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Plio-Quaternary vertical motions and the subduction of the Nazca Ridge, central coast of Peru

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ABSTRACT

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The coastal region of south-central Peru displays raised marine terraces indicating that, unlike the central Peruvian coast, it underwent a strong uplift since the Late Pliocene. These recent vertical movements, which were probably the most rapid motion experienced along the Pacific coast of South-America, are commonly considered to be closely related to the subduction of the aseismic Nazca Ridge. However, several questions regarding the geometry and the precise mechanism(s) responsible for this deformation have not yet been fully addressed.

The kinematic constraints of the Andean convergence suggest that the deformation of the coastal area between Pisco and Lomas is characterized by a quite continuous sequence of uplift events progressing southwards. In spite of some difficulties encountered in precisely dating the uplifted Quaternary terraces and other remnants of Pliocene marine platforms, it is proposed that uplift rates during the Late Pleistocene reached maximum values of the order of 700 mm/10^3 y (as against a recently proposed estimate of 470 mm/10^3 y). The reconstructed finite deformation as recorded by the study area for the last 3 Ma presents a NW–SE-oriented, asymmetric dome-shaped pattern. It is emphasized that the strongest uplift has been occurring immediately south of the inland projection of the Nazca Ridge, and not along the ridge axis as envisioned by the previously constructed physical models.

Introduction

A decrease in seismic activity, an inhibition of arc volcanism and coastal geomorphic modifications are reportedly the main effects of the subduction of aseismic ridges (Vogt et al., 1976; DeLong and Fox, 1977; Nur and Ben Avraham, 1981). In most cases, these effects are considered to be associated with a relative slab buoyancy produced by density contrasts between the ridge-bearing slab and the surrounding lithosphere (Keheller and McCann, 1977). While the inhibition of arc volcanism is explained by the disappearance of the asthenospheric wedge which induces partial melting (Barazangi and Isacks, 1976), neither the diminution of seismic energy release nor the striking forearc deformation have been modelled accurately. This paper reviews some problems encountered in two models previously proposed for the coastal deformation associated with the subduction of the Nazca Ridge, in the light of the kinematics of plate convergence and of recent data on Quaternary marine terraces.

Andean subduction and the Nazca Ridge

Since Mesozoic times, the geodynamics of the Peruvian Andes has been controlled by the subduction of the oceanic (Nazca-Farallon) plate beneath the continental South-American Plate (James, 1970; Dewey and Bird, 1970; Mégard,

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1978). The Nazca Ridge is a major, 250-km-wide, aseismic and volcanic bathymetric high, which reaches more than 1.5 km above the surrounding ocean floor, and it is being subducted between 14° and 16°S (Schweigger, 1947; Rüegg, 1962; Fisher and Raitt, 1962; Mammerickx et al., 1975)

