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Seismicity of the Huancayo Basin (central Peru) and the Huaytapallana Fault

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Abstract—A microearthquake survey of the Huancayo region (central Peru) shows that most of the seismicity bordering the basin is situated along the Huaytapallana Fault. Nevertheless, some activity is observed for the first time on the eastern flank of the Western Cordillera, along the Altos del Mantaro Fracture Zone. Hypocenters on the Huaytapallana Fault are shallower than 10 km. Their spatial distribution and focal mechanisms are in agreement with the geometry, mechanisms, and neotectonic observations of the two 1969 large earthquakes. Reverse faulting is produced on a plane dipping 50° to the east. Observed surface breaks, 5 km long for the July event and 9 km long for the October event, are separated by a 4-km gap. Precise relative determination of hypocenters shows clustering around this long seismic gap, which was not broken during the 1969 crisis, as well as north of the northern fault segment. Thus, earthquakes of sizes similar to those of 1969 may be expected in the future in these places. The seismicity west of the basin defines a 40-km-long band in a NW/SE direction. The positions and depths of hypocenters agree with field observations of the steeply dipping Altos del Mantaro Fracture Zone to the west.

Resumen—Un estudio microsísmico de la región de Huancayo muestra que la mayoría de la sismicidad que bordea a la cuenca está situada a lo largo de la falla de Huaytapallana. De no menos importancia, se determina por primera vez actividad sísmica en el flanco oeste de la Cordillera Occidental, a lo largo de la zona de fallas de Altos del Mantaro. Los hipocentros en la falla de Huaytapallana están situados a profundidades menores que 10 km. La distribución espacial y los mecanismos focales concuerdan con la geometría, mecánica y las observaciones neotectónicas de los dos grandes terremotos de 1969. Las fallas inversas ocurren en planos buzantes 50° al este. Rasgos de fractura en la superficie, con una longitud de 5 km para el evento de julio y de 9 km para el de octubre, están separados entre sí 4 km. Una precisa determinación relativa de los hipocentros muestra la concentración de los mismos alrededor de esta zona entre las fracturas, la cual no fue modificada durante el episodio de 1969, así como al norte de el segmento de fallas septentrionales. De este modo, terremotos de magnitud similar al del año 1969 pueden suceder en el futuro en estos sectores. La sismicidad al oeste de la cuenca se define en una banda de 40 km de longitud orientada NO/SE. La posición y profundidad de los hipocentros está de acuerdo con observaciones de campo de la zona de fallas de alto ángulo de los Altos del Mantaro.

INTRODUCTION

THE HIGH ANDES of central Peru are commonly subdivided into three zones which differ from one another in morphology and structure: the Western Cordillera, the High Plateaux, and the Eastern Cordillera (Fig. 1). These zones are separated from each other by major fault systems oriented NW/SE, whose Mesozoic and Tertiary history shows several tectonic episodes.

The Western Cordillera contains folded and thrusted Mesozoic marine rocks unconformably covered by moderately folded to undisturbed Tertiary volcanic rocks. Moreover, it is the site of most of the Oligo-Miocene magmatic activity. Volcanism is absent at present due to the subhorizontal shape of the subducted slab (Sacks, 1977; Isacks and Barazangi, 1977).

The High Plateaux are formed by moderately folded and thrusted marine Mesozoic and continental Paleogene rocks, covered by few undeformed Miocene volcanics.

The Eastern Cordillera is mainly formed by folded and faulted Precambrian and Paleozoic rocks. The contact between the High Plateaux and the

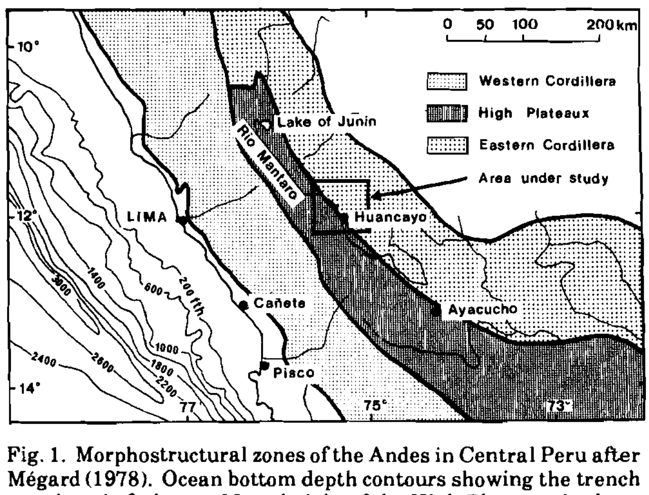

Fig. 1. Morphostructural zones of the Andes in Central Peru after Mégard (1978). Ocean bottom depth contours showing the trench are given in fathoms. Mean height of the High Plateaux is about 4000 meters. The Eastern and Western Cordilleras may exceed 5000 meters at certain peaks. The area of study is within the square.

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Eastern Cordillera is covered by Cenozoic basins oriented NW/SE (from north to south: the Junin, Huancayo, and Ayacucho Basins).

Within the area under study (Fig. 2), we need to look at the structures in greater detail. We find the following features from west to east:

- *The Altos del Mantaro High Plateau.* This zone presents a very simple geometry, with cylindrical, long, wavelength folds whose axes, striking N135° to N150°, may be followed over some tens of kilometers (Mégard, 1978).

- *The Altos del Mantaro Fracture Zone.* Mégard (1978) and Blanc (1984) mapped a discontinuous system of faults on the southwestern border of the Mantaro Basin, which can be followed from 12°S down to at least 12°30'S. These reverse faults have a general direction of N140° and dip to the southwest. They do not exhibit any clear evidence of recent activity.

