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Provenance of the Upper Cretaceous to upper Eocene clastic sediments of the Western Cordillera of Ecuador: Geodynamic implications

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Abstract

The Late Cretaceous–Eocene clastic deposits of the Western Cordillera of Ecuador record significant changes in the source areas, grain size, and location of the depocenters, related to the accretion of oceanic terranes that constitute the present-day Western Cordillera and Coast. Major changes in the source areas occurred in the ?late Maastrichtian and ?late middle Eocene. They are interpreted as corresponding to the accretion of the Guaranda and Macuchi oceanic terranes, respectively. Major increases in the grain sizes occurred in the ?late Maastrichtian, late Paleocene(?), and ?late middle Eocene, and seem to coincide with the accretion of the Guaranda, Piñón, and Macuchi terranes, respectively. The increasing occurrence of plutonic or metamorphic fragments and the westward shift of the depositional areas through the Paleocene–upper Eocene interval indicate an increasing uplift and erosion of the Cordillera Real. Continuous, although jerky, uplift of the latter during the Maastrichtian–Eocene period, supports the idea that the accreted oceanic material contributed to the crustal thickening and relief creation of the Ecuadorian Andes.

Keywords: Ecuador; Campanian–Eocene; Clastic sediments; Sedimentary petrography; Source areas

1. Introduction

Ecuador comprises from east to west (Fig. 1): (1) the Oriente Basin, which received marine deposits during part of the Cretaceous and constitutes the present-day retroarc basin, (2) the Subandean Zone, which is part of the Cretaceous Oriente Basin, floored by a thick Jurassic volcanic arc uplifted during the

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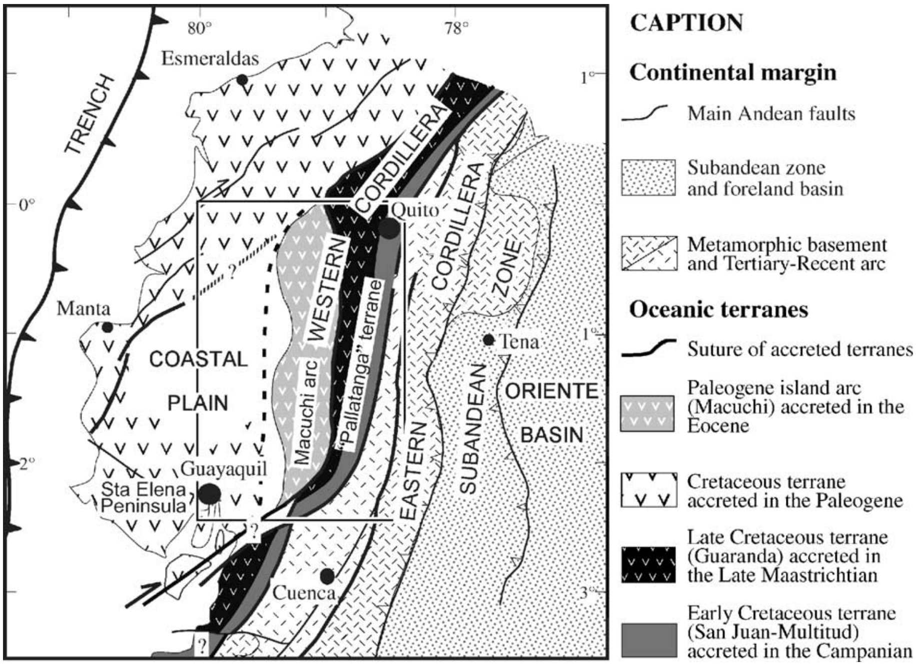

Fig. 1. Structural sketch of Western Ecuador, and main accreted oceanic terranes.

Andean orogeny, (3) the Cordillera Real composed of exhumed metamorphic rocks, (4) the Western Cordillera, constituted mainly by mafic magmatic rocks, and (5) the Coastal Zone, which received Paleogene to Neogene forearc deposits. The Eastern and Western cordilleras are separated by the Inter-Andean Valley, largely filled up by Neogene to recent volcanic arc products.