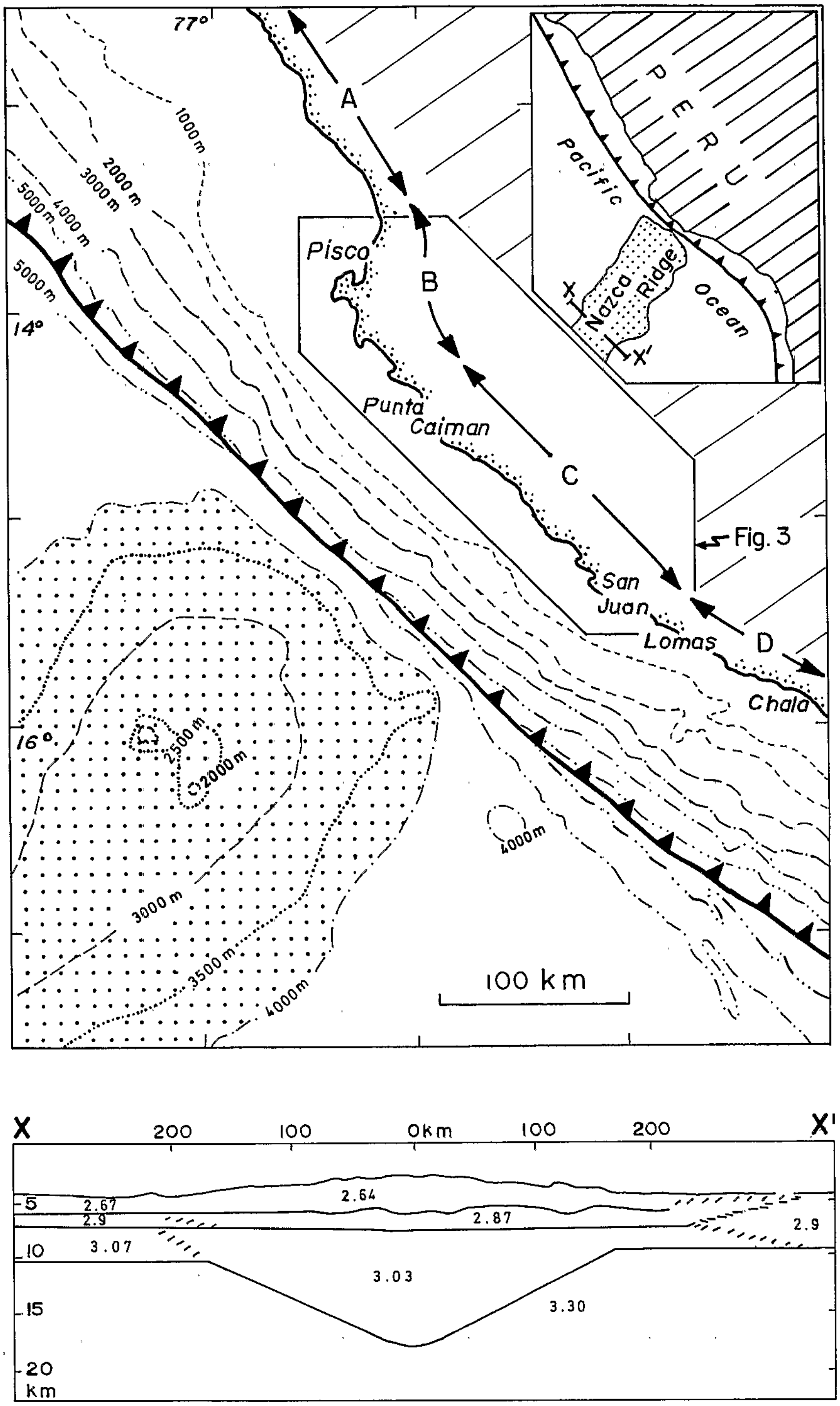

Fig. 1. Bathymetry of the Nazca Ridge and adjacent continental margin (contour interval every 1,000 m), after Prince et al. (1980). The heavy jagged line is the trench. *A* to *D* refer to four coastal segments with distinct tectonic behavior (see text). Below, is shown the crustal structure across the Nazca Ridge, with density distribution (simplified after Couch and Whitsett, 1981).

(Fig. 1). The distribution of gravity anomalies through the ridge indicates that its relief is compensated by a crustal root about 10 km thick (Couch and Whitsett, 1981) (Fig. 1). Several tectonic and magmatic effects of the subduction of the Nazca Ridge have already been recognized. They include the cessation of the Cenozoic arc volcanism to the north, a lowering of the seismicity level (Barazangi and Isacks, 1976; Mégard and Philip, 1977; Noble and McKee, 1977; Cross and Pilger, 1982), and a major coastal uplift which we further discuss below.

Attempts at modelling the coastal deformation

Qualitative hypotheses on the influence of the Nazca Ridge upon onshore geology have been proposed by Rüegg (1962) and Teves (1975). More recently, two quantitative models attempted to explain the coastal uplift as an effect of the subduction of the Nazca Ridge. The first one is a simple geometric model based on the "similarity" between the longitudinal topographic profile along the 14° to 16° sector of the Coastal Cordillera and the bathymetric profiles across the Nazca Ridge (Hsu, 1988). This model assumes that the topography of the forearc region expresses the form of the subducted part of the ridge. It thus implies that the flexural rigidity of the overriding plate is negligible and that deep-rooted vertical, normal faults transverse to the margin should accomodate the deformation (Fig. 2A).

Moretti (1982) tested a static physical model that considers the Nazca Ridge as a density heterogeneity which induces an upward stress field of 0.35 kbar on a 200 × 400 km rectangular-shaped surface below an elastic homogeneous continental plate (Fig. 2B). With the assumption that the upper plate is thick, rigid, and completely emerged, Moretti's model predicts an oval dome-shaped uplift of more than 800 m but which involves a much wider area (600 km along the trench strike and 600 km landward) than that observed in the field (Fig. 2B). This calculation is improved by taking into account the submerged continental edge with a minor flexural rigidity, thus the calculated anomaly would extend over 500 km along the coast and reach a maximum height of 1,100 m. The outputs of this model appear strongly dependent on two parameters: the ridge width and the flexural rigidity of the overriding plate.

