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PLIO-QUATERNARY TECTONO-MAGMATIC ZONATION AND PLATE TECTONICS IN THE CENTRAL ANDES

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Seismic provinces in Peru and northern Chile may be defined in direct relation to the geometry of parts of Nazca plate that are being subducted under the Americas plate. Recent tectonism and calc-alkaline volcanism appear also to have a clear relationship to that same geometry of the subducted slab. Under northern and central Peru, the slab plunges at 10–15° to the northeast, and becomes almost horizontal farther east; at surface in the same region, recent calc-alkaline volcanism is absent and recent tectonics are mostly compressional. Under southern Peru and northern Chile, the slab plunges regularly at about 30° to the east; at the surface, calc-alkaline volcanism is still active and recent tectonism appears to be mostly extensional.

Au Pérou et dans le nord du Chili, on peut définir des provinces sismiques dont les limites correspondent à des changements dans la géométrie de la partie ouest de la plaque de Nazca en cours de subduction sous la plaque des Amériques. Il semble que la tectonique récente et le volcanisme calco-alcalin plio-quaternaire soient également liés à cette géométrie variable. Ainsi, sous le Pérou nord et central, la plaque de Nazca plonge à 10–15° sous la côte puis devient subhorizontale plus à l'est; à cette géométrie correspondent en surface une tectonique récente essentiellement compressive et une absence à peu près complète de volcanisme calco-alcalin récent. A l'opposé, ce volcanisme a été très intense et étendu dans le sud du Pérou et le nord du Chili au Plio-Quaternaire, il y est encore actif de nos jours; la tectonique récente y est essentiellement distensive; correlativement, la plaque océanique plonge régulièrement à 30° sous le continent.

1. Introduction

The study of the distribution of hypocenters and the focal mechanisms of the earthquakes has led to a rather accurate definition of the shape and dips of the Nazca slab that is presently being subducted under Peru and northern Chile [16,17,42,43,45,48].

These studies demonstrate that the geometry of the subducted slab is fundamentally different north of 13°S and south of 15°S so that one may distinguish a north and central Peruvian seismic province from a south Peruvian and north Chilean one [15,16,35,45, 50]; in between, one may define a transition zone (TZ) [6] that appears as a geographic discontinuity on both seismicity and strain release maps of Ocola [34] and on the diagram of seismic belts of western South America by Teisseyre et al. [46]. The latitude of the TZ corresponds to that of the juncture of Nazca ridge with the Peru trench; but on the continent, the TZ corresponds also to the Abancay deflection along which the Andean chain departs from its N30°W to N50°W mean trend and takes an east-west direction between latitudes 13°S and 15°S [12,25,2].

Under northern and central Peru, the subducted slab plunges first at a small dip of 10–15° under the Peruvian margin but 250 km to the northeast of the trench, it becomes quite horizontal (see Fig. 3, A_1) [43]. Under southern Peru, northern Chile and northwestern Bolivia the slab plunges uniformly at about 30° to the northeast (Fig. 3, B_1) north of 18°S, and 30–18° to the east farther south [48,43]. Under the TZ a contortion or even a tearing of the subducted slab can be postulated [16,37].

In the following paragraphs, we assume that the geometry of both decoupled parts of the subducted Nazca plate has been nearly the same during the last 5 m.y. and we examine the surficial tectonism and the magmatism of this recent epoch in order to determine whether or not they may be related to the above-defined seismic provinces. In doing so, we shall focus our attention on intracontinental phenomena and disregard the narrow belt of west-vergent overthrusts that lies under the lower continental slope and part of the upper continental slope all along the Peru-Chile trench. This belt is documented by seismic reflection profiling [18,37] and by the focal mechanisms of the shallow foci located under the continental slope [16, 35,43] and also, farther south in Chile, by surficial tectonics related to the earthquakes [38].

2. Regional analysis of the recent tectonics and magmatism

The study of recent tectonic features has been performed (1) by mapping structures that are kilometric to hectometric in size, and (2) by measuring the orientation and dips of the slickensides and of the striae they often bear and the vertical and/or horizontal offsets of the faults. The interpretation of the latter microstructures has been made using Arthaud's graphic method [1] which gives satisfactory results in most natural cases [3,4].

2.1. Central and northern Peru

In central Peru, most detailed neotectonic observations have been made (1) in the Huancayo and Junin basins carved in the high plateau that lies in the axis of the Andes of central Peru, and (2) farther east in the Eastern Cordillera (Fig. 1).

