NASA

Technical Memorandum 86160

# ANDEAN TECTONICS: IMPLICATIONS FOR SATELLITE GEODESY

R. J. Allenby

SEPTEMBER 1984

National Aeronautics and
Space Administration

**Goddard Space Flight Center**
Greenbelt, Maryland 20771

# ANDEAN TECTONICS: IMPLICATIONS FOR SATELLITE GEODESY

by
R. J. Allenby

September, 1984

Goddard Space Flight Center
Greenbelt, Maryland 20771

ABSTRACT

This paper summarizes current knowledge and theories of large scale Andean tectonics as they relate to site planning for the NASA Crustal Dynamics Program's proposed high-precision geodetic measurements of relative motions between the Nazca and South American plates. The Nazca Plate and its eastern margin, the Peru-Chile Trench, is considered a prototype plate marked by rapid motion, strong seismicity and well-defined boundaries. Tectonic activity across the Andes results from the Nazca Plate subducting under the South American plate in a series of discrete platelets with different widths and dip angles. This, in turn, is reflected in the tectonic complexity of the Andes which are a multitude of orogenic belts superimposed on each other since the Precambrian. Sites for Crustal Dynamics Program measurements are being located to investigate both interplate and extraplate motions. Observing operations have already been initiated at Arequipa, Peru and Easter Island, Santiago and Cerro Tololo, Chile. Sites under consideration include Iquique, Chile; Oruro and Santa Cruz, Bolivia; Cuzco, Lima, Huancayo and Bayovar, Peru; and Quito and the Galapagos Islands, Ecuador. Based on scientific considerations, it is suggested that Santa Cruz, Huancayo (or Lima), Quito and the Galapagos Islands be replaced by Isla San Felix, Chile; Brazilia or Petrolina, Brazil; and Guayaquil, Ecuador. If resources permit, additional important sites would be Buenaventura and Villavicencio or Puerto La Concordia, Colombia; and Mendoza and Cordoba, Argentina.

# INTRODUCTION

## GENERAL

The Nazca Plate is probably the best-defined, most active and fastest-moving member of the global plate system. Its east boundary, the Peru-Chile Trench (Figure 1), was one of the seismic zones from which Benioff (1954) inferred the nature of subduction zones, and many tectonic studies have been focussed on it. The Nazca Plate, in short, can be considered a prototype or classic plate, and Goddard's Crustal Dynamics Project has accordingly planned many measurements across the interface between the Nazca and South American plates to obtain data on their relative motions. Although simple in principle, the details of this interface are extremely complex. The continental edge is made up of a series of little understood, large and distinctive tectonic provinces. The present high levels of volcanic and seismic activity indicate currently high levels of extraplate and intraplate motion. In order to obtain maximum scientific returns from a South American program it is important that the continental sites be located so that, without jeopardizing the extraplate studies, the baseline data maximizes the intraplate studies.

The purpose of this paper is to:

1. Identify and characterize the major Andean tectonic provinces.

2. Determine how the presently planned observational sites will contribute to an increased understanding of these features.

3. Suggest site changes that will, without compromising higher priority objectives, increase the total scientific value of the results.

BACKGROUND

The major guidance on site locations within South America has been furnished by the following three approved NASA Crustal Dynamics Principal Investigators:

1. Dr. Ramón Cabré S.J., Observatorio San Calixto, La Paz, Bolivia
2. Dr. Edgar Kausel, Universidad de Chile, Santiago, Chile
3. Dr. Leonidas Ocola, Institute Geofisico del Peru, Lima, Peru.

Additional site selection help was furnished by Dr. Minard (Pete) Hall, Escuela Politecnica Nacional, and Mr. Vernon Perdue, Director IAGS Ecuador Project, both located in Quito, Ecuador.

A current suggested list of 12 mobile Satellite Laser Ranging (SLR) sites in Ecuador, Peru, Bolivia and Chile, culled from a much longer candidate list, is approximately the total number that can be supported by the Project's financial and observing system resources. Elimination of the additional sites was based on scientific merit, operational difficulties, problems of access and poor observing weather (the SLR systems must have clear visibility). In addition to the proposed mobile sites, the Project is currently operating a fixed laser site at Arequipa, Peru and considering three existing fixed Very Long Baseline Interferometry (VLBI) sites at Santiago, Chile; São Paulo, Brazil; and Quito, Ecuador.

Three of the Chilean mobile SLR sites, Easter Island, Santiago and Cerro Tololo, have already been occupied, and an observing pad has been constructed near Iquique. Exact locations for the other 9 candidate sites were located during recent field trips.

The Project's initial plan was, beginning in 1985, to combine NASA's four highly mobile laser systems with the two existing Europeans systems (Dutch and West German) and conduct, each year, a five month joint observing session in South America and a five month campaign in the Mediterranean area. Budget cuts precluded this program. It is now planned to conduct one joint campaign each year beginning with the Mediterranean in 1986 followed by South America in 1987. While the delay in the South American program is unfortunate, it does allow the Project ample time to permit and construct the needed observational pads and make any locational changes that are desirable. It is expected that the lifetime of the Project will be extended in order to obtain a statistically significant number of baseline measurements.

## ANDEAN TECTONICS

### GENERAL

The Peru-Chile Trench, a major global tectonic feature extending some 8,000 km from the coast of western Colombia to Tierra del Fuego, marks the convergent boundary between the Nazca and South American plates. The shape, depth, sediment load and angle of subduction varies considerably along the trench. On the seaward side large oceanic ridges, scarps and fracture zones are gradually being incorporated into, or consumed by, the leading edge of the Continent. On the landward side the converging plates are not only responsible for the orogeny of the Andean Cordillera with its transcurrent fault zones and megashears, but also for volcanism and the distribution of earthquakes. Physiographically the margin is spectacular in its relief, rising from a maximum trench depth greater than 8 km to mountain peaks approaching elevations of 7 km over a horizontal distance of several hundred kilometers. This results in some of the largest regional topographic gradients in the world (Hayes, 1974).

## MAJOR TECTONIC REGIONS

Three extensive tectonic regions can be recognized in South America (Figure 2). The oldest, and by far the largest, is the South American Platform. South of this platform on the Atlantic coast side is the small Patagonian Platform. The third major region is the Andean Cordillera bordering the entire western edge of the continent. The major exposures of Precambrian basement are in the Guyana, Central-Brazil and Atlantic Shields. The rest of the South American Platform is covered with sediments dating from the Silurian and include huge basins with sediment depths of over 5,000 meters (UNESCO, 1978).

The basement of the Patagonian Platform, which forms the greater part of the non-Andean area of Argentina, stabilized during the upper Paleozoic. The basement is almost entirely covered and is relatively unknown. This platform also contains large, deep basins with sediments over 5,000 meters thick.

The western edge of the continent consists of the Andean Cordillera running along the edge of the Pacific and the Caribbean Mountain system facing the Caribbean. Basically, the mountains consists of linear chains or Cordilleras trending generally north-south. Depending on the latitude, the Cordilleras vary from one to three parallel ranges broadly identified as the Eastern, Central and Western (Oriental, Central and Occidental) Cordilleras, although local names are often applied to individual segments.

In spite of the broad simplified tectonic picture presented by the plate tectonics model, the Andes were not uniformly built up either in time or space and, instead of a uniform orogen, are a multitude of orogenic belts superimposed on each other since the Precambrian. The ranges, with the exception of coastal Colombia and northern Equador, rest on a Precambrian or early Paleozoic continental basement (Zeil, 1979).

The foundation of the Andes was laid in late Paleozoic times when a broad trench on the west side of the South American proto-continent began filling with continental sediments from the eastern continental mass and volcanic materials from the western offshore volcanoes. The time of initiation of sedimentation varies with location. In northern Peru it started during the Upper Triassic and continued until the Upper Cretaceous. Actual building of the Andean mountains began relatively recently in late Cretaceous and early Cenozoic times and was accomplished by east-west compression, vertical uplift and increased volcanic activity (Caldas, 1983).

While intensive compressional structures are exhibited in the Andean basement rock, such structures occur only locally in the overlying rocks of the Cordilleras (Zeil, 1979). On the other hand, the Sub-Andean Foreland east of the Andean Ranges exhibits predominately thick or thin skin thrusting along low angle, listric faults (Jordan et al., 1983).

The main mountain building force for the Andean mountains is uplift induced by the subducting Nazca plate. This has resulted in large blocks of geosynclinal material (interspersed volcanic and continental rocks) being raised along nearly vertical, normal or reversed faults extending deep into the crust (Myers, 1975; Gough, 1973). The Cordilleras are, basically, uplifted horsts separated by large grabens (Acosta, 1983).

Folding has accompanied this orogen, so that the present day Andes consist of intensely folded and uplifted sediments intermixed with volcanic and intrusive rocks. Volcanic activity in Cenozoic time has been almost exclusively confined to the western Cordilleras which are mostly capped by Cenozoic volcanic rocks (James, 1971a). The high level of present day earthquake activity indicates that the crustal movements are still continuing.

The transition from the Andean mountains to the South American Platform is through the Sub-Andean Foredeep, a thick section of folded and faulted sediments of mostly continental origin (Unisco, 1978). As mentioned previously, east-west compression and low angle listric thrust faults predominate in this area with only minor uplifting and high angle faulting. The Altiplano of southern Peru and northern Bolivia is a large intra-mountain depositional basin containing at least 20 km of interbedded post-Devonian continental deposits and Tertiary volcanic rocks (James, 1971b).

