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Geomorphic and tectonic evolution of the Ecuadorian Andes

M. Coltorti [a,*], C.D. Ollier [b,1]

[a] *Dipartimento di Scienze della Terra, Università di Siena, Via di Laterina, 8-53100 Siena, Italy*
[b] *Centre for Resource and Environmental Studies, Australian National University, Canberra 0200, Australia*

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Abstract

In Early Miocene times the Cordillera did not exist and the Pacific Ocean reached the Oriente. In the Middle Miocene, the uplift of an elongated swell, consisting of Palaeozoic and older rocks, created the Eastern Cordillera. Decollements were activated diverging away from the Eastern Cordillera. In the eastern trench, located approximately in correspondence with the present day Interandean Depression, many thousands of meters of sediments were deposited. A planation surface was created at the end of Lower Pliocene from the Costa to the Oriente graded to sea level. Later, ignimbric flows covered much of the planation surface. Uplift brought the planation surface to 3500–4000 m. The Interandean Depression, bounded by normal faults, was created during the Upper Pliocene, and large strato-volcanoes erupted at this time. The volcanic activity contributed to the filling of an accumulation plateau preserved today in many parts of the Interandean Depression. The creation of the Interandean Depression is the result of lateral spreading activated as a consequence of uplift of the Cordillera. In the Middle and Late Pleistocene the Cordillera and the Accumulation plateau were mostly affected by downcutting with minor episodes of accumulation during the cold phases.

Keywords: geomorphology; tectonic; planation surface; uplift; Ecuador; Andes

1. Introduction

The Ecuadorian Andes (Figs. 1 and 2) constitute part of the mountain chain that runs along the western side of South America. It separates a relatively narrow belt facing the Pacific Ocean from the large Amazonian Basin. In Ecuador the chain is 600 km long but is only 150–180 km wide. This is the narrowest part of the Andes, and very suitable for regional study. It is commonly subdivided into two ridges separated by a tectonic depression, but to the north, in the easternmost part, a third ridge (called Napo Uplift by Baldock, 1982) exists which reaches its maximum development in Colombia. West of the Ecuadorian Andes is a dissected plateau, about 500 m high, called the Costa (not a coastal plain), and to the east is the region of Amazonia.

A striking feature of the Cordillera is a planation surface, preserved as slightly dissected remnants extending for tens of kilometers. Planation surfaces are described at the top of many important mountain chains of the world (Davis, 1899; King, 1962, 1976; Pecsi, 1970; Adams, 1975; Ollier, 1981; Widdowson, 1997). Most of the authors agree that they represent erosion surfaces created close to the sea level and later uplifted, creating the present high

* Corresponding author. Fax: +0039-577-233814/233938.
E-mail addresses: coltorti@unisi.it (M. Coltorti), cliffol@cres.anu.edu.au (C.D. Ollier).
[1] Fax: +61-6-2490757.

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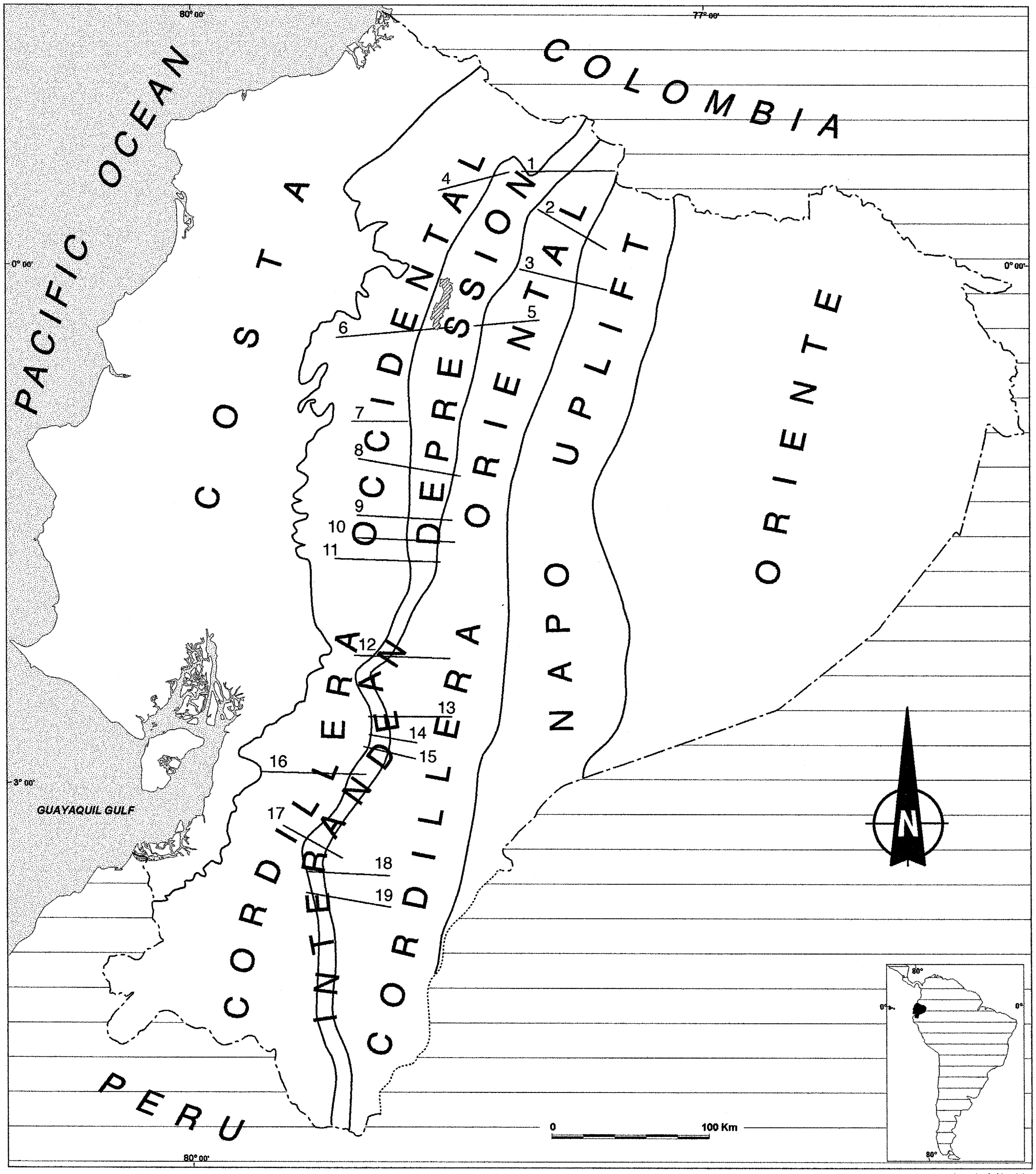


Fig. 1. The main physiographic regions of the Ecuadorian Andes with the location of the sections of Fig. 2.

relief. The rocks affected by planation were previously folded, faulted and sometimes overthrust for tens of kilometers. A planation surface, preserved on top of the mountain chain, clearly indicates that ''mountain building processes'', that is the uplift, occurred after the creation of these older structures.

In Ecuador, Pleistocene and recent volcanoes cover parts of this planation surface. The volcanoes rise up to 6000 m, well above the mean elevation of the planation surface which is about 3500 m. Sometimes the planation surface is tilted or displaced by younger faults. In most places it is also dissected by glacial erosion and may be reduced to ''accordant summits''. All these modifications, which occurred later in the history of the Cordillera, however, fail to mask the evidence of the planation processes.

We aim to illustrate the geomorphological evolution of the Ecuadorian Andes and especially the significance of the planation surface. The planation surface is a starting point for the recent evolution of the Andean Cordillera, constraints the nature of tectonic processes, and provides a better understanding of the other geomorphic units, such as the volcanic chains and the Interandean Depression.