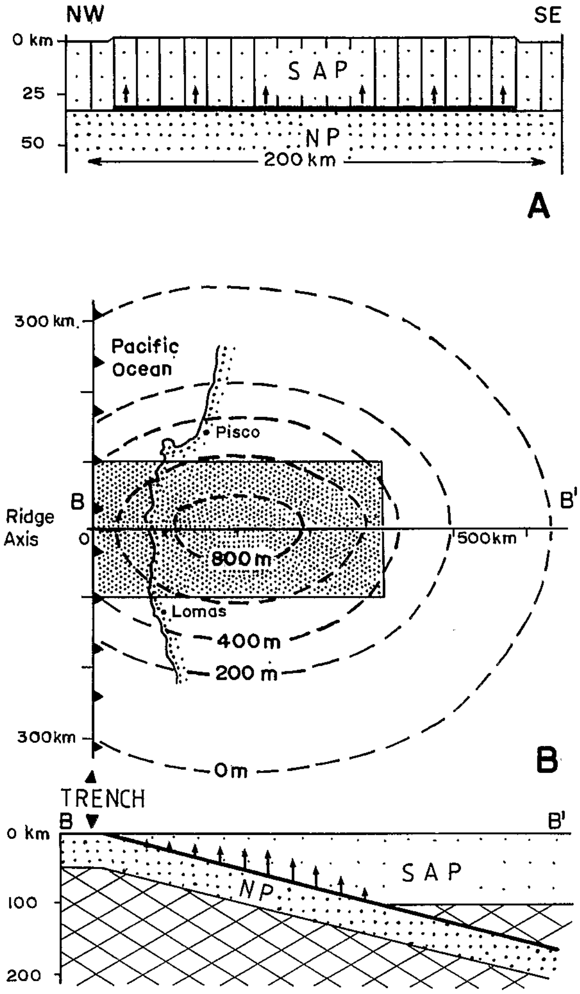

Fig. 2. Two previously proposed models for the forearc deformation involving the Nazca Ridge subduction: (A) after Hsu (1988), and (B) after Moretti (1982).

(A) NW–SE crustal section along the Coastal Cordillera showing the deformation of the topographic surface, according to Hsu's model (1988). *SAP* = block-faulted overriding South American Plate; *NP* = subducted Nazca Plate with the trapezoidal Nazca Ridge on top (in black).

(B) Horizontal projection and cross-section, according to Moretti's model (1982). In the sketch map, the shaded area is the upward-pushing part of the Nazca Ridge, and the dashed lines are contours of equal uplift. In the section, *SAP* is the elastic South American Plate, and *NP* is the Nazca Plate with the Nazca Ridge in black; the hachured zone is the asthenospheric "liquid".

Considering the differences in their conceptual bases, these two models deserve closer examination in the light of available geological and geophysical data.

Coastal deformation along the Pisco-Lomas region

The region affected by the subduction of the Nazca Ridge extends more than 200 km along the Peruvian coast from Pisco to Lomas (Fig. 3). From late Eocene to Pliocene times, this region was the site of development of the Pisco forearc basin (Petersen, 1954; Newell, 1956; Rüegg, 1956; Macharé, 1987). Since the Late Pliocene, the stratigraphic record and the geomorphic evolution (sequential westward shifts of the shoreline) indicate the emersion of the Pisco basin and differential uplift movements. These phenomena should be related to the last pulsation of Andean