The data reported here have been collected by the authors and by J.P. Soulas; part of them have been published by the latter in Peru [41]. A relative chronology of the Quaternary deposits has been established in the Huancayo basin [10] where the early Quaternary lacustrine deposits of the Jauja Formation are followed by three younger terraces t''', t'' and t'. The Jauja Formation has been slightly deformed prior to the deposition of t''' that covers it unconformably; later both Jauja Formation and t''' have been folded into wide flat synclines and narrow NW–SE-trending anticlines [28,11,36] that veer longitudinally to flexures; the dips reach frequently 30° in the flanks of the anticlines and 70° in some flexures; some inverse northeast-vergent faults with a N20°W to N45°W direction are observed within the Jauja Formation and at its contact with the Mesozoic basement. Within the Jauja, two phases with an almost horizontal foreshortening direction "*z*" have been distinguished by microstructural analysis. "*z*" is trending N75°E for the oldest one and N6°E to N4°W for the youngest one; the oldest could be post-Jauja and pre-t''' and the youngest post-t''' and pre-t'' as t'' and t' remain undeformed. In this case, the huge NW–SE folds in t''' would represent the surficial response to strike-slipe faulting of the Mesozoic basement along NNW–SSE trends; this interpretation is supported by the right-hand "en échelon" setting of some of these folds along the southwestern border of Huancayo basin [41]. Some dispersed observations made on the northernmost outcrops of Huancayo basin t''' deposits, on periglacial deposits correlative of t''' between Jauja and Tarma and on deposits correlative of Jauja Formation in the southeastern end of the Junin basin show that the folding along NW–SE-trending axis is a widespread phenomenon.

In the Eastern Cordillera between 11°S and 12°30'S two recent faults have been studied. The Cayesh fault has a normal vertical offset of 8 m. It is 16 km long but is made of several segments, each of them several hundred meters to a few kilometers long, that trend N10°W to N30°W and are arranged in a left-hand en échelon pattern that could well fit in with a NW–SE foreshortening direction; the Cayesh fault cuts both basement rocks and moraines of the t'' epoch. East of Huancayo, the Huaytapallana fault moved during the July and October 1969 earthquakes; it has a N55°W trend and is an inverse west-vergent sinistral fault with a vertical throw attaining 1.6 m and an horizontal offset of 0.7 m [7]. The study of surficial metric-scale structures [29] shows that the foreshortening direction is about N65°E at the surface; that is to say about 30° farther east than the *P*-axis trend determined by Stauder [43] through the determination of the focal mechanisms of the Huaytapallana earthquakes. At the western border of the Eastern Cordillera, in the San Ramon area, old Quaternary conglomerates possibly correlative either of Jauja Formation or of t''' are tilted with dips up to