The basement of the Coastal Zone and the Western Cordillera of Ecuador (Fig. 1) is formed by several oceanic terranes accreted successively to the Andean margin between the Late Cretaceous and the Eocene (Goossens and Rose, 1973; Feininger and Bristow, 1980). Although the nature and geodynamic significance of these terranes have been specified (Lebrat et al., 1987; Cosma et al., 1998; Reynaud et al., 1999; Kerr et al., 2002), the number of oceanic terranes, their boundaries, and the timing of their accretion are still poorly constrained. Most authors agree that accretions took place between 85–80 Ma and 40–35 Ma, i.e. between the Campanian and late Eocene (e.g. Egüez, 1986; Lebrat et al., 1987; Daly, 1989; Bourgois et al., 1990; Jaillard et al., 1997; Reynaud et al., 1999; Hughes and Pilatasig, 2002; Kerr et al., 2002). Early uplift stages experimented by the Cordillera Real of Ecuador, recently constrained by thermochronological methods, have been proved to be broadly coeval with the accretion periods (Litherland et al., 1994; Spikings et al., 2000, 2001; Ruiz et al., 2002, 2004). This led to the hypothesis that the accretion and underplating of oceanic material contributed to the crustal thickening and subsequent uplift of the Andean margin (Guillier et al., 2001; Jaillard et al., 2002).

In order to test this interpretation, we undertook a study of the Late Cretaceous–Eocene clastic deposits of the Western Cordillera of Central Ecuador (0°30′ S–3°S). Because the petrography of clastic sediments depends on the nature of the source areas, and provides information about the depositional environments and processes, this petrographic study aims to determine the source areas and their evolution through time, thereby specifying the early tectonic evolution of the Andes related to the successive accretions. In this paper, we present the results of a petrographic study of the Upper Cretaceous to upper Eocene clastic sediments of the Western Cordillera of Central Ecuador (0°30′ S–2°30′ S), which supports the idea that each accretion is followed by significant uplift, erosion rejuvenation, and subsequent clastic sedimentation.

2. Geological setting

Two oceanic terranes are classically distinguished in the Western Cordillera of Central Ecuador. To the east, the Pallatanga Terrane is interpreted as a fragment of a Cretaceous oceanic plateau accreted to the Andean margin during the Late Cretaceous (85–80 Ma, Lebrat et al., 1987; Reynaud et al., 1999; Lapierre et al., 2000; Hughes and Pilatasig, 2002; Kerr et al., 2002). To the west, the Macuchi Terrane is an island arc accreted in the Eocene (Kehrer and Van der Kaaden, 1979; Bourgois et al., 1990; Cosma et al., 1998; Hughes and Pilatasig, 2002; Kerr et al., 2002). On the other hand, Jaillard et al. (1997) proposed that the southern part of coastal Ecuador (Santa Elena Peninsula) was accreted in the late Paleocene (see also Daly, 1989).

Recently, Lapierre et al. (2000) and Mamberti et al. (2003, 2004) suggested that the Pallatanga Terrane actually comprises two oceanic plateaus of distinct ages and origin. New stratigraphic results support the latter assumption (Jaillard et al., 2004). These data allowed to refine the stratigraphic successions of the accreted terranes, and to demonstrate that the Pallatanga Terrane may be divided into: (1) an eastern, San Juan–Multitud Terrane of Early Cretaceous age, accreted around 85–80 Ma, and (2) a western, Guaranda Terrane of Late Cretaceous age, accreted in the late Maastrichtian (68–65 Ma) (Jaillard et al., 2004).

In Central Ecuador (Fig. 1), the Pallatanga Terrane is associated with Late Cretaceous to Paleogene, mainly turbiditic deposits, which comprise various formations (Fig. 2). The Yunguilla Formation ($\approx$500 m thick) is composed of black cherts, feldspathic greywackes, and calciturbidites of late Campanian–early Maastrichtian age (Figs. 2 and 4), and is present only on the San Juan–Multitud Terrane. Meanwhile, the Guaranda Terrane received red- or green-coloured radiolarites, overlain by fine-grained, radiolarian-bearing, pelagic black cherts, devoid of detrital quartz, interpreted as oceanic basin deposits. These oceanic black cherts ($\approx$400 m) yielded late Campanian–Maastrichtian radiolarians (Jaillard et al., 2004).