Offshore, the Nazca plate contains many large structural features, such as ridges and fracture zones, which are in the process of being subducted under, or incorporated into, the continental plate. This process has a profound impact on the onshore tectonics. As Jordan et al. (1983) wrote "The coincidence of lateral variations in the geometry of the descending Nazca plate and in Andean physiography and geology is remarkable." The result is that the leading continental edge is broken up into many distinct tectonic segments.

## SEISMICITY

Seismology is the most informative method for studying the plate interface along the subduction zone. Figure 3 outlines the approximate locations and depth of earthquakes. The shallow earthquakes (0-70 km) generally occur under, and directly to the east of, the trench. Intermediate depth earthquakes (70-320 km) occur in a non-uniform pattern under the coastal and near coastal inland regions with definite aseismic gaps, possibly associated with tears in the descending plate. The pattern is somewhat confusing, because many intermediate earthquakes occur in the continental lithosphere and are not associated with the Benioff zone (Ocola, 1983). The deep earthquakes (below 525 km) occur only in two narrow, roughly north-south, bands in western Brazil and southern Bolivia/ northern Argentina (Stauder, 1975; Barazangi and Isacks, 1976; Ocola, 1983). This pattern suggests a relationship between the deep earthquakes and the shallow dipping segments of the Nazca subducting plate. It is not clear why there is an almost total lack of seismic activity from depths of 320 to 525 km (Barazangi and Isacks, 1976).

## SUBDUCTING PLATE CHARACTERISTICS

It is generally agreed that the Nazca plate is subducting along the entire western coast of South America in a series of discrete and probably separate platelets (Cabre, 1983), but beyond this the models are conflicting. Barazangi and Isacks (1976) suggest that the abrupt change in dip between the flat north and central Peru segment and the steeper southern Peru segment is accompanied by a tear in the descending plate. This tear would be beneath the northern limit of the Altiplano about 200 km south of the projection of the oceanic Nazca Ridge down the subduction zone. Rodriguez et al. (1976) also concluded that the subducting plate consisted of small, tonque-like pieces with different directions and dip angles, particularly going around the big bend at the Peru-Chile border. In a detailed analysis of seismic activity in northern and central Chile (Swift and Carr, 1974), seven segments differing in strike and dip and varying in width from 300 to 850 km were identified. On the other hand, Hasegawa and Sacks (1981) and Boyd et al (1984) studying the dipping plate in southern Peru found that, while the angle of dip varied with latitude, particularly in the intermediate zones below 50 km, the change was gradual and the distorted subducting plate appeared continuous with no sudden rips or tears.

Figure 4 shows the average dips of relatively uniform segments of the subducting plate. Looking in detail at each of the segments, beginning in the north; the plate under Colombia and northern Ecuador has what might be considered "normal" dip. Intermediate depth seismicity defines a 35° south-east dipping Benioff zone (Pennington, 1981). Focal plane solutions of several recent, large offshore earthquakes show a slightly shallower dip angle of about 20° (Kanamori and McNally, 1982; Mendoza and Deevey, 1984).

It should be noted that the seismicity under coastal Colombia and Ecuador does not form as clear a pattern and is difficult to interpret, leading to disagreements on subduction details, particularly under Ecuador. It is generally postulated that the subducting plate maintains a roughly 30° dip under coastal Ecuador and then changes to a flat 10° dip under northern and central Peru. However, Pennington (1981) has found seismic evidence to suggest, in the Gulf of Guayaquil, a plate segment dipping 35° to the N35°E. An alternate possibility is that this seismic data is associated with a tear between the steeply dipping northern segment and the flatter Peruvian segment.

It has been generally accepted that anomalously flat subduction is occurring under north and central Peru (Barazangi and Isacks, 1979; Barazangi and Isacks, 1976; Stauder, 1975). However, James (1978) proposes that, rather than a 10° dip, the plate descends at the more usual angle of 30° but is aseismic below a depth of 100 km. He suggests that the intermediate, interior events used by earlier reseachers as a locus for shallow dip are, in reality, occurring in a thick continental crust, and are not associated with the Benioff zone.

In a similar vein, Hasegawa and Sacks (1981) and Sacks (1983) propose that the oceanic plate initially plunges at 30° under the continent until it reaches the top of the asthenosphere at a depth of around 100 km. The relatively young plate, being then too buoyant to continue sinking, flexes upward and continues nearly horizontally under the continent. The subducting plate's density increases with age until, at around 800 km inland from the trench, it bends downward and again subducts at about 30°. Along the same line, Ocola (1983) explains the pattern by postulating two 30° dipping Benioff zones connected by a horizontal detachment zone. The eastern seismicity is associated with a deep (greater than 150 km), old Benioff zone nearing extinction, while the western earthquakes are from a new, shallower, developing zone.

Additional evidence for the steeper dip is presented by analysis of the ScSp converted seismic wave phases by Snoke et al. (1979). Nur and Ben-Avraham (1981) discuss the possibility that the thrusting on the Nazca Ridge into the subduction zone might be contributing to the disruption and distortion of the descending slab.

A clearer picture emerges from the seismicity north of, and around, the large concave coastal bend at Arica at the Peru-Chilean border. In this vicinity the slab is dipping at around 30°. According to Rodriquez et al. (1976), the sharp bend results in severe tensional strain in the slab leading to rips and tears in the descending plate. Hasegawa and Sacks (1981) agree the plate is distorted, but prefer a continuous, distorted slab not broken up by tears. Clarifying the tectonic strains in this area would be an important achievement for the Crustal Dynamics Project.

The dips shown in Figure 4 along the Chilean coast are averaged from Swift and Carr's (1974) results. While continental distortions are associated with the changes in Chilean slab dip, these effects are smaller than those discussed above, and are not pertinent to the Project's primary goals.

In broad terms, regional gravity (Free-air offshore and Bouguer onshore) supports the seismic interpretations. A large, linear negative correlates with the trench axis. Landward of this, along the contact between the oceanic and continental material, is a high gravity trend, while a large, linear negative, further removed from the coast, is associated with the deep crustal roots underlying the Andean Cordilleras (Shepherd and Moberly, 1981; Couch and Whitsett, 1981).

## ANDEAN CORDILLERAS

The complexities of the subduction zone are clearly reflected in the tectonics of the leading edge of the continent. The general patterns of the mountain ranges are shown in Figure 4. In Colombia the Andes consist of three Cordilleras that are gradually compressed together as they progress south into Ecuador. In Ecuador the Andes are subjected to tremendous compression along the edge of the Continental and Oceanic plate (Acosta, 1983) and, as a result, the Eastern range all but disappears and the distance between the Central and Western ranges narrows. In the vicinity of the Gulf of Guayaquil the ranges are not only extremely distorted but the prevailing directional trend undergoes a 60° change, swinging from south-west to south-east. The Western range then curves westward into the northern region of the Gulf and the Central range performs a similar bend into the southern Gulf. In this same region the symmetry of the three Cordilleras rising from northern and central Peru is completely broken up at the Peru-Ecuadorian border.

Further south, inland from Lima and Pisco, the ranges again undergo considerable deflections. The eastern range disappears, the central and western ranges open up to accommodate the Altiplano region, a large molasse basin of thick sedimentation, and a coastal range, rising at Pisco runs southeast to Arica on the Peru-Chilean border. Arica is also the locale for the second large change in the trend of the Andean ranges which undergo a 45° change in direction from southeast to almost due south.

The general regions of active volcanism are also shown in Figure 4. Present day activity is associated primarily with the western Cordillera and, to a much smaller extent, the Central. In contrast with the deep earthquakes being associated with the shallower dipping interface, active volcanism appears associated with the steeper dipping plate sections.

## MAJOR TECTONIC FEATURES

Figure 5 shows the major tectonic features of the continental leading edge that are large enough to be of scientific interest to the project. In other words, consistant with the primary goal of measuring motions across the plate interface, the observing sites should be positioned to provide information across or between as many of these land features as possible. Because of the sparsity of data and the difficult field conditions in many locations, most of these features are only poorly understood. In general, it is not possible to make estimates of current motion along or across these features, although present-day seismic activity shows motions are taking place. While this is no guarantee of positive results within the lifetime of the Project, even reliable upper limits would be a significant contribution to South American tectonics.

The east-west trending deflections (or megashears or megafaults) cutting approximately transverse to the Andean Ranges are evident by their large scale geomorphic effects. Such effects include sudden termination or changes in direction of a mountain range (or ranges) or changes in the average size or elevations of the mountains. These shears also effect drainage pattern by causing sudden and large changes in the direction of flow of major rivers. The rivers also tend to be more linear when flowing along the shear zones. The scale of these changes is indicative of the large motions that occurred (or are occurring) along these zones.

In the north the first major deflection is the Guairapungo Fault Zone along the Colombia-Ecuador border. The southern section of the Colombian Eastern Cordillera terminates against this zone, the other two Cordilleras are deeply fractured by the lowest pass south of Antioquia (in central Colombia) and several rivers change from flowing along the mountain trend to flowing across the ranges to the sea (Acosta, 1983).