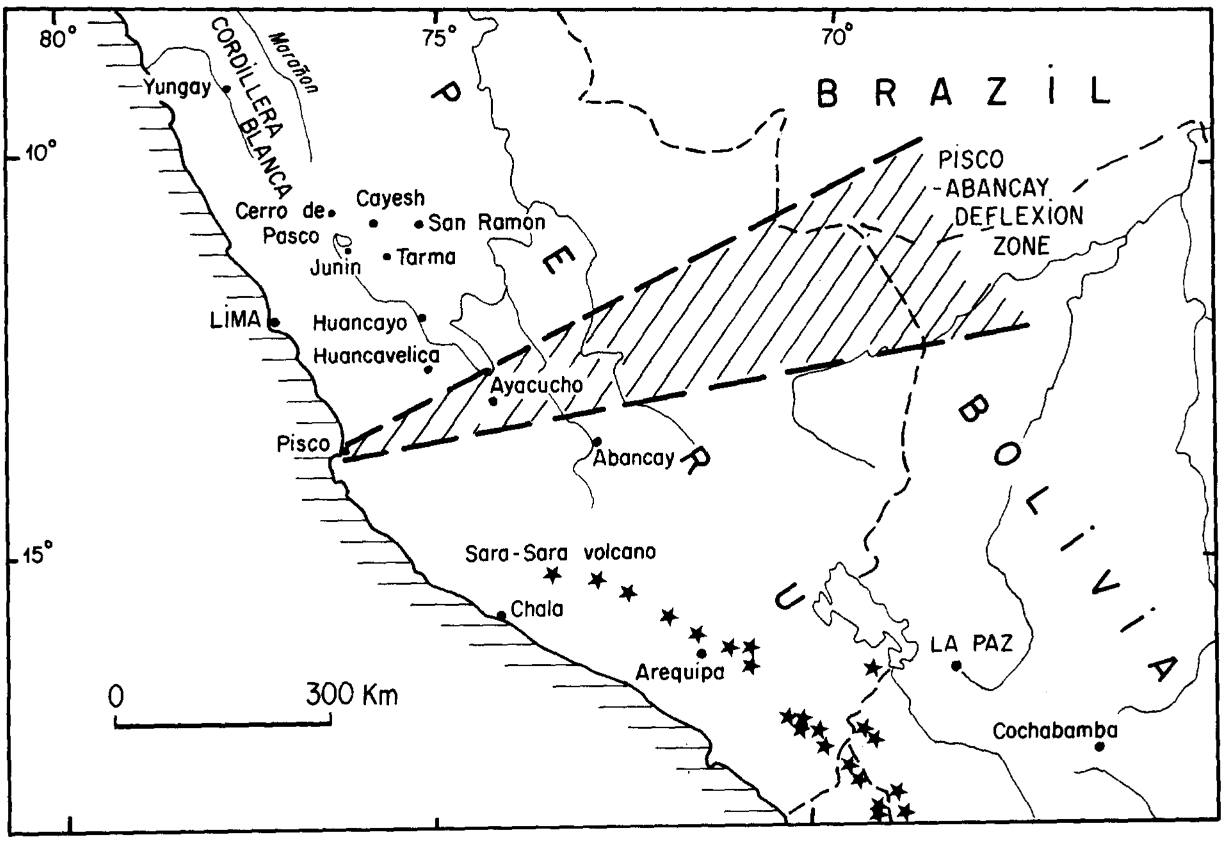

Fig. 1. Index-map of the localities mentioned in the text. The stars represent the recently active volcanoes.

70° and display many flat shear surfaces with N40°W-trending striae that are coaxial with "z".

In the coastal region of central Peru, one recognizes [10] old piedmont formations and gravel terraces correlative of t''' but they are nowhere extensively deformed; remarkable differences in thickness have been noted in these and in younger deposits so that the subsidence of some areas and uplift of others is likely to have occurred but the nature of the tectonic efforts that generates these apparently vertical movements is not known.

In northern Peru, neotectonic data are very scarce and restricted to the Cordillera Blanca district. On the eastern flank of this cordillera, the N44°W to N58°W-trending fault of Quiches has been active in 1946 [13]; it was inclined to the west and apparently normal and the maximum vertical displacement was 3.5 m. Nevertheless, the fault-plane solution given by Hodgson and Brenner [14] corresponds to a fault with a N45°W strike; but it dips northeast and has an almost pure strike-slip motion. The western flank of Cordillera Blanca has been considered for long as an exclusively normal fault at least 70 km long with a N40°W strike, that has been active at several epochs of the Quaternary and possibly earlier [47,5]. A survey of recent tectonics has been carried on both in the western border of the granitic batholith that forms the Cordillera and in the moraines of its western flank. Radiometric K–Ar ages of the batholith are bracketted between 12 m.y. and 2.7 ± 0.4 m.y. [44] and thus the observed deformation is uppermost Miocene to Recent in age. Two distinct phases of brittle deformation may be distinguished within the batholith: the first one involves almost pure inverse faulting along fractures dipping 60–80° to the southwest and west and a nearly horizontal strike-slip movement along N50°E to N95°E-trending fractures; the mean "z" is almost horizontal and its direction is about N70°E. The second phase involves north-vergent inverse faulting along N50°E to N75°E-trending fractures and horizontal displacements that are dextral for the faults with a northwest strike and sinistral for faults trending N15°W to N–S so that the mean "z" direction is about N35°W. A study of the faults that trend N40°W to N55°W and cut the t'' and t' and even the younger moraines shows an overall left-hand en échelon pattern of these faults at the scale of the cordillera and at a smaller scale. Along each individual fault segment one notes a normal offset of the topographic surface that may reach 60 m, with a downthrown southwestern block; this throw decreases towards the end of each individual segment until it is reduced to zero. Along the same fault segments, one observes also horizontal offsets that may amount to 20 m; when both horizontal and vertical offsets are observable along the same segment, the horizontal displacement exceeds the vertical one in 60% of the cases. Horizontal offsets are either left-hand or right-hand for individual segments whose trends differ by a few degrees. This fact points out that the "z" fore-shortening direction registered by faulting of the moraines is nearly identical to the trend of the faults, that is to say, is near to N35°W. The associated "x" extension direction would be nearly horizontal with an approximate N55°E trend; this is in line with the observed normal throws.

