Geophys. J. Int. (1995) **121,** 279–300

A Pliocene–Quaternary compressional basin in the Interandean Depression, Central Ecuador

Alain Lavenu,[1,2] Thierry Winter[3]* and Francisco Dávila[4]

[1]*ORSTOM, UR 13, TOA, 213 rue La Fayette, 75 480 Paris cedex 10, France*
[2]*Laboratoire de Géodynamique et Modélisation des Bassins Sédimentaires, UPPA, avenue de l'Université, 64 000 Pau, France*
[3]*Laboratoire de Tectonique, Mécanique de la Lithosphère, IPGP, 4 place Jussieu, 75 252 Paris cedex 05, France*
[4]*Departamento de Geología, EPN, Ap. 2759, Ouito, Ecuador*

Accepted 1994 September 29. Received 1994 September 29; in original form 1993 April 12

SUMMARY

The segment of the Interandean Depression of Ecuador between Ambato and Quito is characterized by an uppermost Pliocene–Quaternary basin, which is located between two N–S trending reverse basement faults: the Victoria Fault to the west, and the Pisayambo Fault to the east. The clear evidence of E–W shortening for the early Pleistocene (between 1.85 and 1.21 Ma) favours a compressional basin interpretation. The morphology (river deviations, landslides, folded and flexure structures) demonstrates continuous shortening during the late Quaternary. The late Pliocene–Quaternary shortening reached 3400 ± 600 m with a rate of 1.4 ± 0.3 mm yr^{-1}. The E–W shortening is kinematically consistent with the current right-lateral reverse motion along the NE–SW trending Pallatanga Fault. The Quito–Ambato zone appears to act as a N–S restraining bend in a system of large right-lateral strike-slip faults. The compressive deformation which affects the Interandean Depression during the Pliocene is apparently coeval to the beginning subduction of very young oceanic lithosphere north of the Gulf of Guayaquil. The relatively buoyant new crust may have significantly increased the mechanical coupling in the subduction zone from Pliocene to Present.

Key words: Andes, compressional basin, Ecuador, neotectonics, reverse faults.

INTRODUCTION

The subduction of the Nazca Plate beneath the South American continent occurs at a rate of 7.8 cm yr^{-1} (DeMets *et al.* 1990) and has produced crustal deformation in the Andean range during the past 25 Myr. Several Tertiary and Quaternary tectonic Andean basins have developed along major regional faults which cut both the Pacific and Amazonian piedmonts and the Andean range itself. Plio-Quaternary deformation in such basins has been described for the southern and central Andes in Chile (Lahsen 1982; Armijo & Thiele 1990), Bolivia (Lavenu 1978; Lavenu & Ballivian 1979; Martinez 1980; Lavenu & Mercier 1993) and Peru (Philip & Mégard 1977; Sébrier *et al.* 1985, 1988; Cabrera, Sébrier & Mercier 1989) and for the northern Andes in Venezuela (Schubert & Sifontes 1970; Jordan 1975; Schubert 1981, 1982; Soulas 1981; Aggarwal 1983; Giraldo 1985), Colombia (Pennington 1981; Soulas 1988) and Ecuador (Hall, Basabe & Yepes 1980; Hall & Yepes 1980; Winter & Lavenu 1989a,b; Soulas *et al.* 1991; Winter, Avouac & Lavenu 1993).

The NE–SW trending 'Dolores–Guayaquil Megashear' (DGM) (Campbell 1975), a strike-slip fault system oblique to the continental margin of Ecuador, has been interpreted as a Mesozoic suture between accreted terranes and the South American continent (Case *et al.* 1971, 1973; Campbell 1974a,b; Feininger & Bristow 1980; Feininger & Seguin 1983; McCourt, Aspden & Brook 1984; Bourgois *et al.* 1985; Lebrat *et al.* 1985a,b). The DGM cuts across the Western Cordillera from the Gulf of Guayaquil to a latitude of 2°S (Riobamba), and then runs along the western boundary of the Interandean Depression, which is 350 km long, from 1°N in southern Colombia to 2°30′S in central Ecuador, and ends between Riobamba and Alausi. The Gulf of Guayaquil probably opened up at the trailing edge of the DGM, generating WSW–ENE normal-right-lateral faults during the Miocene (Fig. 1) (Malfait & Dinkelman 1972; Faucher & Savoyat 1973; Campbell 1974a,b; Benitez 1986). Recent and Present activity of the DGM has been recently recognized in the Western Cordillera (Winter & Lavenu 1988, 1989a,b;

*Now at: Coyne et Bellier 9 Allée des Barbanniers, 92 632 Gennevilliers Cedex, France.

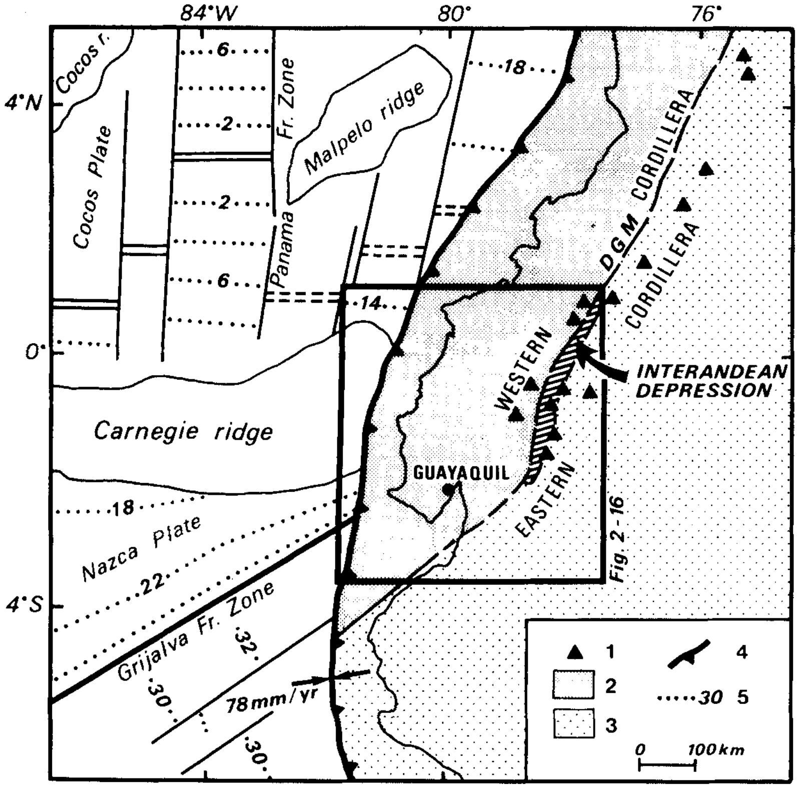

Figure 1. Schematic structural map. Relationships between Cocos–Nazca plates and the Ecuadorian–Colombian zone (from Lonsdale 1978, modified). DGM: Dolores–Guayaquil Megashear; black arrows indicate the motion of the Nazca Plate; the box represents Figs 2 and 16. 1: active volcanoes; 2: accreted oceanic crust; 3: South American plate; 4: Perú–Ecuador–Colombia Trench, active subduction zone; 5: age of oceanic crust (Myr).

Lavenu, Winter & Avouac 1990; Soulas *et al.* 1991) as having right-lateral-reverse kinematics. Mean horizontal slip-rates of 2.9–4.6 mm yr^{-1} during the past 250 kyr, have been documented by Winter (1990) and Winter *et al.* (1993). This segment of the DGM, locally called the 'Pallatanga Fault', may be the source of the 1797 February 4 major earthquake of modified MSK intensity 11 (Winter & Lavenu 1989b; Winter 1990).

Evidence for recent activity in the northern segment of the DGM was looked for in the Interandean Depression (Fig. 2). Large earthquakes have been recorded since 1687 in the southern part of the depression. Instrumental seismic records complete the historical records. The 1976 October 6 (Pennington 1981) and the two 1987 September 22 earthquakes (USGS 1988) yield E–W compressive focal mechanisms with N–S nodal planes (Fig. 2).

The first analysis of Quaternary tectonics in the Ecuadorian Interandean Depression was part of an attempt to correlate epicentres from a microseismic survey with lineaments observed on aerial photographs (Hall *et al.* 1980). According to these authors, the Interandean Depression is a N–S trending graben bounded by normal faults and recently affected by NE–SW trending right-lateral strike-slip faults. However, the methodology applied during these studies can be questioned because: (i) locations of low-magnitude earthquakes are not very accurate, (ii) small earthquakes may not be representative of major crustal movements and (iii) most of the faults and lineaments that have presumably generated earthquakes have not been checked in the field.

Despite microseismic studies and, more extensively, instrumental and historic seismic records (Kelleher 1972; Stauder 1975; Barazangi & Isacks 1976; Pennington 1981; Chinn & Isacks 1983; Suarez, Molnar & Burchfield 1983) confirming intense active crustal deformation in Ecuador, only a limited number of studies have been devoted to late Quaternary tectonic activity (Lavenu & Noblet 1989; Winter 1990; Soulas *et al.* 1991; Ego *et al.* 1993; Winter *et al.* 1993). This paper presents a detailed study of the recent geodynamic evolution of the Ecuadorian Andes, particularly in the southern Interandean Depression. Evidence is provided to state that the Interandean Depression is not a graben bounded by normal faults (Sauer 1965; Cotecchia & Zezza 1969; Hall & Ramon 1978; Hall *et al.* 1980; Hall & Yepes 1980; Baldock 1982; Hall & Wood 1985; Barberi *et al.* 1988; Maldonado & Astudillo 1989; Hall & Beate 1991; Tibaldi & Ferrari 1992), but is a compressional basin ('push-down' type) bounded by N–S trending reverse faults which have been active since the Miocene.

STRATIGRAPHY OF THE LATACUNGA–AMBATO AREA

The Interandean Depression is flanked to the east by the Eastern Cordillera (or Cordillera Real) which consists of sedimentary, magmatic and metamorphic rocks ranging in

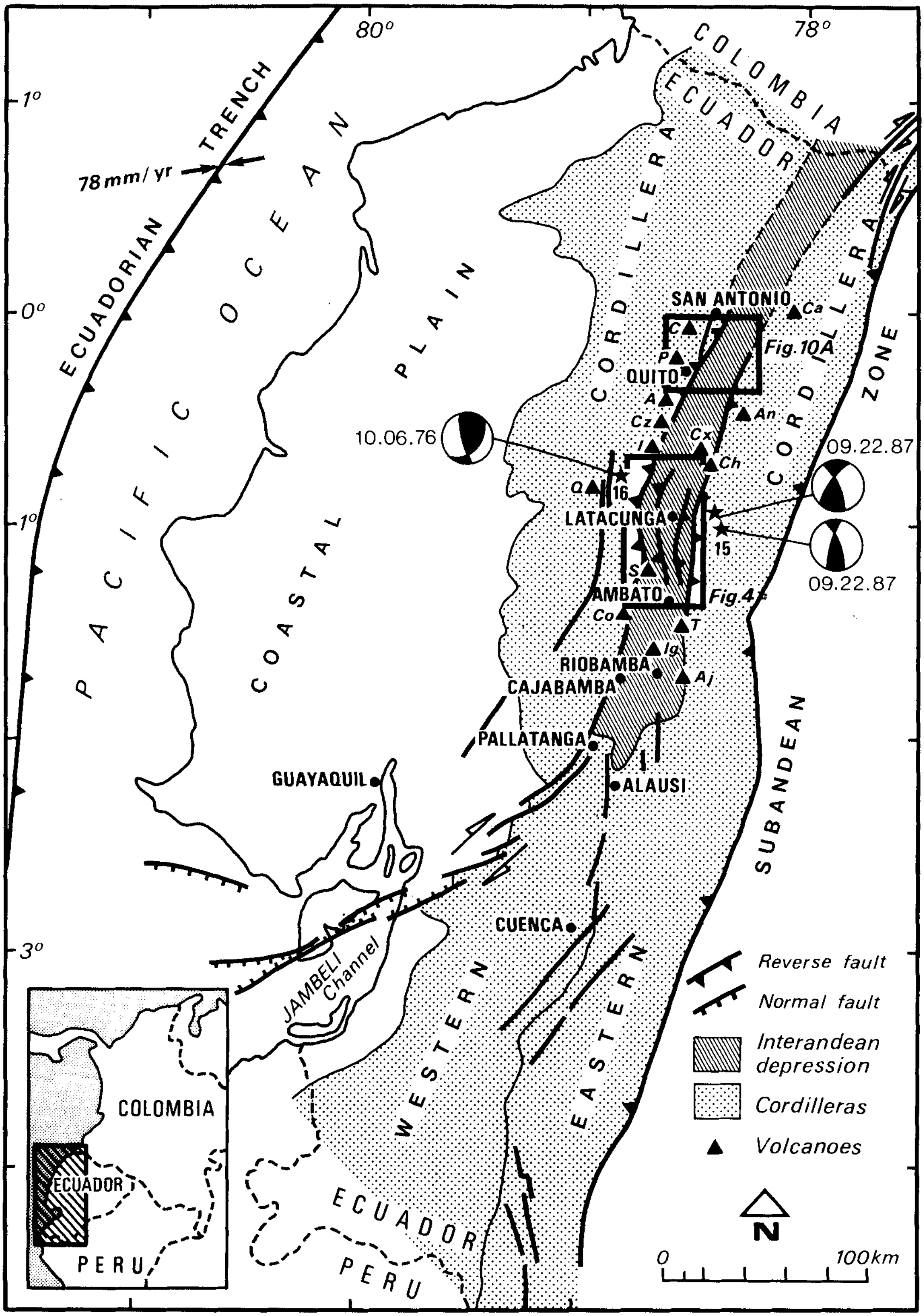

Figure 2. Schematic tectonic map of the major active faults from Interandean Depression with existing focal mechanisms. Mean volcanoes from study area—A: Atacazo, Aj: Altar, An: Antisana, C: Casitagua, Ca: Cayambe, Ch: Chalupas, Co: Chimborazo, Cz: Corazon, Cx: Cotopaxi, I: Iliniza, Ig: Igualata, P: Pichincha, Q: Quilotoa, S: Sagoatoa, T: Tungurahua. Three focal mechanism solutions: numbers beside them indicate estimated focal depths in kilometres (after Pennington 1981 and USGS 1988).

age from Palaeozoic to Cretaceous (Kennerley 1971, 1980; Baldock 1982; Feininger 1982; Aspden, Litherland & Salazar 1988). To the west of the Interandean Depression, the Western Cordillera consists of tholeitic and andesitic magmatic rocks of the Macuchi Arc and their correlative Upper Cretaceous to Eocene sedimentary rocks (Faucher & Savoyat 1973; Pichler, Stibane & Weyl 1974; Henderson 1979; Baldock 1982; Lebrat *et al.* 1985a,b; Egüez & Bourgois 1986; Mégard *et al.* 1987; Bourgois *et al.* 1990).

Between Quito and Riobamba (Fig. 2), the southern part of the Interandean Depression is filled with volcaniclastic, fluviatile and lacustrine sedimentary rocks. On maps by DGGM (1978) and Baldock (1982), these beds are assigned to the Pleistocene (Cangahua and Latacunga formations, Altar volcanic deposits), Pliocene (Pisayambo and Sicalpa formations, Igualata and Sagoatoa volcanic rocks), Miocene (Moraspamba Formation, in the Western Cordillera) and Oligocene (Alausi Formation, to the south of the Interandean Depression).