The Gulf of Guayaquil, farther south, is the most complex tectonic region of the leading edge. In this area the angle of subduction changes from about 30° to about 10° with the possibility of an anomalous segment under the Gulf (Pennington, 1981). Offshore three major ridges, the Carnegie, Grijalva and Sarmiento, are being consumed by the subduction process. The major portion of the Gulf proper is occupied by the Progresso Basin, probably a pull-apart structure formed by the right lateral motion of the northwest trending Guayaquil Fault (Shepherd and Moberly, 1981). While the picture is not completely clear or agreed on, Case et al. (1971) and Shepherd and Moberly (1981) propose that the Guayaquil Fault is the southwest end of the northeast trending Dolores Fault of Colombia (Campbell, 1974a)--the entire system forming the Dolores-Guayaquil Megafault or Megashear. This major feature, extending from the Gulf of Guayaquil to west-central Colombia, separates oceanic crust on the west from continental crust to the east (Case et al. 1973; Ramirez et al., 1983; Mooney et al., 1979). The coastal region of Colombia and Ecuador north of the Gulf is a complexly deformed ophiolite suite known as the Piñon formation in Ecuador (Lonsdale, 1978) and the Dagua and Espinal groups in Colombia (Ramirez et al., 1983; Jacobs et al., 1963). It has been postulated that this region is an uplifted oceanic horst (Case et al., 1973), an obducted or accretionary oceanic wedge (Lonsdale, 1978; Lonsdale and Klitgord, 1978; Irving, 1975) or a separate mini-plate sliding northward along the coast (Mooney et al., 1979; Pennington, 1981; Shepherd and Moberly, 1981). The paucity of earthquakes along the megashear indicates a present low level of activity although some earthquakes do occur (Campbell, 1974a).

East of the Dolores-Guayaquil feature and roughly parallel to it, is a seismically defined right lateral fault designated by Pennington (1981) as the Eastern Andean Frontal Fault Zone. The presence of seismic activity indicates current motion along this fault.

In summary, while the details are still in dispute, obviously the western coast of Colombia and northern Ecuador is an anomalous, oceanic terrane that is being compressed and underthrust from the east by the South American plate and from the west by the Nazca plate and is pinching out to the north-northeast (Pennington, 1981). The project could provide valuable tectonic information about this region even though the current rates of motion may be small.

It should be mentioned in passing that a large, extensive active fault system exists in northern Colombia (see for example, Alvarez, 1971; Case and MacDonald, 1973; Irving, 1975) and northern Venezuela (Bell, 1974; Schubert, 1979; Schubert and Laredo, 1979) but this area is a part of the South American-Caribbean plate interface and is not germane to this discussion.

In the vicinity of the Gulf are also two major east-west trending left lateral megashear zones: the northern Tumbes-Guayana and the southern Huancabamba. Between these zones, which might once have been the boundaries of an aulacogen (Shepherd and Moberly, 1981), the Andean elevations are about 1000 meters lower than to the north or south, and the Cordillera trend changes abrupty almost 70° from southwest to southeast. The two Andean ranges in Ecuador are bent and terminated in the vicinity of the northern Tumbes-Guayana shear, and the three major Cordilleras trending northwest out of northern Peru terminate against the southern Huancabamba zone (Shepherd and Moberly, 1981). Of the two, the Huancabamba is the most spectacular, constituting a major transverse structure separating the northern and southern areas of South America. It exhibits a close connection with the Carnegie Ridge and Galapagos Fracture Zone in the Pacific and the Romanche Fracture Zone in the Atlantic (Acosta, 1983). According to Campbell (1974a), the Huancabamba deflection forms a major break between the Northern Andes, which border the Guayana Shield, and the Southern Andes, which border the Brazilian Shield. These two shields form very different orogenic belts. The deflection also corresponds to a paleogeographic gap in the Andes, the Marañon Portal, which is a western extension of the Amazon Graben separating the two shields.

Shepherd and Moberly (1981) propose that the two shear zones may coincide with and control the north and south sides of the Amazon Basin.

The next major trans-Andean fault zone to the south is the Pisco-Abancay which trends east-northeast from Pisco, Peru. A gap in the Eastern Cordillera and an eastern displacement of the southern section of the range correlates with this zone (Ham and Herrera, 1963). The Central Cordillera of northern and central Peru terminates in this zone where it crosses the northern end of the Altiplano. In addition, a new, coastal mountain range begins just to the south of Pisco and the Fault Zone (Ocola, 1983).

Suprisingly enough, the collision, just south of Pisco, of the aseismic Nazca Ridge with the Continental margin appears to have only a minimal effect on the Andes. Seismic refraction and gravity data suggest that the ridge is composed of continental material. It lacks a strong gravity anomaly, so is nearly completely isostatically compensated (Couch and Whitsett, 1981). At present, it is evidently being consumed along the plate boundary (Nur and Ben-Avraham, 1981). While the ridge has no onshore gravity signature indicative of tectonic effects, electrical conductivity data show a significant anomaly corresponding to its presumed extension under the continent (Ocola, 1983).

Several trans-Andean fracture zones have been proposed trending inland from the large, concave coastal bend at Arica on the Peru-Chile border. The Andean Cordilleras and the Nazca subduction zone roughly follow this same bend and change 50° in direction from souteast to almost due south. The strain in this area can probably be attributed to the westward motion of the Central Brazil Shield relative to the southern part of the continent. The Arica Deflection, also called the Elbow Line, separates the Eastern and Central Cordilleras of the north from the mountainous region of eastern

Bolivia in the south. Sonnenberg (1963) suggests that this poorly defined line may divide the continent into two halves and runs from the bend of the coast at Arica, slightly north of Santa Cruz, Bolivia and eastward to join the rim faults of the Brazilian Shield. The northern section is uplifted and presumably offset to the west relative to the southern section (Zeil, 1979). The coastal range that begins south of Pisco disappears in the vicinity of Arica. In the course of this large bend in the mountain ranges, the Central and Western Cordilleras open up and are separated by the large, deep Altiplano Basin. Lineaments and faults abound in this area, but a major continuous megashear zone has not yet been identified.

Evidence of minor tectonism is found all down the Chilean coast (Lowrie and Hey, 1981), but these disturbances are not of the same scale as discussed above and will not be considered here. The Neuquen-Colorado Fault Zone while a major feature (Baldis and Febrer, 1983) is probably associated with the Chile Rise and the southern border of the Nazca plate and is not germane to present Project objectives.

One further area of large scale tectonic interest is the Pompeanas Ranges in northwest Argentina approximately 500 km east of the Peru-Chile Trench. The core of these ranges consists of Precambrian crystalline rocks with flanks of late Paleozoic, Mesozoic and Tertiary continental deposits (Herrero-Ducloux, 1963). These ranges, resulting from the compressional stresses generated at the plate interface, result in reverse-block-faulted terrane of late Cenozoic age (Cross and Pilger, 1982). Thick-skin thrusting, beginning in the Pliocene, has elevated basement blocks up to 6 km above their previous levels (Jordon et al., 1983). If it is assumed that 4 km of slip along the faults are required to create 1 km of uplift, approximately

16 km of horizontal compression would be needed to create the present day elevations of one of the three (perhaps four) ranges. This translates into an average horizontal east-west compression across all the Pampeanas ranges of 1 to 1.5 cm/yr (Reilinger and Kadinsky-Cade; 1984). Present day seismicity indicates that this motion is still continuing.

North of the Pampeanas Ranges in the western Argentina Sub-Andean Belt of thin skinned thrusting, a palinspastic reconstruction by Allmendinger et al. (1983) shows that an east-west shortening of 60 km or 33% has taken place since late Miocene or early Pliocene, which translates into a shortening rate of up to 1.2 cm/yr (Reilinger, 1984). The Sub-Andean Zone is continuous along the entire eastern edge of the Andes and is quite often accompanied by seismicity. Thus, around 10% of the expected convergent motion of the Nazca and South American plates may be occurring within the narrow thrust strip between the eastern edge of the Andean Cordilleras and the western edge of the Precambrian cratons. Hence, the importance of at least one observing site firmly anchored to the old cratonic area of the continent.

## SITE LOCATIONS

An important objective of the Project, determining relative motions between the Nazca and South American plates, is already underway. Figure 1 (adapted from Lowman, 1981) places the Nazca-South American interplate sites into a global context. A fixed satellite laser system is in continual (weather permitting) operations at Arequipa, Peru ("A" in Figure 1), and a highly mobile satellite laser system has occupied Easter Island, Chile (E) in 1983 and 1984. Initial laser measurements were made at Santiago, Chile (S) and Cerro Tololo, Chile (C) in 1984. Candidate sites on the Galapagos Islands, Ecuador (G) and Isla San Felix, Chile (F) are discussed below. Planned yearly reoccupations of the Easter Island, Santiago and Cerro Tololo sites will continue to provide information on extraplate baseline changes from Eastern Island to Arequipa, Santiago and Cerro Tololo. It should be noted that, in conjunction with the rest of the Project's global plate motion studies, baselines from the above sites will be measured to other satellite laser ranging systems on the other major plates.

In addition, consideration is being given to utilizing fixed radio antennas at Santiago, Chile, São Paulo, Brazil and Quito, Ecuador to contribute to the Project's ongoing Very Long Baseline Interferometry (VLBI) plate motion investigations.

Figure 6 shows the locations of all the sites discussed in this report. Triangles represent those locations where a reconnaissance crew has identified a definite site or where an observing pad has already been completed. It is recommended that several of the already identified sites be dropped in favor of proposed new sites (circles) that would enhance the scientific returns. The large tectonic features shown in Figure 5 are indicated on Figure 6, but not identified.