- *The Mantaro Basin.* This is an asymmetric basin whose southwestern side is steeper than its northeastern one. The basin rocks on the southwestern side have been strongly deformed by Altos del Mantaro Fracture Zone activity during the late Pliocene-early Quaternary. Simultaneously, an uplift of the Altos del Mantaro Plateau occurred. However, the northeastern border does not show any clear evidence of deformation, and it is not separated from the Eastern Cordillera by any fracture zone — the Ricran (see Fig. 4) and Huaytapallana Fracture Zones being part of the Eastern Cordillera.

- *The Huaytapallana Fracture Zone.* This is a 30-km-long NW/SE active fault system, dipping about 50° to the northeast, located on the southwestern

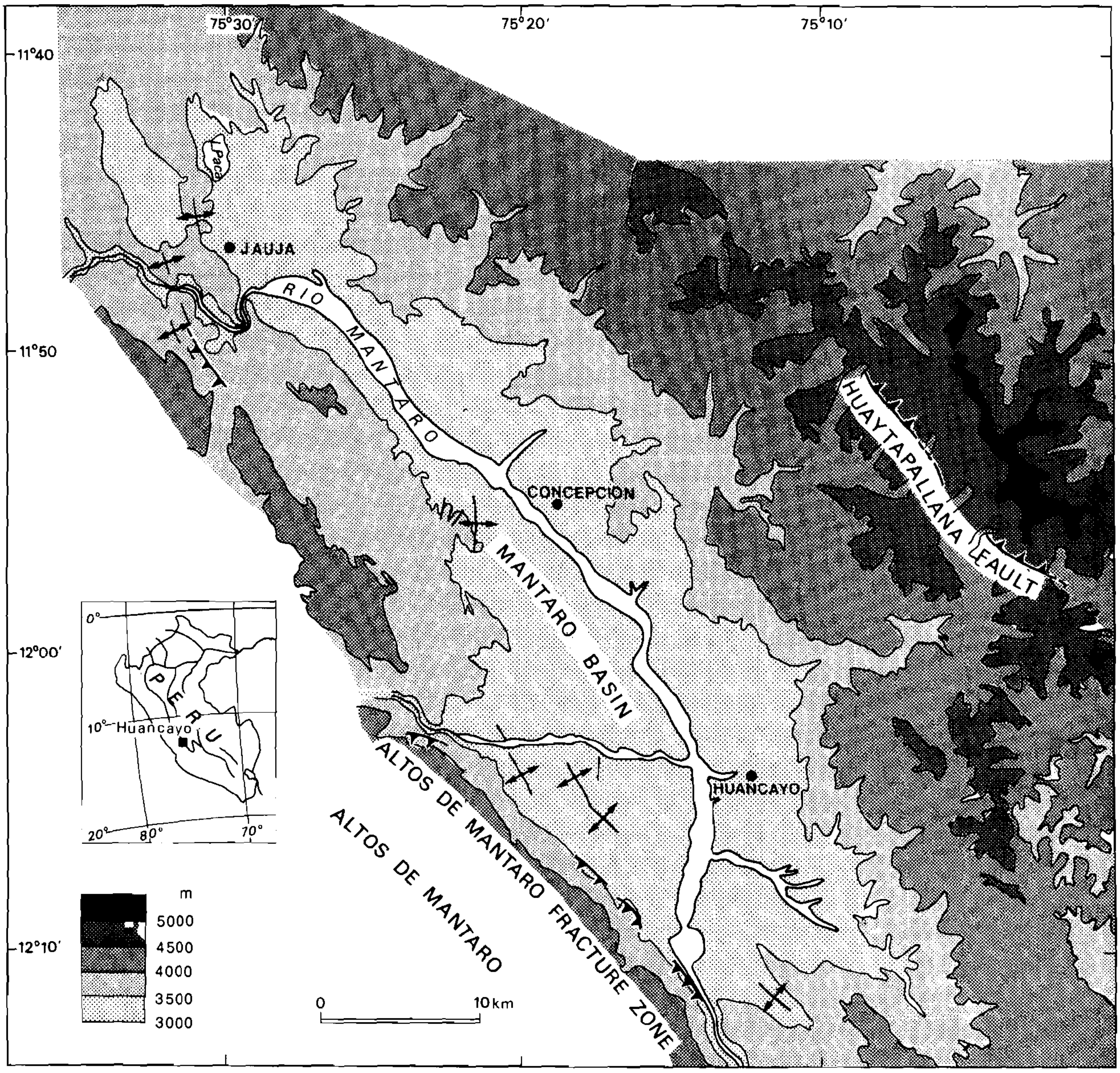

Fig. 2. Topographic and tectonic map of the area under study (modified from Blanc, 1984). The inset shows the location of the study area within Peru. The Mantaro Basin is asymmetric, being thicker at the western edge. Mapped active reverse faults are indicated by toothed lines, anticlines by axes. The Huaytapallana Fault (right) was reactivated during the 1969 events.

side of the Cordillera de Huaytapallana, which culminates at more than 5500 meters elevation. Geological data and satellite imagery suggest that its length may reach up to 100 km.

The seismotectonic characteristics of the region under study were not well known until recently. Mégard (1978) was the first to produce a detailed structural synthesis of the High Andes of Central Peru. Philip and Mégard (1977) studied the surface breaks of the 1969 Huaytapallana earthquakes. Blanc (1984) completed these latter observations and added a number of tectonic measurements around the Mantaro Basin. Suarez *et al.* (in press) conducted a microearthquake survey in the region, with a local network designed to record crustal and subduction zone activity simultaneously.