2. The planation surface

In the Andean Cordillera the presence of large flattened or gently rolling parts, recognized since the beginning of the century, were often described as the ''puna surface'' (Bowman, 1916; Cobbing et al., 1981; Tosdal et al., 1984) because they are often preserved at the elevation of the ''puna'', the upper vegetational belt of the Cordillera. Many authors recognize multiple planation surfaces (Dollfus, 1973; Dresch, 1973; Cobbing et al., 1981; Tosdal et al., 1984; Kennan et al., 1997). In Bolivia they have been recognized on top of the Cordillera and in the Oriente (Dresch, 1958). In the Argentinean–Chile Cordillera several surfaces has been referred to as Miocene (Segerstrom, 1963; Viers, 1964; Borde, 1966; Clark et al., 1967; Galli, 1968; Paskoff, 1970). In the Colombian Andes planation surfaces have been recognized (Khobzi and Usselmann, 1973; Page and James, 1981; Ruiz, 1981; Soeters, 1981; Kroonenberg et al., 1990). Most authors agree that the genesis of the planation surface pre-dates the creation of the Interandean Depression.

During the Plio-Pleistocene, the Cordillera was uplifted more than 3000 m since the formation of the ''puna surface''. The progressive transition from a tropical lowland to a mountain is revealed in Plio-Pleistocene deposits (Radelli, 1967; Van Der Hammen et al., 1973; Hooghiemstra, 1989), whose base is about 2740 ka old (Andriessen et al., 1994). Plio-Pleistocene deposits are located in the Interandean Depression of Colombia and indicate uplift during the Upper Pliocene and the Quaternary.

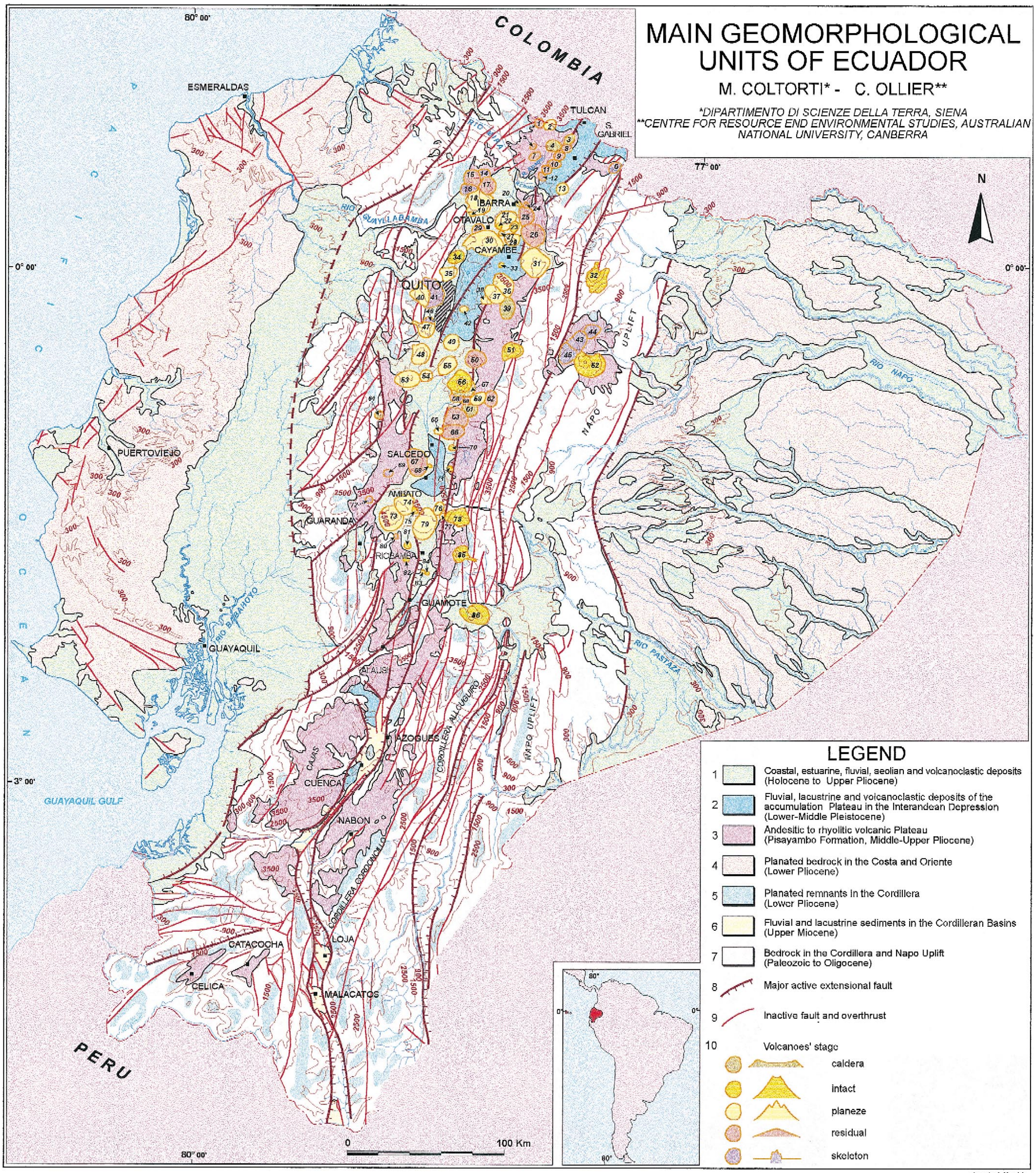
Kohn et al. (1980) and Kroonenberg et al. (1990) reviewed geological and geomorphic evidence, and fission-tracks and K/Ar dating to establish the age and rates of uplift for the Colombian Andes. Hoorn (1993) and Hoorn et al. (1995) studied the change in drainage pattern in the Cordillera and Amazonian basin. They concluded that the Cordilleras started to rise in the Miocene, but important uplift occurred during the Plio-Pleistocene, with some differences in the age of the planation surface from one block to another.

2.1. Rocks and tectonic structures underlying the planation surface in the Ecuadorian Cordillera

Above a metamorphic Paleozoic and possibly Precambrian basement lies a sequence of Mesozoic and Tertiary rocks over 10,000 m thick (Sauer, 1965; Faucher and Savoyat, 1973; Kennerley, 1980; Baldock, 1982; Litherland et al., 1993) (Fig. 3). The basement is represented by orthogneiss, amphibolites, schists and quartzites. It is locally covered by a series of basaltic to andesitic lavas, volcanoclastics, sandstones, conglomerates and lutites deposited from Cretaceous to Oligocene. Later, between 26 and 19 Ma, a thick series of rhyolitic to andesitic lavas covered much of the Cordillera (Hungerbuhler et al., 1995; Lavenù et al., 1995), overlain in places by sandstones, conglomerates and clays. The whole Cordillera was intruded by granite and granodiorite batholiths which gave K/Ar ages from 214 to 10 MY (Baldock, 1982; Hall and Calle, 1982) and constitutes one of the largest batholiths in the world (Gansser, 1973).

The sedimentary sequence has been affected by a series of overthrusts verging either toward the Oriente or the Costa and creating a structural setting that diverges from the Cordillera where the older rocks are preserved (Kennerley, 1980; Baldock, 1982; Litherland et al., 1993). Thick slices of metamorphic rocks, intercalated in the thrust units (Paute sequence of Baldock, 1982), reveal that the basement was involved in these movements. The structure was largely created before planation.

To understand the tectonic movements that affected the Cordillera before planation, the age, sedimentological and structural setting of the first continental deposits, preserved in the Interandean basins and lying unconformable over the previous units, are particularly important. These Upper Miocene continental formations include alluvial fan, fluviatile, lacustrine and volcanoclastic deposits (Chota, Sibambe,



Cuenca, Nabon. Loja, Rio Playas and Malacatos) (Berry, 1929, 1945; Bristow, 1973; Kennerley, 1973, 1980; Baldock, 1982; Lavenù et al., 1995; Hungerbuhler et al., 1995) (Figs. 2 and 3). K/Ar dating of the volcanic layers of the Chota Formation, which was planated, reveal an age at the end of the Miocene (Ch 535: 6.30 ± 0.6 Ma; CH 537: 6.31 ± 0.10 Ma; Barberi et al., 1988). The Upper Miocene Formations, filling the Nabon basin of southern Ecuador, were deposited between 8.5 and 7.9 Ma (fission tracks, Hungerbuhler et al., 1995). In the Cuenca Basin the outcropping formations were deposited between 22 and 8 Ma (non calibrated K/Ar, Lavenù et al., 1995).