All the candidate sites will satisfy the project's goal of studying the motions between the two plates, but they are also located to optimize the return of continental tectonic data. Table 1 lists what the author considers the most significant Andean tectonic problems. In regard to these features, several site changes should enhance the scientific returns without compromising the plate motion observations.

The present candidate sites are shown in Table 2. The site priority, assigned by the author, reflects his assessment of the scientific merit of the site. It is recommended that all priority 2 sites be dropped for the following reasons:

1. Santa Cruz, Bolivia is planned as a cratonic anchor point, but a thick sedimentary cover lies above the Precambrian basement. It is felt that one of the Brazilian sites recommended below, on cratonic outcrop, would be a more stable location.

2. Huancayo, Peru will furnish valuable continental strain information, but it is rather close to Lima. It is felt some of the new sites recommended below will prove more scientifically valuable. Conversely, if more operationally desirable, Lima could be dropped and Huancayo retained.

3. Quito, Ecuador was attractive because the large radio antennas of the former NASA tracking station will permit intercomparison measurements between VLBI and SLR systems. However, this concept is no longer valid because the identified SLR site is 80 km north of the VLBI site. Furthermore, budget problems will probably preclude any VLBI measurements. Finally, Quito is in, or very near, the postulated Dolores–Guayaquil Megashear so any detected movements could be ambiguous.

4. The Galapagos Islands are located near the interface of the Cocos and Nazca plates (Hey, 1977) which may complex the crustal strain rates. The islands also present expensive and difficult operational problems.

The authors' recommended new sites are listed in Table 3. The three priority 1 locations are considered critical to advancing our understanding of Andean tectonics and should replace the sites recommended above for elimination. The four priority 2 sites would greatly enhance the scientific returns of the program--it is hoped they can be implemented if the Project's budget and systems availability permit.

The three top priority sites are:

1. San Felix Island is a Chilean Naval Base already recommended by the Chilean Principal Investigator. The Chilean government appears amenable to our using this site, but a reconnaissance has not yet been carried out. At present, our only implemented Nazca plate site is on Easter Island, whose motion may be affected by the proximity of the East Pacific Rise and a possible Easter Platlet (Kulm et al., 1983). Isla San Felix is located in the middle of the plate well away from any identified tectonic disturbances. These are no other practical Nazca plate sites with these attributes.

Maximum rates of change between the Nazca and South American plates are predicted to be over 9 cm/yr (Minister and Jordon, 1978) which translates into a convergence of 6.9 cm/yr between San Felix and Arequipo, Peru, and 8.4 cm/yr between the Island and the recommended Brazil site (see #2 below) (Mead, 1981).

2. Brazilia or Petrolina, Brazil. One of these recommended sites should be chosen to replace Santa Cruz, Bolivia. Either site is on the Central-Brazil or Atlantic Shields on exposed Precambrian basement and should provide a firm anchor to the stable continent. Convergence to San Felix or Easter Island should be over 8 cm/yr. Pretrolina has been recommended as having clearer weather than Brazilia (Kaufmann, 1984). The Brazilian Aerospace Technological Center is also located in Petrolina, which is an operational advantage.

3. Guayaquil, Ecuador. The most active tectonic zone of the continent leading edge is around the Gulf of Guayaquil, but the only presently planned

site north of the Gulf is Quito, which is on or near the presumed active Dolores-Guayaquil Megashear. At least one stable site is needed to the north to measure strain across the Gulf. While the city of Guayaquil is on Quaternary sediment, several volcanic outcrops occur about 20 km north of the city along a major road. This site will form a good baseline with Bayovar, Peru for measuring expansion across the Gulf and the expected northern motion of the Ecuador coastal province.

Four additional sites of somewhat lower scientific importance, are recommended for the following reasons:

1. Buenaventura, Colombia establishes a second location on the anomalous Ecuador-Colombian coastal block to back-up results from Guayaquil and measure possible motion across the Guairapungo Fault Zone at the Colombian-Ecuadorian border. Combined with an eastern Colombian site it would greatly strengthen our understanding of the anomalous north-west corner of South America.

2. Villavicencio or Puerto La Concordia, Colombia. Puerto La Concordia is the better location because it is definitely east of the postulated East Andean Frontal Fault, but it is more isolated and harder to reach than Villavicencio. The values of this site are the same as in #1 above.

3. Mendoza, Argentina is reached by a good, all-weather road from Santiago. In conjunction with Santiago and Cordoba it will identify the strain rate across the Andean Cordillera versus that across the eastern foredeep (Pompeanas Ranges).

4. Cordoba, Argentina lies at the eastern edge of the Pompeanas Ranges. As mentioned earlier, perhaps 10% of the Nazca/South American covergence motion is occurring across the Pompeanas Ranges. The difference between the Nazca Plate/Santiago Baseline and the Nazca/Cordoba Baseline will

provide the strain across the entire Andean Province. Data from Cordoba, located between the Andean Cordillera and the Pompeanas Ranges will apportion the strain between the two regions.

Table 4 is a complete list of the implemented and recommended sites. The right hand column assesses the Andean tectonic features in Table 1 that will primarily be addressed by each site.

## ACKNOWLEDGEMENTS

The author would like to thank Charles Schnetzler, Paul Lowman and Herb Frey for critically reviewing this manuscript and for many fruitful discussions on plate tectonics and the plans and operations of the Crustal Dynamics Project. Robert Reilinger and Katharine Kadinsky-Cade were very obliging in calling the author's attention to the tectonic significance of the Pompeanas Ranges. Beth Creamer was very helpful in assembling the manuscript and creating the figures. Barbara Conboy suffered cheerfully through many retypes and unfamiliar South American names and locations.

REFERENCES

Acosta, C.E., 1983. Geodynamics of Ecuador. In: R. Cabre, S.J. (editor). Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs. Am. Geophys. Union Geodynamic Series, 9:53-63.

Allmendinger, R.W., Ramos, V.A., Jordan, T.E., Palma, M. and Isacks, B.L., 1983. Paleogeography and Andean Structural Geometry, Northwest Argentina. Tectonics, 2:1-16.

Alvarez, W., 1971. Fragmented Andean Belt of Northern Colombia. In: T.W. Donnelly (editor). Caribbean Geophysical, Tectonic, and Petrologic Studies. Geol. Soc. Am. Mem., 130:77-96.

Baldis, B.A.J. and Febrer, J., 1983. Geodynamics of the Argentine Arc and Related Regions. In: R. Cabre, S.J. (editor). Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs. Am. Geophys. Union Geodynamic Series, 9:127-135.

Barazangi, M. and Isacks, B.L., 1976. Spatial Distribution of Earthquakes and Subduction of the Nazca Plate Beneath South America. Geology, 4:686-692.

Barazangi, M. and Isacks, B.L., 1979. Subduction of the Nazca Plate Beneath Peru: Evidence from Spatial Distribution of Earthquakes. Geophys. J. Roy. Astr. Soc., 57:537-555.

Bell, J.S., 1974. Venezuelan Coast Ranges. In: A.M. Spencer (editor). Mesozoic-Cenozoic Orogenic Belts. Scottish Academic Press, Edinburgh, 683-703.

Benioff, H., 1954. Orogenesis and Deep Crustal Structure: Additional Evidence from Seismology. Geol. Soc. Am. Bull., 65:385-400.

Boyd, T.M., Snoke, J.A., Sack, I.S., and Radriguez, B.A., 1984. High-Resolution Determination of the Benioff Zone Geometry Beneath Southern Peru. Bull. Seismol. Soc. Am., 74:559-568.

Cabre, R., 1983. Geophysical Studies in Central Andes. In: R. Cabre, S.J. (editor). Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs. Am. Geophys. Union Geodynamic Series, 9:73-76.

Caldas, V.J., 1983. Tectonic Evolution of Peruvian Andes. In: R. Cabre, S.J. (editor). Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs. Am. Geophys. Union Geodynamic Series, 9:77-81.

Campbell, C.J., 1974a. Colombian Andes. In A.M. Spencer (editor). Mesozoic-Cenozoic Orogenic Belts. Scottish Academic Press, Edinburgh, 705-724.

Campbell, C.J., 1974b. Ecuadorian Andes. In: A.M. Spencer (editor). Mesozoic-Cenozoic Orogenic Belts. Scottish Academic Press, Edinburgh. 725-732.

Case, J.E. and MacDonald, W.D., 1973. Regional Gravity Anomalies and Crustal Structure in Northern Colombia. Geol. Soc. Am. Bull., 84:2905-2916.

Case, J.E., Duran, L.G., Lopez, A.R., and Moore, W.R., 1971. Tectonic Investigations in Western Colombia and Eastern Panama. Geol. Soc. Am. Bull., 82:2685-2711.

Case, J.E., Barnes, J., Ingeominas, G.P.Q., Gonzalez, I.H., Vina, A., 1973. Trans-Andean Geophysical Profile, Southern Colombia. Geol. Soc. Am. Bull., 84:2895-2904.

Couch, R. and Witsett, R.M., 1981. Structures of the Nazca Ridge and the Continental Shelf and Slope of Southern Peru. In: L.D. Kulm, J. Dymond, E.J. Dasch and D.M. Hussong (editors). Nazca Plate: Crustal Formation and Andean Convergence. Geol. Soc. Am. Memoir, 154:569-586.

Cross, T.A., and Pilger, R.H., Jr., 1982. Controls of Subduction Geometry, Location of Magmatic Arcs, and Tectonics of Arc and Back-Arc Regions. Geol. Soc. Am. Bull., 93:545-562.