The Yunguilla Formation (San Juan–Multitud Terrane) and black cherts (Guaranda Terrane), both of Campanian–Maastrichtian age, are unconformably overlain by the Saquisilí Formation ($\approx$1000 m) of early to middle Paleocene age, composed of siltstones and fine- to medium-grained quartz–sandstones, rich in muscovite (McCourt et al., 1998; Hughes et al., 1999; Fig. 2). Although exhibiting the same composition as the Saquisilí Formation, the overlying Gallo Rumi Conglomerates ($\approx$1000 m) are much coarser-grained. They are ascribed to the upper Paleocene, and grade upwards into siltstones and very fine-grained sandstones ($\approx$300 m), referred to as the Upper Gallo Rumi Member (Jaillard et al., 2004).

At 2°S, an angular unconformity separates the Upper Gallo Rumi Member from the middle Eocene Apagua Formation (Jaillard et al., 2004). Further north (1°S), the Apagua Formation ($\geq$1000 m) mainly comprises medium-grained quartz–sandstones deposited by turbidity currents. The Apagua Formation grades upward into siltstones, sandstones, and quartz- and chert-bearing conglomerates of the Rumi Cruz Formation (1600 m, Fig. 2), assigned to the upper Eocene (Hughes et al., 1999). The Rumi Cruz Formation is mainly continental, but includes marine deposits (Faucher et al., 1971). So far, the Apagua and Rumi Cruz formations have been recognized only in the western part of the Guaranda Terrane.

3. Sampling and method

The studied sections are located in two areas of Central Ecuador (Fig. 3): west of Latacunga (0°40′ S–1°15′ S), and west of Riobamba (between the Chimborazo Volcano and Pallatanga, 1°30′ S–2°S). We focused our study in the Upper Campanian–upper Eocene interval, which includes the Yunguilla, Saquisilí, Apagua, and Rumi Cruz formations. In these areas we collected representative samples located throughout the succession, which were studied using the petrographic microscope.

We studied 133 samples from the Yunguilla (34 samples, among which 28 are shales and siltstones and are not quoted here), Saquisilí (44), Apagua (28), and Rumi Cruz (27) formations. Due to the fact that clasts that conform conglomerates are too large to be studied under thin sections, and because microscopic analysis must be carried out between samples of comparable grain sizes (Tucker, 2001), the conglom-