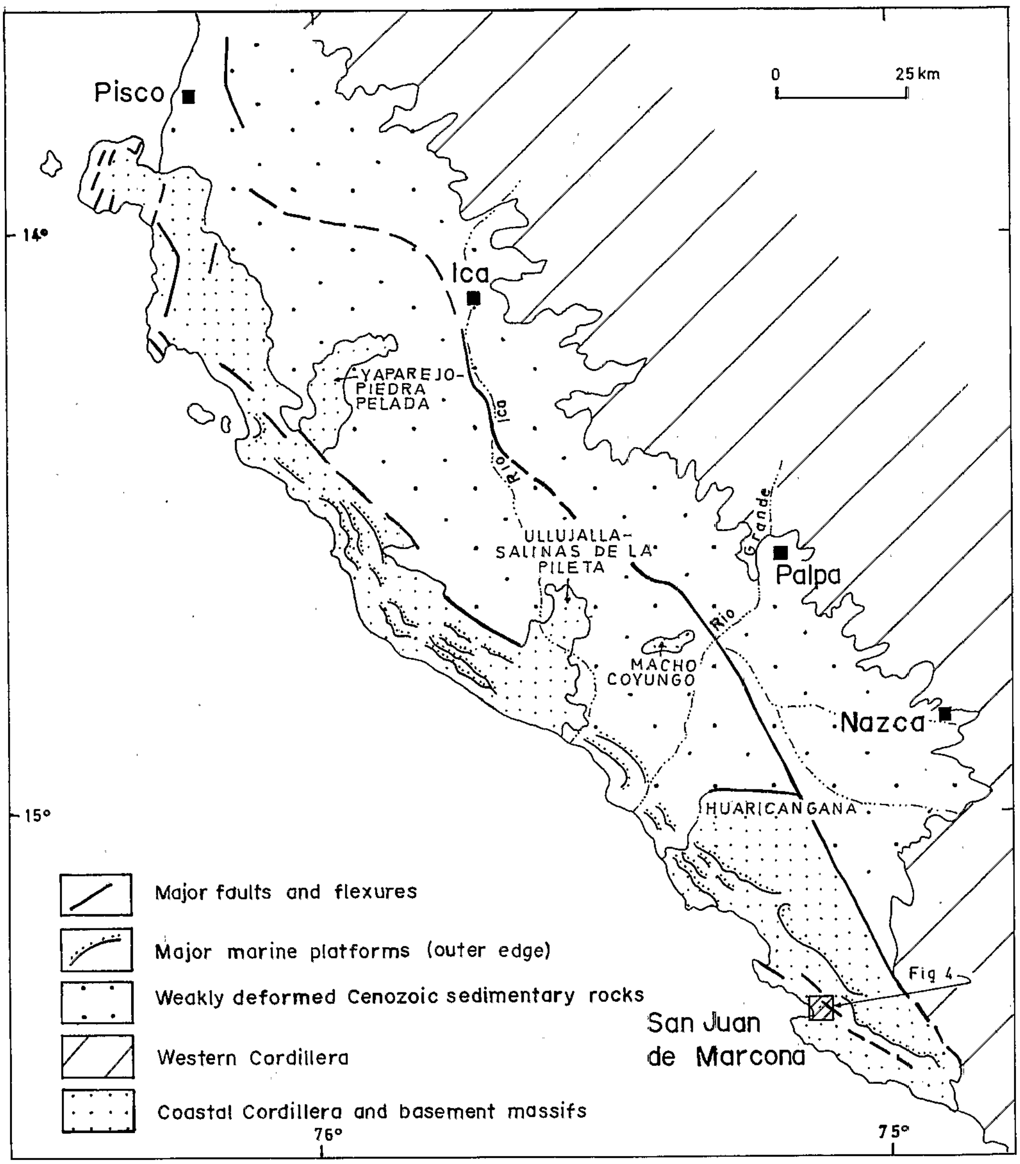

Fig. 3. Tectonic sketch map of the Pisco Basin region, with main morphostructural units, major faults, and distribution of the major Late-Cenozoic marine platforms (see text).

compression and uplift (Sebrier et al., 1985, 1988), and specially to the arrival of the Nazca Ridge at the subduction front, offshore of the study area.

Regional tectonic setting

The main morphostructural zones of the study area are represented in Figure 3. These comprise, from east to west: (a) the foothills of the Western Cordillera which recorded the maximum reach of Cenozoic seas; (b) a longitudinal trough created by Quaternary compressional tectonic activity; (c) elevated plains lying at 600–700 m altitude upon Tertiary marine basinal sediments; and (d) the Coastal Cordillera, a discontinuous range of hills composed of pre-Cenozoic rocks and reaching 1,000 m altitude.

The Coastal Cordillera constituted, during the Tertiary, a structural high to the east of the Pisco Basin. In Quaternary times, this zone was subjected to differential uplift, as revealed by large sequences of Plio-Quaternary marine platforms (Broggi, 1946; Legault, 1960; Teves, 1975, Macharé and Huamán, 1982; Hsu, 1988).

The present-day distribution of coastal features in the study area allows us to recognize four zones from northwest to southeast, that are useful in interpreting the recent regional tectonic history (Fig. 1):

(1) In zone A, where the coastal plain is very narrow, the Coastal Cordillera is absent and Pleistocene marine terraces are not developed. This coastal area has not been uplifted and may have actually subsided during the Quaternary. These characteristics extend northwards to latitude 7° S (Sébrier et al., 1982; Macharé et al., 1986; Devries, 1986, 1988; Ortlieb and Macharé, 1990a).

(2) In zone B which is separated from zone A by a westward shift of the Pacific shoreline, the Coastal Cordillera is represented by discontinuous, fault-bounded, low-relief massifs. Only a few remnants of partly-eroded marine terraces (Middle Pleistocene?, as envisioned by Hsu, 1988) have been observed. This zone seems to have undergone an Early-Pleistocene uplift event, followed by more recent subsidence.

(3) In zone C, the Coastal Cordillera displays significant relief with flat summits reaching 1,000 m above present mean sea level (MSL). Quaternary marine terraces are well preserved and commonly developed in a staircase morphology. Latest Pliocene-Early Pleistocene terrace deposits are found at up to ca. +800 m. The northernmost occurrence of the terrace formed during the last interglacial highstand is reported to be located at Punta Caimán (Fig. 1) (Hsu, 1988). Zone C can be considered as that of maximum uplift along the whole Peruvian coast.

(4) Zone D extends to southern Peru, and is characterized by a well-developed Coastal Cordillera where the highest Pleistocene shorelines reach about 250 m above MSL.

Morphology and geology of the terraces

The Quaternary marine terraces of the Pisco-Lomas coastal segment generally correspond to staircased platforms eroded onto the Pacific slope of the Coastal Cordillera. The bedrock is mainly composed of Paleozoic and Mesozoic igneous or metamorphic rocks, and less commonly of Tertiary sedimentary rocks (Macharé, 1987). In favourable places, the platforms may be quite extensive (several km wide); however, they are morphologically and sedimentologically distinct from the wide marine terraces of northernmost Peru, known as "tablazos" (Devries, 1986, 1988). The preservation of the marine platforms from subaerial erosion, which is much better than in numerous other intertropical areas, is a direct consequence of the general aridity that prevailed along the coast in the Quaternary (Ortlieb and Macharé, 1989). Eolian deflation – not rainfall and runoff – has been the main erosive agent, and has had a limited effect on the emerged marine platform's morphology.