The purpose of this paper is to continue the observations of Suarez *et al.* (in press) in order to locate the places where active faulting occurs in the High Andes, to obtain good determinations of the mechanism of the associated earthquakes, and to give precise elements for modelling crustal deformation in this region.

HISTORICAL AND INSTRUMENTAL SEISMICITY BEFORE 1969

The bulletins of the International Seismological Center (ISC, formerly ISS), of the National Earthquake Information Service (NEIS), and the *Hypocenter and Intensity Catalog of Earthquakes for South America* (CERESIS, 1985) provide reports of only three presumed crustal earthquakes in the region of study: September 20, 1939; January 22, 1963; and September 21, 1968. Their depths were estimated at 60, 40, and 7 km, respectively. The quality of the last determination is good, so that we may say it really occurred in the crust. The uncertainties on the focal parameters of the first two events, and the fact that the subducted slab is only 100 km below the region of study (Barazangi and Isacks, 1979), do not allow us to make such a clear statement. With regard to the 1939 event, we selected the Gutenberg and Richter determination, as the CERESIS catalog did, because it provides the smallest P-residual at the Huancayo seismological station. An event occurred on July 7, 1962 at a depth given at 91 km; therefore, it is probably related to the subducted slab. No magnitudes were reported for the first two earthquakes, but the third is given a value $m_b=5.0$. In any case, according to the CERESIS catalog, these shocks were not felt by the population.

The first accurately located earthquakes in the neighborhood of the Mantaro Basin are the two events of 1969 — July 24 ($M_s=5.7$) and October 1 ($M_s=6.2$). These were widely felt over the entire area, producing severe damage in the villages of Acaopalca, Chilifruta, and Pariahuanca, 20 to 40 km east of Huancayo. One hundred and thirty persons died. The Huaytapallana Fault was reactivated showing surface breaks. The intensity was moderate (I=IV to V Mercalli Modified) at Jauja, near the northern border of the Mantaro Basin and at Huancayo, the main town of the department, to the south of the basin. The intensity reached VII M.M. in Concepción, between Jauja and Huancayo, in the central part of the basin (Silgado, 1978). Intensities of the same level and higher have been reported in the past in Jauja and Huancayo for earthquakes occurring in distant zones, particularly those of the Sub-Andean seismic belt that limits the High Andes to the east (Dorbath *et al.*, 1986). For example, the January 11, 1947 Satipo earthquake ($M_s=7.5$) whose epicenter is located 150 km east of Huancayo, has been felt all along the Mantaro Basin with an intensity of VI M.M. The Eastern Cordillera and the Sub-Andean Zone are sparsely populated; consequently, there is lack of information concerning macroseismic effects of ancient earthquakes. Thus, one cannot distinguish between events in the vicinity of the Mantaro Basin and those occurring in the Sub-Andean Zone prior to the advent of instrumental seismology. We cannot determine, from these poor historical data, whether events comparable in size to those of 1969 have occurred since the Spanish conquest. The only way to estimate the recurrence time of such events is by paleoseismic study in trenches of the Huaytapallana Fault scarp itself (Blanc, 1984).

SEISMICITY OF HUAYTAPALLANA AND THE MANTARO BASIN (1969 TO PRESENT)

The Huaytapallana Fault

The two Huaytapallana earthquakes are the only major crustal events that have occurred in the High Andes of Peru since the development of modern seismology, and they have been extensively studied (Stauder, 1975; Suarez *et al.*, 1983; Chinn and Isacks, 1983). Their depths were less than 10 km and they produced surface breaks along the Huaytapallana Fault. The fault was known at that time, but not as an active one (Mégard, personal communication). Surface deformations have been studied by Deza (1971), Philip and Mégard (1977), Blanc (1984), and Sébrier *et al.* (1988).

Two different segments were reactivated, separated by a 4 km gap where no rupture was observed (Fig. 3). The southern segment is oriented N300° and is about 4 km long. The average horizontal displacement is a 0.7 meter left-lateral strike-slip, while the vertical offset is 1.8 meters. Oblique *en echelon* shears, often associated with small faults, are developed all along the main fault (Philip and Mégard, 1977). The northern segment is 9.5 km long and strikes N320°. It exhibits a 2 meter vertical offset and there is no evidence of a strike-slip component (Blanc, 1984). Field observations clearly

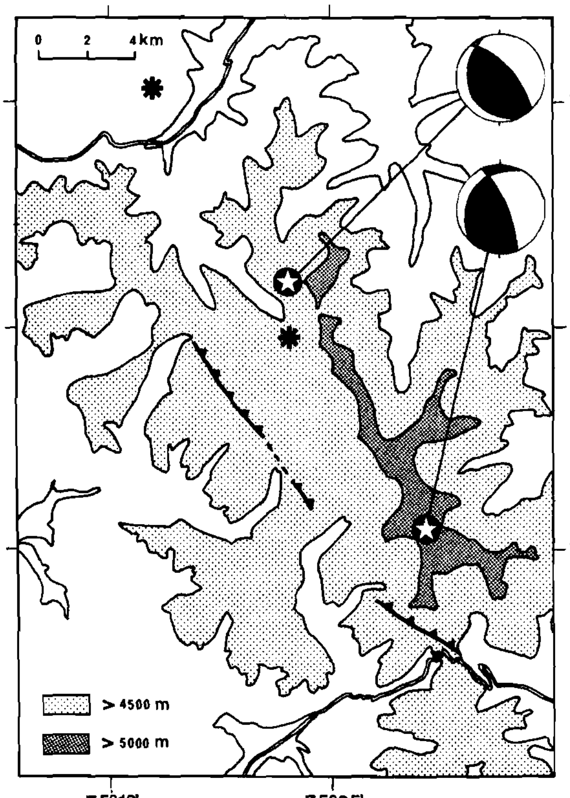

Fig. 3. Hypocenters from ISC and focal mechanisms from Suarez *et al.* (1983) for the two 1969 Huaytapallana events. The ISC determinations are plotted as closed stars; we shifted them (open stars) to the northern ends of the fault segments seen by Blanc (1984).

indicate reverse vertical motion on both segments, on planes dipping rather steeply to the northeast.