Volcanic activity and synsedimentary tectonics complicate the sedimentation. The Cuenca basin has been interpreted (Lavenù et al., 1995) as a pull-apart basin, associated with strike slip movements along N–S and right-lateral normal movements along N20–N40 faults. In the Nabon basin (Hungerbuhler et al., 1995) the deformation has been interpreted as resulting from the activity of master reverse faults bounding the basin to the west. No proof exists of the synsedimentary activity of the faults. Detailed sedimentological study of the Nabon basin indicates that the sediment comes mainly from land to the east and north-east. The inferred syntectonic movements did not have any role in the subdivision of the sedimentary environments. Similar flow directions and sedimentary environments are found in the present day coastal area of Ecuador, to the north of the Guajaquil fault, without the presence of a Cordillera bounded by a reverse fault to the west. In any case, the limits of the sediments correspond more or less to normal faults bounding the Interandean Depression (Kennerley, 1980; Baldock, 1982) which, as described later, were activated or reactivated during the Pleistocene.

We explain the genesis of these basins in another way. In the Punin area (Fig. 3b, Section 10), south of Rio Bamba, Cretaceous red beds (Silante Fm) are lying horizontally and unconformably on conglomerates of the Guamote Fm (Jurassic). Over the Cretaceous are more than 1000 m of severely faulted and folded sediments (Upper Cretaceous to Upper Miocene) which extend up to the coastal area. In the Chota valley (Carchi Province) (Fig. 3a-4), near Ambuqui slightly westward tilted continental Cretaceous deposits are lying unconformably over Paleozoic (?) schists. To the west, Upper Miocene continental sediments (Chota Group), similar to the ones described in Cuenca and Nabon, are again severely folded and faulted. In both cases the underlying rocks are not folded or faulted.

We suggest that east and west vergent low angle normal faults affected the sequence overlying the basement and, in places even the basement, and gave rise to typical thick-skinned tectonics. The extention, which allowed the outcrop of the basement in the Eastern Cordillera, was compensated by the piling up of rocks involved in east and westward overthrusts. Extentional and compressional processes are directly associated and constitute a relatively superficial feature. The detachment tectonics affected rocks which

Fig. 2. Geomorphological map of Ecuador showing places and features mentioned in the text. Volcanoes stage of erosion (Ollier, 1987): Intact (I); Planeze (P); Residual (R); Skeleton (S); Caldera (C); with recent cones (wc); active (a); collapsed (c). (1) Cerro Negro de Marasquer (Rwc); (2) Chiles (Pwc); (3) Chalpatan (C); (4) Potrerillos (C); (5) Chiltazon (R); (6) Soche (S); (7) Iguan (R); (8) Horqueta W (R); (9) Cerro Maiurco (R); (10) Azufral (R); (11) Boliche (R); (12) Cerotal (R); (13) Mangus (P); (14) Pilavo (S); (15) Negro Puno (R); (16) Yanaurco (S); (17) Chachimbiro (R); (18) Cotacachi (P); (19) Cuicocha (Ia); (20) Yahuarcocha (C); (21) Imbabura (P); (22) Cerro de Araque (I); (23) Cerro Cubilche (I); (24) Guangaba (R); (25) Redondo (R); (26) Rumiloma (R); (27) Laguna S.Pablo (C); (28) Cusin (P); (29) Cushnirrumi (R); (30) Moyanda (P); (31) Cayambe (P); (32) Reventador (I); (33) Cananvalle (I); (34) Pululagua (C); (35) Casitagua (P); (36) Pambamarca (P); (37) Las Puntas (Pwc); (38) Cotourcu (P); (39) Chacana (C); (40) Guagua Pichincia; (41) Ruhu Pichincia; (42) Ilalo (P); (43) Pan de Azucar (S); (44) Cerro Negro (R); (45) Loa Guacamayos (S); (46) Cerro Pailon (S); (47) Atacazo (P); (48) Corazon (P); (49) Pasochoa (P); (50) Sincholagua (R); (51) Antisana (Ia); (52) Sumaco (Ia); (53) Iliniza (P); (54) Loma Santa Cruz Chica (R); (55) Ruminahui (P); (56) Cotopaxi (Ia); (57) Morurco (C); (58) Agualongo Nord (R); (59) Quilindana (P); (60) Morro (R); (61) Chalupas (C); (62) El Descanso (R); (63) Titsulo (R); (64) Quilotoa (Ia); (65) Putzulagua (P); (66) Paturcu (R); (67) Sagoatoa (R); (68) Cerro Chuquirahua (S); (69) Unamancho (I); (70) not visited; (71) not visited; (72) Cerro Puevulo (S); (73) Chimborazo (Iwc); (74) Carihuairazo (P); (75) Punalica (I); (76) Llimpi (P); (77) Mulmul (P); (78) Tungurahua (Ia); (79) Igualata (P); (80) Cerro Shohulurcu (R); (81) Calpi (I); (82) Loma Luyuc (Iwc); (83) Tulabug (I); (84) Bellavista (I); (85) El Altar (Ic); (86) Sangay (Ia).