Despite the relative scarcity of the available data, it seems clear that most recent tectonics in central Peru and in part of northern Peru are compressive, that is to say related to an almost horizontal foreshortening. Nevertheless, two mean "z" directions are recorded: an older one that trends about N70°E and is transverse relative to the main features of the Andean chain and a younger one that is longitudinal and veers between N–S and N40°W. The first one is easy to relate with the almost N70°E-trending vector of convergence (Fig. 2) of the Nazca and America plates [30], not so the younger foreshortening direction whose origin is a major unanswered question.

No significant Plio-Quaternary calc-alkaline volcanism has ever been mentioned in Peru north of 14°S. The more recent volcanics in northern and central Peru appear to be acidic ash-flow tuffs and some "basaltic" flows. The silicic tuffs and ash-flow tuffs cover significant areas in the Cordillera Blanca region (Yungay, Rio Fortaleza), west of Cerro de Pasco (Bosque de Piedra) and north and east of Huancavelica; their K–Ar ages ([31], Farrar and Noble, unpublished manuscript) are late Miocene to earliest Pliocene (7–5 m.y.); a 2.8-m.y. age has also been determined for the Atunsulla welded tuff, located about 30 km west of Ayacucho [32]. According to Noble et al. [33], the "basalts" of Huari, 15 km northeast of Ayacucho, are low-Si latites 3.7 m.y. old; neither isolated manifestations of acidic tuffs nor of low-Si latites seem to be related in a simple way to the geometry of a sinking plate.

Anyway, these few volcanic outbreaks are in no way comparable in volume with the widespread and mainly calc-alkaline volcanism of Plio-Quaternary age present in the western Cordillera and in the Altiplano of southern Peru; the northern limit of this latter volcanism is approximately the 14°S parallel, and it coincides with the limit between the north-central Peruvian and the south Peruvian seismic provinces. This is shown clearly by Fig. 2.

2.2. Transition zone

Few neotectonic data have been collected in the transition zone. On the coast, normal faults with a mean N85°E strike predominate between 13°45′S and Chala [22]; the scarce striae have a pitch nearly equal to the dip of the slickensides [21] and imply a nearly vertical "z". Near Pisco (13°45′S) some NNW-trending normal faults that have been active during the Quaternary have been also mentioned [40].

In the Andes, recent vertical movement along the E–W-trending Abancay fault-system have been recorded [25]. However, the only intracontinental shallow earthquake studied in this region has a strike-slip mechanism with an almost horizontal E–W-striking P-axis [43].

Recent volcanism in the transition zone is restricted to the acidic ash-flow tuffs that cover the floor of some valleys in the Abancay-Andahuaylas region [25].

2.3. Southern Peru and neighbouring Bolivia

In southern Peru, some observations have been made in the coastal region by Lavenu and Soulas [22] and by the authors. All the recent faults display only normal throws. South of 14°S, these faults are grouped into two perpendicular sets with variable trends but the few striae that have been observed imply a vertical

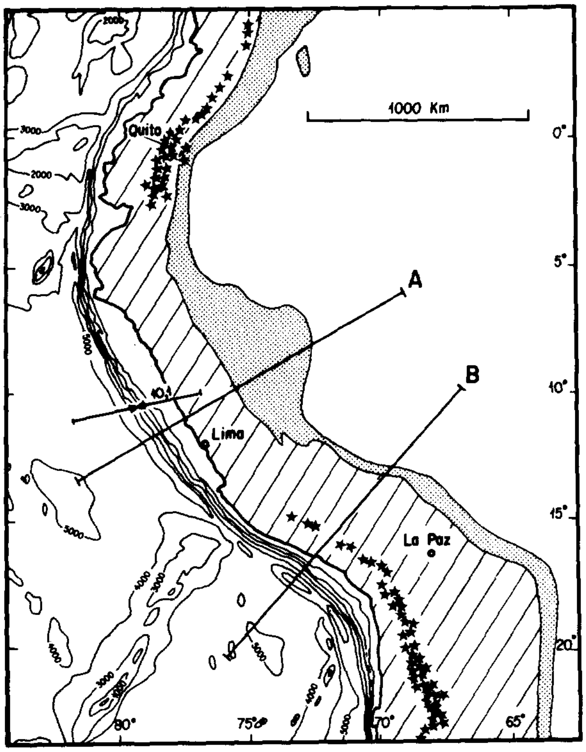

Fig. 2. Structural relations of the Andean and sub-Andean belts and of the recently active volcanoes with the Eastern Pacific. Depth curves in meters are after Gansser [J. Geol. Soc. 129 (1973) 93–131]. Arrows represent the convergent relative motion of the Nazca and America plates after Minster et al. [30]. Stars represent the recently active volcanoes. The solid lines pattern denotes the Andean belt and the dotted pattern the sub-Andean belt. Lines *A* and *B* denote the cross-sections of Fig. 2.