The seismic moments were 1.8×10^{25} and 9.8×10^{25} dyne-cm respectively, according to Suarez *et al.* (1983). Assuming that the observed offsets — 1.8 meters and 2.0 meters, respectively — represent the mean slip along the faults, we calculate that the rupture lengths were about 5 and 12 km (from $M_0=\mu\ L\ l\ \Delta u$). These dimensions are in fairly good agreement with the lengths of the two reactivated segments observed on the field. The ISC location of the October shock is situated 12 km northwest of the July shock (Fig. 3), and these elements lead one to associate each segment with a particular earthquake: the southern segment with that of July and the northern one with that of October. Figure 3 presents the two epicenters as determined by ISC together with the two points obtained, shifting them by 10 km parallel to the general fault direction. These two points roughly coincide with the northern extremity of each activated segment. Ten-kilometer errors on epicentral positions are not unusual in such a region with weak seismic monitoring, but it is reasonable to expect the same error on events close together and of comparable magnitude, as is the case here.

The rupture of the 4-km gap separating the two segments would produce an earthquake quite comparable in magnitude to that of July 24, 1969. It is worth noting that the precursor, which occurred on September 21, 1968 was located by the ISC at the same place as the July 1969 earthquake. Its magnitude, m_b = 5.0, and the fact that it was not felt in the area indicate that it was too weak to fill this gap, which therefore acted as a barrier during the 1969 rupture process and was not an asperity previously broken.

The analysis of surface deformations associated with the southern segment led Philip and Mégard (1977) to propose a mean N65° shortening direction. Slip vector measurements made by Blanc (1984) on the same southern fault segment are consistent with a maximal principal stress striking N75°. These values are also compatible with the focal mechanism deduced by Suarez *et al.* (1983) from long-period P-wave modelling for the July earthquake, which shows a pressure axis striking N77° (Fig. 3).

The focal mechanism corresponding to the October earthquake shows only a very small strike-slip component, which is in agreement with the field observations of the northern segment. Its P-axis trends N53°. The difference in the amount of strike-slip motion reflects the change of direction of the faults. The compression is nearly horizontal in both cases.

Only three reliable events that could be related to the Huaytapallana Faults have been located by ISC and NEIS since January 1970: September 29, 1970 (m_b=4.5); November 23, 1970 (m_b=4.9); and August 16, 1980 (m_b=4.7). Hence, there seems to be a 10-year period of seismic silence. However, a careful examination of the seismograms of the Huancayo Observatory, using S-P times and polarization of P-waves, reveals a permanent activity with an average of 1 to 3 microearthquakes per week.

The November 23, 1970 event was followed by 75 aftershocks during the next week, and that of 1980 by 13 aftershocks in the same period of time. A temporary network was set up in the region during May and June, 1980, and 25 events were located in the vicinity of the Huaytapallana area (Suarez *et al.*, in press).

The Mantaro Basin

Few crustal events have been located to the west of the Mantaro Basin, under the Western Cordillera, according to ISC and NEIS. These determinations are poorly constrained. Some events have been felt and are roughly located a few kilometers to the west of the Huancayo Observatory, next to the Altos del Mantaro Fault Zone (A. Giesecke, former Director of the Observatory, personal communication). The existence of crustal seismicity was confirmed by Blanc (1984), who located several events recorded at the Huancayo Observatory between 1978 and 1982, with S-P times ranging from 2 to 5 seconds. The nearest epicenters (S-P=2 sec) were estimated to be south-southwest of the Observatory, according to the polarization of the P-waves, and the furthest ones to the south-southeast. Thus, the seismicity follows the general direction of the Mantaro Basin and associated structures. A re-examination of the seismograms of the Huancayo Observatory recorded before 1978 led us to the same conclusions.

FIELD WORK AND OBSERVED SEISMICITY

A microearthquake network was operated by ORSTOM, the Institut de Physique du Globe de Strasbourg, and the Instituto Geofisico del Peru during July and August of 1985. The description of the seismic array is given in Dorbath *et al.* (1986). Our general goal was to monitor the crustal seismicity of the Eastern Cordillera and the Amazonian foothills of the Andes and to pay particular attention to the Huaytapallana area. Ten out of the 20 stations, including 5 three-component digital stations, were located less than 40 km from the fault (Fig. 4). However, no station was installed on the Western Cordillera west of the Mantaro Basin during this experiment.