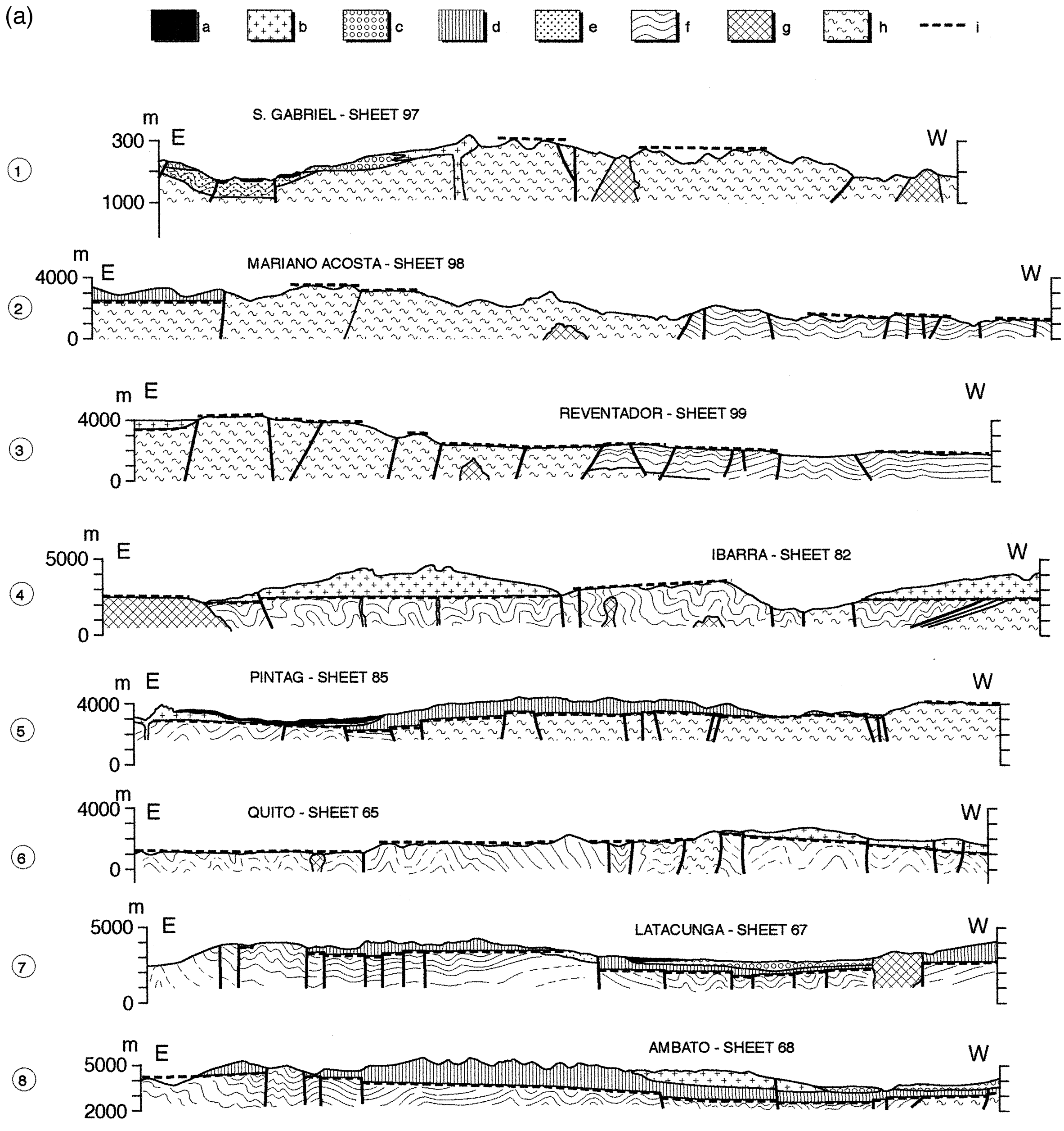


Fig. 3. (a and b) Geological cross sections across the Cordillera from north to south. (a) Fluvial, lacustrine, aeolian, landslides and volcanoclastic (Holocene–Middle to Lower Pleistocene); (b) intrusive, lava flows and pyroclastics (Holocene–Middle to Lower Pleistocene); (c) conglomerates and pyroclastics with subordinate lavas (Accumulation Plateau, Upper Pliocene–Lower Pleistocene); (d) lavas and ignimbrites (Volcanic plateau, Pisayambo Formation, Middle–Upper Pliocene); (e) alluvial fan, fluviatile and lacustrine deposits in the tectonic depressions of the Cordillera (Upper Miocene); (f) continental and marine sediments (Upper Miocene–Cretaceous); (g) intrusive rocks; (h) basement (Paleozoic); (i) planation surface. In correspondence to the Chota valley (Section 4; Ambuqui area) and Punin (Section 10, south of Rio Bamba) the basement is unconformably covered by horizontal or gently dipping Cretaceous Red Beds. These are covered by strongly folded and thrusted rocks from Cretaceous (Yunguilla Fm) to Upper Miocene (Chota Group) which allow us to recognize the presence of a detachment surface which affected the sedimentary cover. The planation surface, modelled during the Early Pliocene, has been recognized on top of the Napo Uplift as well as on the westernmost part of Oriente.

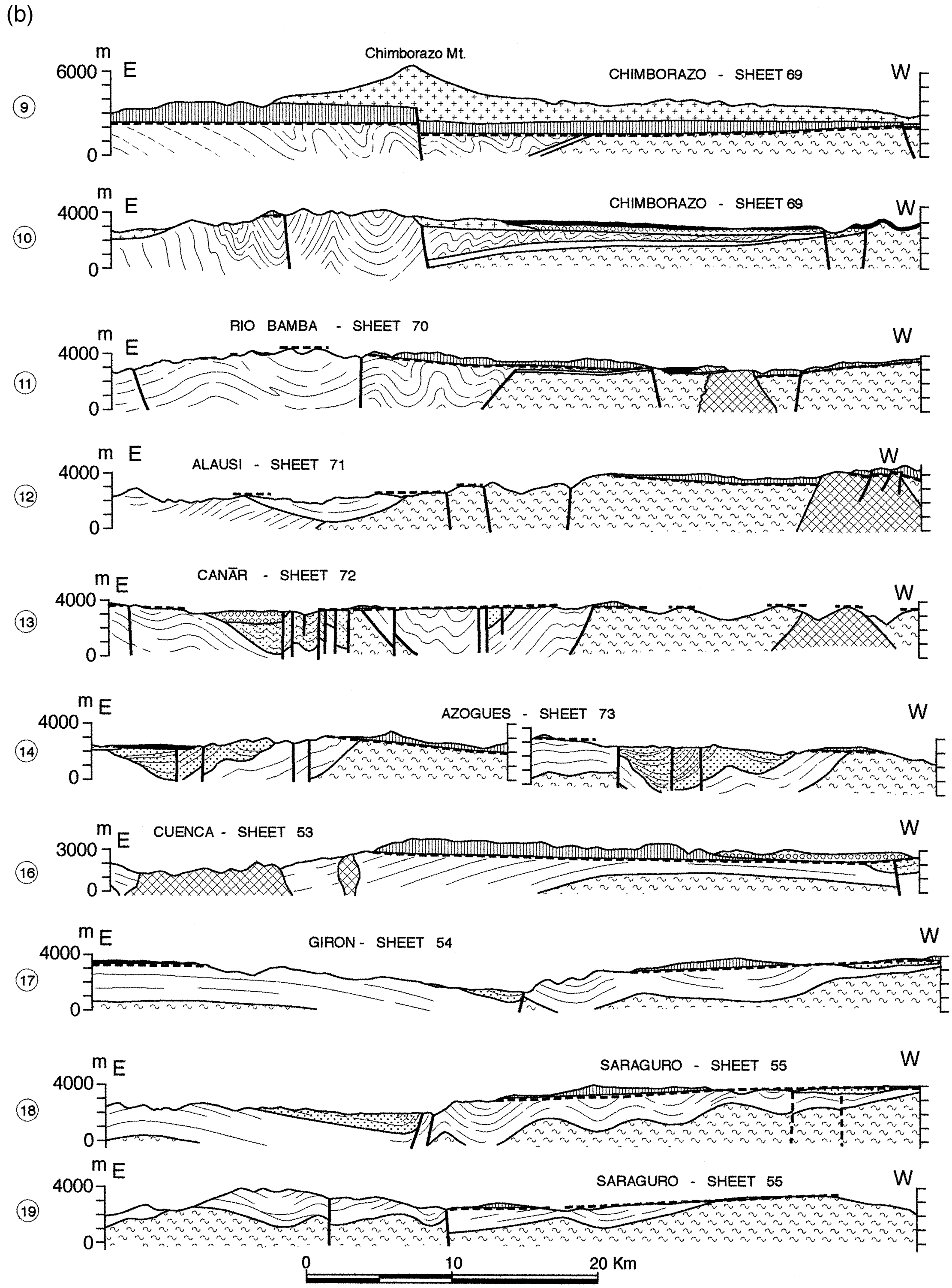


Fig. 3 (*continued*).

were once submarine deposits on the margin of the Pacific ocean, with potential glide planes. After uplift, the steepness of the continental margin could influence the activation of this large-scale gravity tectonics (Fig. 4). The main glide surface occurred in Cretaceous clayey continental sequences and at the contact with the basement. Other minor glide surfaces (low angle normal faults) could occur at different levels in the sequence corresponding to marly layers. Taking into account that the relief created after these movements supplied the Upper Miocene continental basins with metamorphic rock, and that similar structures are present in the Oriente, uplift movements must be invoked. High elevations were reached in the Cordillera during Plio-Pleistocene times but it is possible to infer some uplift at the end of the Miocene. The planation surface testifies to cessation of uplift, when erosion was able to remove the older relief.

The gravitational movement created a large elongated trench which was the site of a series of depressions close to the base of what today is the Eastern Cordillera. The filling of these basins, especially the Nabon basin which contains the youngest sediments (7.9 Ma), post-date the large-scale gravitational movement and testify to the later reactivation, still in the Miocene (Fig. 4). Evidence for huge deep-seated gravitational movements has been found in the continental escarpment of Northern Perù (Bourgouis et al., 1990). The whole series, including the Late Miocene basins, was later eroded and planated. Much later in the Pleistocene, it was uplifted by normal faulting (Fig. 4). A planation surface has also been recognized in the Costa, although described as a ‘‘general unconformity’’ (Kennerley, 1980). It cuts folded sandstones, siltstones, shales and clays with intercalated tuff, limestones and calcareous shells layers deposited in a shallow water marine environment (Borbon and Progreso Formations) during Upper Miocene–Lowermost Pliocene (Bristow and Hoffstetter, 1977; Baldock, 1982). The planation process, therefore, extends to the Earliest Pliocene.

In the Oriente, clastic sediments coming from the erosion of the Cordillera were emplaced over large areas in the Late Miocene. The Curaray Formation is composed of clays and gypsum with limited amount of sands. It contains a fresh to brackish water fauna of Late Miocene age and suggests a connection to the Pacific Ocean, before the Cordillera was developed. It is overlain by a coarse clastic formation (Chambira Fm) that contains sediments derived from basement rocks.