Recent studies (Dávila 1990; Lavenu *et al.* 1992) challenge the theory that the youngest (uppermost Pliocene and Pleistocene) part of the Interandean Depression basin fill is composed of four distinct sedimentological units (Fig. 3). The first unit, U1, reaches a thickness of up to 400 m, and is essentially composed of lahars, pyroclastic flows, and interstratified andesite lavas. In contrast, the top 120 m consist of concordant lacustrine and fluviatile deposits, making up thin consolidated beds. Unit U2, which lies in syntectonic onlapping unconformity on top of the previous unit, consists of unconsolidated fluviatile and lacustrine deposits 50–80 m thick. According to Lavenu *et al.* (1992), units U1 and U2 together make up the Latacunga Formation. Unit U3 overlies unconformably the older units and corresponds to the Chalupas unconsolidated pyroclastic tuff, which covered the entire region. Unit U4 is composed of pyroclastic tuffs of the Cangahua Formation. The four units were later dissected by rivers which deposited the alluvial terrace system.

K/Ar radiometric ages (Lavenu *et al.* 1992; Barberi *et al.* 1988) accurately date the stratigraphic sequence described above. Three ages of 1.85 ± 0.19, 1.73 ± 0.35 and 1.44 ± 0.29 Ma were obtained (Lavenu *et al.* 1992) from volcanic flows at the top of unit U1. These dates give a late Pliocene–early Pleistocene age to that section of the Latacunga Formation. The Chalupas caldera, source of the U3 pyroclastic tuff, has been dated as early Pleistocene (1.21 ± 0.05 Ma) (Barberi *et al.* 1988). The entire Latacunga Formation may be considered of late Pliocene–early Pleistocene age if the Plio-Pleistocene boundary is placed at 1.75 Ma (Odin 1994) after the Olduvaï positive magnetic reversal.

In the southern Interandean Depression, fluvio-lacustrine and volcanic rocks underlie the basinal deposits. These rocks have yielded Pliocene (Sicalpa Formation at 2.65 ± 0.21 and 3.59 ± 0.28 Ma, and Altar volcanics at 3.53 ± 0.94 Ma) and Miocene (7.9 ± 0.4 Ma) ages (Lavenu *et al.* 1992). The latter was obtained on an andesitic flow, coeval with the 8.12 and 7.1 Ma ages published by Barberi *et al.* (1988) for the Alausi Formation.

At the latitude of Latacunga, the Eastern and Western Cordilleras are overlain by the thick volcaniclastic Pisayambo Formation, which has yielded Miocene ages ranging from 6.1 ± 0.6 Ma (Barberi *et al.* 1988) near the top, to 9.1 ± 0.5 to 10.0 ± 1.3 Ma (Lavenu *et al.* 1992) near the base. These volcanic rocks and the basement of the southern Interandean Depression apparently belong to the same formation, thus providing a maximum age for the formation of the Interandean Depression. In the Western Cordillera the Pisayambo Formation unconformably overlies the Moraspamba Formation.

Quaternary volanic activity is represented by a large number of stratovolcanoes 11 of which are still active (Hall 1977; Simkin *et al.* 1981). Basic to intermediate lava as well as pyroclastics of dacitic and rhyolitic composition are the main products. Numerous eroded volcanic structures of possible Pliocene age (Baldock 1982) are buried underneath unit U1 of Latacunga Formation. The activity of these volcanoes could have been coeval with the beginning of infilling of the Interandean Depression.

MORPHOLOGY OF THE INTERANDEAN DEPRESSION

Three major morphological features have been identified from the analysis of the Interandean Depression on Landsat images and in the field (Figs 4 and 5): volcanoes, characterized by radial drainage due to their conical shapes, Eastern and Western Cordilleras, characterized by hummocky topography; and the Interandean Depression which forms an almost planar surface.

Most volcanoes are located along the edges of the Interandean Depression. Pichincha, Antisana, Cotopaxi and Tungurahua are active stratovolcanoes with rather well-preserved shapes. Old volcanoes (Iliniza, Sagoatoa, Igualata, Altar, Chimborazo) are intensely eroded by glaciers and streams (Hall 1977). Lahar flows cover the post-Cangahua stream terraces between the Cotopaxi volcano and Latacunga, i.e. later than unit U4.

The boundary between the Western Cordillera and the Interandean Depression is defined by a 40 km long, N–S trending scarp (La Victoria scarp), whose height is more than 500 m (Figs 4 and 6). This sharp boundary runs from Sagoatoa volcano to Iliniza volcano. Although the scarp appears to be linear at a regional scale, it is irregular in detail. Except for some deeply incised rivers, several streams (especially between Pujili and Saquisili) appear to have developed from the Interandean Depression by headward erosion, and they have strongly eroded the scarp. Pediments on Plio-Quaternary deposits of the Latacunga Formation cut across the scarp and extend westward into the Western Cordillera. Other pediments are younger and have developed on the scarp itself. These field observations suggest that the mountain-front sinuosity is relatively old—at least Pliocene—according to criteria established by Bull & McFadden (1977). No observations along the scarp's trace support present-day rejuvenation. The non-linear trace of the La Victoria scarp, its uneven convex slope, and the absence of faceted spurs suggest that this scarp is actually due to a west-dipping reverse fault. The La Victoria scarp has a 28–30 per cent slope, whereas pediments on both sides of the scarp have slopes of only 1–4 per cent (Fig. 5).

North and south of the investigated zone, at the latitudes of Quito and Riobamba respectively, the scarp disappears beneath volcanoes: Atacazo, Corazon and Iliniza to the

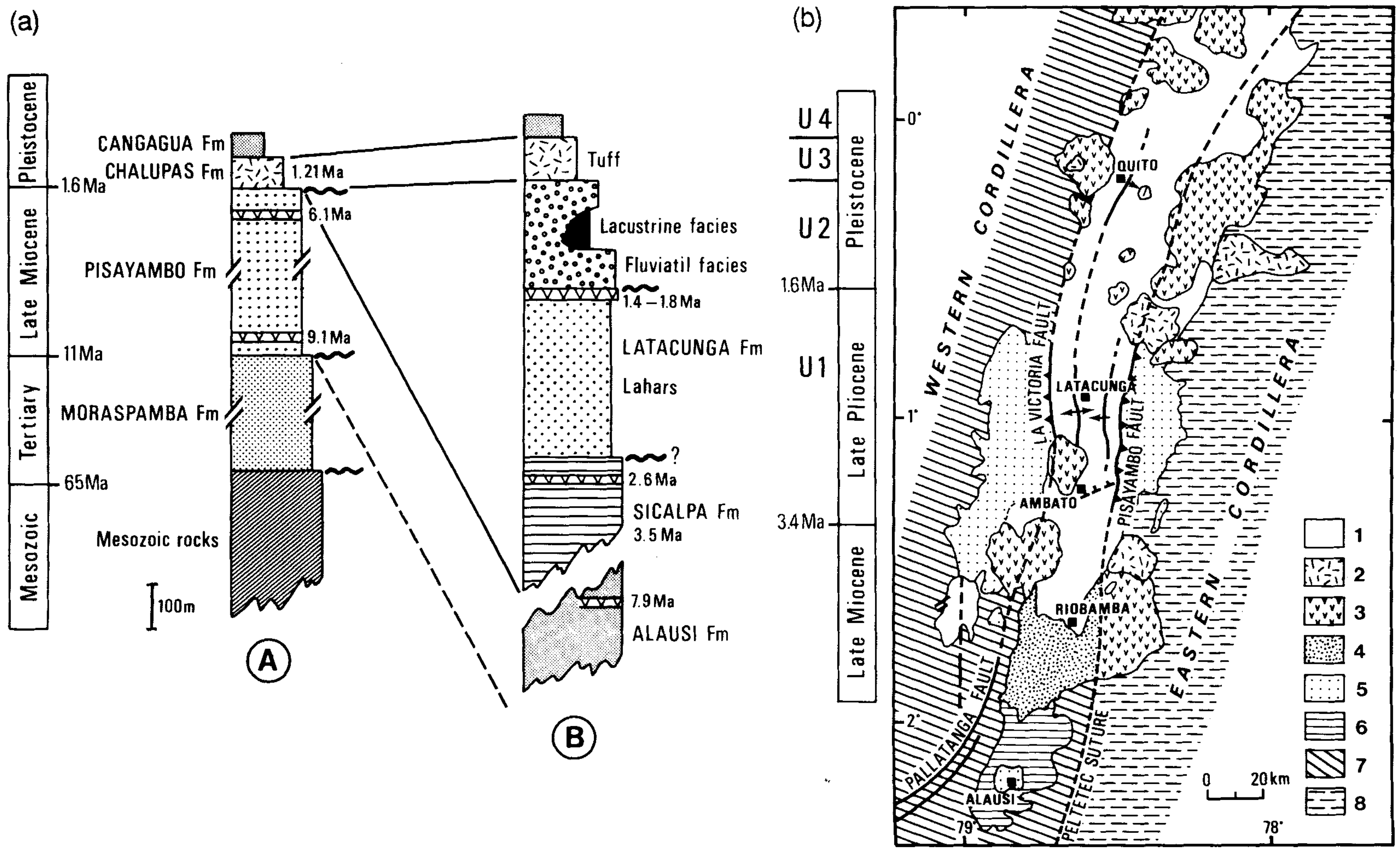

Figure 3. (a) Synthetic stratigraphic sections from the Western Cordillera (A) and Interandean Depression (B) in Central Ecuador: radiometric dates from Barberi *et al.* (1988) and Lavenu *et al.* (1992). (b) Schematic geological map of the south Interandean Depression (after DGGM 1982, modified). 1: Quaternary deposits; 2: Quaternary volcanic rocks; 3: Pliocene volcanic rocks; 4: Pliocene sedimentary rocks; 5: Miocene sedimentary and volcanic rocks; 6: Oligocene rocks; 7: Western Cordillera; 8: Eastern Cordillera.

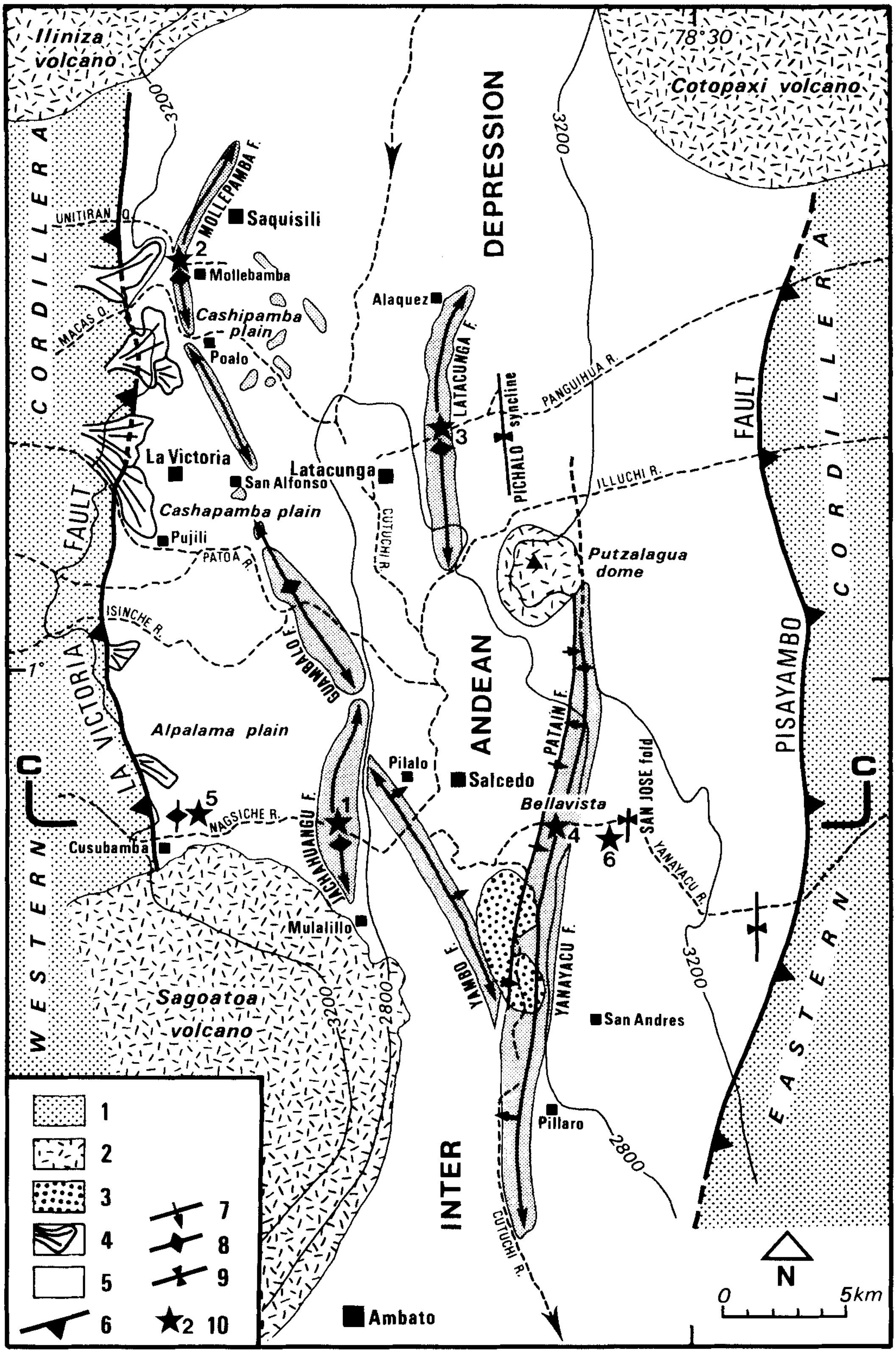

Figure 4. Structural and morphological sketch map of the Latacunga–Ambato area. CC: cross-section of Figs 6 and 11. 1: Pre-Pliocene cordilleran basement; 2: Quaternary magmatic rocks; 3: landslide; 4: pediment; 5: Plio-Quaternary deposits of the Interandean Depression; 6: reverse fault; 7: flexure; 8: anticline, 9: syncline, 10: stars locate fold stereograms. Folds and flexures in grey.

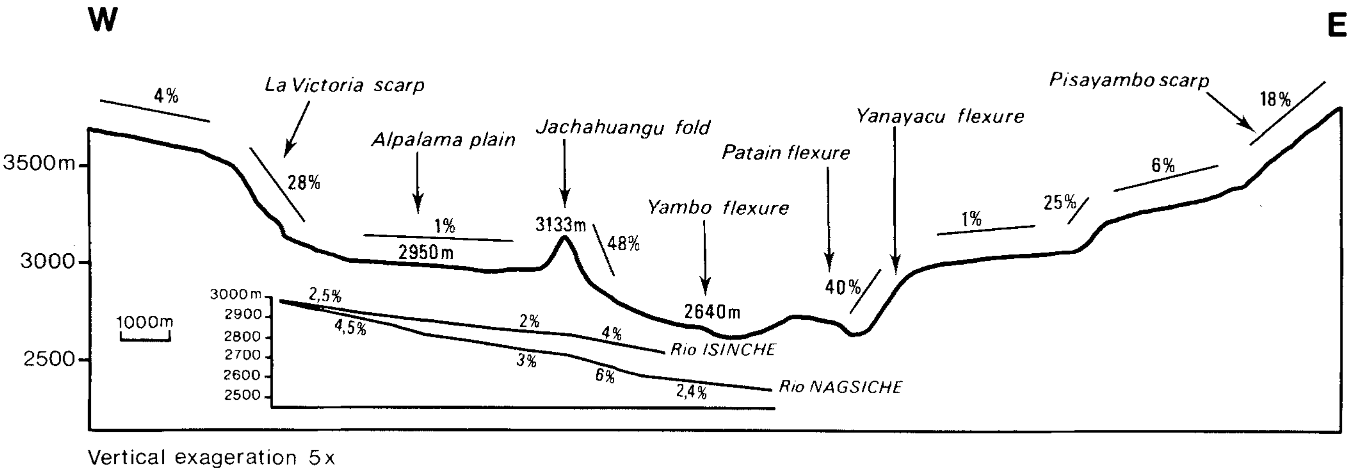

Figure 5. Topographic profile across the Interandean Depression along line CC of Fig. 4 showing the different per cent slopes. Longitudinal profile of equilibrium of Río Isinche and Río Nagsiche through the Jachahuangu fold. East of the fold axis, the stream gradient locally increases.

north; Sagoatoa, Igualata and Chimborazo to the south. Stratigraphic analyses indicate that the Pliocene activity of volcanoes such as Iguatala and Sagoatoa was contemporaneous with the basin's infilling.