The earthquakes were located using the HYPOINVERSE computer program (Klein, 1978), following the same procedure already described in a previous paper (Dorbath *et al.*, 1986). The velocity structure is poorly known in Central Peru. We used a model (Table 1) based on reflection studies in southern Peru, Bolivia, Colombia, and Ecuador (Ocola *et al.*, 1971; Ocola and Meyer, 1972; Meissner *et al.*, 1976),which produces the smallest root mean square (RMS) values of the travel-time residuals. The mean RMS value corresponding to 40 earthquakes located close to the Huaytapallana fault system is 0.11 seconds; the mean standard errors on epicentral position and depth respectively, given by HYPOINVERSE, are 1.1 and 4.3 km with mean standard deviation of 0.7 and 1.7 km. The true errors probably are greater than these values, which are, however, useful in estimating the quality of the locations. Suarez *et al.* (in press) used a velocity model with a slower surface layer, more suitable for the Altiplano region where most of their network was set up. We checked this latter model and found a mean change of 0.7 km in epicentral positions and 2.5 km in depth; the RMS values increased slightly. Far from the network the quality of the locations is poorer; the errors on epicentral position and depth may be estimated at twice the values they have inside the array or in its vicinity. Table 2 gives the coordinates and depths of all the events located during the experiment.

The Huaytapallana Fault

Most of the seismicity we recorded in the Eastern Cordillera is related to the Huaytapallana fault system and to its northern and southern extensions (Fig. 5). However, some shallow events (depths less than 10 km) cluster on the western flank of the Eastern Cordillera about 20 km north of Concepción (Fig. 4). We call this the "Sacsacancha" group. Another cluster appeared at the southeastern extremity of the region during a two-day crisis (Pampas group, Fig. 4). About 10 events have been located in this cluster, but their distances to the nearest stations are too large to allow a good resolution in focal depth, which probably does not exceed 15 km. These two small seismic clusters fall on the Ricran Fracture Zone (Fig. 4), which has been considered inactive until now.

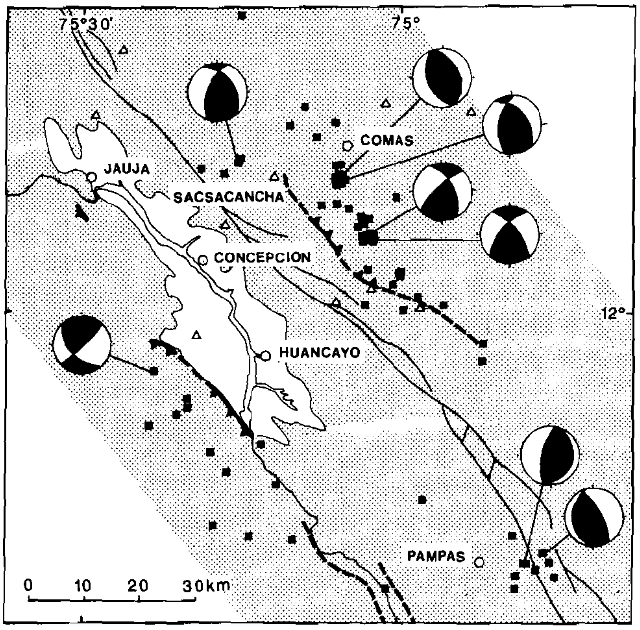

Fig. 4. Seismicity of the Mantaro Basin (closed squares) and focal mechanisms of selected events. Open triangles are seismic stations, open circles are towns. Shaded regions are above 3500 meters elevation. Solid and segmented lines are faults after Mégard (1978) and Blanc (1984). Light continuous lines are the Ricran Fracture Zone, which appears to be inactive except for the Pampas nest.

Some 45 earthquakes were located in the immediate vicinity of the Huaytapallana fault system during the eight weeks of field work. Nearly all of the epicenters lie east of the surface breaks formed during the 1969 events (Fig. 5). They follow the same general direction (NNW/SSE) as the reactivated faults, but at a distance of about 5 km. The microearthquakes are shallow, with depths between 2 and 10 km, most of them clustering around 5 km. This spatial distribution is in close agreement with geologic and neotectonic field observations and with the 45-50° east-dipping nodal plane of the 1969 earthquakes. If we define the fault's length L to be the length of the surface ruptures, it results from the seismic moment values that the width l of the

Table 1. Velocity models.

Mountain		Jungle	
0 km	5.8 km/s	0 km	5.8 km/s
15 km	6.2 km/s	12 km	6.2 km/s
30 km	6.8 km/s	25 km	6.8 km/s
50 km	8.0 km/s	40 km	8.0 km/s

The mountain model was assigned to the stations located in the High Andes, the jungle model to those in the Sub-Andean Zone. These two models simulate the increase in crustal thickness from east to west.

faults may vary between 5 and 10 km, and therefore the faults reach to a depth of about 7 km. Thus the main part of the seismic activity we have recorded took place on the deepest part of the faults.

The most interesting feature of Fig. 5 is that some of the 1985 events are observed opposite the two broken segments, but most of them are concentrated into two clusters about 12 km apart. The southern cluster is opposite the southern end of the northern segment, and the northern one is at the upper edge of this segment broken during the October 1969 earthquake.

Suarez *et al.* (in press) located about 15 events in the same area during the four-week 1980 experiment. The spatial distribution of these events is different from the one we obtained in 1985. More than half of the 1980 microearthquakes lie in a 2×5 km zone adjacent to the northern 1969 fault, a region of weak activity during the 1985 campaign. On the other hand, no earthquakes were located in 1980 within the two 1985 clusters. These different patterns cannot be explained in terms of hypocentral location errors. In both cases, the determinations are well constrained by stations close to the fault. A few weeks after the Suarez *et al.* (in press) experiment ended, on August 16, an earthquake with a magnitude of 4.7 (according to ISC) occurred in this region. We make the assumption that this earthquake, though once again located by ISC too far north, ruptured that part of the fault where most of the activity was observed a few weeks before. Hence the stress released during this event explains the decrease in activity in this particular area.