In Colombia and Venezuela the Upper Miocene sediments reveal a fluviatile environment with marine influences, including marine palinomorphs, mangrove pollen, mollusk and ostracods tolerant of brackish conditions (Hoorn et al., 1995). These formations are unconformably covered by a clastic formation coming from the erosion of the Cordillera, similar to the Chambira of Ecuador. It is, therefore, suggested that the Cordilleras of Colombia and Venezuela underwent the same processes recorded in Ecuador. Similar events seem to occur in Bolivia (Kennan et al., 1997).

2.2. The planation surface in Ecuador

The planation surface is preserved at similar elevations over long tracts of the central Ecuadorian Cordillera (Fig. 5). Only one planation surface exists, although it changes gradually in elevation from one part of the Cordillera to another. Fault escarpments that displace the surface are easy to recognize, and no evidence of pediplanation at the base of any escarpment has been identified. The major fault escarpments which delimit the remnants of the planation surface are steep and slightly dissected by erosion and locally covered by surficial deposits.

The elevation of the planation surface can be measured only where it is not covered by extensive lava and ignimbrite fields. It is particularly well preserved on the outcrops of metamorphic rocks of the Eastern Cordillera in the southern part of the country, where from the Peruvian border across the so-called Cordillera Cordoncillo and the Cordillera de Allcuiguir, east of Ingapirca is located around 3000–3500 m. Similar elevations have been observed in the planation remnants bevelling the Paleozoic rocks outcropping east of Guamote and Ambato. East of Quito it is preserved at 3500–4000 m and similar elevations are recorded going toward the Colombian border.

The Western Cordillera is similarly flattened at 3000–3500 m in the southern part of the country where it planates rocks from Cretaceous to Pale-

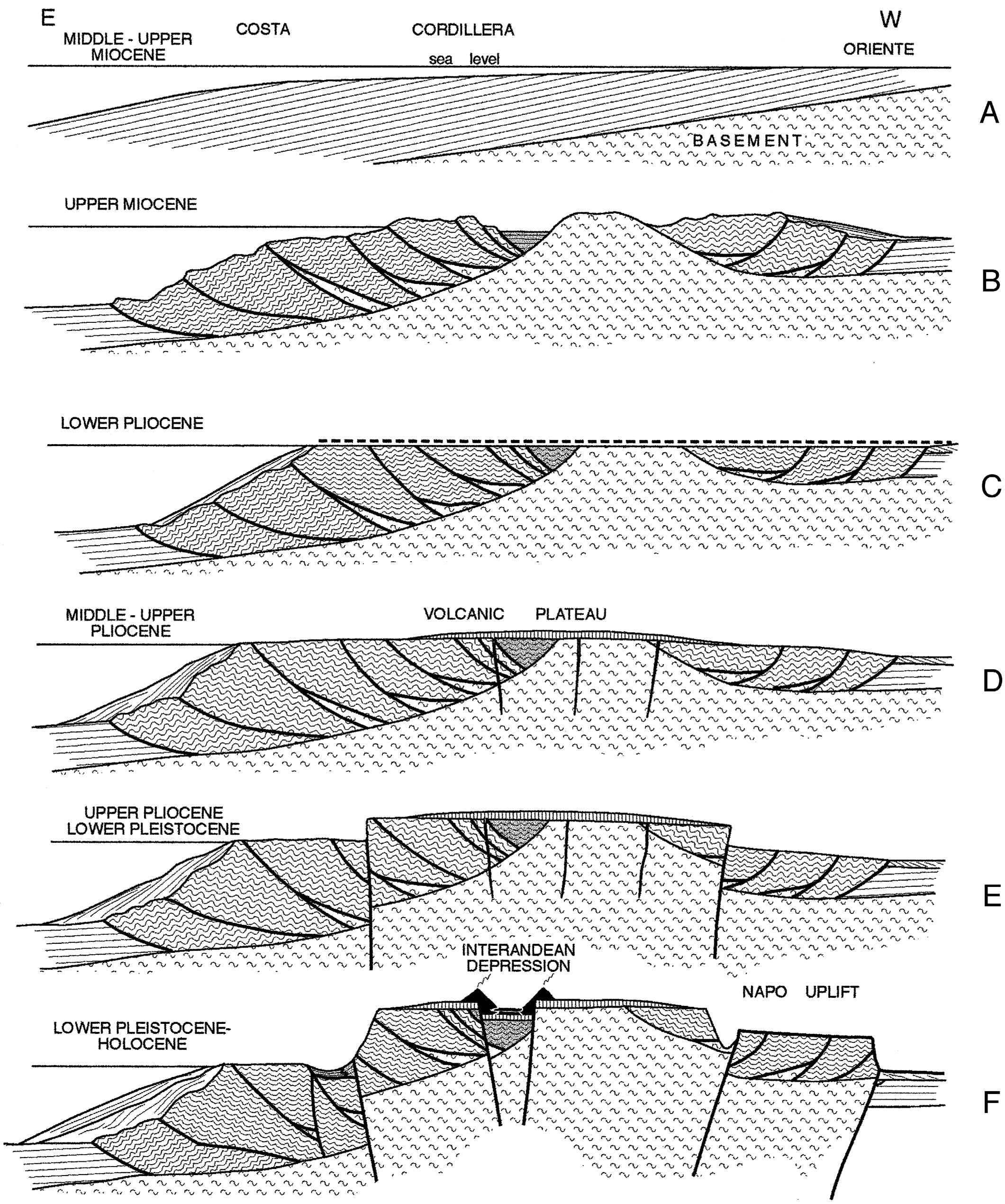


Fig. 4. Sequence of the events which led to the build up of the Cordillera. (A) Cratonic area bordering a sedimentary platform on the Pacific side of south America (Middle–Upper Miocene). (B) Beginning of the uplift of the Eastern Cordillera (Upper Miocene). Tectonic denudation of the sedimentary cover and activation of a detachment movements in a thick skinned tectonics framework. As a consequence folded and thrusted rocks toward the Amazonian basin as well as toward the Pacific were created. The trench created on the western side was the site of continental sedimentation which was further deformed due to the contamination of the detachment movements; (C) modelling of the planation surface across the Costa, the Cordillera and part of the Oriente (Lower Pliocene); (D) a widespread effusive activity led to the emplacement of a Volcanic Plateau (Middle–Upper Pliocene); (E) progressive uplifting in the order of 3–4000 m in ca. 4 Ma. (F) Activation of lateral spreading in the Cordillera with creation of the Interandean tectonic depression. Another huge trench formed since the Pliocene along the Pacific side with the creation of a depression hosting continental and estuarine sedimentation (Guayaquil Gulf and Guayaquil Babahoyo line). Activation of the volcanoes in tectonic depression.

ocene, including some granite and granodiorite batholiths. West of Rio Bamba it has been observed on the watershed, at elevations close to 3900 m, cut across the (gravity) folded Cretaceous conglomerates and sandstones (Yunguilla Fm) as well as over the succeeding formations up to the Oligocene ignimbrites (Saraguro Fm). The planation surface cuts across many formations, unaffected by the different resistance of the rocks, as shown on most of the official maps made by the Geological Survey of Ecuador. The mean elevation decreases toward the Costa and the Oriente and large flattened parts are preserved at about 2000 m and even at lower elevations. The Napo Uplift, which characterizes the eastern part of the Cordillera at the border with the Oriente, is also at about 2000 m. Further north the progressive rise to the third Cordillera of Columbia (Tschopp, 1953; Faucher and Savoyat, 1973) is flattened at around 2000 m.

The lowering of the planation surface toward the flanks of the Cordillera can occur progressively if it is slightly warped, or in a stepped way if it is faulted. Usually, two major fault escarpments separate the Cordillera from the other two physiographic regions, the Costa and the Oriente, where the planation surface is located at elevations of 400–600 m .

Establishing the extent of the planation in the Oriente is difficult. It developed after the emplacement of the Arajuno and Curaray Upper Miocene Formations which were deposited under fluvial, lacustrine and estuarine conditions. The planation surface also developed after the deposition of the deformed Mio-Pliocene Chambira formation.