The eastern boundary of the Interandean Depression is marked by the N–S trending Pisayambo fault scarp which is less well defined than the western boundary. There, east of San José, at the foot of an 18 per cent slope (less than the slope of the La Victoria scarp), Palaeozoic rocks thrust westwards onto Miocene and Pliocene–Quaternary rocks.

The Latacunga zone is drained mainly by the Río Cutuchi which flows from north to south. The Río Cutuchi is fed by E–W tributaries coming from both cordilleras. On the right bank, the tributaries are deeply entrenched (Nagsiche and Isinche rivers). Some of them, such as Quebradas (ravines) Macas and Unitiran and Ríos Patoa and Illuchi appear to be diverted by hills while others disappear into flat-bottomed swampy plains (Cashapamba and Cashipamba plains) bordered by hills, with no outlets or with very shallow slopes. These localized overdeepened depressions and disruptions of the E–W drainage outline elongated, narrow N–S to NW–SE trending anticlinal hills which culminate between 3032 m and 3133 m and can be followed from Saquisili to the north, to Mulalillo to the south.

The development of the anticlinal folds, which are 500–1000 m wide and about 30 km long, may explain the lack of effective drainage on the Alpalama plain. Only the Nagsiche and Isinche rivers have had sufficient energy to avoid diversion and to cut through the folds by antecedence, forming localized overentrenched valleys. The minor lateral extent of erosion features on the perched plain, associated with the steep riverbed slopes (35° to 40°) suggest that the Nagsiche and Isinche rivers have cut into the plain only recently (200–300 m), and are therefore very young—early Pleistocene (i.e. Chalupas tuff, dated 1.21 Ma) at the oldest. Streams that did not have enough energy to cut through the folds as they were forming were deviated parallel to the topography. They disappeared into marshy areas as they were isolated from the hydrographic draining system of the Interandean Depression (Río Cutuchi and its main tributaries).

A fold on the left bank of the Río Cutuchi, east of

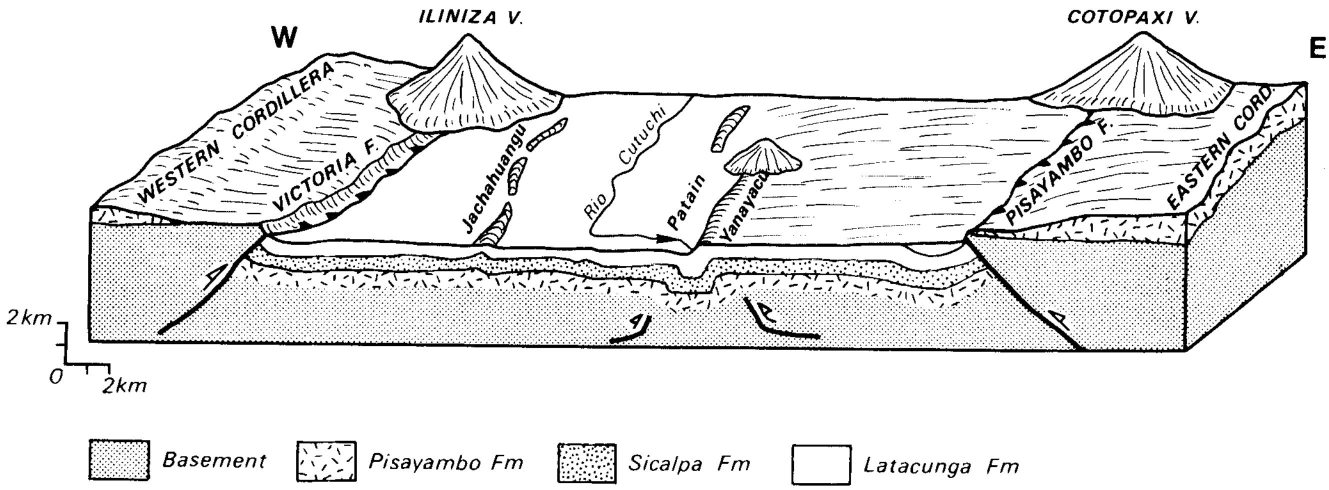

Figure 6. Cross-section of the Interandean Depression along line CC of Fig. 4.

Latacunga, is exposed over a distance of about 12 km between the villages of Alaquez and Tiobamba. It is 500–1000 m wide and reaches an elevation of 2905 m. Farther south, a N–S to NNE–SSW scarp can be followed for over 25 km, between the Putzalagua rhyolitic dome and Ambato. This 300 m high scarp at an altitude of 2912 m in the north and 2700 m in the south, is generated by a west-facing flexure. Although it is regionally linear, its trace displays some local irregularities. Its steep slope (40 per cent) (Fig. 5) is the cause of frequent large-volume rock slides from the upper volcanic layers of the Latacunga Formation, towards the Río Cutuchi valley (e.g. the rock slide south of Bellavista). These landslides have been erroneously interpreted as belonging to the Pisayambo Formation (DGGM 1980, 1982). Only two moderately large-discharge streams, the Río Illuchi south of Latacunga and the Río Yanayacu east of Salcedo, cut across the flexure. However, several ravines incised in the scarp have developed from the main valley by headward erosion. No pediments have developed on either side of the flexure, as they have at the western La Victoria scarp. On the other hand, terraces that developed along Río Cutuchi tributaries have settled at the foot of the flexure. Between Bellavista and the southern part of the flexure, the Río Cutuchi flows along the flexure and locally hinders the development of terraces on the left bank. The topographic scarp cannot be ascribed to lateral erosion by the Río Cutuchi, which follows the flexure only partially. The fresh aspect of the scarp, its steep slope with active gravitational instabilities, and the control on the landscape by the flexure indicate that this flexure is currently growing. These observations also suggest a very young age for it (early Pleistocene, post 1.44 Ma), later than the La Victoria or Pisayambo faults.

The referred folds, as well as the slopes they form, provide a certain morphological symmetry. The boundaries (La Victoria Fault and Pisayambo Fault) approximately define linear scarps with 28–18 per cent slopes (Fig. 5). The two main folds (Jachahuangu to the west, and Yanayacu, to the east) have 40 and 48 per cent slopes, respectively, whereas the pediments that link them to the basin boundaries have slopes of only 1 per cent. The morphology of the southern part of the Interandean Depression, between Ambato and Riobamba, is not as clear. For instance, volcanoes (Sagoatoa, Chimborazo, Igualata, Tungurahua) conceal the boundaries and partially cover the sedimentary infilling deposits.

The small Riobamba basin, located at the southern end of the Interandean Depression, is filled with sedimentary rocks of possible Pleistocene age (DGGM 1978). These deposits are about 100 m thick and composed of subhorizontally lying laharic, fluviatile, lacustrine and volcaniclastic rocks. This series is the lithologic and stratigraphic equivalent of the Latacunga Formation.

Analysis of morphological anomalies in the Latacunga–Ambato area, such as scarp boundaries, antecedence of certain rivers, hydrographic network disruptions, development of pediments and/or terraces or gravitational instabilities, provides evidence for Pleistocene deformation within the Ecuadorian Interandean Depression. Plio-Quaternary infilling of the Interandean Depression has been affected by folds and faults. Their geometry, kinematics and degree of current activity must be specified.

TECTONIC ANALYSIS

Folding in the western part of the Latacunga–Ambato area

Morphological analysis of the western Interandean Depression has helped to identify elongated narrow N–S to NW–SE trending folds which affect the Latacunga Formation in front of the La Victoria Fault. Three major folds have been identified between Mulalillo, to the south, and Saquisili, to the north: they are the Jachahuangu, Guambalo and Mollepamba anticlines. North of Saquisili, the morphological ridge disappears beneath pyroclastic deposits of the Iliniza volcano. These folds, which are 500–1000 m wide and reach 3032 to 3133 m have a structural relief ranging from about 100 m in the north to 500 m in the south, above the highest terraces of the Río Cutuchi.

The Jachahuangu anticline

The Jachahuangu structure is an upright, slightly asymmetric anticline forming a significant N–S relief in the centre of the Interandean Depression (Fig. 4). The anticline reaches 3133 m, separating two almost flat highlands of 2950 m and 2640 m mean elevation, located to the west and the east, respectively (Fig. 5). The Río Nagsiche cuts deeply through the fold in an E–W direction, thus providing a complete geologic section. This anticline is mainly made up of lahar deposits belonging to unit U1 of the Latacunga Formation. The subhorizontal or slightly deformed layers located beneath the surface of the Alpalama plain dip sharply 20° to 25° in the western limb of the anticline and 35° to 40° in the eastern limb. The axis of this cylindrical fold, as obtained from stereographic analysis, locally plunges 7° towards N165°E (Fig. 7).

The profile of equilibrium of the deeply incised rivers is affected cross-cutting through the anticline (Schumm 1986). For instance, the Río Nagsiche gradient increases east of the fold axis from 3 per cent west of the anticline to 6 per cent east of the anticline (Fig. 5). In the east limb, fluviatile deposits (conglomerates) overlain by lacustrine (mudstone) and again fluviatile rocks of unit U2 (Latacunga Formation) form an onlap wedge over lahar deposits. The fact that the fluvio-lacustrine sedimentary rocks are present exclusively in the eastern limb of the anticline suggests that U2 was deposited after the onset of unit U1 deformation. Furthermore, the near-constant SE direction of the palaeocurrents, deduced from imbricated pebbles at the base of fluvial deposits, indicates that the morphologic ridge created by U1 folding was sufficiently high to control the N–S flow along the front of the anticline. The U2 fluvio-lacustrine layers reach a total thickness of about 80 m. Onlap wedges in this unit (Fig. 8) demonstrate that folding continued during deposition as slumps in lacustrine layers confirm the instability of the sedimentary slope on the eastern limb of the Jachahuangu fold. All of the fluvio-lacustrine deposits were progressively included in the synsedimentary folding. Dips in these wedges vary from 20–30° east at the base, decreasing upward to near 0°.

The pyroclastic flow in unit U3 (Chalupas Formation) appears to be moulded onto the topography. It unconformably overlies folded units U1 and U2. Its thickness varies

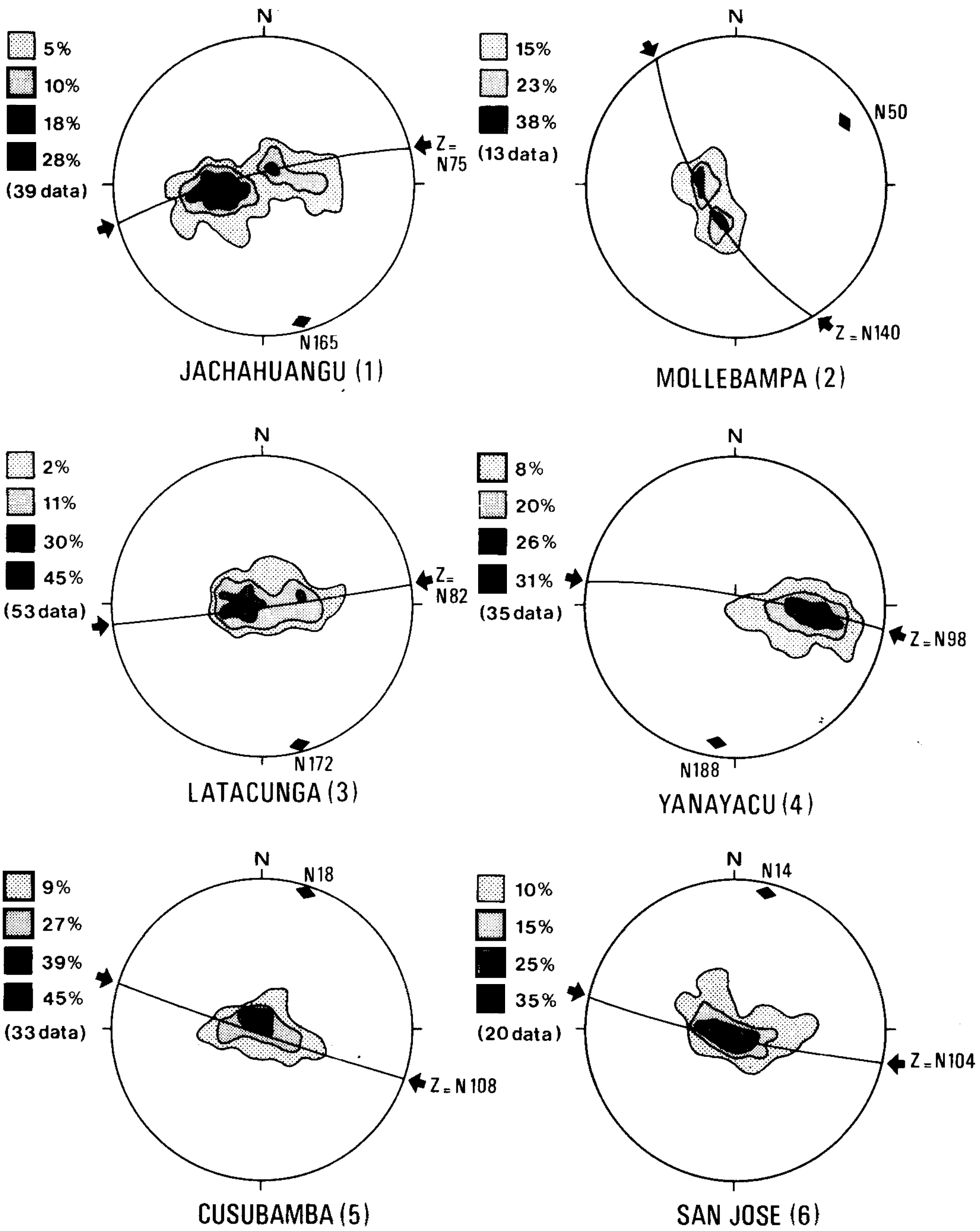

Figure 7. Equal-area stereographic projections depicting poles to bedding in Latacunga zone (lower hemisphere). Contour lines enclose areas of like density of occupation. All the synsedimentary folds and flexures (location, Fig. 4) characterize the E–W Pliocene–Quaternary shortening.

significantly, and may exceed 50 m (Beate 1985). The Chalupas tuff is itself partly overlain by the Cangahua Formation (U4) pyroclastic deposit.