Neither the ISC nor the NEIS located any earthquakes in the neighborhood of the Huaytapallana Fault since 1980. Therefore, the activity observed in 1985 within the gaps unbroken during the 1969 sequence may appear as precursory phenomena announcing two major earthquakes. Under this hypothesis, the first one may occur where the Huaytapallana Fault changes its direction from N120° to N140°. This bend may have played the role of a barrier during the 1969 sequence and might play the role of an asperity now. This earthquake may have a magnitude similar to that of July 24, 1969. The second one may occur on a northern extension of the

Table 2. Catalog of events

Yr Mo Da	Origin			Lat S	Lon W	Depth	Mag
85-07-18	6	44	45.57	12°15'69"	75°16'43"	16.91	1.5
85-07-18	13	10	12.16	11°58'63"	74°58'30"	2.15	2.8
85-07-19	8	28	39.78	11°59'35"	75°03'24"	6.63	1.1
85-07-20	4	01	07.06	11°56'36"	75°00'01"	6.42	1.9
85-07-20	15	51	22.40	11°48'85"	75°00'34"	22.59	2.8
85-07-20	23	55	22.92	11°57'49"	75°00'66"	2.57	1.2
85-07-21	10	19	45.46	11°41'97"	75°10'64"	2.89	1.2
85-07-29	7	28	22.75	11°47'11"	75°05'91"	5.73	2.7
85-07-29	8	08	54.32	11°41'64"	75°06'21"	6.20	1.7
85-07-29	14	59	53.24	11°47'17"	75°06'23"	7.25	2.5
85-07-29	17	25	04.78	12°04'93"	74°52'04"	2.49	2.1
85-07-30	15	05	05.89	11°51'75"	75°04'04"	2.19	1.7
85-07-31	10	56	01.94	11°31'63"	75°15'53"	9.11	1.4
85-07-31	21	53	24.78	11°46'96"	75°05'46"	4.62	2.9
85-07-31	22	08	29.63	11°45'87"	75°06'02"	3.78	1.5
85-08-01	2	03	39.26	11°46'60"	75°05'70"	4.71	1.6
85-08-01	9	27	53.11	12°22'04"	75°10'01"	11.52	1.9
85-08-01	14	15	50.05	12°26'69"	74°48'88"	27.46	2.0
85-08-01	14	46	45.22	12°25'87"	74°45'03"	13.10	3.3
85-08-01	14	52	13.04	12°24'22"	74°48'06"	17.69	3.1
85-08-01	14	53	37.79	12°25'01"	74°46'82"	16.07	1.5
85-08-01	14	54	18.11	12°23'30"	74°46'28"	16.04	3.2
85-08-01	14	56	24.93	12°24'25"	74°47'90"	18.61	0.9
85-08-01	15	00	28.08	12°18'37"	74°57'67"	25.00	2.3
85-08-01	15	17	39.77	12°24'19"	74°45'70"	12.81	2.2
85-08-01	17	49	22.39	12°21'42"	74°49'06"	21.59	2.7
85-08-01	18	00	10.44	11°59'33"	74°55'89"	05.56	1.0
85-08-01	18	16	46.82	12°25'50"	74°48'68"	19.65	2.2
85-08-01	18	23	48.68	11°46'66"	75°05'68"	5.04	2.0
85-08-03	4	02	17.83	11°55'88"	75°02'96"	4.82	1.6
85-08-03	7	33	16.11	11°46'75"	75°05'71"	5.74	1.9
85-08-03	8	43	05.79	11°46'70"	75°05'44"	4.38	1.9
85-08-05	1	31	08.04	11°53'41"	75°03'48"	7.92	3.8
85-08-05	2	15	06.70	11°53'24"	75°03'66"	7.32	1.4
85-08-05	3	30	04.92	11°52'84"	75°03'29"	5.17	1.7
85-08-05	9	17	12.22	11°47'58"	75°05'38"	5.90	2.0
85-08-05	15	46	43.39	11°47'71"	75°05'75"	7.30	1.7
85-08-05	16	17	23.52	11°53'01"	75°03'52"	4.16	2.3

(continued)

Table 2 (continued)