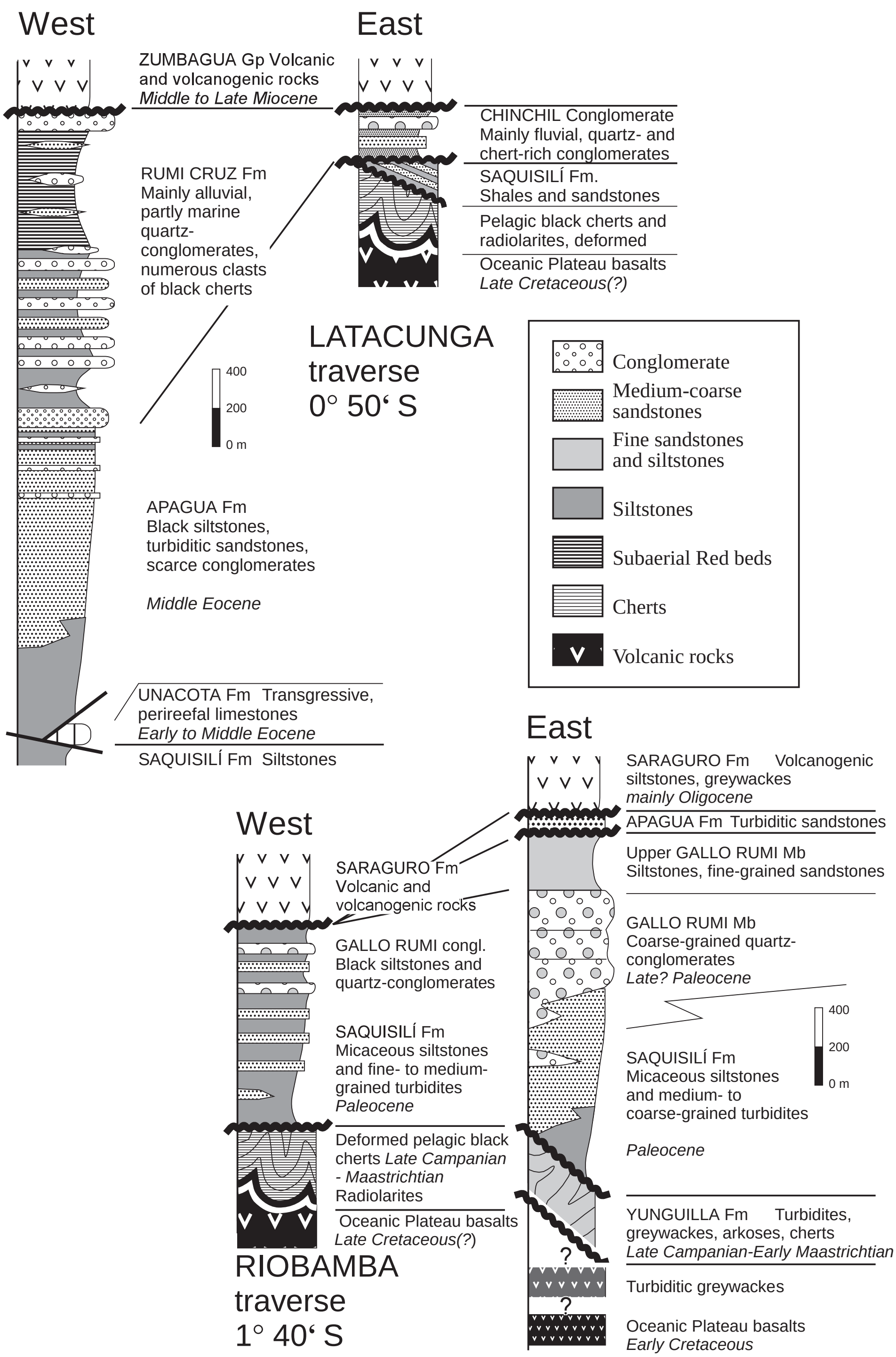

Fig. 2. Simplified stratigraphic successions of the Upper Cretaceous to upper Eocene deposits along the Latacunga and Riobamba traverses.