The Guambalo anticline

The Guambalo anticline reaches a lower elevation (3047 m) and is less deeply incised than the Jachahuangu fold. The western limb dips 15° whereas the eastern one dips 22°. The fold axis is subhorizontal and trends N160°E. As in the Jachahuangu fold, unit U1 is exposed in the core of the anticline. An onlapping wedge of fluvio-lacustrine sedimentary rocks from unit U2 overlies U1 on the eastern limb. The lacustrine layers have also been affected by slumping, indicating an unstable east-dipping sedimentary slope.

The Río Patoa does not incise the northern part of the anticline. It is diverted southward and flows along the western part of the fold for 3 km and then joins the Río Isinche, crossing through the fold. This deviation shows that the Patoa River could be younger than the fold. On the other hand, the Isinche River cuts directly through the anticline: the profile of equilibrium increases eastward of the fold axis from 2 per cent to 4 per cent (Fig. 5). This could be explained by continuous Quaternary growth of the fold.

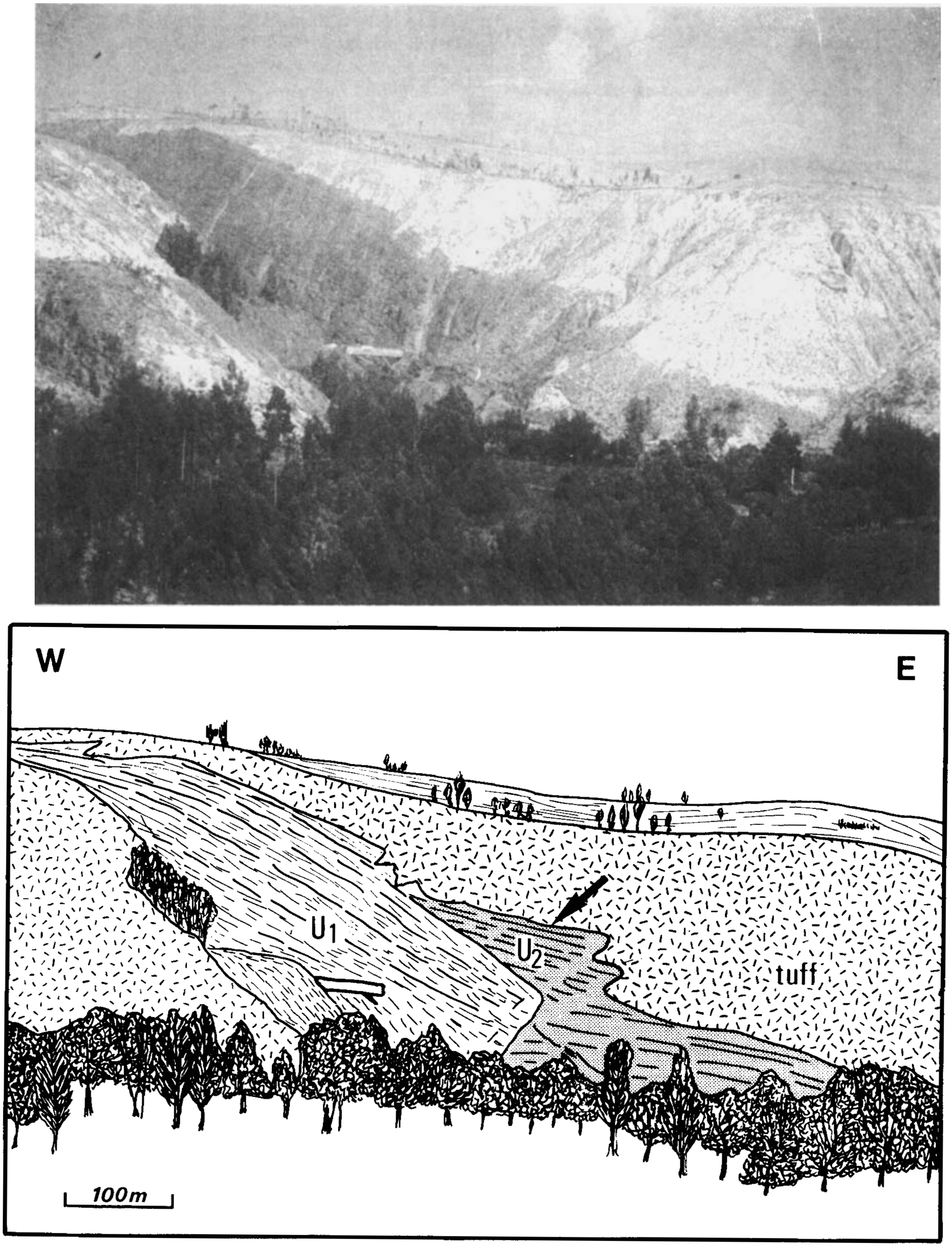

Figure 8. Illustration of the onlap wedges (arrow) on the eastern limb of Jachahuangu fold.

The Mollepamba anticline

This fold trends N150°–N170°E between San Alfonso and Mollepamba. The course of the Quebrada Macas turns south more than 3 km along the western limb of the fold before cutting it westward. This stream cuts through the upper layers of the Chalupas tuff only, thus providing the only morphological argument in favour of the fold ongrowing after deposition of the Chalupas Formation.

Near Mollepamba, the anticline changes direction from N150°–N170°E in the south, to N25°E in the north. The Quebrada Unitiran, also deviated towards the south, cuts deeply through the structure. It exposes only fluviatile and volcanic layers of uppermost Latacunga Formation (U2), and the overlying Chalupas tuff. These deposits are apparently symmetrically folded with 30° dips. The fold axis also trends N50°E. The Chalupas tuff, slightly thicker on the anticline limbs than on the hinge, overlies unit U2 in apparent conformity and could be folded.

The youngest alluvial terrace of the Quebrada Unitiran, about 3 m above the active stream, does not appear to be folded. Despite the proximity of the Interandean Depression boundary, no proximal coarse clastic facies have been observed, nor has any indication of synsedimentary tectonics been detected. The folding of the lacustrine beds from the upper Latacunga Formation, the deviation of the Quebrada Unitiran and Quebrada Macas, and the ridge morphology assign a relatively young age to this fold.

Folding in the eastern part of the Latacunga–Ambato area

The Latacunga anticline

East of Río Cutuchi, the Latacunga structure is an upright N–S trending fold, 500–1000 m wide and about 12 km long, which lies about 100 m above the Latacunga alluvial plain. North of Alaquez, this topographic structure disappears under recent volcanic lahars whose flows coming from the Cotopaxi volcano have been detected from satellite imagery. To the south, the anticline disappears west of the Putzalagua rhyolitic dome (Fig. 4).

The Río Panguihua has deeply incised this structure by antecedence and exposes geological sections of the anticline. It consists of laharic and fluviatile deposits of the Latacunga Formation unit U1. An andesitic flow located at the base of these deposits has yielded a K/AR age of 1.85 ± 0.19 Ma (Lavenu *et al.* 1992). The horizontal fold axis trends N172°E and both limbs dip 15° to 20° (Fig. 7).

The Chalupas tuff, apparently not folded, unconformably overlies the fluviatile deposits. The tuff varies from less than 5 m thick near the crest of the anticline to about 20 m on the limbs. The flat-bottomed Pichalo depression corresponds to the hinge of a widely open syncline.

The Yanayacu flexure

A N08°W trending abrupt west-facing scarp, 25–30 km long, extends from the Putzalagua dome in the north, to Pillaro in the south. The Yanayacu flexure separates the Río Cutuchi alluvial plain to the west, whose elevation varies from 2400 m to 2600 m, from a wide pediment to the east, at an elevation of 2900–3000 m, and with a 1 per cent pediment slope.

Ravines sloping from 20 to 40 per cent erode this scarp at present. They have developed by headward erosion from the Río Cutuchi alluvial plain. The Río Yanayacu cuts deeply through the scarp, which corresponds to a flexure of the entire Latacunga Formation, thus providing an excellent geological section (Fig. 9). The Chalupas tuff (U3) lies in erosional unconformity over this flexure. The tuff deposits are thicker west of the fold (>50 m) than east of it (<40 m). Unit U1 layers are horizontal or slightly undulating east of the scarp, then dip sharply within 500 m, reaching up to 70°W. They can be locally vertical. At the toe of the asymmetric fold, coarse-grained fluviatile deposits (unit U2) form 30 m thick onlap wedges like those described in front of the Jachahuangu anticline. Their dips vary from 60° for the lower layers of the unit, to horizontal for the upper ones.

The Patain flexure

West of the Yanayacu flexure, a N190°E east-facing flexure affects the Latacunga Formation (Fig. 4). The Patain flexure extends 15–20 km south of Putzaluga Dome; with a 2000 m elevation it is less well developed than the Yanayacu flexure, and its eastern limb dips vertically.

The Yambo flexure

A small flexure, trending N130° to N150°E, has been mapped between Pilalo and Yambo (Fig. 4). This morphologic feature is poorly marked as recent Río Cutuchi alluvial deposits blanket it. Elevations are higher west of the flexure (2680 m) than east of it (2600 m). The upper layers of the Latacunga Formation (U2) dip from 40° to 50°NE in this flexure. To the south, it is partly concealed by rock slides which affect the Yanayacu scarp.

Evidence of early deformation

Prior to the above-mentioned large-scale folding, the sedimentary deposits of unit U1 were also affected by a synsedimentary N–S axis folding deformation. Folds ranging from 10 m (Cusubamba) to 200 m wide (San José) (Fig. 10) appear on the vertical banks of the Río Nagsiche and the Río Yanayacu. Their amplitudes are 10 m and 100 m, respectively. Their length is not known, but in San José, the folds affect both sides of the valley, which is more than 1 km wide. These folds were progressively filled by unconformable syntectonic deposits. Both the folded and the overlying layers are involved in the Jachahuangu and Yanayacu folding. This synsedimentary folding suggests an early E–W shortening during the infilling of the Interandean Depression, prior to 1.85 Ma.

Geometric relationships between Latacunga, Chalupas and Cangahua formations

The Chalupas tuff covers a large portion of the Interandean Depression from Quito in the north, to Ambato in the south (Beate 1985). The tuff is draped onto the previously described anticlinal ridges. Its thickness is always greater on the limbs than at the crest of the structures. The Nagsiche and Yanayacu rivers cut through the formations, exposing relationships between the volcaniclastic series, the Latacunga Formation and the Chalupas tuff. The tuff unconformably overlies the Latacunga Formation where it is folded (Fig. 8). The angle of unconformity is always higher between the tuff and unit U1 (up to 40°) than between the tuff and unit U2 (where it is sometimes concordant). This suggests that the tuff was deposited after the Latacunga Formation was folded and eroded. This erosion surface developed channels and conglomerate layers. Folding has not been found in the Chalupas tuff.

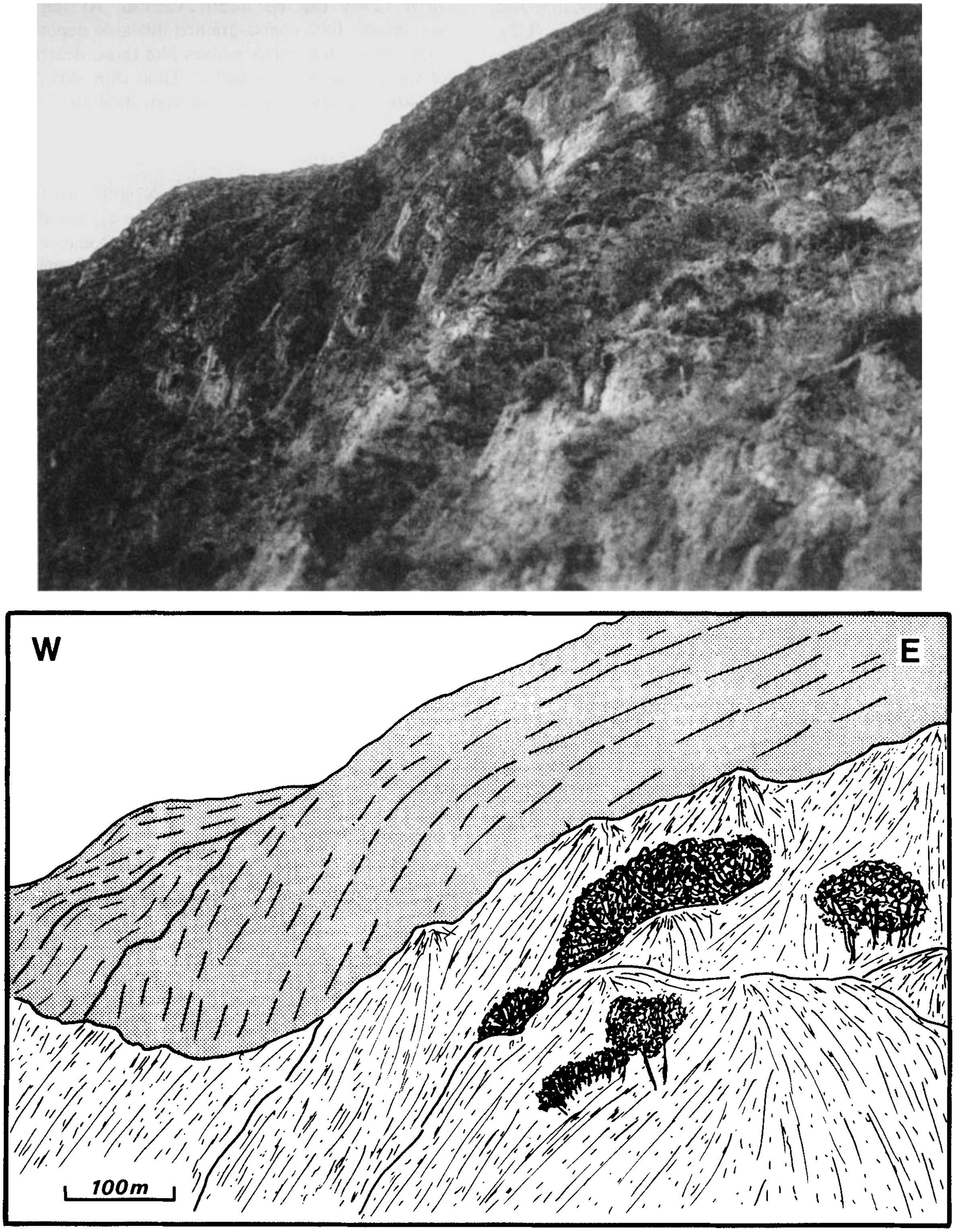

Figure 9. Illustration of the Yanayacu flexure near Bellavista.