3. The volcanic plateau

A series of volcanic deposits, grouped together in the Pisayambo Formation (Litherland et al., 1993) lies on top of the Planation surface and creates a volcanic plateau (Figs. 3 and 4). The Cuenca area (Cajas) was the centre for these volcanic spreads in the south although some minor volcanic sheets occur further to the south (Celica e Catachoca) and to the north (Guamote–Alausi area). These horizontally layered materials cover an area over 80 km across and include ignimbrites, agglomerates, tuffs and lavas (Tarqui Formation of Baldock, 1982; Hall and Beate, 1991). The composition is rhyolitic to andesitic and the thickness is reported to be over 1000 m. No eruptive centre has yet been identified and it has been suggested that they may result from fissure eruption. The volcanics erupted before the creation of the tectonic depression. These volcanic products were deposited all along the Cordillera, including the margin of the eastern Cordillera, where they are thinner. If the depression had already existed, it would have been filled with volcanics and the volcanic deposits would have been thicker in the depressed area. In the north the volcanic deposits do not become thicker inside the tectonic depression, although in most places of this area they are completely missing, probably eroded in more recent times.

In the area north of Rio Bamba, in both Cordilleras, the planation surface is covered by pyroclastics and massive basaltic–andesite flows which are reported to be more than 2000 m thick in places (Kennerley, 1980; Baldock, 1982). In the areas that we visited, however, they are not thicker than 500 m.

We classified the volcanoes of the Cordillera according to the degree of erosion (Ollier, 1987; Figs. 2 and 7). North of Rio Bamba we recognized many skeleton volcanoes on the planation surface and on the volcanic plateau. South of Ibarra the Las Puntas is a residual volcano at the transition to the skeleton stage. West of Ambato old necks give rise to isolated peaks (Cerro Puevulo and Cerro Chuquirahua). Skeleton volcanoes have also been observed at the contact between the Cordillera and the Napo Uplift (Pan de Azucar; Cerro Pailon, Cerro Negro), as well as south of Tulcan (Soche). In the western Cordillera skeleton volcanoes have been recognized west of Otavalo (Pivalo, Yanaurcu). Volcanic plateaus did not cover the entire planation surface along the whole Cordillera, and many non-volcanic flattened parts remained exposed.

These volcanics were regarded as Plio-Pleistocene by Hall and Calle (1982), but have since been K/Ar dated by Barberi et al. (1988) as Mio-Pliocene (Ec 158: 4.78 ± 0.50 Ma; CH 682: 6.10 ± 0.60 Ma). A K/Ar dating of 6.3 ± 1 Ma has been obtained in the Nabon Basin (Lavenù et al., 1995; Hungerbuhler et al., 1995). The ages obtained for the ignimbrites of the Cuenca province, once regarded as Tarqui For-

Fig. 5. Planation surface on the Cordillera. (a) Eastern Cordillera, north of Alausi, over Cretaceous folded rocks; (b) Western Cordillera, east of Bolivar, over metamorphic rocks.

mation (Baldock, 1982) are completely unreliable. They were first based on ^{14}C datings of fossil wood intercalated in the volcanic effusions which gave an Upper Pleistocene age (Bristow and Hoffstetter, 1977), whereas Barberi et al. (1988) on non-calibrated K/Ar datings (whole rock) attributed them to the Middle Miocene. They have to be younger than 6.0 Ma because all along the Cordillera they cover folded rocks such as Chota Formation of this age. It is possible that they are Lower Pliocene in age, thus giving the supposed age of the planation surface they cover. This then is the span of time available for the uplift of the Cordillera and its deep dissection, and for the erosion of the skeleton volcanoes.

4. The Pleistocene volcanoes and the Interandean Depression

A series of strato-volcanoes erupted during the Quaternary and many of them are still active (Hall, 1977; Hall and Calle, 1982; Simkin et al., 1981; Barberi et al., 1988; Mothes and Hall, 1991; Bigazzi et al., 1992). We recognized a total of 86 major volcanoes (Fig. 2). Most of the active volcanoes occur along the edge of the Interandean Depression and only a few of them are located in the middle. A few volcanoes are located in the Eastern Cordillera.

The skeleton stage has been reached only by the volcanoes located on the planation surface. The residual stage has been reached in many cases. Most of them are aligned with the borders of the tectonic depressions and, therefore, with some of the main active faults of the country. The Sagoatoa, the Cushnirrumi and the Chachimbiro, quite far from one another, are the only volcanoes which reached this skeleton stage on the western border of the depression, south of the Chota valley. Northward of this area many residual volcanoes are clustered together (Boliche, Cerotal, Azufran, Cerro Maiurcu, Horqueta W) and are also close to the Chalpatan and Potrerillos Calderas (Chiltazon and Iguan). The residual volcanoes in the western border of the Eastern Cordillera (Sincholagua, Agualongo, El Descanso, Titsulo, Paturcu, Guangaba, Redondo, Rumiloma, etc.) are aligned with the NNE–SSW faults which created the tectonic depression.

Numerous volcanoes exist in the planeze stage and many in a transitional stage between planeze and skeleton. The Llimpi, the Putzulagua, and further north, the Pambamarca, Las Puntas, Cusin and the Mangus perfectly fit the faults aligned with the eastern border of the depression; the Cotacachi, Mojanda, Casitagua, Ruhu Pichinca, Atacazo, Corazon, Iliniza, Chimborazo and Carihuairazo fit the other border and reveal the continuous activity of the faults that delimit the Interandean Depression during the Quaternary. Almost all the active volcanoes of the Central Cordillera are similarly aligned with NNE–SSW faults. Also, the Quilotoa, a recent pyroclastic volcano located close to the western border of the Cordillera, is aligned with these NNE–SSW fault. In many places, as for example east of Quito or from Ibarra to Tulcan, these faults have a vertical displacement of many hundreds of meters and create fault escarpments tens of kilometers long. Erosion of the scarp by lateral valleys creates typical triangular and trapezoidal facets.

Some volcanoes, such as the Mojanda–Cusin–Imbabura, and the Iliniza–Loma S.Cruz Chica–Ruminahui seem to have lineaments that are transverse to the Cordillera. These lineaments, which were not present in earlier times, could indicate the activation of NE faults in the Pleistocene. Slightly less eroded, in the planeze stage, are Cotacachi, Carihuarazo, Cayambe and Imbabura.

Some volcanoes, like Sangay, are located in the eastern side of the Cordillera and affect areas where no other volcanic products were emplaced before. The northern ones (Sumaco and Reventador), also located to the east, however, erupted in areas where skeleton volcanoes already existed.

The K/Ar datings of Barberi et al. (1988) are not always in agreement with the stage of erosion of the different volcanoes. They noted that the strato-volcanoes became active after 1.8–1.5 Ma and recognized a long gap between the older products of the volcanic plateau and the more recent ones. This gap is also recognizable on geomorphological grounds as the skeleton volcanoes were eroded before the plateau was affected by normal faults. More dates, using Ar/Ar dating, are necessary to confirm the ages estimated by Barberi et al. (1988).

The Ilalo, a volcano in the planeze stage that rises in the middle of the Interandean Depression, was eroded by glaciers which created a U-shaped valley down to 2500 m (Quebrada Togllahuacu, west side). The lower limits of the snow line in Ecuador during the Quaternary has been estimated by Clapperton

(1987) at no lower than 3000 m. Therefore, a lowering of the whole area around the volcano of about 500 m occurred since the late Middle Pleistocene.

Winter and Lavenù (1989) and Tibaldi and Ferrari (1992) related the creation of the Interandean Depression to strike–slip faulting which in turn is related to the deep-seated Guajaquil fault. But the Interandean Depression is only coincident with the Guayaquil line for part of its length and diverges southward.

5. The accumulation plateau

In the Interandean tectonic depression a thick sequence of sediments accumulated when the stratovolcanoes were active (Fig. 6). In the north, the sequence outcrops along the Panamerican Highway and in the deep gorge of the Apachi (Rumichaca) river, at a mean elevation of 2500–3200 m, and is mainly composed of conglomerates with thin and rare layers of sands and pyroclastics. A few lava flows, breccias and agglomerates, are also intercalated. In the upper part of the sequence the sandy layers increase in number and some lahars and mud flow are also present.