"z". Lavenu [21] has found in the late Pliocene ash-flow tuffs of Arequipa and Moquegua almost vertical faults without any marked preferential strike; all the striae are subvertical so that the movement is an almost pure vertical sliding with a very minor horizontal extension in every horizontal direction.

In the northern Altiplano of Bolivia, extension along NW–SE-trending normal faults is the dominant process during the Plio-Quaternary, although subordinate compressive processes are registered (1) just before the eruption of the 2.5 m.y. old Perez ignimbrite, and (2) just after the deposition of the lake Ballivian lacustrine strata of Pleistocene age [27]. This latter phase is recorded by strike-slip faulting with little horizontal displacement in these lacustrine beds.

In the Cochabamba basin of the Eastern Cordillera of Bolivia, lacustrine beds that might be Pliocene in age (Tomasi, map in preparation) were folded along N30°W-trending axis, before the deposition of the old-

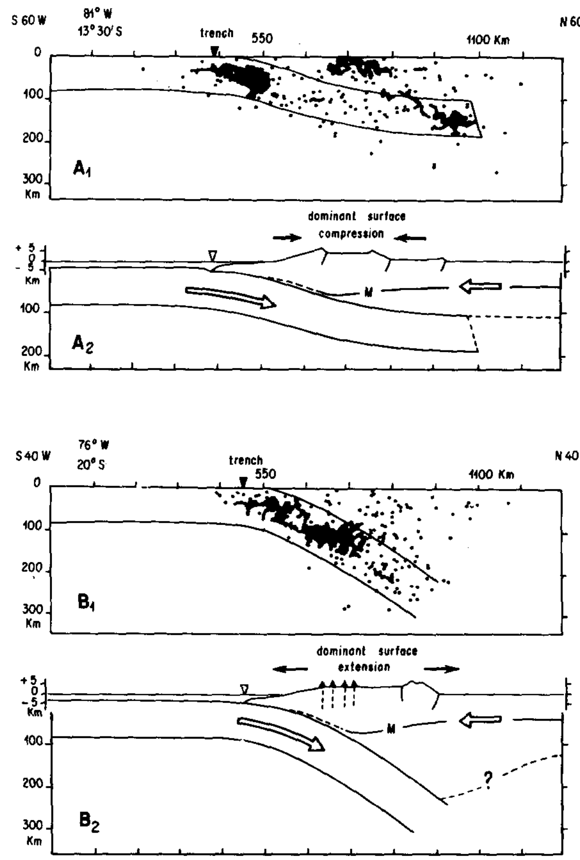

Fig. 3. Cross-sections along lines *A* and *B* showing the relations of Benioff plane geometry with surface structures. A_1 and B_1 show the location of hypocenters and correspond to the *D'* and *E'* sections of Stauder's fig. 8 [43]. A_2 and B_2 are interpretative sections along the same lines; in B_2, the black triangles at the surface represent active volcanoes. The dashed line under Mohorovičić (M) discontinuity denotes the approximate location of the lower limit of the American plate. The hypocenters located beneath the lower limit of the subducted slab in A_1 and B_1 are evidently anomalous. Their anomalous location might be due to the choice of the reference hypocenters in the joint hypocenter determination. Anyway, as pointed out by Stauder [43] in discussing Okada's model favouring a steeper dip for the plate [51], the arguments based in the type and distribution of the earthquakes support strongly the Isacks and Molnar's model adopted by Stauder and reproduced here.

est Quaternary moraine; later both the moraine and the lacustrine beds were deformed by normal faults with the same N30°W trend. On another hand, Kussmaul (in [26]) correlates the Plio-Quaternary volcanism of the Chile-Bolivia border with the opening of fractures with preferential N–S, E–W, NE–SW and NW–SE strikes.