The Quito area

Farther north, in the Quito area (Fig. 11), the eastern boundary of the Interandean Depression sharply marks the landscape, whereas its western boundary is partly covered by volcanic rocks from the active Pichincha and extinct Casitagua volcanoes. The city of Quito is located on a bench at an elevation of 2800 m on a previously marshy flat, between the volcanoes' foothills and a N–S trending alignment of hills, whose elevations vary from 2920 to 3170 m. This bench dominates the Interandean Depression which lies at an elevation of 2200–2500 m. The 500–600 m

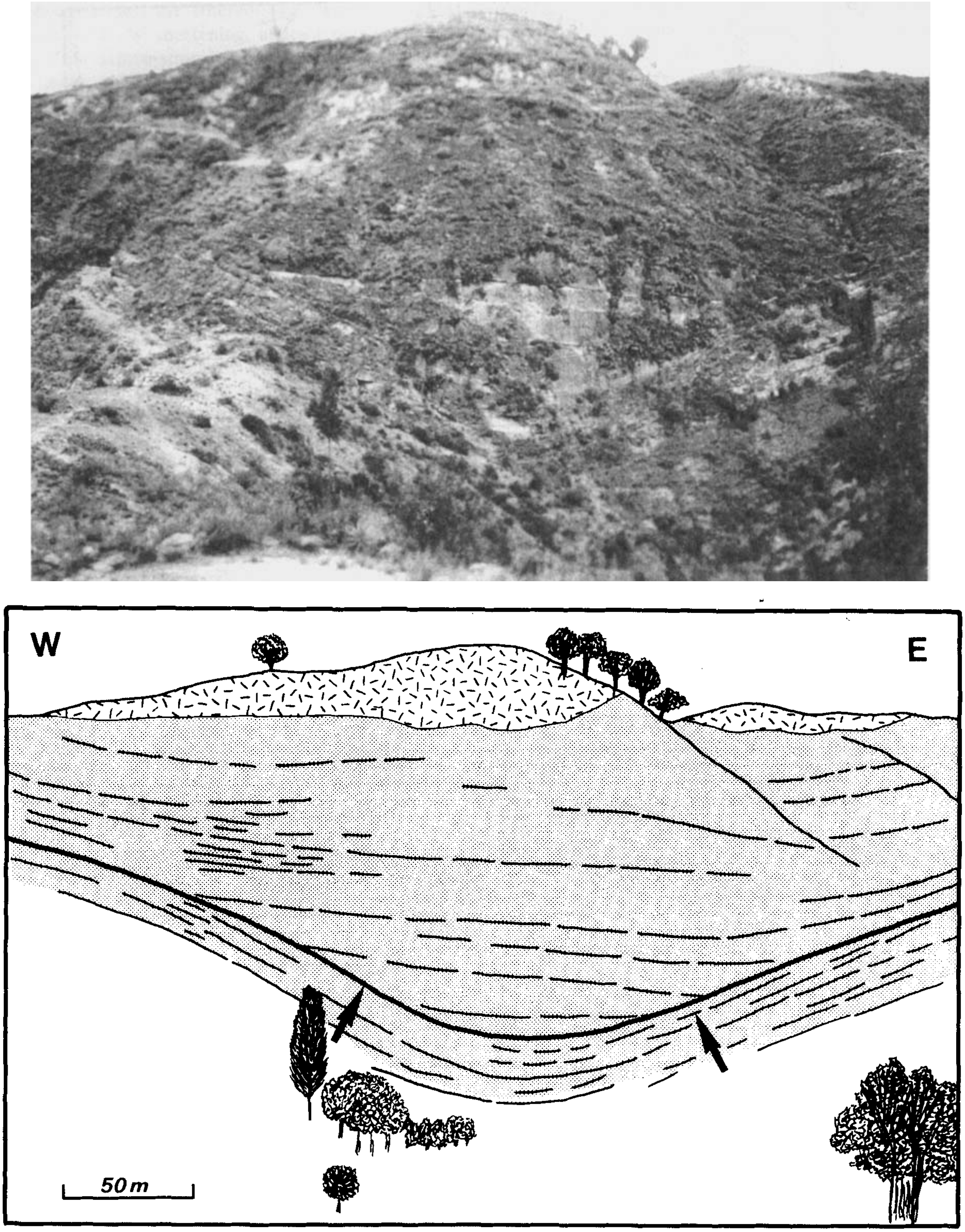

Figure 10. Illustration of the synsedimentary deformation near San José. Arrows show the base of progressive unconformity.

high east-facing scarp was previously considered as a graben boundary fault (Sauer 1965; Cotecchia & Zezza 1969; Hall & Ramon 1978; Hall *et al.* 1980; Hall & Yepes 1980; Baldock 1982; Hall & Wood 1985; Barberi *et al.* 1988; Maldonado & Astudillo 1989; Hall & Beate 1991). Based on morphology and folding deformation, the bench is now interpreted as being uplifted along a west-dipping reverse fault (Soulas 1988). The scarp is cut by canyons (Quebrada Zumbiza east of Quito and Quebrada San Antonio north-east of Quito), clearly exposing the folded pyroclastics erupted from the active Pichincha volcano. The morphology and deformation of the Quito flexure are similar to the

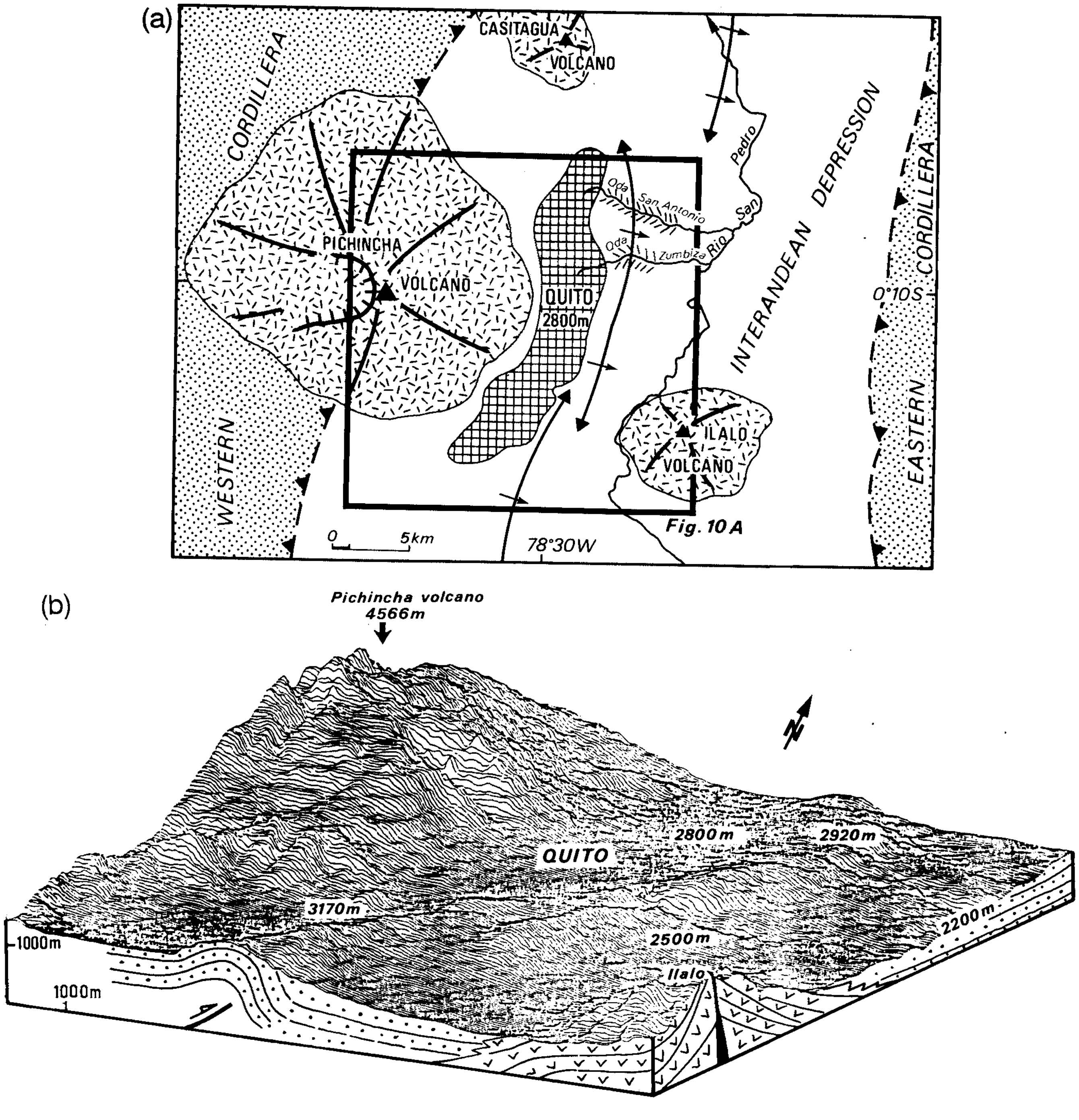

Figure 11. (a) Map and (b) computerized representation of Quito area located between Pichincha volcano and aligned hills.

Yanayacu flexure at Bellavista, and favour the interpretation of the west-dipping reverse fault. As in the Latacunga region, the relative chronology of events, i.e. the formation of the Interandean Depression, the quaternary activity of the Pichincha volcano (1.32 ± 0.13 Ma to present; Barberi *et al.* 1988) and the formation of the Quito flexure, is apparently identical.

ESTIMATION OF E–W SHORTENING SINCE LATE PLIOCENE

In Ecuador, between Ambato to the south and San Antonio to the north, the Interandean Depression is characterized by a large late Pliocene–Quaternary basin located between reverse faults rooted in the basement which are well exposed in the Latacunga region (La Victoria and Pisayambo faults). This basin infilling overlies the upper Miocene–Pliocene volcaniclastic and sedimentary deposits exposed in the southern part of the Interandean Depression, between Riobamba and Alausi.

Although formation of the Interandean Depression probably began in the late Miocene after deposition of the Pisayambo Formation, the E–W shortening, which generates the reverse faults, is best documented since the late Pliocene (Latacunga Formation). It became more pronounced during and after deposition of unit U1 (latest

Pliocene–early Pleistocene). Structural analysis described above demonstrates that the Interandean Depression was subjected to major E–W shortening, at least between 1.85 and 1.21 Ma. This deformation began while U1 sediments were being deposited, and it increased in rate during deposition of the U2 fluvio-lacustrine unit. The growing of the above-mentioned anticlines and flexures and the induced morphological modifications (deviated rivers, local overentrenchment, rock slides) suggest that the shortening was still active during the late Quaternary. The fact that the basin is not completely filled confirms the rapid uplift of the folds. Although no major reverse fault has been detected in outcrops at the foot of the scarps, they are likely to have resulted from blind thrusts. Seismicity and focal mechanisms (e.g. Pennington 1981) highlight the present-day persistence of the E–W shortening. All of these arguments favour the interpretation of a compressional (push-down) basin located within a restraining bend. Similar tectonic structures were observed in the Ventura basin, California (Yeats 1977; Brown 1990) and in Xinjiang (Avouac *et al.* 1993).

Shortening of the Plio-Quaternary (post 2.5 Ma) within the Interandean Depression was estimated from surface geological data using two different approaches. The first one is based on principles of balancing applied to each fold and flexure (Suppe 1983; Medwedeff 1989; Suppe & Medwedeff 1990; Al Saffar 1993). The second one used the Locace software (Moretti & Larrère 1989) attempting to 'reverse' the folded base of the Latacunga Formation. In both approaches, the thickness of each formation is assumed to be constant. Since there is no stratigraphic equivalent of the Interandean Depression infilling onto both Eastern and Western Cordilleras, the maximum vertical throw along the La Victoria and Pisayambo faults should not be higher than the Latacunga Formation thickness (600 m), and thus the amount of the deduced shortening has to be considered as a minimum value. A mean dip of the La Victoria and the Pisayambo fault planes was assumed to range from 30° to 45°. Thus the amount of shortening absorbed by the two reverse faults (respectively) has been estimated yielding twice 820 ± 220 m, i.e. a total of 1640 ± 440 m.

Within the basin, the shortening is estimated from the superficial attitude of each folded structure: the Jachahuangu anticline, and the Yambo, the Patain and the Yanayacu flexures. The confidence interval on a mean shortening is estimated by assigning to each individual value an uncertainty equal to 20 per cent. The uncertainty mainly takes into account dip variations in the stratigraphic markers. The Jachahuangu anticline is assumed to be a flexural-slip fold whereas the Yambo, Yanayacu and Patain flexures are fault-propagation folds associated with blind thrust faults. Shortening yields 300 ± 60 m for the Jachahuangu fold, 100 ± 20 m for the Yambo flexure (Fig. 12), 870 ± 175 m for the Yanayacu flexure (Fig. 13) and 450 ± 90 m for the Patain flexure. Thus, the amount of Pliocene–Quaternary shortening recorded within the Interandean Depression is about 1720 m $\pm$ 350 m.

With the Locace software, the computed shortening of the deposits within the Interandean Depression reaches 2000 ± 400 m (20 per cent uncertainty) (Fig. 14). This value is consistent with the previous estimation of 1720 ± 350 m.

Since the amount of shortening absorbed by the La Victoria and the Pisayambo reverse faults has been estimated above to be 1640 ± 440 m, the total late Pliocene–Quaternary shortening is about between 3360 ±

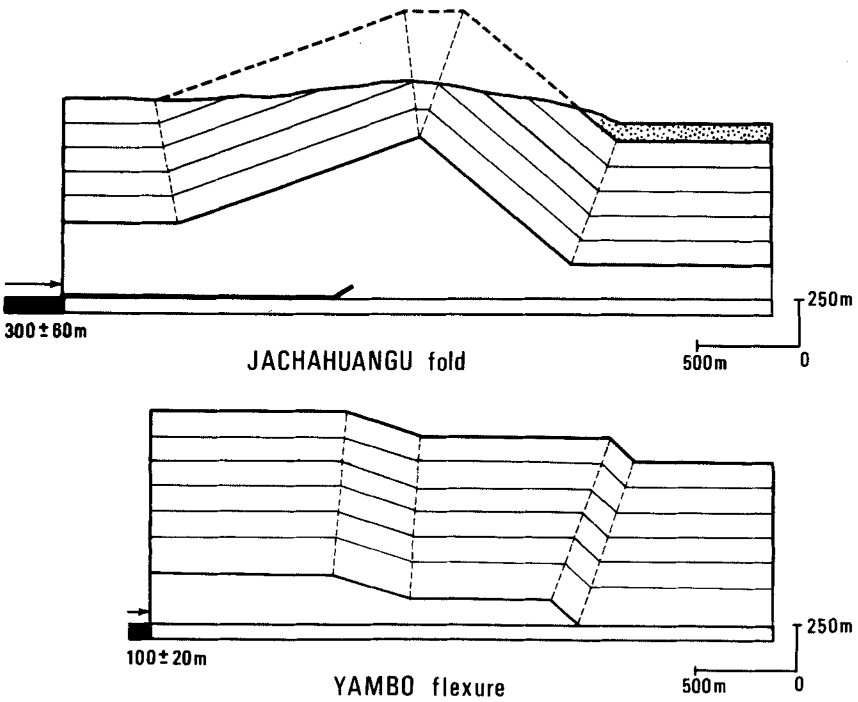

Figure 12. Measured shortening across the Jachahuangu fold (300 ± 60 m) and the Yambo flexure (100 ± 20 m).