Yr Mo Da	Origin			Lat S	Lon W	Depth	Mag
85-08-05	18	18	53.31	12°21'85"	75°14'31"	19.93	2.1
85-08-05	18	50	16.95	11°52'36"	75°02'69"	1.29	1.0
85-08-07	11	01	55.74	12°11'23"	75°23'98"	33.93	3.5
85-08-08	19	14	03.47	11°49'64"	75°07'46"	1.93	1.8
85-08-09	12	24	09.95	12°20'80"	75°17'78"	7.18	2.5
85-08-09	15	19	32.57	11°59'92"	74°59'53"	4.64	1.8
85-08-11	9	24	13.94	11°52'38"	75°03'30"	1.00	2.2
85-08-11	21	56	53.99	11°52'21"	75°02'99"	0.41	1.8
85-08-12	4	04	33.98	11°53'08"	75°02'45"	8.93	2.3
85-08-12	9	42	30.58	11°42'96"	75°07'92"	0.80	1.0
85-08-12	10	52	28.32	11°51'15"	75°03'04"	7.73	1.5
85-08-12	15	47	56.69	11°46'81"	75°05'35"	5.14	1.6
85-08-12	20	11	14.18	11°52'56"	75°02'77"	2.94	2.7
85-08-13	21	22	48.38	11°53'04"	75°02'68"	4.11	2.1
85-08-15	11	15	53.35	11°50'82"	75°03'62"	4.87	2.0
85-08-15	15	30	20.43	12°16'79"	75°11'60"	9.15	1.8
85-08-16	6	20	17.71	11°45'86"	75°05'90"	4.45	1.1
85-08-16	10	50	40.64	11°50'91"	75°02'82"	4.88	1.8
85-08-16	11	45	32.89	11°52'74"	75°03'65"	1.74	2.2
85-08-16	18	37	00.89	12°09'39"	75°20'23"	9.97	1.6
85-08-17	2	08	37.39	11°40'12"	75°09'21"	2.38	0.9
85-08-17	2	17	46.48	11°45'13"	75°15'31"	8.13	1.5
85-08-17	5	05	00.31	11°45'46"	75°15'52"	8.17	1.1
85-08-17	5	12	06.77	11°46'68"	75°17'02"	5.99	1.6
85-08-17	23	23	38.45	11°52'89"	75°03'14"	4.80	2.0
85-08-18	1	18	19.55	12°08'66"	75°20'26"	9.21	2.2
85-08-18	23	08	48.93	11°49'53"	75°05'97"	17.75	1.2
85-08-19	2	16	57.78	12°10'00"	75°21'03"	5.04	1.3
85-08-19	3	13	26.84	12°03'16"	74°51'96"	4.57	2.2
85-08-19	20	04	54.73	11°51'57"	75°03'28"	4.42	1.8
85-08-20	12	05	02.52	11°56'38"	74°59'80"	4.53	2.3
85-08-21	8	06	03.80	11°56'66"	74°59'95"	7.41	0.9
85-08-22	11	47	12.77	12°13'79"	75°17'97"	4.83	2.1
85-08-22	16	33	30.57	12°13'00"	75°12'98"	11.38	2.3
85-08-22	22	57	11.49	11°47'88"	75°06'10"	12.77	1.0
85-08-24	8	01	08.59	11°49'89"	75°04'95"	6.14	0.9
85-08-24	13	59	53.61	12°05'83"	75°23'40"	5.14	2.9
85-08-26	21	38	36.57	11°46'23"	75°19'16"	7.42	1.5
85-08-27	13	35	10.40	12°26'68"	75°01'20"	10.46	2.8

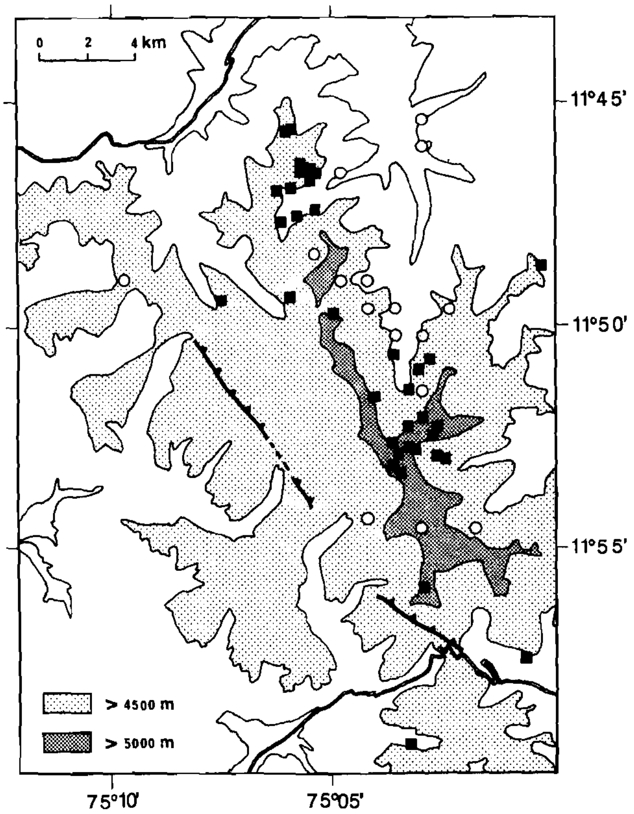

Fig. 5. Seismicity of the Huaytapallana region. Closed squares, epicenters from this study. Open circles, epicenters from Suarez *et al.* (in press) experiment. Thick solid lines are the Huaytapallana Fault segments after Blanc (1984). Triangles indicate the dip.

Huaytapallana Fault, an extension that has not been recognized up to now. Thus, it is difficult to predict the size of an eventual future earthquake there. In any case, according to the dimensions of the clusters, it may be at least as strong as the first one.

The Altos del Mantaro Fracture Zone

For the first time, to our knowledge, a noticeable and fairly well constrained crustal seismicity is registered underneath the Western Cordillera in the High Plateaux (Fig. 4). The quality of the locations suffers from the large distances to the nearest stations of our temporary network, but benefits from the proximity of the Huancayo Observatory whose data substantially increased the precision of the determinations. These events define a 40-km-long band, in a NW/SE direction, parallel to the Mantaro Basin. Their depths are poorly constrained but do not seem to exceed 15 km. All the epicenters lie to the west of the Altos del Mantaro Fracture Zone at a mean disance of 8 km. As the faults of this zone dip to the west, it seems reasonable to associate the observed seismic activity with the Altos del Mantaro Fracture Zone, which therefore appears to be a zone of actual active deformation. A careful examination of the Huancayo Observatory seismic bulletins since 1960 reveals a continuous activity in the S-P time range from 0 to 3.5 seconds. Since the corresponding distances range from 0 to 20 km, these events correspond to the Altos del Mantaro and there is no possibility of confusion with another seismic zone, such as the Huaytapallana Fault.

FOCAL MECHANISMS

Focal mechanisms of the Huaytapallana area are well constrained by a good distribution of the polarity data. Others, in particular those of the Pampas group, are poor. Thus, some of the focal mechanisms presented here are constructed not only from first motion data, but also taking into account structural observations such as direction and dip of the faults on the field.