The depositional sedimentary cover of the terraces is generally very thin (typically less than 1 m), and consists in conglomerates and sandstones with variable amounts of marine invertebrate shell material. These sediments were deposited in nearshore, or sublittoral, environments, shortly after the transgressive maxima coeval with interglacial (or interstadial) stages.

In the south of the study area, the emerged Quaternary coastal sediments cannot be described as typical terrace deposits but rather correspond to beach ridge sequences. In this case, the sand and/or shingle accumulations are thicker and less fossiliferous. These regressive deposits postdate the abrasion surface on which they rest, and cannot be correlated with high seastands. For these reasons, they are less suitable for chronostratigraphic and neotectonic studies than marine terraces which often record the maximum position of high sea stands.

The terrace remnants are not continuous along the coastal region. This is partly due to the heterogeneities of the substrata and to their varying capabilities to develop and preserve these coastal landforms (Hsu, 1988). Therefore, the marine terraces appear in discontinuous sequences which require correlation to determine the style, magnitude, rates, and timing of the deformation.

Methodological approach for marine terrace studies

Morphostratigaphic studies of emerged marine terraces aim at determining whether the staircased platforms recorded global (climatically induced) sea-level variations combined with regular uplift, or if instantaneous (coseismic?) rapid motions also occurred, and finally, what the uplift rates through time have been. However, these objectives can only be fulfilled for the Late Quaternary, or at most for the last two or three climatic cycles.

It remains difficult to identify precisely the remnants of every high sea-stand of the Early Pleistocene (1.8–0.7 Ma) and of the early part of the Middle Pleistocene (0.7–0.15 Ma). The presently available geochronological methods for coastal deposits only apply to the Late Pleistocene (150–10 ka) and latest Middle Pleistocene (isotopic stages 7 and 9). The older paleoshorelines can only be tentatively correlated with the global sea-level fluctuations deduced from the isotopic climatostratigraphy elaborated on deep-sea core data (Shackleton and Opdyke, 1973, 1976; Chappell, 1974, 1983; Imbrie et al., 1984; Martinson et al., 1987; Williams et al., 1988).

Furthermore, reconstructions of sea-level evolution through time also imply assumptions regarding the former position of the geoid during each highstand. Some detailed paleoceanographic and geomorphic studies show that the sea level has been slightly above the present datum during three of the four last interglacial maxima (isotopic stages 5, 9 and 11) and probably below present MSL during the remaining Middle-Pleistocene high stands (Shackleton, 1987; Ortlieb, 1987).

For Pliocene times, there are still more uncertainties regarding the precise age of the highstand periods and the position of the paleo-sea level during these high stands.

Terrace age and uplift rate estimates in San Juan Marcona area

Since the precursory work of Broggi (1946), the San Juan de Marcona region, with its well-developed series of terraces, has become a key area for the assessment of recent vertical deformation of the Peruvian coast. The most spectacular sequence of marine platforms is found on the southwestern flank of Cerro el Huevo, east of San Juan de Marcona (Fig. 4) (Broggi, 1946; Atchley, 1957). However, there remain some doubts in the time correlation of the youngest terraces, and consequently in the estimation of the local uplift rates (see recent discussions in: Hsu, 1988; Hsu et al., 1989; Ortlieb et al., 1990; Ortlieb and Macharé, 1990a,b; Goy et al., 1990).

According to an early study of the San Juan de Marcona terraces (Atchley, 1957, cited in Legault, 1960), the mollusc fauna from the uppermost terrace, found at +780 m, would be identical to that found on lower terraces and on present-day beaches. On this basis, Teves (1975) interpreted that the whole terrace system should be assigned to the Quaternary. A subsequent revision of the Atchley collection (J. Terry-Smith and T. DeVries, pers. commun., 1985) and new collections on distinct terraces by Macharé and DeVries, led the latter to confirm a Pleistocene age for most of the San Juan de Marcona terraces, but they proposed that the fauna of the oldest and highest elevated one should be assigned to the latest

Pliocene (Macharé, 1987). Thus, it is assumed that the coastal sediments now found at +780 m are close to the Plio-Pleistocene boundary (2–1.8 Ma old?). This age estimate leads us to calculate a local mean uplift rate of the order of 400 mm/10^3 y. This value corresponds to a net uplift rate, which of course may not have been steady.

For the study on the youngest and lower terraces of the area, two distinct chronostratigraphic approaches have been followed by recent workers. A first one (Macharé, 1987) focussed on geometrical considerations and correlations with the global variations of sea level as recorded by the deep-sea core isotopic curves (Shackleton and Opdyke, 1973; Imbrie et al., 1984; Shackleton, 1987). Such a correlation of the lower 15 terraces of the Cerro el Huevo sequence (Fig. 4) with the main peaks of the oxygen-isotope curves of deep oceanic cores lead Macharé (1987) to propose age estimates for each terrace below 360 m, and to calculate a hypothetical mean uplift rate of about 700 mm/10^3 y.