Southward, as far as Otavalo, the accumulation plateau is deeply dissected and faulted. Deeply weathered remnants occur only to the NE of Ibarra. The accumulation plateau is well preserved from Cayambe to Pifo. In places a thick sequence of lacustrine sediments have been recognized in the upper part of a thick conglomerate sequence (Zezza, 1974).

An impressive series of small-scale folds, faults and overthrusts, only a few tens of meters thick, affect these sediments north of Quito on the road to Cayambe. These structures have been generated during the emplacement of a slump deposit that is intercalated within undisturbed horizontally layered sediments. It provides a model for the larger scale gravitational movements which, as suggested earlier, affected the sediments older than the planation surface during Early Pliocene times.

The accumulation plateau, easily recognizable to the south, as in the area between S. Miguel de Salcedo and Guano, is affected by a series of exten-

Fig. 6. Accumulation plateau in the Bolivar area (Carchi).

sional faults associated with huge, deep-seated gravity slides. In the Cuenca area, at the foot of the Cajas Ignimbrite Plateau, it corresponds to the accumulation of a thick sequence of conglomerates, fluvial sands, clays, tuffs and volcanic breccias, named the Turi Formation (Baldock, 1982), whose top is located at about 3200 m (Huasiloma, south west of Banos). The stratigraphic position of this formation has been recently corrected (Litherland et al., 1993). The upper part of this formation is affected by deep weathering which created a red argillic horizon hundreds of meters thick. The evolution of this kind of feature takes a very long time to develop in a tropical humid climate, usually on the order of hundreds of thousand years (Ollier and Pain, 1996). Deposition of this formation probably ended in the lower Pleistocene. The absence of this weathering horizon outside the Cuenca area may indicate an important erosional event which affected the upper part the formation in the rest of the country.

In most parts of the Interandean Depression the accumulation plateau is deeply dissected by fluvial erosion which created the Guayalabamba gorge, east of Quito, and the Apaqui River gorge, north of the Chota River. The formation of these deep gorges seems to correspond to the cañon stage of the various authors in the rest of South America (cited in Tosdal et al., 1984).

In the vicinity of the intact or planeze stage volcanoes, as in the area of Cotacachi, Imbabura and Cayambe in the north, and Chimborazo, Carihuarazo, Tungurahua and El Altar in the south, the accumulation surface can be deeply buried under recent fluvial, glacial, lahar and debris flow sediments. In other places, especially in the vicinity of NNE–SSW fault escarpments delimiting the Interandean Depression, the accumulation surface can be affected by huge landslides which can be many kilometers long and up to 800 m thick (Coltorti and Dramis, 1992; Falsini, 1995). East of Quito, both faults delimiting the Interandean Depression activated huge, thick landslides. The one on the west side is a deep-seated landslide which begins west of Calderon and can be followed to the Guayabamba River. It is over 4 km long, 2 km wide, and over 600 m thick. On the other side is a landslide 8 km long, 2 km wide and over 300 m thick. The town of Guayalabamba is built on it.

The lacustrine sediments that gently dip toward the Interandean Depression have provided glide surfaces. The deep river dissection created the conditions of gravitational instability, and the high seismicity of the area provided many triggering shocks.

The tectonic depression of Ecuador probably corresponds to the one hosting the lacustrine sediments of the Bogotà region. If so, the 2740 ka age of the sediments reported by Andriessen et al. (1994) could be about the age of the tectonic depression of Ecuador. If this is the case, the volcanic activity on its borders started after the Interandean Depression was created. This together with the Pleistocene ages of the interlayered volcanics in the Interandean Depression would support the Pleistocene age for the cañon stage, recognized in many other parts of the South American Cordillera (Mclaughlin, 1924; Wilson et al., 1967; Myers, 1976; Tosdal et al., 1984; Kennan et al., 1997).

6. The Middle and Upper Pleistocene events

Inside valleys and gorges which dissect the accumulation plateau, at least two alluvial terraces, located at progressive elevations on the valley floor, have been recognized (Falsini, 1995). They are deeply buried and in places interfinger with a series of aeolian sands, tephra layers and paleosols which constitute the Cangahua Formation (Sauer, 1965; Clapperton, 1987, 1993; Clapperton and Vera, 1986; Ficcarelli et al., 1992). The thickness of this sequence is over 100 m in the Carchi province, up to 60 m in the vicinity of Quito, and about 40 m in the Rio Bamba area. It becomes thinner southward and is reduced to patches a few meters thick in the Cuenca basin. It was deposited during the colder phases of the Middle and Upper Pleistocene. The source material was pyroclastic products of the main volcanoes, and the absence of Pleistocene volcanic activity in the southern part of the country seems to be the main reason for its progressive thinning. At higher elevation the glacial advances were important in re-shaping the planation surface, the volcanic plateau, and the strato-volcanoes (Clapperton, 1987). They generated glacial cirques, glacial valleys and moraines, but only two glacial events are well recorded in this part of the Cordillera. In older times, the higher parts of the mountain may have been too low to generate glacial morphologies although climatic fluctuations are well recorded in the Interandean Depression of Columbia (Hooghiemstra, 1989; Andriessen et al., 1994).

Few indications of Upper Pleistocene–Holocene fault activity have been observed, mostly on the western side of the Interandean Depression where a series of huge landslides are aligned with the fault escarpment and the Cangahua deposits are severely displaced. On the eastern side the tectonic activity can be inferred from the alignment of volcanoes with recent activity (Bigazzi et al., 1992). In the Costa a series of marine terraces (Tablazo Fm di Baldock, 1982) lying at progressive elevations above sea level (up to 225 m) reveal the interference of Quaternary climatic changes with the uplift of the area. In the Oriente, the Mesa and Mera Formations (Baldock, 1982; Iriondo, 1994), consist of terrace, alluvial fan and fluviatile sediments which also indicate interplay of climate and tectonic uplift.

7. The Plio-Pleistocene geological evolution of the Cordillera

The planation surface, which was formed during the Early Pliocene, allows us to separate the tectonic movements which affected the area at the end of the Miocene and in the Earliest Pliocene from the ones occurring during the Plio-Pleistocene. This planation surface is the most significant event, separating as it does pre-planation tectonics from post-planation tectonics.

At the end of the Miocene tectonic uplift created a long swell, a ridge elongated parallel to the present-day Eastern Cordillera. This could be associated with gravity tectonics activated at low angle extentional faults which denuded the upper part of this ridge and created large outcrops of Paleozoic rocks. The giant gravitational slide moved along the contact between the basement and the Cretaceous–Upper Miocene sedimentary cover as well as in the basement itself. Extention was compensated by faulting, folding, east and westward thrusting of the latter in a thick-skinned context. Continental Upper Miocene formations filled depressions created on the western side of the denudated areas (East Cordillera). The continuation of these movements later deformed these rocks, today preserved in the Interandean Depression and Western Cordillera before planation. These movements affected the continental slope. The Eastern Cordillera, where Palaeozoic rocks outcrop, represents the denuded area and the Western Cordillera, the Costa and the Continental escarpment is where the detached formations piled up before uplifting occurred. Slices of basement were involved in these thrusts in some places. The presence of large-scale gravity slides in the southern part of the country were suggested by Brown (1938). These movements have limited lateral displacement and did not affect the whole sequence. At places such as in the Chota valley, very deformed successions are in contact with undeformed ones. Intraformational deformation between undeformed strata is a hallmark of gravity sliding. Large-scale gravity sliding can occur in a relatively short time, and ample time exists for the deposition of the succeeding formations.

On the Pacific side, gravity sliding generated a huge trench aligned with the Cordillera and created a series of depressions in which continental sediments accumulated between 8.9 and 7.9 Ma. Erosion of the East Cordillera ridge shed sediments in coarse alluvial fans and fluvial deposits to the Amazonian basin as well as the areas today located in the western Cordillera. Volcanic activity was also important at that time. Gravitational movement continued after the deposition of the Upper Miocene sediments, which are severely deformed (Lavenù et al., 1995; Hungerbuhler et al., 1995). The Lowermost Pliocene Formations outcropping in the Costa were involved in these movements.