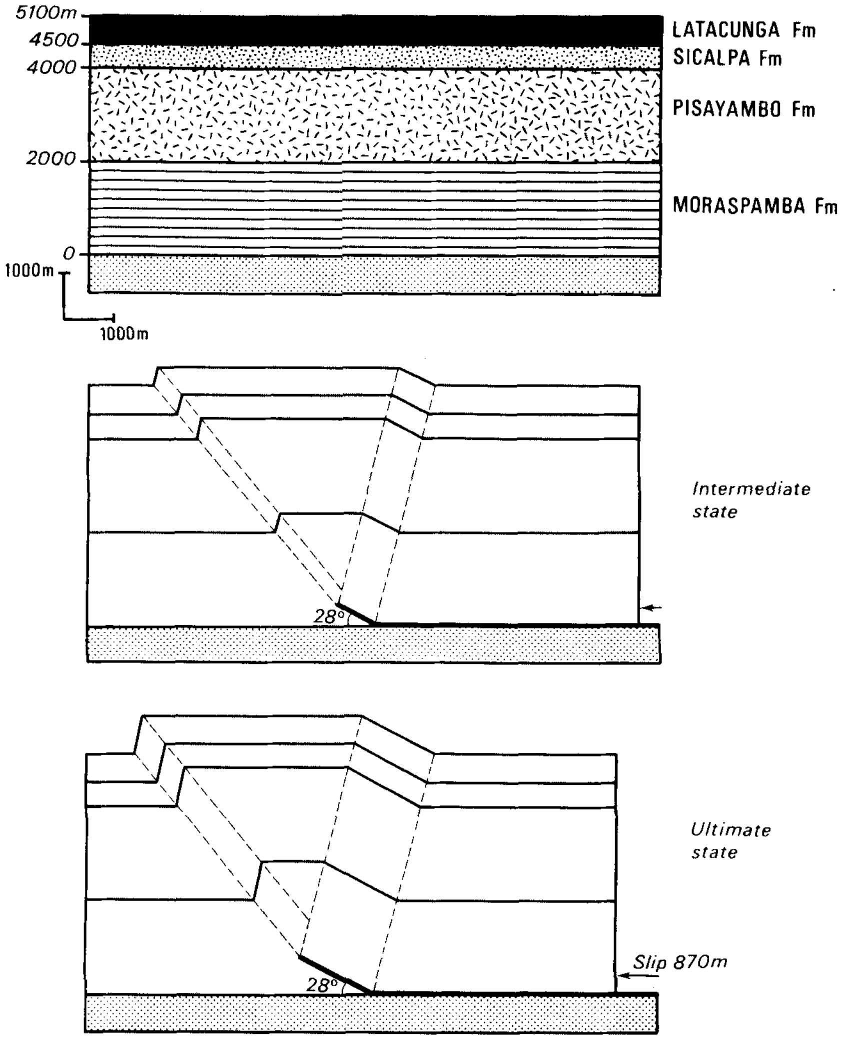

Figure 13. Theoretical retrodeformable models showing the progressive development of the simple step fault-propagation fold of Yanayacu.

800 m (first estimation) and 3640 ± 800 m (second estimation). Both methodologies give similar results and the mean shortening implies a shortening rate of 1.40 ± 0.3 mm yr^{-1}.

PLIO-QUATERNARY DEFORMATION IN CENTRAL ECUADOR

In the Ecuadorian Interandean Depression, the E–W shortening proposed above is kinematically consistent with both the NE–SW trending right-lateral Pallatanga active fault—which crosses the Western Cordillera from the Gulf of Guayaquil—and the NE–SW trending right-lateral active fault system (Cauca-Patia, Garzon, Romeral faults) observed in southern Colombia (Geological Map of Colombia, INGEOMINAS 1976; Blés *et al.* 1990). Consequently, the Interandean Depression segment between Quito and Ambato appears to be a compressive N–S restraining bend in a large right-lateral strike-slip fault system (Fig. 15).

To the south, along the Pallatanga Fault, the slip vector strikes N35°E and the estimated Pleistocene–Holocene (post 250 ka) slip rate is about 3.8 ± 0.9 mm yr^{-1} (2.9–4.6 mm yr^{-1}; Winter *et al.* 1993). The E–W shortening component has thus a rate of 2.6 ± 0.6 mm yr^{-1}.

On the other hand, the opening of the Gulf of Guayaquil (Fig. 16) has been related to right-lateral movements since the Miocene along the DGM (Malfait & Dinkelman 1972; Goossens 1973; Faucher & Savoyat 1973; Campbell 1974a,b; Moberly, Shepherd & Coulbourn 1982), part of which is the Pallatanga Fault. Studies of oil wells in the Gulf of Guayaquil have documented the accumulation of more than 10 000 m of sublittoral and deltaic Neogene and Quaternary deposits (Faucher & Savoyat 1973). In the Jambeli channel, the Pliocene–Quaternary deposits reach up to 4500 m in thickness in depocentres, which are elongated along ENE–WSW directions and interpreted as grabens (Benitez 1986). The amount of Plio-Quaternary extension through these grabens can be roughly estimated, assuming two normal bordering faults with dips from 45° to 70°. Thus, during the last 5.3 Myr (Miocene–Pliocene transition), the NNW–SSE trending extension reaches 6150 ± 2850 m with a rate of 2.5 ± 1.1 mm yr^{-1}. The right-lateral movement along the N30°E-trending Pallatanga Fault associated with this extension might be 4.3 ± 2 mm yr^{-1}. This value is compatible with a minimal late Quaternary velocity of

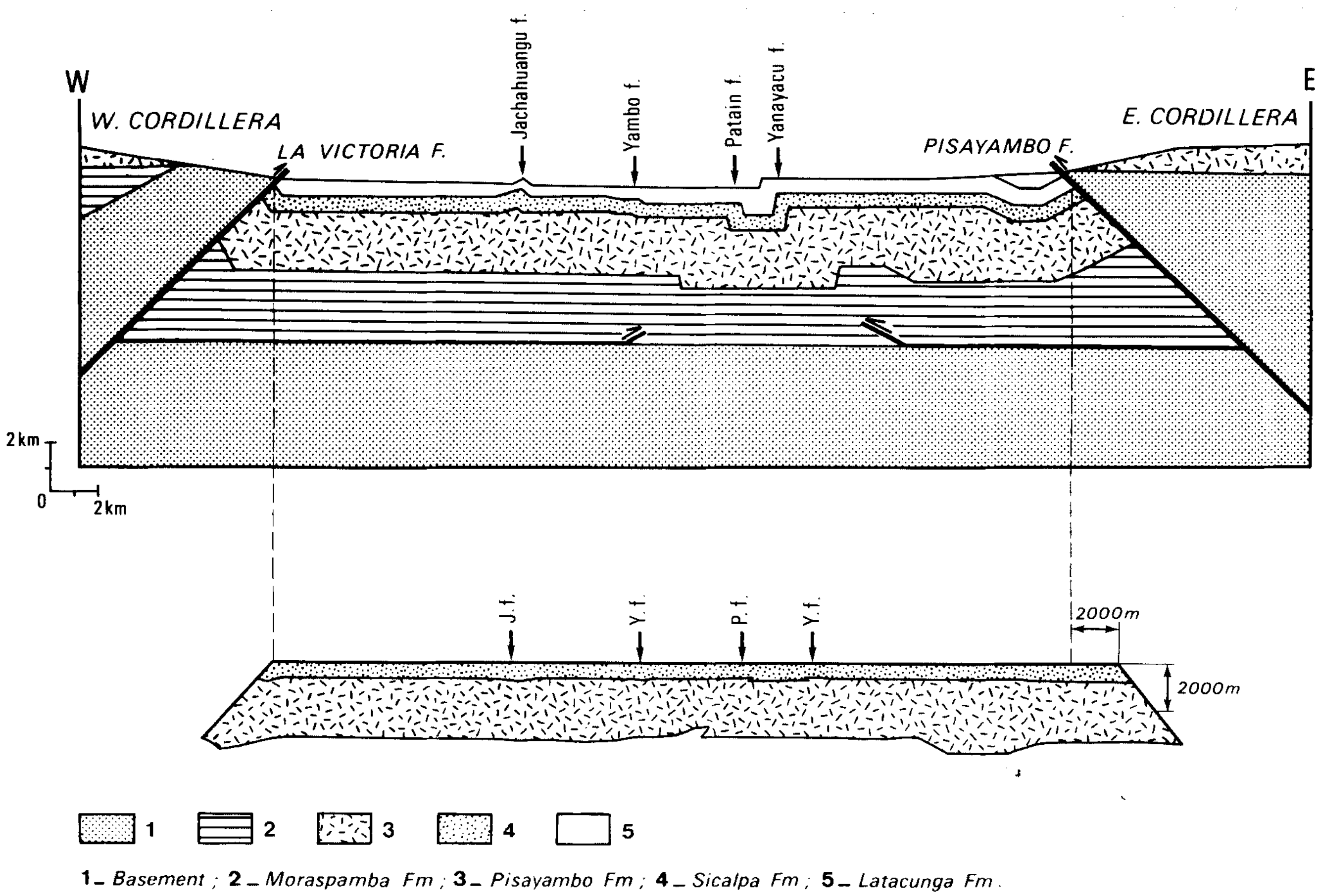

Figure 14. Interpretative cross-section of the Interandean Depression near Latacunga. Reverse faults of La Victoria and Pisayambo are assumed to dip 45°. This cross-section was used to estimate the 2000 m E–W shortening (Locace software).

3.8 ± 0.9 mm yr^{-1} recorded on the Pallatanga Fault (Winter *et al.* 1993). Consequently, the Pallatanga Fault seems to have kept a constant rate during Pliocene and Quaternary periods.

Although a good kinematic consistency is observed between the studied Interandean Depression, the Pallatanga Fault and the Gulf of Guayaquil (Fig. 15), the Plio-Quaternary E–W shortening calculated above for the Interandean Depression (rate of 1.4 ± 0.3 mm yr^{-1}) represents only 50 per cent of the deformation described on the Pallatanga and Gulf of Guayaquil faults.

ORIGIN OF PLIO-QUATERNARY DEFORMATION IN CENTRAL ECUADOR

The causes of the deformation previously described are probably related to the subduction of the Nazca Plate beneath the Ecuadorian margin. The global plate model NUVEL 1 proposes a N78°E present convergence between the Nazca and South American plates, with velocities of 78 mm yr^{-1} (DeMets *et al.* 1990). The compressive tectonic regime prevailing above a subduction zone is generally related to a strong mechanical coupling in the Benioff zone (Barazangi & Isacks 1976; Cross & Pilger 1982; Jarrard 1986). This regime may be induced by the low dip of the Benioff zone, a high convergence rate, subduction of an aseismic ridge, and/or the young age of the subducted oceanic lithosphere.

Strong mechanical coupling is generally accepted between plates in subduction zones where the Benioff zone has a shallow dip. Sébrier *et al.* (1985, 1988) discussed this approach and suggested that the subduction angle has an influence on the relative extent of the domains affected by compression and those affected by extension induced by high relief (e.g. Fleitout & Froidevaux 1982; Froidevaux & Isacks 1984; Armijo *et al.* 1986). In Ecuador, the distribution of intermediate and deep seismicity indicates a lateral variation of the subduction dip (Stauder 1975; Barazangi & Isacks 1976; Lonsdale 1978; Hanus, Vanek & Sandoval 1987). North of latitude 2.5°S, and along the first 30 km in depth, the oceanic slab has an eastward dip from 25° to 30°. To the south, this angle is 10°. In the southern Ecuadorian Andes (Cuenca), Quaternary deformation seems to be extensional (Winter 1990; Winter *et al.* 1990; Lavenu, Noblet & Winter 1993). Consequently, the subduction dip is not by itself the origin of the compressive deformation in the Interandean Depression.

The Cretaceous to present-day velocities between the Nazca and South American plates in Ecuador have been determined by Daly (1989) by extrapolating the study of Pardo-Casas & Molnar (1987). It suggests almost constant, oblique convergence directions (N80°E) during the Tertiary,

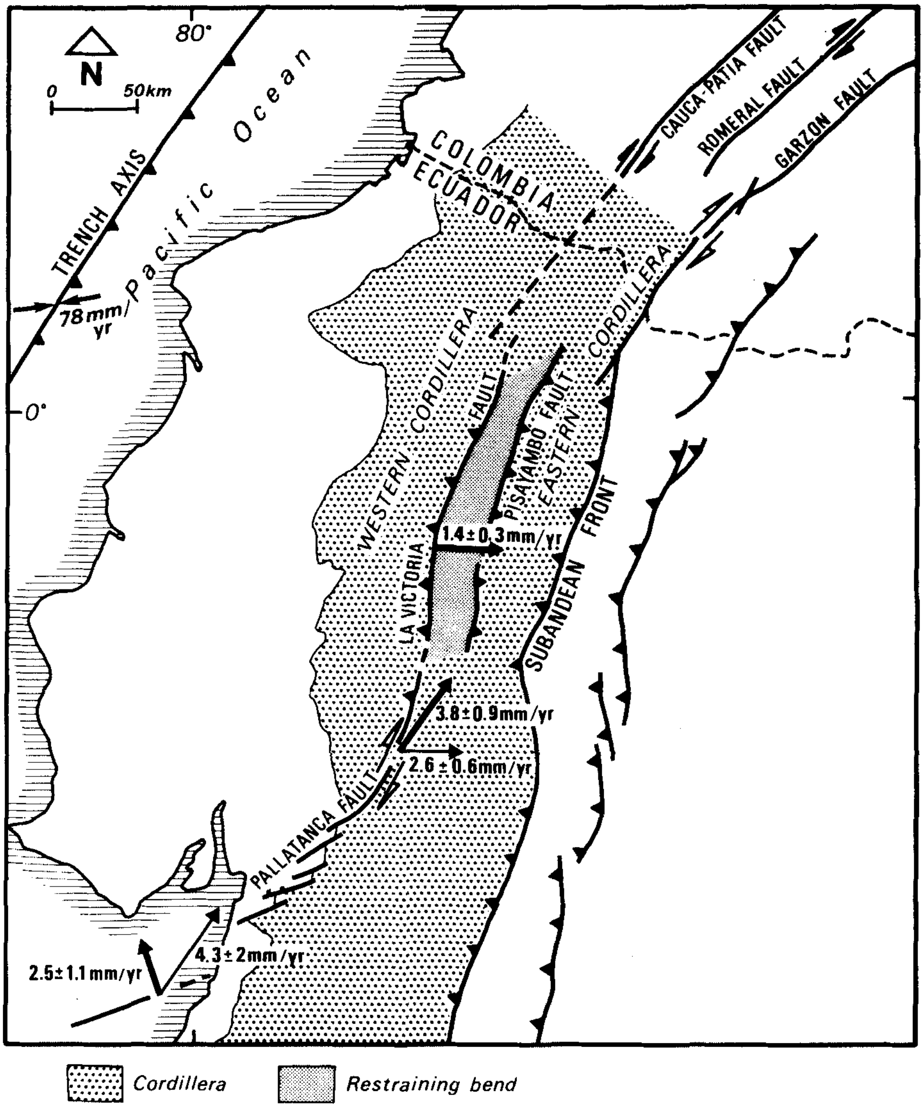

Figure 15. Interpretation of the restraining bend of Ecuador in the general content of right-lateral faulting of central Ecuador–southern Colombia. The wide arrows show the 2.5 ± 1.1 mm yr^{-1} opening rate along normal faults in the Gulf of Guayaquil, the 3.8 ± 0.9 mm yr^{-1} right-lateral displacement rate along the Pallatanga Fault, and the 1.4 ± 0.3 mm yr^{-1} shortening rate in the Interandean Depression. The small arrows show the deduced N35°E and E–W rates along the faults of the Gulf of Guayaquil and Pallatanga, respectively.

and high convergence rates in the Middle to Upper Eocene (204 ± 80 mm yr^{-1}) and since the Miocene (125 ± 33 mm yr^{-1}). The opening of the Gulf of Guayaquil, which began in the Miocene, is thus synchronous with a convergence speed up. Thus, there is a delay between the beginning of the opening of the Gulf of Guayaquil and the maximum Pliocene shortening in the Interandean Depression.