Through another approach, Hsu (1988; Hsu et al., 1989) used distinct chronological methods to try to assess the age of the lower terraces in the San Juan de Marcona area. After some hesitation

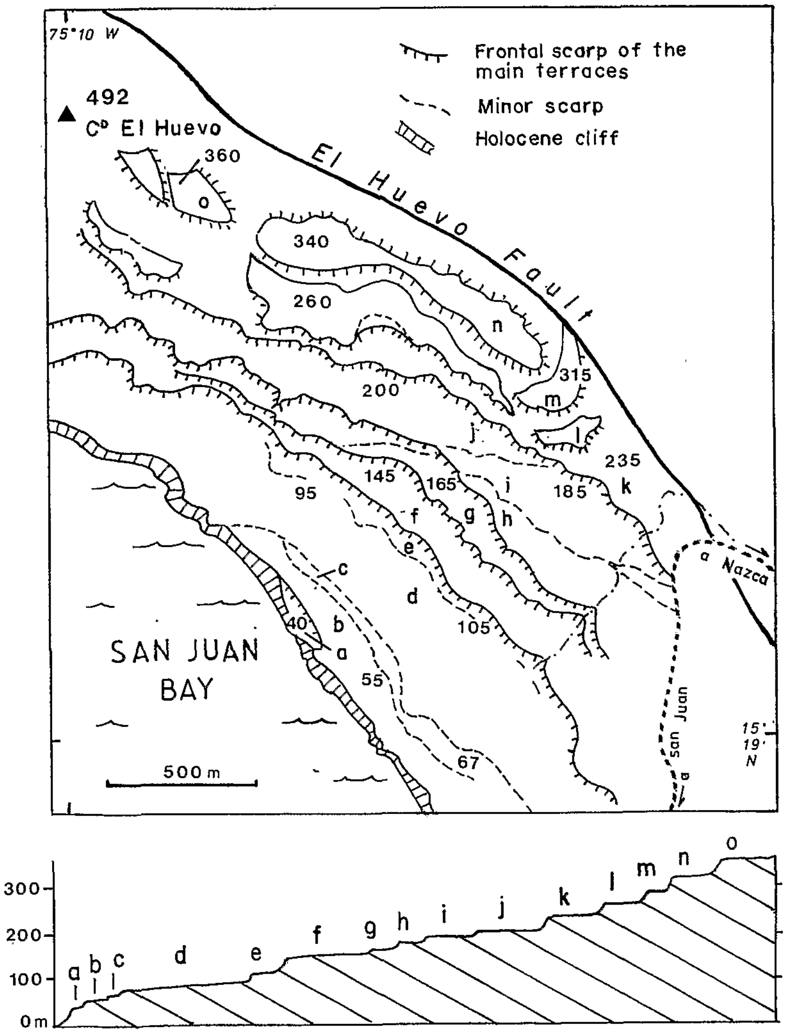

Fig. 4. Simplified morphological map and composite cross-section showing the lowest-lying (Middle and Late Pleistocene) marine terraces at Cerro El Huevo (San Juan de Marcona area). Numbers indicate elevation in meters above MSL of the paleo-shorelines (inner limit of the marine platforms).

as to which terrace was formed during the last interglacial maximum (isotopic substage 5e, 125 ka) (Hsu and Bloom, 1985; Hsu and Wehmiller, 1987), this author intepreted that the +65-m terrace in the Cerro el Huevo sequence should be correlated with the 125 ka highstand (Hsu, 1988; Hsu et al., 1989). This hypothesis relied heavily on an aminostratigraphical interpretation itself based on a few Th/U and ESR (electron spin resonance) age estimates and on inter-regional comparisons of amino-acid racemization data between California and southern Peru. According to this interpretation, the maximum uplift rate observed in the Cerro el Huevo area would have been about 470 mm/10^3 y for the last 0.5 Ma.

Several inconsistencies in the aminostratigraphic results, the absence of a true calibration on sound radiometric data, and various geomorphic evidence, lead us to contest the chronological model proposed for the regional aminostratigraphy, and Hsu's chronostratigraphic interpretation of the lower part of the Cerro el Huevo sequence (Ortlieb and Macharé, 1990b). A new detailed morphological analysis strongly suggests that the 5e high-stand remnants are located at a maximum elevation of +105 m (Fig. 4). Geometric relationships between shoreline remnants in the San Juan de Marcona area, and some morphological features (minor scarps represented in Fig. 4) indicate that episodic, local, tectonic deformation has been occurring beside the regional uplift motion (Ortlieb and Macharé, 1990b). A calculation of the net maximum uplift rate, which integrates the regional uplift motion and the minor local deformation at Cerro el Huevo, yields a 700 mm/10^3 y value for the Late Quaternary (last 130 ka). On-going research which takes into account paleo-sea level reconstructions during the last few interglacial maxima tends to imply that the net local uplift rate has generally been increasing through time in the Middle-Late Pleistocene.