We determined two fault-plane solutions for each Huaytapallana cluster. Those corresponding to the southern group show reverse faulting with left-lateral strike-slip motion on fault planes striking N320° and N330° and dipping 55° and 65° respectively (Fig. 4). These two mechanisms are quite comparable to that of the July 24, 1969 event. The P-axis is subhorizontal in the east/west direction and the T-axis is in the north/south direction. These orientations agree with the neotectonic observations of Sébrier *et al.* (1988). The two focal solutions for the northern group show a reverse faulting with a very slight or no strike-slip component. The values of the strikes and dips are close to those of the southern cluster: the P-axis is horizontal and trends N70°, the T-axis is nearly vertical. These mechanisms are similar to the solution proposed by Suarez *et al.* (1983) for the October 1, 1969 earthquake.

The fault plane solutions for the Pampas and Sacsacancha groups also correspond to reverse faulting with little or no strike-slip motion. The P-axes are along the east/west direction in general.

For the event to the southwest of the Mantaro Basin, we used additional information to obtain the solution presented here. One of the two nodal planes and the strike of the second one are well constrained by the polarities. The dip of this latter plane is free to vary within a large range of values. If we accept the general direction of the Altos del Mantaro Fracture Zone for the strike, then we can select this not well defined plane as the fault plane. Finally, we assigned a dip of 50° to the southwest to this plane according to the field observations previously described. The resulting mechanism is a combination of left-lateral strike slip and reverse faulting.

CONCLUSIONS

The Mantaro Basin is surrounded by two important active fault zones: the Altos del Mantaro Fracture Zone and the Huaytapallana Fault. The activity of the Huaytapallana Fault was already known, but this is the first time that numerous fairly well-determined epicenters have been found on the eastern flank of the Western Cordillera (Altos del Man-

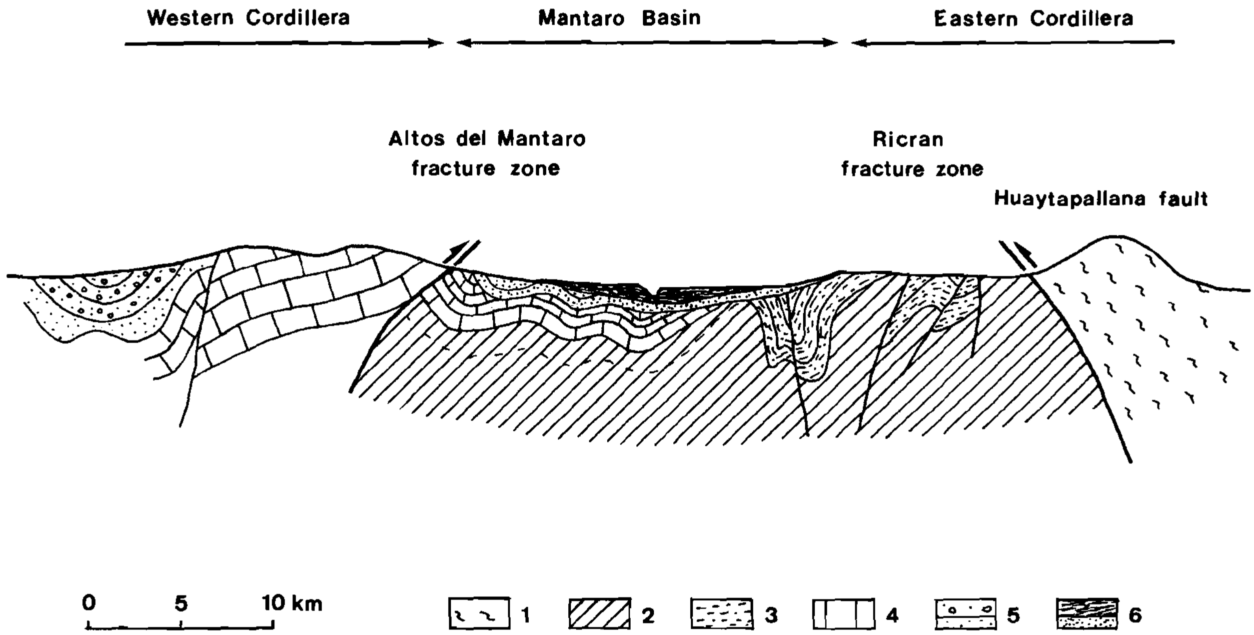

Fig. 6. Vertical cross-section through the Mantaro Basin from the Western to the Eastern Cordillera, in a N55° direction (modified from Mégard, 1978): 1, Precambrian; 2, Paleozoic; 3, Permian and Triassic; 4, Jurassic; 5, Cretaceous; 6, Quaternary.

taro). Some activity might also be associated with the Ricran Fracture Zone.

Most of the tectonic features discussed in this paper suggest a compressional state of stress with the principal compressive stress transverse to the axis of the chain. Focal mechanisms within the region indicate reverse faulting with a left-lateral strike-slip component, which may be small in some cases but dominant in others, according to the local orientation of the faults with respect to the stress tensor.

The cross-section in Fig. 6 summarizes our interpretation of the tectonics of the Mantaro Basin.

The comparison between the 1980 and the 1985 observations shows a noticeable migration of the activity of the Huaytapallana Fault (Fig. 5). Hypocentral determinations are precise enough to establish this fact. The 1980 clusters may be interpreted as foreshocks of the August 16, 1980 earthquake. The 1985 clusters, on the other hand, result from stress concentration at the extremities of the broken segments and may announce future continuation of the breaks.

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