The subducting plate beneath the centre and the north of Ecuador includes the Carnegie Ridge which is more than 200 km wide and 1000 m higher than the surrounding oceanic floor. Lonsdale (1978) estimated that about 100 km of Carnegie Ridge have already been subducted. The influence at the surface of the subduction of an aseismic ridge has been disputed in studies of the Japan Trench (Lallemand, Malavieille & Calassou 1992) and of the Peruvian margin facing the Nazca Ridge. Macharé (1987) and Sébrier *et al.* (1988) have shown that the subduction of a high-relief ridge induces only minor and local changes in the stress state of the continental plate above the subduction zone. Furthermore, considering the convergence velocity of 78 mm yr^{-1}, Carnegie Ridge probably reached the trench at the beginning of the Quaternary. Its subduction is therefore not the cause of the E–W shortening in the Interandean Depression which began in the Pliocene.

The Carnegie Ridge located north of the Grijalva fracture zone belongs to the young oceanic lithosphere (Nazca Plate). Both the Carnegie Ridge and the Malpelo Ridge, which lies farther north, probably formed simultaneously in the Lower Miocene, when the Nazca Plate passed over the Galapagos hot spot located near the Cocos–Nazca Ridge 16 Myr ago (Hey 1977; Lonsdale 1978; Lonsdale & Klitgord 1978). The Malpelo Ridge has not reached the Colombian Trench yet. Its distance from the trench is about 200 km. Magnetic anomalies testify to the oceanic nature of this crust (Lonsdale 1978). The extension of the Carnegie Ridge to the

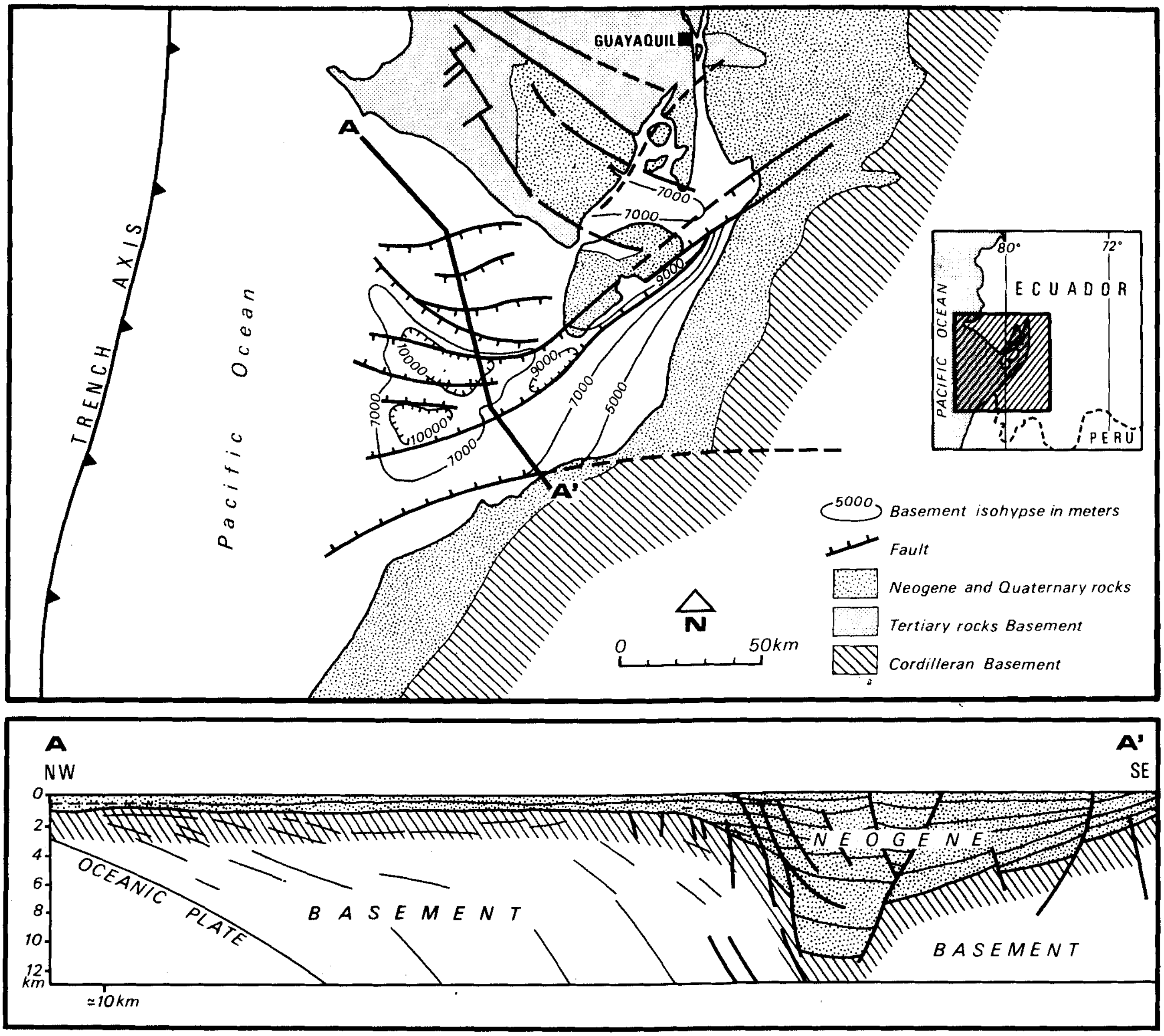

Figure 16. Simplified geological sketch map of the Gulf of Guayaquil and NW–SE cross-sections through the Jambeli channel showing the 10 000 m thickness of Neogene deposits (modified after Benitez 1986).

east under the continent should have a morphology similar to that of the eastern part of the Malpelo Ridge. Thus, taking into account the width of the strip of young oceanic floor located east of the Malpelo Ridge, the rate of convergence, and assuming that the Carnegie Ridge began to subduct at the beginning of the Quaternary, subduction of the young part of the Nazca Plate would have begun, at the very latest, at the beginning of the Pliocene. This is consistent and coeval with the start of the Interandean Depression formation.

CONCLUSION

Since 2.5 Ma, the Plio-Quaternary shortening rate of the Interandean Depression has been about $1.4 \pm 0.3\,\mathrm{mm\,yr^{-1}}$. To explain the geometry and nature of deformation in Central Ecuador, two parameters can be considered. The first parameter is the convergence obliquity (N78°E) in relation to the Ecuadorian coast (≈N30°E). The normal component to the coast is absorbed by the subduction while the tangential component is largely absorbed by the displacement along the Pallatanga Fault. The second is the subduction of the young oceanic plate.

From early Miocene, with fast convergence, the tangential component is enough to activate the Pallatanga Fault and to open the Gulf of Guayaquil. During early Pliocene, the young oceanic plate reached sufficient depth to increase mechanical coupling. This probably induced significant E–W shortening and built the restraining bend, while the Gulf of Guayaquil continued to open.

From early Neogene, and during more than 20 Myr, 10 000–12 000 m thick deposits filled the Gulf of Guayaquil, with only 4500 m during the last 5.3 Myr. So, for 15 Myr, the opening rate was $0.7 \pm 0.3\,\mathrm{mm\,yr^{-1}}$, and then $2.5 \pm 1.1\,\mathrm{mm\,yr^{-1}}$ during the last 5.3 Myr. This demonstrates that during the first 15 Myr, the gulf opening rate was equal to one-third the rate of the last 5.3 Myr. It is likely that in the Central Ecuadorian Andes, the E–W shortening induced by the slow and continuous displacement along the Pallatanga Fault was not rapid enough to build a restraining bend.

Although rather good continuity is documented between both the Pallatanga and the Interandean restraining bend (Winter 1990; Winter & Lavenu 1989b), relations between the restraining bend and the strike-slip faults of southern Colombia are not established yet. Only 50 per cent of the displacement rate along the Pallatanga Fault is absorbed by the shortening rate of the restraining bend of the Interandean Depression. The remaining 50 per cent can be absorbed either along Eastern Cordilleran reverse faults and Subandean Front or along more rapid right-lateral strike-slip faults in southern Colombia.

ACKNOWLEDGMENTS

The authors thank Robert Yeats. Drafts of the paper benefited greatly from his substantial reviews. We acknowledge François Mégard and an anonymous reviewer for constructive and thorough reviews. Special thanks are due to Michel Sébrier, Marie-Odile Bockel, Mohammed Al Saffar, Arturo Egüez, Hugo Yepes and José Cembrano for fruitful discussions, Anne-Marie Wawrzkow for her helpful English translation and Monique Morales for the illustrations. This study was supported by the Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM) [IPGH-EPN-CLIRSEN-ORSTOM Convention in Ecuador] and Institut Français d'Études Andines (IFEA). UR 13, TOA Dept, ORSTOM contribution.

REFERENCES

Aggarwal, Y.P., 1983. Plate-tectonics evolution of western Venezuela and eastern and northern Colombia, *XXXIII Conv. An. ASOVAC*, **34,** 1, 525, ed. FUNVISIS, Caracas.

Al Saffar, M., 1993. Geometry of fault-propagation folds: method and application, *Tectonophysics*, **223,** 363–380.

Armijo, R. & Thiele, R., 1990. Active faulting in northern Chile: ramp stacking and lateral decoupling along a subduction plate boundary, *Earth planet. Sci. Lett.*, **98,** 40–61.

Armijo, R., Tapponnier, P., Mercier, J.L. & Han, T.L., 1986. Quaternary extension in southern Tibet: field observations and tectonic implications, *J. geophys. Res.*, **91,** 13 803–13 873.

Aspden, J.A., Litherland, M. & Salazar, E., 1988. Una interpretación preliminar de la historia colisional del centro y sur del Ecuador y posibles controles para la geología cenozoica y de mineralizaciòn polimetálica, *Politécnica Monografía de geología 5*, **XIII,** 3, 49–75.

Avouac, J.P., Tapponnier, P., Bai, M., You, H. & Wang, G., 1993. Active thrusting and folding along the northern Tien shan and late Cenozoic rotation of the Tarim relative to Dzungaria and Kazakhstan, *J. geophys. Res.*, **98** (B4), 6755–6804.

Baldock, J.W., 1982. *Geology of Ecuador: Explanatory Bulletin of the National Geological Map of the Republic of Ecuador, Scale 1:1 000 000, Min. Rec. Nat. Energ.*, Quito.

Barazangi, M. & Isacks, B.L., 1976. Spacial distribution of earthquakes and subduction of the Nazca plate beneath South America, *Geology*, **4,** 686–692.

Barberi, F., Coltelli, M., Ferrara, G., Innocenti, F., Navarro, J.M. & Santacroce, R., 1988. Plio-Quaternary volcanism in Ecuador, *Geol. Mag.*, **125**(1), 1–14.

Beate, B., 1985. El flujo piroclástico de Chalupas como causante de un desastre natural en el Cuaternario de los Andes septentrionales del Ecuador, *Actas I Symp. Latin. Amer. sobre Desatres Naturales*, 21–27.

Benitez, S., 1986. Síntesis geológica de la cuenca Progreso-Ecuador, sección Geológica regional, *IV Cong. Ecuat. Geol. Min. y Petrol.*, **I,** 91–110, CIGMP, Quito.

Blés, J.L., Marin, W., Paris, G., Sauret, B. & Vergara, H., 1990. Néotectonique du sud-ouest de la Colombia: résultats microtectoniques et application à l'étude de l'aléa sismique sur le site de Popayan, *First International Symposium on Andean Geodynamics*, pp. 123–124, Grenoble.

Bourgois, J., Toussaint, J.F., Gonzales, H., Orrego, A., Azema, J., Calle, B., Desmet, A., Murcia, A., Pablo, A., Parra, E. & Tournon, J., 1985. Les ophiolites des Andes de Colombie: évolution structurale et signification géodynamique, in *Géodynamique des Caraïbes*, pp. 475–493, ed. Mascle, A., Technip, Paris.

Bourgois, J., Egüez, A., Butterlin, J. & De Wever, P., 1990. Evolution géodynamique de la Cordillère Occidentale des Andes d'Equateur: la découverte de la formation éocène d'Apagua, *C.R. Acad. Sci., Paris*, **311** (II), 173–180.

Brown, R.D. Jr., 1990. Quaternary deformation, in *The San Andreas Fault System, California*, pp. 83–113, ed. Wallace, R.E., US Geological Survey Professional Paper 1515.

Bull, W.B. & McFadden, L.D., 1977. Tectonic geomorphology north and south of the Garlock Fault, California, in *Geomorphology in Arid Region*, pp. 18–138, ed. Doehring, D.O., George Allen and Unwin, London.

Cabrera, J., Sèbrier, M. & Mercier, J.L., 1989. Plio-Quaternary geodynamic evolution of segment of the Andean Peruvian Cordillera located above the change in the subduction geometry: the Cuzco Region, *Tectonophysics*, **190,** 331–362.

Campbell, C.J., 1974a. Ecuadorian Andes, in *Mesozoic–Cenozoic Orogenic Belts*, pp. 725–732, ed. Spencer, A.M., Spec. Publ. Geol. Soc., **4,** London.

Campbell C.J., 1974b. Colombian Andes, in *Mesozoic–Cenozoic Orogenic Belts*, pp. 705–724, ed. Spencer, A. M., Spec. Publ. Geol. Soc., **4,** London.

Campbell, C.J., 1975. Ecuador, in *The Encyclopedia of World Regional Geology. Part I, Western Hemisphere*, pp. 261–270, ed. Fairbridge, R.W., Dowden, Hatchinson & Ross, Stroudsburg, USA.

Case, J.E., Duran, L.G., Lopez, A. & Moore, W.R., 1971. Tectonic investigations in Western Colombia and eastern Panama, *Geol. Soc. Am. Bull.*, **82,** 2685–2712.

Case, J.E., Barnes, J., Paris, G., Gonzalez, M. & Vina, A., 1973. TransAndean geophysical profile, southern Colombia, *Geol. Soc. Am. Bull.*, **84,** 2895–2905.

Chinn, D.S. & Isacks, B.L., 1983. Accurate source depths and focal mechanisms of shallow earthquakes in western South America and in the New Hebrides Island Arc, *Tectonics*, **2** (6), 529–563.

Cotecchia, V. & Zezza, F., 1969. The Eocene basement of the interandean corridor in the Latacunga–Ambato trough (Ecuador), *Geol. appl. Idrogeol.*, **4,** 43–48.

Cross, T.A. & Pilger, R.M., 1982. Controls of subduction geometry, location of magmatic arc and tectonics of arc and back arc regions, *Geol. Soc. Am. Bull.*, **93,** 545–562.

Daly, M.C., 1989. Correlations between Nazca/Farallon plate kinematics and forearc basin evolution in Ecuador, *Tectonics*, **8** (4), 769–790.

Dávila, F., 1990. Geodinámica plio-cuaternaria de la cuenca de Latacunga–Ambato. Callejon interandino: Sector entre Salcedo y Pillaro, *unpublished thesis*, EPN, Quito.

DeMets, C., Gordon, R.G., Argus, D.F. & Stein, S., 1990. Current plate motions, *Geophys. J. Int.*, **101,** 425–478.

Dirección General de Geologia y Minas (DGGM), 1978. *Mapa geológico del Ecuador, 1/100 000, hoja Ambato*, Ministerio de Recursos Naturales y Energéticos, Quito.