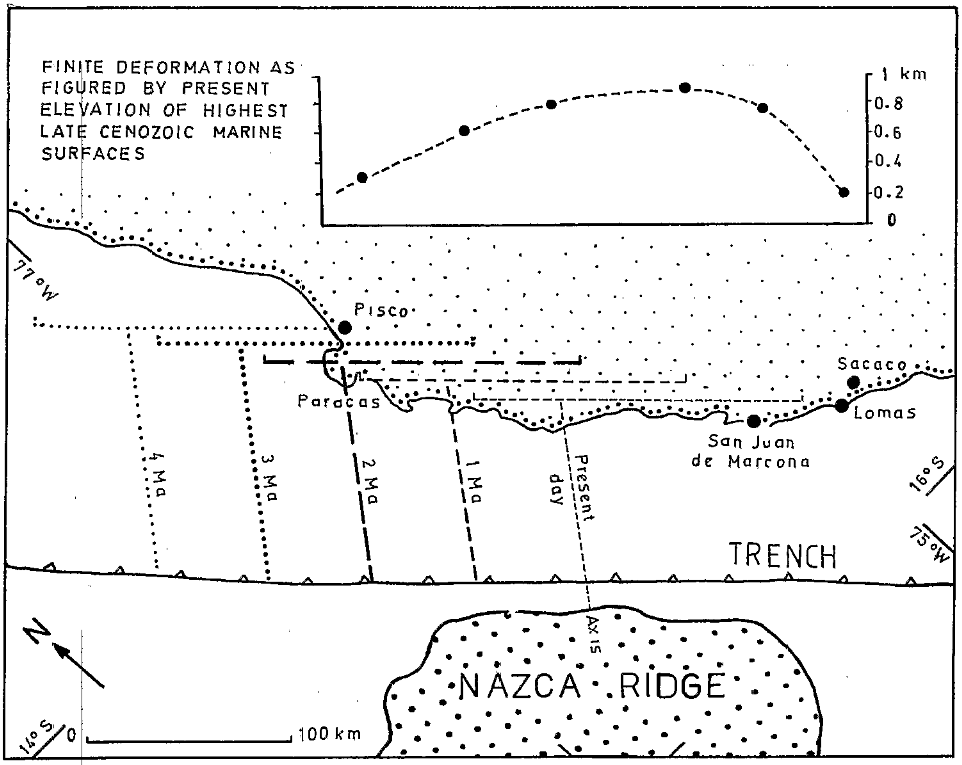

Fig. 5. Hypothetical reconstruction of the successive positions of the Nazca Ridge axis and indication of the affected inland area. In inset is plotted the present-day elevation of the highest Plio-Quaternary marine surfaces surveyed in the coastal region below. The asymmetrical dome-shaped curve represents the net deformation recorded in the study area.

Pattern of the deformation

The geometrical distribution of the highest marine surfaces eroding the Coastal Cordillera, should be useful in interpreting the pre-Quaternary longitudinal deformation recorded by the study area. The main difficulty encountered in this task is that these old abrasion surfaces formed during the last marine invasions that encroached into the Pisco Basin, are diachronous. This diachronicity has been established in the few sections where Late-Cenozoic (Pliocene to Pleistocene) sediments were exposed and dated (Muizon and DeVries, 1985; Macharé, 1987). In a few localities, it seems that remnants of some of these surfaces could be as old as Upper Miocene. Nevertheless, by trying to take into consideration these age differences, we propose an elevation vs. latitude plot of these well-developed surfaces (Fig. 5). This plot displays an asymmetrical parabola-shaped deformation pattern along the coast. The asymmetrical character is partly due to the fact that the northern slope actually reflects late subsidence superimposed on a previous uplift episode, while the maximum net uplift is observed ahead (southward) of the projection of the migrating ridge axis (presently located near Lomitas, south of Punta Caiman, Fig. 1).

The strong uplift decreases rapidly from the coastal zone to 60 km inland, where the effect of the subducted ridge seems to disappear. This deformation comprises slight block tilting (0.5% for the central plateaus) and important slip motions along major reverse faults trending parallel to the forearc (Fig. 3), similar to those which define the western boundary of the Ica-Nazca Trough (Macharé and Sébrier, in prep.). However, there is no evidence that these faults have been active after the Early Pleistocene.