A comparison of these data with the focal mechanisms of present shallow earthquakes under the Andes is not possible due to the lack of published information. In sharp contrast with central and northern Peru, Upper Pliocene and Quaternary calc-alkaline volcanism is well developed in southern Peru and western Bolivia. The most recent volcanic belt is still partly active and builds a concave arc that is parallel to the Peru-Chile trench at a distance of about 250 km to the northwest or west of it; the northernmost end of this belt is the Sarasara volcano, located at 15°19'S and 73°28'W. In southern Peru there is a clear zonal disposition of the Quaternary lavas parallel to the trench; the rocks nearer to the trench belong to a calc-alkaline suite and the more distant are shoshonitic [23]. There is an evident spatial relationship at least between the calc-alkaline series and the plunge of the Benioff zone, even if these rocks do not generate directly from the melted uppermost part of the subducted plate [19,20,39].

The situation in southern Peru and northern Bolivia is shown in a schematic way in Fig. 3, B_2.

3. Conclusion

The striking differences of the geometry of the subducted Nazca plate under Peru to the north and to the south of a transition zone located at about 15°S are clearly reflected during the Plio-Quaternary in the volcanic activity and, to a lesser degree, in the tectonic behaviour of the corresponding parts of the continent. To the flat and relatively shallow subducted slab present north of the transition zone correspond a lack of recent and active volcanism and mostly compressive neotectonics (Fig. 3, A_2). On the contrary, to the slab that dips regularly at about 30° to the northeast that is present south of 15°S, corresponds a well-developed Plio-Quaternary volcanism and dominantly extensional recent tectonics (Fig. 3, B_2).

One wonders of course if these "rules" are likely to be extended to other segments of the Andes. A similar change occurs actually at about 2°S: north of this latitude, the subducted slab recovers a regular 30° dip to the east and a dominantly calc-alkaline volcanism reappears in Ecuador and southern Colombia. South of Peru, in northern and central Chile, the facts are more complicated: at about 26°S, the 30–18° east-dipping Benioff zone present under northern Chile passes newly to a flat Benioff zone [42,48]; concurrently the recent volcanism stops between 25°S and 33°S. South of 33°S, it reappears, despite the flatness of the relatively shallow Benioff zone; but the eastern shoshonitic belt that is well-developed north of 25°S [23,49] is entirely lacking here and the contents of large-ion lithophile elements and of rare earth elements in the calc-alkaline suite are much lower and are more similar to the ones of the average circum-Pacific andesites [24]. Thus it seems that the dip of the Benioff zone is not always the predominant controlling factor of the calc-alkaline volcanism.

As regards neotectonics, we lack detailed studies that would allow a comparison with either Chile south of 26°S or with Ecuador and Colombia north of 2°S. Anyway, if the correlation of the Benioff plane geometry with predominant compression or predominant distension in the overlying continental plate is valid, it involves evident and important consequences for the understanding of the compressive processes that generate Andean-type orogens, that is to say orogens exclusively related to the subduction of an oceanic plate under a continental one.

One may also try to generalize this correlation to older epochs and particularly to the Pliocene. Then one notes that the area where the Pliocene compressive phase extended the farthest to the west is the one lying between 2°S and 14°S, where the sub-Andean belt of folds and upthrusts is wider than either to the north or to the south and involves apparently a large foreshortening (Fig. 2). This could be interpreted as an evidence in favour of a flat Benioff zone under this region in Pliocene times.

The nature of the relation of the dip of Benioff zones with surface tectonism and with magmatism is a further problem. As regards surface compressional tectonics, one may think that a larger friction energy is created at the contact of both plates under continental slope and coastal area in the case of a flat Benioff zone, because this geometry of subduction implies a larger friction surface; part of this energy would be transferred to the continental plate farther east and cause both shallow earthquakes with a nearly horizontal *P*-axis and predominantly compressional surface tectonics. If one accepts that calc-alkaline arc volcanism is either a direct product of the melting of part of the subducted slab or the result of a release of water from the subduction zone that causes the melting of part of the upper mantle above, then the temperature distribution in and around the subducted slab should be the main controlling factor. This factor depends obviously on the dip of the Benioff zone and on the length of the plate [8,9]. In the case of a flat Benioff zone, melting of the sinking plate would be prevented both by the closeness to the colder continental plate and by the relatively shallow depth attained by the sinking oceanic lithosphere. Exceptions to this correlation "rule" might be related to other factors able to influence the temperature distribution in the sinking slab; these factors would become the determining ones in some particular cases; in Chile for example, one is tempted to correlate in some way the thinning of the continental plate southward with the new onset of calc-alkaline volcanism south of 33°S, in an area where the Benioff zone is extremely flat.

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