Direcciòn General de Geologia y Minas (DGGM), 1980. *Mapa geológico del Ecuador, 1/100 000, hoja Latacunga*, Ministerio de Recursos Naturales y Energéticos, Quito.

Dirección General de Geologia y Minas (DGGM), 1982. *Mapa geológico del Ecuador, 1/1000 000, hoja Latacunga*, Ministerio de Recursos Naturales y Energéticos, Quito.

Ego, F., Sébrier, M., Lavenu, A., Yepes, H. & Egüez, A., 1993. Quaternary state of stress in the northern Andes and the restraining bend model for the Ecuadorian Andes, in *II International Symposium on Andean Geodynamics*, pp. 89–92, ORSTOM/Oxford University, Paris.

Egüez, A. & Bourgois, J., 1986. La Formacion Apagua: edad y posición estructural en la Cordillera occidental del Ecuador, in *Mem. IV Congr. Ecuat. IGMP*, pp. 161–178.

Faucher, B. & Savoyat, E., 1973. Esquisse géologique des Andes de l'Equator, *Rev. Géogr. Phys. Géol. Dyn.*, XV, 1–2, 115–142.

Feininger, T., 1982. The metamorphic 'basement' of Ecuador, *Geol. Soc. Am. Bull.*, **93,** 87–92.

Feininger, T. & Bristow, C.R., 1980. Cretaceous and paleogene geologic history of coastal Ecuador, *Geologischen Rundschau,* **69**(3), 849–874.

Feininger, T. & Seguin, M.K., 1983. Simple Bouguer gravity anomaly field and the inferred crustal structure of continental Ecuador, *Geology*, **11,** 40–44.

Fleitout, L. & Froidevaux, C., 1982. Tectonics and topography for a lithosphere containing density heterogeneities, *Tectonics,* **1**(1), 21–56.

Froidevaux, C. & Isacks, B.L., 1984. The mechanical state of the lithosphere in the Altiplano–Puna segment of the Andes, *Earth planet. Sci. Lett.*, **71,** 305–314.

Giraldo, C., 1985. Neotectónica y sismotectónica de la región de El Tocuyo–San Felipe (Venezuela centro-occidental), *VI° Cong. Geol. Venez.*, **10,** 6639–6656.

Goossens, P., 1973. Structural control and hydrothermal alteration pattern of Chaucha porphyry copper, Ecuador, *Mineral Deposits*, **8,** 321–331.

Hall, M., 1977. *El volcanismo en Ecuador.* Biblioteca Ecuador, IPGH, Quito.

Hall, M.L. & Beate, B., 1991. El volcanismo Plio-Cuaternario en los Andes del Ecuador, in *El Paisaje Volcánico de la Sierra Ecuatoriana*, pp. 5–17, ed. Mothes, P., Estudios de Geografía, vol. 4, Quito.

Hall, M.L. & Ramon, P., 1978. Estudio microsísmico del Valle Interandino entre Latacunga y Guayllabamba, Dirección Nacional de Defensa Civil, unpublished Report.

Hall, M.L. & Wood, C.A., 1985. Volcano-tectonic segmentation of the northern Andes, *Geology*, **13,** 203–207.

Hall, M.L. & Yepes, H., 1980. Fallamiento y actividad microsismica en el Valle interandino, Ecuador, *Revista Geofísica, IPGH*, **13,** 36–44.

Hall, M.L., Basabe, P. & Yepes, H., 1980. Estudio de las fallas tectonicas y la actividad microsísmica del Valle interandino, entre Pastocalle y Ambato, *Politécnica, Monogr. Geol.*, **V,** 2, 57–78.

Hanus, V., Vanek, J. & Sandoval, G., 1987. Zonas falladas sismicamente activas y la distribución de las fuentes termales en el Ecuador, *Politécnica, Monogr. Geol.*, **XII,** 2, 7–24.

Henderson, W.G., 1979. Cretaceous to Eocene volcanic arc activity in the Andes of Northern Ecuador, *J. geol. Soc. Lond.*, **136,** 367–378.

Hey, R., 1977. Tectonic evolution of the Cocos-Nazca spreading center, *Geol. Soc. Am. Bull.*, **88,** 1404–1420.

INGEOMINAS, 1976. *Geological Map of Colombia, 1/1500 000, Ministerio de Minas y Energia.*

Jarrard, R.D., 1986. Relations among subduction parameters, *Rev. Geophys.*, **24**(2), 217–284.

Jordan, T., 1975. The present-day motions of the Caribbean plate, *J. geophys. Res.*, **80,** 4433–4439.

Kelleher, J.A., 1972. Rupture zone of large south american earthquakes and some predictions, *J. geophys. Res.*, **77**(11), 2087–2103.

Kennerley, J.B., 1971. Geology of the Llanganates area, Ecuador, *unpublished report of I.G.S.* (*Overseas Direction*), 21, London.

Kennerley, J.B., 1980. Outline of the geology of Ecuador, *Overseas Geol. & Miner. Resour.*, **55.**

Lahsen, A., 1982. Upper Cenozoic volcanism and tectonism in the Andes of northern Chile, *Earth Sci. Rev.*, **18,** 285–302.

Lallemand, S., Malavieille, J. & Calassou, S., 1992. Effects of oceanic ridge subduction on accretionary wedges: experimental modeling and marine observations, *Tectonics*, **11**(6), 1301–1313.

Lavenu, A., 1978. Néotectonique des sédiments plio-quaternaires du Nord de l'Altiplano bolivien (région de La Paz, Ayo Ayo, Umala), *Cahiers ORSTOM, série Géologie*, **X**(1), 115–126.

Lavenu, A. & Ballivian, O., 1979. Estudios neotectónicos de las cuencas de las regiones de Cochabamba, Sucre, Tarija, Cordillera oriental Bolivia, *Revista Academia Nacional de Ciencias*, **2**(3), 107–129.

Lavenu, A. & Mercier, J.L., 1993. Evolution du régime tectonique de l'Altiplano et de la Cordillère orientale des Andes de Bolivie du Miocène supérieur à l'Actuel: un effet des forces de gravité et des forces aux limites, *Géodynamique,* in press.

Lavenu, A. & Noblet, C., 1989. Synsedimentary tectonic control of Andean Intermontane strike-slip basins of South Ecuador (South America), in *International Symposium on Intermontane Basins*: *Geology and Resources*, pp. 306–317, eds Thanasuthipitak, T. & Ounchanum, P. Chiang Mai, Thailand.

Lavenu, A., Winter, T. & Avouac, J.P., 1990. Premiers résultats des études de failles actives dans les Andes d'Equateur, in *International Symposium on Andean Geodynamics*, pp. 115–118. Colloques et Séminaires, ORSTOM, Paris.

Lavenu, A., Noblet, C., Bonhomme, M.G., Egüez, A., Dugas, F. & Vivier, G., 1992. New K/Ar age dates of Neogene and Quaternary volcanic rocks from the Ecuadorian Andes: Implications for the relationships between sedimentation, volcanism, and tectonics, *J. S. Am. Earth Sci.*, **5**(3/4), 309–320.

Lavenu, A., Noblet, C. & Winter, T., 1993. Neogene on going tectonics in Southern Ecuadorian Andes. Analysis of the evolution of the stress field, *J. Struct. Geol.*, in press.

Lebrat, M., Mégard, F. & Dupuy, Cl., 1985a. Pre-orogenic volcanic assemblages and position of the suture between oceanic terranes and the southamerican continent in Ecuador, *Zbl. Geol. Paläont. Teill*, **H 9-10,** 1207–1214.

Lebrat, M., Mégard, F., Juteau, T. & Calle, J., 1985b. Pre-orogenic volcanic assemblages and structure in the western Cordillera of Ecuador between 1°40'S and 2°20'S, *Geol. Rdsch.*, **74**(2), 685–713.

Lonsdale, P., 1978. Ecuadorian subduction system, *Am. Assoc. Petrol. Geol. Bull.*, **62**(12), 2454–2477.

Lonsdale, P. & Klitgord, K.D., 1978. Structure and tectonic history of the eastern Panama Basin, *Geol. Soc. Am. Bull.*, **89,** 981–999.

Macharé, J., 1987. La marge continental du Pérou: régimes tectoniques et sédimentaires cénozoïques de l'avant arc des Andes centrales, *unpublished thesis*, University Paris XI.

Maldonado, S. & Astudillo, L., 1989. Formation and evolution of intermontane basins of central and northern zones from Ecuador, in *International Symposium on Intermontane Basins*: *Geology and Resources*, pp. 318–325, eds Thanasuthipitak, T. & Ounchanum, P., Chiang May, Thailand.

Malfait, B.T. & Dinkelman, M.G., 1972. Circum Caribbean tectonic and igneous activity and the evolution of the Caribbean plate, *Geol. Soc. Am. Bull.*, **83,** 251–272.

Martinez, C., 1980. Structure et évolution de la chaîne andine dans le nord de la Cordillère des Andes de Bolivie, *Travaux ORSTOM*, **19**.

McCourt, W.J., Aspden, J.A. & Brook, M., 1984. New geological and geochronological data from Colombian Andes: continental growth by multiple accretion. *J. Geol. Soc. Lond.*, **141,** 831–841.

Medwedeff, D.A., 1989. Growth fault-bend folding at southeast Lost Hills, San Joaquin Valley, California, *Am. Assoc. Petrol. Geol. Bull.*, **73**(1), 54–67.

Mégard, F., Roperch, P., Lebrat, M., Laj, C., Mourier, Th. & Noblet, C., 1987. L'Occident équatorien: un terrain océanique pacifique accolé au continent sud-américain, *Bull. Inst. Fr. Et. And.*, **XVI**(1–2), 39–54.

Moberly, R., Shepherd, G.L. & Coulbourn, W.T., 1982. Forearc and other basins, continental margin of northern and southern Peru and adjacent Ecuador and Chile, in *Trench–Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins*, pp. 171–189, ed. Leggett, J.K., Geol. Soc. London. Spec. Pub., 10.

Moretti, I. & Larrère, M., 1989. Locace: computer-aided construction of balanced geological cross sections, *Geobyte*, **89,** 16–24.

Odin, G.S., 1994. Geological time scale (1994), *C.R. Acad. Sci. Paris*, série II, **318,** 59–71.

Pardo-Casas, F. & Molnar, P., 1987. Relative motions of the Nazca (Farallon) and south American plates since late cretaceous time, *Tectonics*, **6**(3), 233–248.

Pennington, W.D., 1981. Subduction of the eastern Panama basin and seismotectonics of northwestern south America, *J. geophys. Res.*, **86** (B11) 10 753–10 770.

Philip, H. & Mégard, F., 1977. Structural analysis of the superficial deformation of the 1969 Pariahuanca earthquakes (Central Peru), *Tectonophysics*, **38,** 259–278.

Pichler, H., Stibane, F.R. & Weyl, R., 1974. Basischer Magmatismus and Krustenbau im südlichen mittelamerika, Kolumbien und Ecuador, *N. Jb. Geol. Palaöt. Mh.*, **2,** 102–126.

Sauer, W., 1965. *Geologia del Ecuador*, Editorial del Ministerio de Educación.

Schubert, C., 1981. Late-Cenozoic pull-apart basins, Bocono fault zone, Venezuela, *J. Struct. Geol.*, **2**(4), 463–468.

Schubert, C., 1982. Neotectonics of Bocono Fault, Western Venezuela, *Tectonophysics*, **85,** 205–220.

Schubert, C. & Sifontes, R.S., 1970. Bocono fault, Venezuelan Andes: Evidence of post-glacial movement, *Science*, **170** (3953), 66–69.

Schumm, S.A., 1986. *Alluvial River Response to Active Tectonics*, Studies in Geophysics, Active Tectonics, National Academy Press, Washington, DC, pp. 80–94.

Sébrier, M., Mercier, J.L., Mégard, F., Laubacher, G. & Carey-Gailhardis, E., 1985. Quaternary normal and reverse faulting and the state of stress in the Central Peru. *Tectonics*, **4**(7), 739–780.

Sébrier, M., Lavenu, A., Fornari, M. & Soulas, J.P., 1988. Tectonics and uplift in Central Andes (Peru, Bolivia and Northern Chile) from Eocene to Present. *Géodynamique*, **3**(1–2), 85–106.

Simkin, T., Siebet, L., McClell, L., Bridge, D., Newhall, C. & Latter, J.M., 1981. *Volcanoes of the world*, (Smithsonian Institutions) Dowden, Hutchinson and Ross, Strondsburg, PA.

Soulas, J.P., 1981. Recent changes in the Quaternary stress field of the Venezuelan Andes, *EOS*, **62,** 1026.

Soulas, J.P., 1988. Informe de misión en el Ecuador. Proyecto UNDRO-EPN. Programa de prevención de planificación para desastres en el ecuador y paises vecinos, unpublished report.

Soulas, J.P., Egüez, A., Yepes, H. & Perez, V., 1991. Tectónica activa y riesgo sismico en los Andes ecuatorianos y el extremo sur de Colombia, *Bol. Geol. Ecuat.*, **2**(1), 3–11.

Stauder, W., 1975. Subduction of the Nazca plate under Peru as evidence by focal mechanisms and by seismicity, *J. geophys. Res.*, **80**(8), 1053–1064.

Suarez, G., Molnar, P. & Burchfield, B.C., 1983. Seismicity, fault plane solutions, depth of faulting and active tectonics of the Andes of Peru, Ecuador, and southern Colombia, *J. geophys. Res.*, **83**(B12), 10 403–10 428.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding, *Am. J. Sci.*, **283,** 684–721.

Suppe, J. & Medwedeff, D.A., 1990. Geometry and kinematics of fault-propagation folding, *Eclogoe geol. Helv.*, **83**(3), 409–454.

Tibaldi A. & Ferrari L., 1992. From latest Miocene thrusting to Quaternary transpression, and transtension in the Interandean Valley, *Ecuador J. Geodyn.*, **15,** 59–83.

USGS, NEIC, 1988. World data center-A for seismology, Listing 1977 to 1988, US Dept. of the Interior.

Winter, T., 1990. Mécanismes des déformations récentes dans les Andes équatoriennes, *unpublished thesis*, University Paris-Sud.

Winter, Th. & Lavenu, A., 1988. Evidencias morfológicas y microtectónicas de una falla de rumbo activa en la parte central del Ecuador, *V° Cong. Ecuad. Geol. Min. Petrol.y Cienc. Afin.*, Loja.

Winter, Th. & Lavenu, A., 1989a. Tectonique active en Equateur: ébauche d'une nouvelle interprétation géodynamique, *Bull. Inst. Fr. Et. And.*, **XVIII**(1), 95–115.

Winter, Th. & Lavenu, A., 1989b. Morphological and microtectonic evidence for a major active lateral strike-slip fault across central Ecuador (South America), *Annales Tectonicae*, **III**(2), 123–139.

Winter, T., Iglesias, R. & Lavenu, A., 1990. Presencia de un sistema de fallas activas en el sur del Ecuador. *Bol. Geol. Ecuat.*, **1,** 53–67.

Winter, T., Avouac, J.P. & Lavenu, A., 1993. Late Quaternary kinematics of the Pallatanga strike-slip fault (Central Ecuador) from topographic measurements of displaced morphological features, *Geophys. J. Int.*, **115,** 905–920.

Yeats, R.S., 1977. High rates of vertical crustal movement near Ventura, California, *Science*, **196**(4287), 295–298.