An additional difficulty in evaluating the part of the deformation associated with the subduction of the Nazca Ridge is the presence of local inherited basement highs oblique to the forearc (i.e., Yaparejo–Piedra Pelada, Lomas de Ullujalla–Salinas de la Pileta–Macho Coyungo, and Huaricangana massifs, Fig. 3). Their stratigraphic and structural relationships with the neighbouring Tertiary strata show that these massifs had already been uplifted by an unknown amount before the Early Pleistocene, and independently from the effect of the Nazca Ridge. In an area like that of San Juan de Marcona, which lies on the southern flank of the Huaricangana massif, the transition between the Tertiary uplift motions and those more directly linked to the Nazca Ridge subduction is still unclear.

Theoretically, it should be possible to deduce the vertical motions experienced by the coastal area during the last million years or so from the present-day elevation of the Middle and Late Pleistocene shorelines. However, as discussed above, there remain many discrepancies regarding the age determination of these paleo-shorelines. The rates proposed for the zone of maximum uplift vary from 470 to 700 $\mathrm{mm}/10^3$ y, at least for the Late Quaternary. These rates decrease rapidly on both sides along the coast: 50 km further north they are close to zero (Hsu, 1988), and 20 km to the south of San Juan de Marcona they reach 100–200 $\mathrm{mm}/10^3$ y (Goy et al., 1990; Ortlieb and Macharé, 1990a).

During the last 2.5 Ma, the Pisco–Lomas region underwent a compressional tectonic event followed by the establishment of a N–S tensional tectonic regime (Macharé, 1987); the same sequence is well known in most of the Peruvian Andes region (Sébrier et al., 1985, 1988, 1989). In the region under study, some Quaternary sites show nearly radial extension, evidenced by high $R[(\sigma_2-\sigma_1)/(\sigma_3-\sigma_1)]$ ratios (Macharé, 1987), that is seemingly the only effect of the subduction of the Nazca Ridge on the state of stress.

Nazca-South American plate kinematics

Because of the N080° azimuth of the Andean convergence (Minster et al., 1974; Pardo-Casas and Molnar, 1987), the Nazca Ridge (oriented N040°) is subducting obliquely under the Peruvian margin (mean strike N145°). Thus, it may be deduced that with a convergence rate of 90–100 km/Ma (Pardo-Casas and Molnar, 1987) the ridge has been scanning the margin southwestward with a mean velocity of 63.5 ± 3.5 km/Ma. From these kinematic reconstructions, it is inferred that the

Nazca Ridge began to affect the 14–16°S coastal segment directly some 4–5 Ma ago (Fig. 5).

Discussion

The two previous models constructed in the study area both aim at determining an adequate crustal mechanism able to explain how the subducted part of the Nazca Ridge produced the coastal deformation. But, as shown above, the actual deformation is more complex than was previously assumed. Hsu's (1988) geometrical model is pertinent in intending to reproduce a well assessed superficial deformation and in taking into account the southward displacement of the ridge with respect to the continent. However, the assumed mechanism of deformation appears to be a weak point of the model. It is not easy to conceive how a subducted bathymetric high measuring 1.2 km in height could be able to displace, by an equal amount, a 35-km-thick continental crust (Cordillera de la Costa). To achieve such a vertical displacement, the model suggests a series of (35 km deep) vertical faults cutting through the whole crust. No seismic or neotectonic evidence supports the existence of such faults (Macharé, 1987; Rodriguez and Tavera, 1990).

The model by Moretti (1982) has a rigorous mathematical basis, but assumes a perfectly elastic crustal response. We consider that the model would be greatly improved by introducing a visco-elastic component and by taking into consideration the velocity of the southeastward migration of the ridge along the margin.

In conclusion, the subduction of the Nazca Ridge beneath the south-central Peruvian margin is accompanied by deformation of the upper part of the Andean forearc. These movements initially produced an inversion of the entire Pliocene continental shelf, and subsequently a strong uplift of an "outer shelf high" (= present-day Coastal Cordillera). Considering a time span of about 3 Ma, the finite deformation has a curviplanar shape resembling an asymmetrical dome, with a maximum altitude of around +900 m. The apex of the dome is not located in the projection of the ridge axis, but at approximately 70 km distance south thereof (Fig. 5). This geometry results directly from the demonstrated fact that the major uplift has been occurring in an area which was initially located well to the south of the projected trace of the southern edge of the ridge (Fig. 5). Landward, the deformation decreases rapidly and seems to be adjusted by tilting and slip along NNW-trending faults.

It is considered that the vertical uplift forces are directly linked to the relative buoyancy of the ridge-bearing slab, buoyancy being due to density contrasts within the upper part of the lithosphere.

No collision-type deformation with tight folds or thrust belts is observed in the study area; this indicates that the ridge does not collide with the South American margin. Instead, open folds, flexures and high-angle reverse faults, similar to those found in other parts of the Peru forearc, reveal moderate horizontal compressional forces (Macharé, 1987). Furthermore, the youngest Andean tectonic events are well recorded in the study area without major local modifications, which supports the interpretation that the ridge does not induce significant changes in the state of stress. The only effect of the Nazca Ridge subduction on the regional state of stress seems to be a radial pattern for the Quaternary extensional regime.

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