The morphology prior to the erosion of the planation surface was not much different from the present day coastal area of Ecuador. This area experienced marine sedimentation during the Plio-Pleistocene which is still in progress in the Guayaquil Gulf. The Guayaquil Gulf itself, and the long and wide valley separating the Cordillera from the planated hills of the Costa, could represent a giant trench. The trench has been affected by a more recent gravitational movement, along what is one of the most continuous continental escarpments in the world.

Between the Gulf of Guayaquil and the Western Cordillera, a series of parallel SW–NE en-echelon strike–slip faults affected the main NS fault escarp-

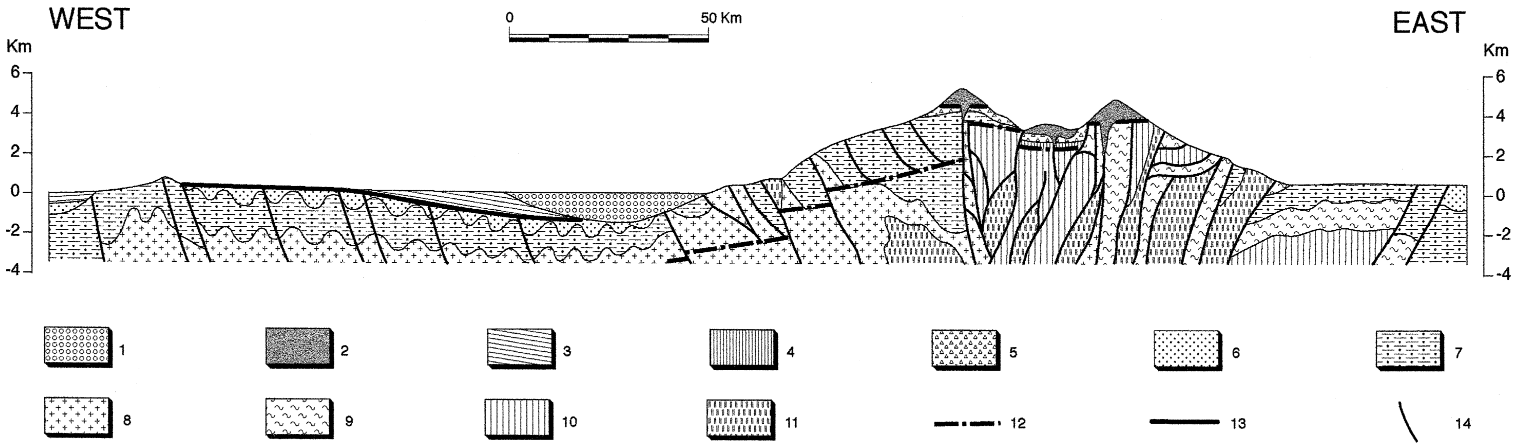


Fig. 7. Geological cross section across the Cordillera (after Litherland et al., 1993, re-interpreted). (1) Fluviatile, estuarine and marine sediments (Pleistocene–Holocene); (2) volcanic sequences (Lower–Middle Pleistocene); (3) fluvial, estuarine and marine sediments (Middle–Upper Pliocene); (4) fluviatile and lacustrine (Accumulation Plateau, Upper Pliocene–Lower Pleistocene); (5) lavas and ignimbrites (Volcanic plateau, Pisayambo Formation, Middle–Upper Pliocene); (6) alluvial fan, fluviatile, lacustrine deposits (Upper Miocene); (7) continental and marine sediments (Upper Miocene–Cretaceous); (8) volcanic rocks (Cretaceous); (9) ofiolite and marine sediments (Jurassic); (10) intrusive rocks; (11) basement (Paleozoic); (12) hypothetical location of the main detachment surface; (13) planation surface; (14) mayor faults.

ment. Barberi et al. (1988) suggest that these are the inland expression of the faults bordering the Carnegie Ridge and contributing to the Quaternary volcanic activity of the northern part of the country. In our opinion, they could represent the expression of another giant gravitational movement with a lateral spreading but which involves a large part of the Cordillera west of the Guayaquil–Babahoyo line. This could also explain the less elevated remnants of the planation surface, and the minor importance of the Interandean Depression in the southern part of the country. This hypothesis is also supported by the impressive vertical fault escarpments east of Naranjal (Baldock, 1982), which continue with a NE direction southward and could be a link of these features with the gravitational movements affecting the continental escarpment of northern Perù (Bourgouis et al., 1990).

A series of overthrusts affected the eastern side of the Cordillera (Baldock, 1982) during the Upper Miocene and were reactivated after the Lower Pliocene. At the boundary between the Cordillera and the Oriente, Palaeozoic rocks were put into contact with Cretaceous–Miocene Formations. Locally, north of Puyo, active reverse faults, affecting the Chambira Formation (Mio-Pliocene), have also been mapped (Baldock, 1982; Litherland et al., 1993). The overthrust displacement is of some kilometers. Eastward from these contacts, in the Amazonian basin, the rocks are only gently folded and are almost horizontal over large areas.

The planation surface developed after these movements and levelled all the earlier topography, which probably had low relief as far as the Oriente. Further east, the surface passes on to Late Miocene–Early Pliocene undeformed deposits.

After the broad planation, the present-day Ecuadorian Cordillera was created by uplift. At the very beginning of this history uplift was not as important as lava and ignimbrite eruptions, which created a volcanic plateau along much of the Cordillera.

Today, the planation surface is preserved at almost the same elevations on the East and West Cordillera. The contacts with the Costa and the Oriente are usually characterized by very long fault escarpments with vertical displacement of about 1500–2000 m. The reverse faults dip eastward in the East and westward in the West, spreading away from the Cordillera axis (Fig. 7). Both sides of the Cordillera are, therefore, bounded by reverse faults. The middle part of the Cordillera, characterized by extensional fault escarpments with vertical displacement of many hundreds of meters, contains many active volcanoes. These are the main tectonic features. Some minor NNE–SSW strike faults (Winter and Lavenù, 1989; Tibaldi and Ferrari, 1992) can be present in places, related to the local stress field. All these secondary movements occurred in a context of very strong generalized uplift of the Cordillera ridge.

The divergent thrust faults are the result of gravitational spreading as the uplifted block relaxed laterally. In the Oriente, broad simple structures seems to prevail. To the west, these movements activated huge gravity tectonic structures (Coltorti and Ollier, in press).

8. Conclusion

A planation surface, cut across the western side of South America during the Early Pliocene, extended right across Ecuador from the Costa to the Oriente. The remnants of this surface are preserved on top of the Cordillera of Ecuador. It cuts the older formations including Palaeozoic rocks in the eastern Cordillera and Mesozoic rocks in the western Cordillera, but also truncates Late Miocene–Earliest Pliocene rocks. Much of the folding of strata, quite independent of mountain formation, is a result of vertical uplift after the formation of the planation surface. The uplift of the Ecuadorian Cordillera started in the Early Pliocene and in approximately 4 Ma reached its present elevation.

Volcanic plateaus, formed at the beginning of the uplift processes in the Early Pliocene, cover large parts of the planated Cordillera. The volcanic activity halted for a while, and was reactivated some million years later in the early Pleistocene, most probably connected with the activity of the faults bounding the Interandean Depression. The depression, filled with hundreds of meters of conglomerates interlayered with volcanic products, ultimately became an accumulation plateau. In the Middle and Upper Pleistocene this plateau was dissected and buried under aeolian sediments. Fluviatile sediments accumulated on the valley bottom and give origin to alluvial terraces.

The Ecuadorian Cordillera was essentially lifted as a great horst, but when lifted beyond the height that the rock strength could bear the horst started to spread laterally, forming divergent faults and an extensional graben (the Interandean Depression) in the middle. The extention is also responsible for the activity of the volcanoes. Although the area is located on one of the most active margins of the world, where subduction is supposed to be continuous since Cretaceous times, a tectonic stand-still occurred that permitted great planation. The present mountain chain was created only during the Plio-Pleistocene.

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