Gough, D.I., 1973. Dynamic Uplift of Andean Mountains and Island Arcs. Nature, 242:39-41.

Ham, C.K. and Herrera, L.J., Jr., 1963. Role of Subandean Fault System in Tectonics of Eastern Peru and Ecuador. In: O.E. Childs and B.W. Beebe (editors). Backbone of the Americas. Am. Assoc. Pet. Geol. Memoir 2:47-61.

Hasegawa, A. and Sacks, I.S., 1981. Subduction of the Nazca Plate Beneath Peru as Determined from Seismic Observations. J. Geophys. Res. 86:4971-4980.

Hayes, D.E., 1974. Continental Margin of Western South America. In: C.A. Burk and C.L. Drake (editors). The Geology of Continental Margins. Springer-Verlag, New York, 581-590.

Herrero-Ducloux, A., 1963. The Andes of Western Argentina. In: O.E. Childs and B.W. Beebe (editors). Backbone of the Americas. Am. Assoc. Pet. Geol. Memoir 2:16-28.

Hey, R., 1977. Tectonic Evolution of the Cocos-Nazca Spreading Center. Geol. Soc. Am. Bull., 88:1404-1420.

Irving, E.M., 1975. Structural Evolution of the Northernmost Andes, Colombia. U.S. Geol. Surv., Prof. Pap. 846:47 pp.

Jacobs, C., Burgl, H., and Conley, D.L., 1963. Backbone of Colombia. In: O.E. Childs and B.W. Beebe (editors). Backbone of the Americas. Am. Assoc. Pet. Geol. Memoir 2:62-72.

James, D.E., 1971a. Plate Tectonic Model for the Evolution of the Central Andes. Geol. Soc. Am. Bull., 82:3325-3346.

James, D.E. 1971b. Andean Crustal and Upper Mantle Structure. J. Geophys. Res. 76:3246-3271.

James, D.E., 1978. Subduction of the Nazca Plate Beneath Central Peru. Geology, 6:174-178.

Jordan, T.E., Isacks, B.L., Allmendinger, R.W., Brewer, J.A., Ramos, V.A. and Ando, C.J., 1983. Andean Tectonics Related to Geometry of Subducted Nazca Plate. Geol. Soc. Am. Bull., 94:341-361.

Kanamori, H. and McNally, K.C., 1982. Variable Rupture Mode of the Subduction Zone Along the Ecuador-Colombia Coast. Bull. Seismol. Soc. Am., 72:1241-1253.

Kaufmann, P., 1984. Personal Communication.

Kulm, L.D., Dymond, J. and Scheidegger, K.F., 1983. Nazca Plate and Andean Forearc Studies. In: R. Cabre, S.J. (editor). Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs. Am. Geophys. Union Geodynamic Series, 9:83-94.

Longsdale, P., 1978. Ecuadorian Subduction System. Bull. Am. Assoc. Pet. Geol., 62:2454-2477.

Longsdale, P. and Klitgord, K.D., 1978. Structure and Tectonic History of the Eastern Panama Basin. Geol. Soc. Am. Bull. 89:981-999.

Lowman, P.D., Jr., 1981. One Carte Globale De L'Activite Tectonique. Bull. De L'Assn. Internationale De Geol. De L'Ingenieur, 23, 37-49.

Lowrie, A. and Hey, R., 1981. Geological and Geophysical Variations Along the Western Margin of Chile Near Lat 33° to 36°S and Their Relation to Nazca Plate Subduction. In: L.D. Kulm, J. Dymond, E.J. Dasch and D.M. Hussong (editors). Nazca Plate Crustal Formation and Andean Convergence. Geol. Soc. Am. Memoir, 154:741-754.

Mead, G., 1981. Personal Communication.

Mendoza, C. and Dewey, J.W., 1984. Seismicity Associated with the Great Colombia-Ecuador Earthquakes of 1942, 1958 and 1979: Implications for Barrier Models of Earthquake Rupture. Bull. Seismol. Soc. Am., 74:577-593.

Minster, J.B. and Jordan, T.H., 1978. Present-Day Plate Motions. J. Geophys. Res., 83:5331-5354.

Mooney, W.D., Meyer, R.P., Laurence, J.P., Meyer, H. and Ramirez, J.P., 1979. Seismic Refraction Studies of the Western Cordillera, Colombia. Bull. Seismol. Soc. Am., 69:1745-1761.

Myer, J.S., 1975. Vertical Crustal Motions of the Andes in Peru. Nature, 254:672-674.

Nur, A. and Ben-Avraham, Z., 1981. Volcanic Gaps and the Consumption of Aseismic Ridges in South America. In: L.D. Kulm, J. Dymond, E.J. Dasch and D.M. Hussong (editors). Nazca Plate: Crustal Formation and Andean Convergence. Geol. Soc. Am. Memoir, 154:729-740.

Ocola, L., 1983. Geophysical Data and the Nazca-South American Subduction Zone Kinematics. Peru-North Chile Segment. In: R. Cabre, S.J. (editor). Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs. Am. Geophys. Union Geodynamic Series, 9:95-112.

Pennington, W.D., 1981. Subduction of the Eastern Panama Basin and Seismo-Tectonics of Northwestern South America. J. Geophys. Res., 86:10753-10770.

Ramirez, J.E., Duque-Caro, H., Goberna, J.R. and Toussaint, J.F., 1983. Geodynamic Research in Colombia (1972-1979). In: R. Cabre, S.J. (editor). Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs. Am. Geophys. Union Geodynamic Series, 9:41-52.

Reilinger, R., 1984. Personal Communication.

Reilinger, R. and Kadinsky-Cade, K., 1984. Personal Communication.

Rodriguez, R., Cabre, R., and Mercado, A., 1976. Geometry of the Nazca Plate and its Geodynamic Implications. In: G.H. Sutton, M.H. Manghnani and R. Moberly (editors). The Geophysics of the Pacific Ocean Basin and its Margin. Am. Geophys. Union Mono., 19:87-103.

Sacks, I.S., 1983. The Subduction of Young Lithosphere. J. Geophys. Res., 88:3355-3366.

Schubert, C., 1979. El Pilar Fault Zone, Northeastern Venezuela: Brief Review. Tectonophysics, 52:447-455.

Schubert, C. and Laredo, M., 1979. Late Pleistocene and Holocene Faulting in Lake Valencia Basin, North Central Venezuela. Geology, 7:289-292.

Shepherd, G.L. and Moberly, R., 1981. Coastal Structure of the Continental Margin, Northwest Peru and Southwest Ecuador. In: L.D. Kulm, J. Dymond, E.J. Dasch and D.M. Hussong (editors). Nazca Plate: Crustal Formation and Andean Convergence. Geol. Soc. Am. Memoir, 154:351-391.

Snoke, J.A., Sacks, I.S. and James, D.E., 1979. Subduction Beneath Western South America: Evidence from Converted Phases. Geophys. J. R. Astr. Soc., 59:919-225.

Sonnenberg, F.P., 1963. Bolivia and the Andes. In: O.E. Childs and B.W. Beebe (editors). Backbone of the Americas. Am. Assoc. Pet. Geol. Memoir 2:36-46.

Stauder, W., 1975. Subduction of the Nazca Plate Under Peru as Evidenced by Focal Mechanisms and by Seismicity. J. Geophys. Res., 80:1053-1064.

Swift, S.A. and Carr, M.J., 1974. The Segmented Nature of the Chilean Seismic Zone. Phys. Earth and Planet. Inter., 9:183-191.

Unesco, 1978. Tectonic Map of South America. The Geol. Soc. Am. Map and Chart Series. MC-32.

Zeil, W., 1979. The Andes - A Geological Review. Gebruder Borntraeger, Berlin, 260 pp.

TABLE 1

MAJOR ANDEAN TECTONIC QUESTIONS

1. Movement of the oceanic coastal block of western Colombia and Northwestern Ecuador.

2. Movement across the Guarapungo Fault Zone.

3. Expansion of the Gulf of Guayaquil.

4. Movement across the Tumbes-Guayana and Huancabamba Fault Zones.

5. Movement across the Pisco Abancay Fault Zone.

6. Movement across the Arica Elbow (Peru-Chile-Bolivian Altiplano Region).

7. Strain across the Andean Cordilleras and Sub-Andean Foredeep (Example: Pampeanas Ranges).

TABLE 2

PRESENT CANDIDATE SLR SITES

| Site | Location | Priority | Comments |
|---|---|---|---|
| Easter Island+ | S. Pacifi | 1 | On Edge of Nazca Plate. |
| Santiago+ | C. Chile | 1 | VLBI/SLR Intercomparisons. |
| Cerro Tololo+ | C. Chile | 1 | Excellent Observing Weather. Horizontal Ranging Possible. |
| Iquique | N. Chile | 1 | Locked Seismic Zone. S. Anchor Across Titicaca/Arica Deflection Zones. |
| Oruro | C. Bolivia | 1 | Trans-Andean Stress. S. Anchor Titicaca/Arica Deflections. |
| Santa Cruz | E.C. Bolivia | 2 | Anchor to Craton. Thick Sedimentary Section. |
| Arequipa+* | S. Peru | 1 | N. Anchor Titicaca/Arica Deflections. Complex Tectonic Location. |
| Cuzco | S.E. Peru | 1 | N. Anchor Titicaca/Arica Deflections. S. Anchor Pisco/Abancay F.Z. Trans-Andean Stress. |
| Lima | W.C. Peru | 1 | N. Anchor Pisco/Abancay Fracture Zone. |
| Huancayo | C. Peru | 2 | N. Anchor Pisco/Abancay F.C. Tectonically Similar to Lima. |
| Bayovar | N.W. Peru | 1 | Close to Trench. S. Anchor Gulf of Guayaquil |
| Quito | C. Ecuador | 2 | Near Possible VLBI site. Complex Tectonic Location. |
| Galapagos Islands | E.C. Pacific | 2 | Complex Tectonic Location. Difficult Logistics. |

+Sites already occupied by Project.
*Fixed laser site.

