in the strata, this indicates that at least the Western Cordillera and the Altiplano experienced an uplift without much deformation. For the Eastern Altiplano to attain similar heights as the Western Altiplano, tectonic stress should have played an important part, as is shown by the abundance of westward dipping reverse faults near the eastern foot of the mountains.

Both the crustal thickening by magma intrusion and crustal shortening by horizontal compression play important roles in mountain uplifting of an arc in a subduction zone. It would be, in general, difficult to resolve these two processes if the arc is narrow in width. In the Central Andes two processes act mainly at the western and eastern ends of the high plateau. The separation was achieved in the Central Andes because a compressional stress regime prevailed and young oceanic lithosphere continued to subduct at a high speed for a substantial time span, enabling the buildup of magmatic material from the western end to inland and producing a hot mantle below the Altiplano. The induced secondary convection in the mantle above the slab is important to make a large supply of melt in the wedge mantle. Continued shallow subduction was the cause of the broad zone of volcanic activities across the arc. Because of this breadth, extensive thickening of the crust by magma intrusion and extensive shortening of the crust by horizontal compression have taken place in spatially separated places, leaving an intermediate zone in between. Such a situation has resulted in two clearly separated mountain ranges, the Western Cordillera and the Eastern Cordillera. The two processes were strongest at each end but also operated to the east and west, with decreasing activity. The superposition of the two processes made the high plateau between the two mountain chains, the Altiplano-Puna. The sediment fill supplied from the two mountain chains also helped increase the plateau thickness, but that was of minor importance. As the amount of magmatic material needed is large, the success of the present model depends critically on the availability of a vast amount of melt in the wedge mantle above a shallowly dipping slab.

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