TABLE 3

RECOMMENDED NEW SLR SITES

| Site | Location | Priority | Comment |
|---|---|---|---|
| Isla San Felix | S.E. Pacific | 1 | Center of Nazca Plate. |
| Brazilia/Petrolina | E.C. Brazil | 1 | On Central Craton. |
| Guayaquil | W.C. Ecuador | 1 | N. Anchor Gulf of Guayaquil. On Piñon (Ophiolitic) Formation. |
| Buenaventura | S.W. Colombia | 2 | On Oceanic (Exotic?) Terrane. |
| Villavicencio/Puerto La Concordia | C. Colombia | 2 | Trans-Andean Stress. E. Anchor of Dolores/ Guayaquil Mega Fault. |
| Mendoza | W.C. Argentina | 2 | Trans-Andean Stress. |
| Cordoba | C. Argentina | 2 | Trans-Andean and Foredeep Stress. |

TABLE 4

COMPLETE LIST OF RECOMMENDED SLR SITES

| Site | Priority | Andean Tectonic Problems Primarily Addressed (See Table 1) |
|---|---|---|
| Buenaventura | 2 | 1,2,3 |
| Villavicencio or Puerto La Concordia | 2 | 1,2,3,4,7 |
| Guayaquil | 1 | 1,2,3 |
| Bayovar | 1 | 1,2,3,4 |
| Lima | 1 | 5 |
| Cuzco | 1 | 5,6,7 |
| Arequipa[+] | 1 | 5,6,7 |
| Oruro | 1 | 6,7 |
| Iquique | 1 | 6 |
| Cerro Tololo[+] | 1 | 7 |
| Santiago[+o] | 1 | 7 |
| Mendoza | 2 | 7 |
| Cordoba | 2 | 7 |
| Brazilia or Petrolina | 1 | 7 |
| San Felix | 1 | 7 |
| Easter Island[+] | 1 | 7 |

[+]Sites already occupied by Project.
[o]Possible VLBI site also.

# FIGURE CAPTIONS

Figure 1: Global tectonic map modified from Lowman (1981). Major plate tectonic investigation sites mentioned in text: E = Easter Island, Chile; G = Galapagos Islands, Ecuador; F = Isla San Felix, Chile; S = Santiago, Chile; C = Cerro Tololo, Chile; and A = Arequipa, Peru.

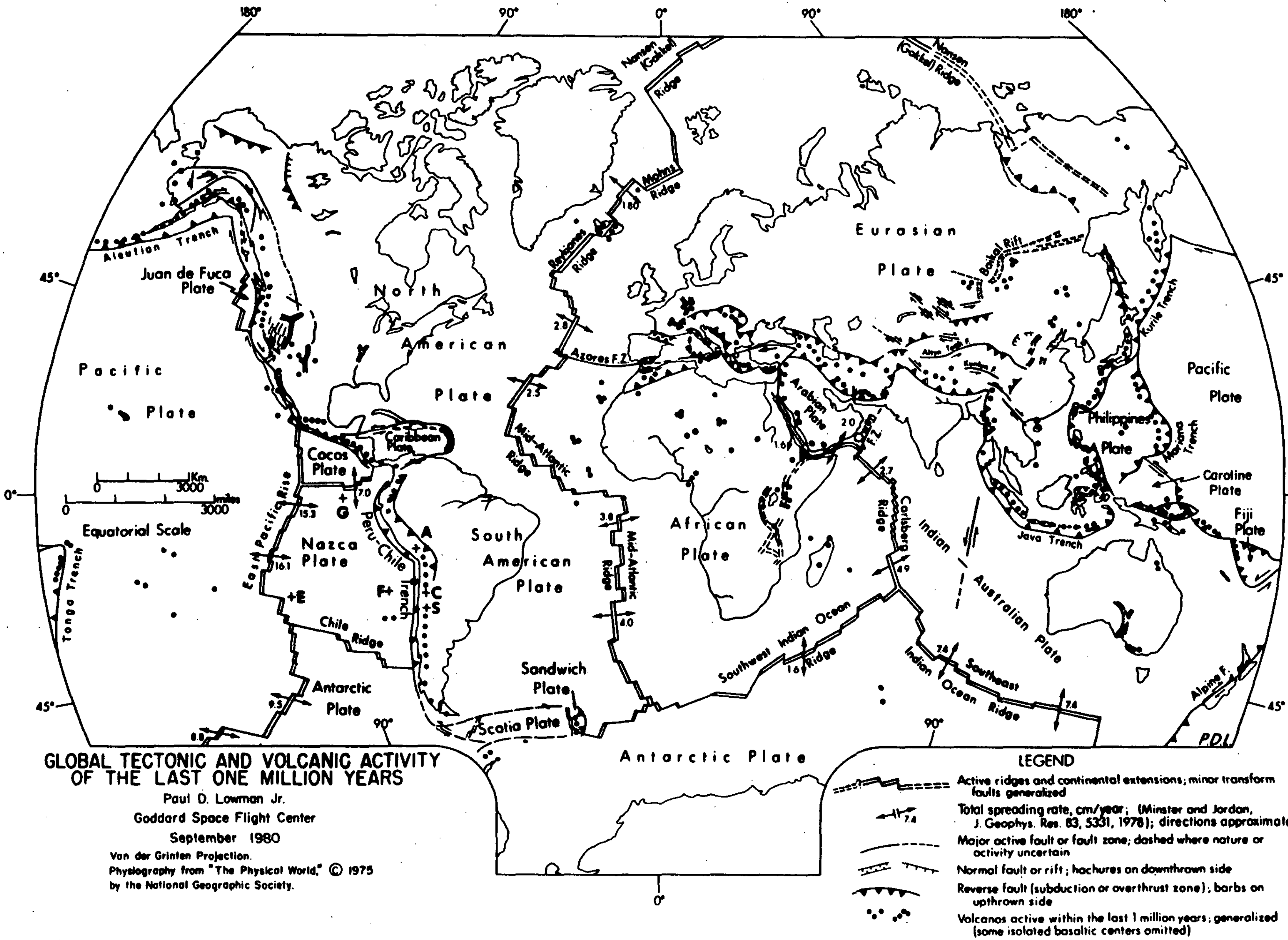
Figure 2: South America consists of three major tectonic regions. By far the largest is the South American Platform, while the smallest is the Patagonian Platform. The entire western continental edge consists of the Andean Cordillera which inludes the Caribbean Mountains along the edge of the Caribbean Sea.

Figure 3: Earthquake depths in South America are correlatable with the interface of the Nazca-South American plates. The two zones of deep seismicity (greater than 525 km) occur inland from the flatter dipping subduction zones.

Figure 4: The angle of subduction of the Nazca plate varies considerably with latitude. The pattern of the Andean Ranges shows considerable variation in directional trends and continuity. Active volcanism occurs inland from the steeper dipping subduction zones.

Figure 5: Major tectonic zones of the Continental leading edge. The major region of distortion is in and around the Gulf of Guayaquil on the southwest edge of Ecuador.

Figure 6: Locations of the observing sites discussed in this report. Tectonic features shown in Figure 4 are reproduced, but not identified.




**GLOBAL TECTONIC AND VOLCANIC ACTIVITY OF THE LAST ONE MILLION YEARS**

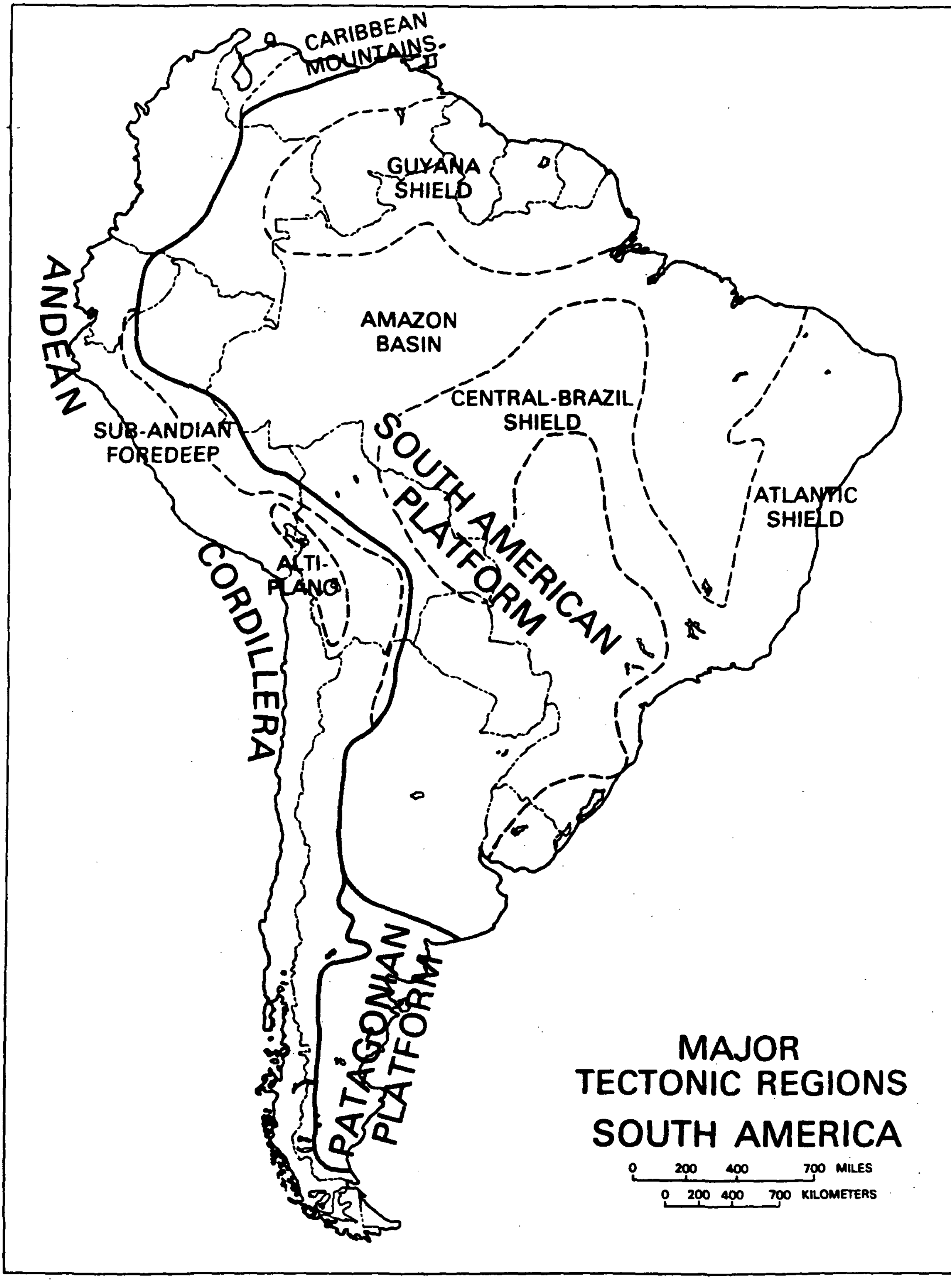
Paul D. Lowman Jr.

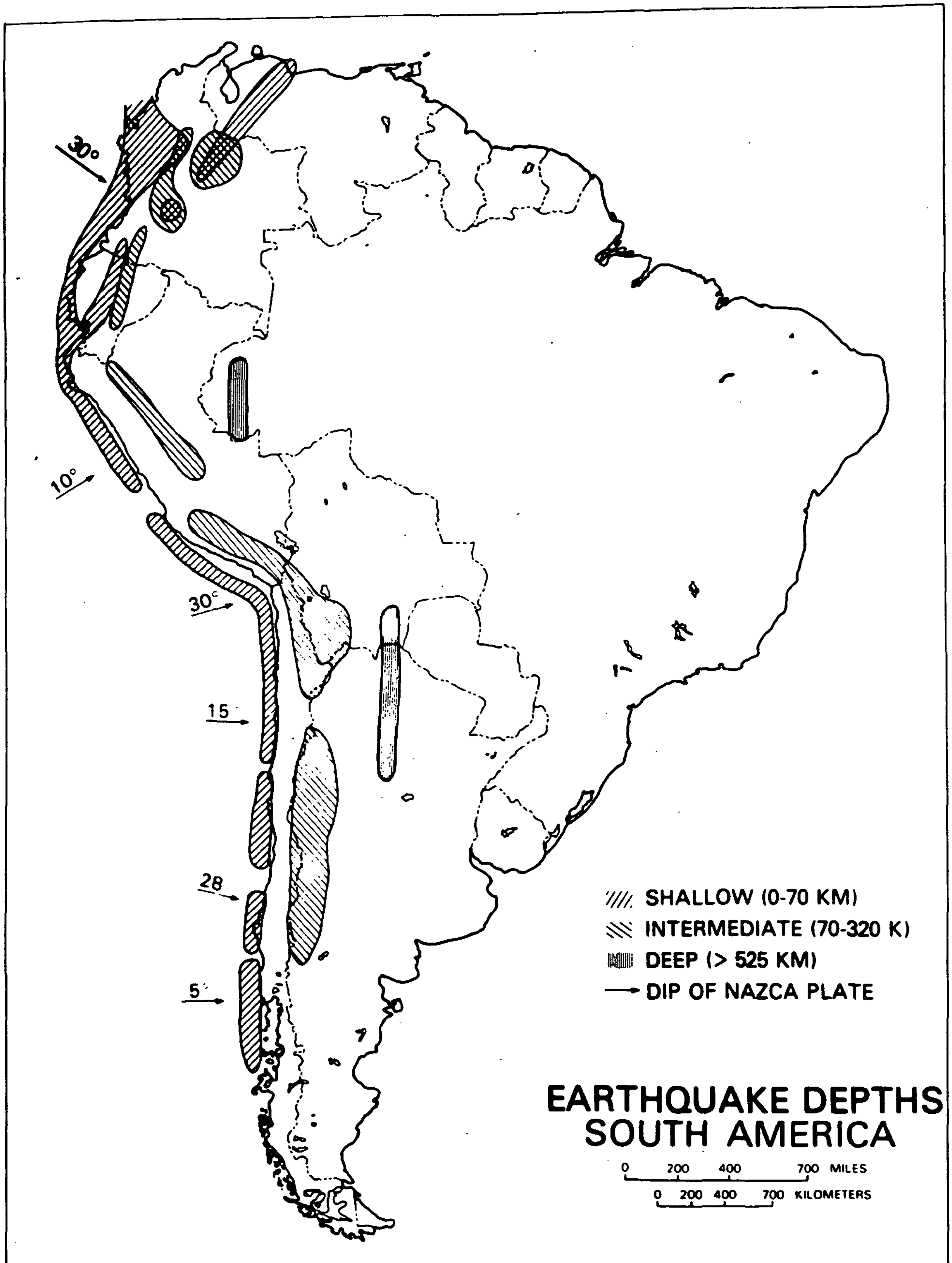
Goddard Space Flight Center

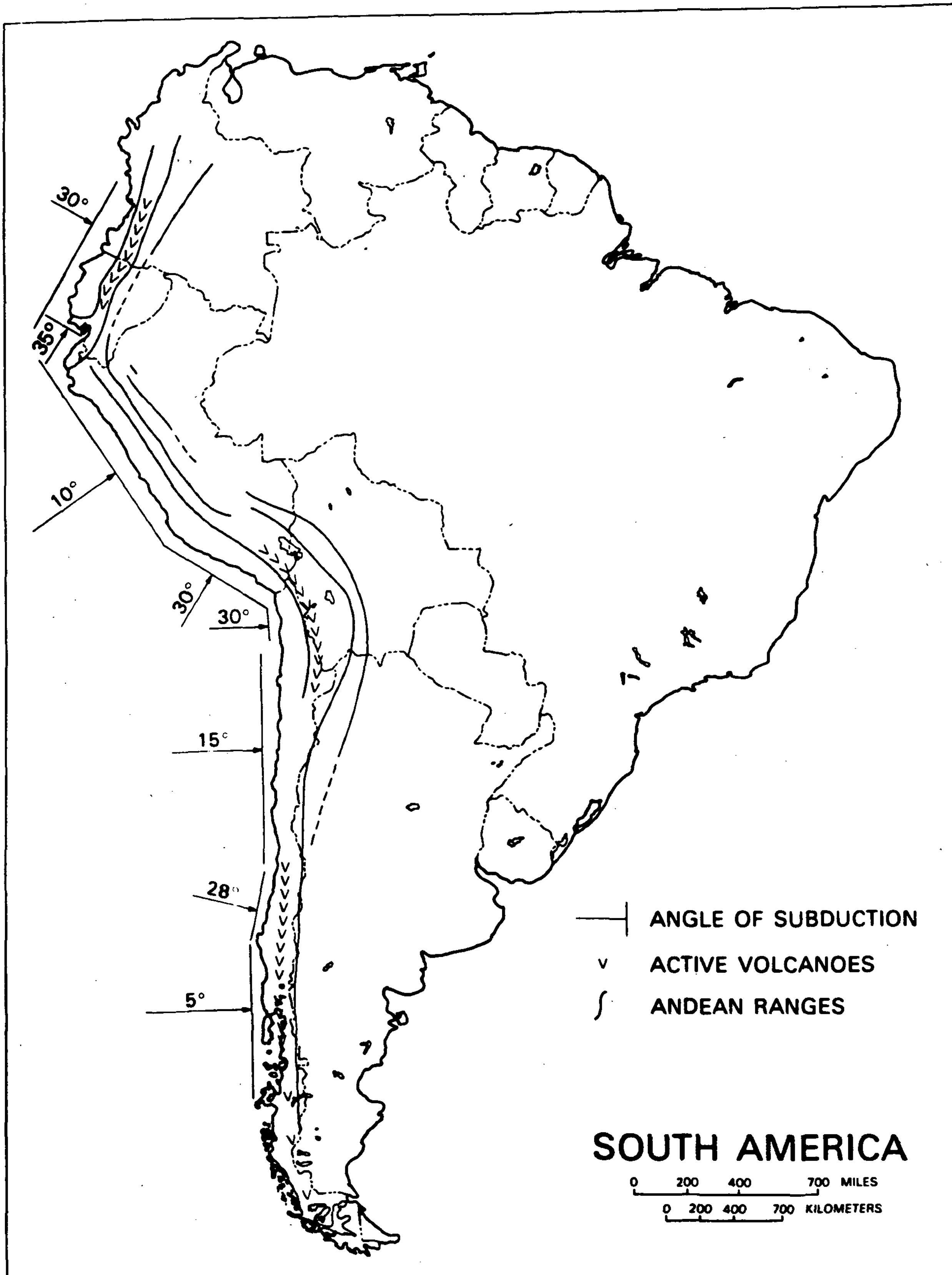
September 1980

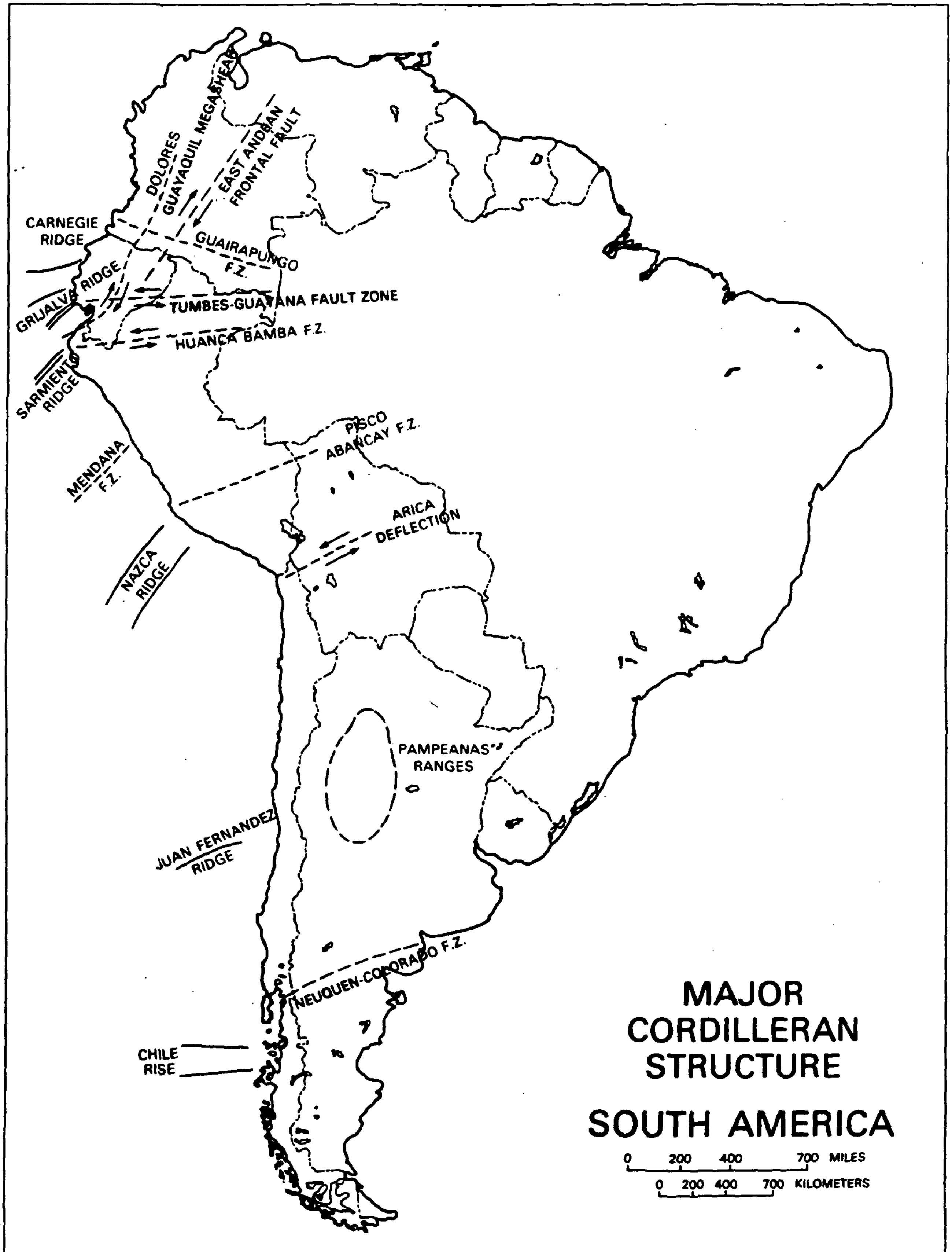
Van der Grinten Projection.

Physiography from "The Physical World," © 1975 by the National Geographic Society.


CARIBBEAN
MOUNTAINS
GUYANA
SHIELD
AMAZON
BASIN
ANDEAN
CENTRAL-BRAZIL
SHIELD
SUB-ANDIAN
FOREDEEP
SOUTH AMERICAN
PLATFORM
ATLANTIC
SHIELD
ALTI-
PLANO
CORDILLERA
PATAGONIAN
PLATFORM
MAJOR
TECTONIC REGIONS
SOUTH AMERICA
0 200 400 700 MILES
0 200 400 700 KILOMETERS


30°
10°
30°
15
28
5
SHALLOW (0-70 KM)
INTERMEDIATE (70-320 K)
DEEP (> 525 KM)
DIP OF NAZCA PLATE
EARTHQUAKE DEPTHS
SOUTH AMERICA
0 200 400 700 MILES
0 200 400 700 KILOMETERS


30°
35°
10°
30°
30°
15°
28°
5°
ANGLE OF SUBDUCTION
ACTIVE VOLCANOES
ANDEAN RANGES
SOUTH AMERICA
0 200 400 700 MILES
0 200 400 700 KILOMETERS


DOLORES
GUAYAQUIL MEGASHEAR
EAST ANDEAN
FRONTAL FAULT
CARNEGIE
RIDGE
GUAIRAPUNGO
F.Z.
GRIJALVA RIDGE
TUMBES-GUAYANA FAULT ZONE
HUANCA BAMBA F.Z.
SARMIENTO
RIDGE
PISCO
ABANCAY F.Z.
MENDANA
F.Z.
ARICA
DEFLECTION
NAZCA
RIDGE
PAMPEANAS
RANGES
JUAN FERNANDEZ
RIDGE
NEUQUEN-COLORADO F.Z.
CHILE
RISE
MAJOR
CORDILLERAN
STRUCTURE
SOUTH AMERICA
0 200 400 700 MILES
0 200 400 700 KILOMETERS


BUENAVENTURA
VILLAVICENCIO
PUERTO LA CONCORDIA
GALAPAGOS
QUITO
BAYOVAR
GUAYAQUIL
PETROLINA
LIMA
HUANCAYO
CUZCO
AREQUIPA
SANTA CRUZ
ORURO
IQUIQUE
BRAZILIA
SAO PAULO
ISLA SAN FELIX
CERRO TOLOLO
CORDOBA
SANTIAGO
MENDOZA
EASTER ISLAND
PROPOSED OBSERVING SITES
FIXED SLR BASE STATION
PRESENTLY LOCATED TLRS SITES
LOCATED SITES RECOMMENDED FOR DROPPING
PROPOSED NEW SITES
TVDS BASE STATION
MAJOR TECTONIC FEATURES
SOUTH AMERICA
0 200 400 700 MILES
0 200 400 700 KILOMETERS

**BIBLIOGRAPHIC DATA SHEET**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| NASA TM- 86160 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| Andean Tectonics: Implications for Satellite Geodesy | 6. Performing Organization Code |
| 7. Author(s) R. J. Allenby | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771 | 10. Work Unit No. |
| | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address NASA- Goddard Space Flight Center Greenbelt, Maryland 20771 | 13. Type of Report and Period Covered |
| | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract This paper summarized current knowledge and theories of large scale Andean tectonics as they relate to site planning for the NASA Crustal Dynamics Program's proposed high-precision geodetic measurements of relative motions between the Nazca and South American plates. The Nazca Plate and its eastern margin, the Peru-Chile Trench, is considered a prototype plate marked by rapid motion, strong seismicity and well-defined boundaries. Tectonic activity across the Andes results from the Nazca Plate subducting under the South American plate in a series of discrete platelets with different widths and dip angles. This, in turn, is reflected in the tectonic complexity of the Andes which are a multitude of orogenic belts superimposed on each other since the Precambrian. Sites for Crustal Dynamics Program measurements are being located to investigate both interplate and extraplate motions. Observing operations have already been initiated at Arequipa, Peru and Easter Island, Santiago and Cerro Tololo, Chile. Sites under consideration include Iquique, Chile; Oruro and Santa Cruz, Bolivia; Cuzco, Lima, Huancayo and Bayovar, Peru; and Quito and the Galapagos Islands, Ecuador. Based on scientific considerations, it is suggested that Santa Cruz, Huancayo (or Lima), Quito and the Galapagos Islands be replaced by Isla San Felix, Chile; Brazilia or Petrolina, Brazil; and Guayaquil, Ecuador. If resources permit, additional important sites would be Buenaventura and Villavicencio or Peurto La Concordia, Colombia; and Mendoza and Cordoba, Argentina.

| 17. Key Words (Selected by Author(s)) | 18. Distribution Statement |
|---|---|
| Andean Tectonics<br>Crustal Dynamics<br>Satellite Geodesy<br>Nazca Plate<br>South American Plate | |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | | |

*For sale by the National Technical Information Service, Springfield, Virginia 22151.

GSFC 25-44 (10/77)