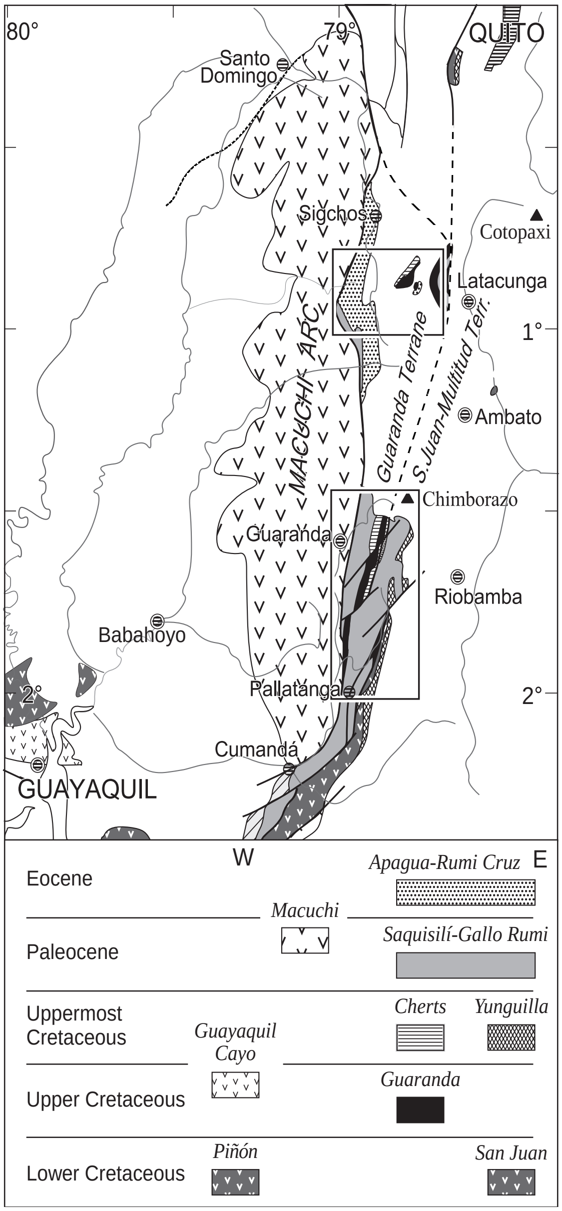

Fig. 3. Structural sketch of the Western Cordillera of Central Ecuador, and location of the studied areas.

erates of the Gallo Rumi Member (upper part of the Saquisilí Formation), and of the Rumi Cruz Formation were not studied.

We studied the provenance of the Upper Cretaceous to upper Eocene clastic sediments of the Western Cordillera of Ecuador using modal framework grain analysis, which are currently represented in standard ternary plots for sandstones (Yerino and Maynard, 1984; Dickinson, 1985; Tucker, 2001). Because all sandstones were well-cemented, the relative abundance of mineral grains and lithic fragments was determined using not stained thin sections (30 μ thick). For each thin section, 350–400 sand-sized grains were identified, and their relative abundance–the modal composition–was calculated using the Gazzi–Dickinson method (Gazzi, 1966; Dickinson, 1970). The size of 150–250 grains was measured with a reticulate eyepiece for each thin section, as described by McManus (1988).

Quantitative sandstone detrital modes, determined by point-counting on thin sections, are usually expressed by Qt–F–L, Qm–F–Lt, Qm–P–K, and Qp–Lv–Ls triangular plots (Dickinson, 1985; Tucker, 2001). In these classical diagrams and in other classification diagrams of sandstones, the categories of identified detrital particles are quartzose grains, feldspar grains, and lithic fragments (Dickinson, 1985 in: Tucker, 2001). Quartzose grains include Q=Qt=total number of quartz grains (Qt=Qm+Qp), Qm=monocrystalline quartz, and Qp=polycrystalline quartz. Feldspar grains are: F=total feldspar grains (F=P+K), P=plagioclase grains, and K=potassium feldspar grains. Lithic fragments consist of: L=Lt=total number of lithic fragments (Lt=Qp+Lv+Ls), Qp=chert and quartzite fragments, Lv=volcanic rock fragments, and Ls=sedimentary rock fragments (Dickinson, 1985; Tucker, 2001).

Identifying certain mineral grains and rock fragments under microscope may present some uncertainties. Especially, microquartz chert grains may derive from the alteration of: feldspar grains (F), fine-grained sedimentary rocks (Ls), and tuffs or microlithic volcanic rocks (Lv). All microquartz chert grains were classified as cherts, except those presenting remnants of primary structures, i.e. twinnings for feldspars, laminations, texture, and microfossil content for sedimentary rocks; and microtabular feldspar crystals and siliceous shards for volcanic rocks.

In order to refine our study, we added two ternary plots: F–Lv–Ls and Q–Mx–OM, where Mx is the total matrix content and OM is the organic matter content. The latter was estimated using the conventional chart proposed by Folk et al. (1970, in Tucker, 2001), which allows to estimate grain abundance by comparing samples with circular fields representative of different percents of grains. The organic matter content (OM) corresponds to the carbonaceous and bituminous matter contained in the matrix and in the biogenic grains, which are usually black or brown in thin section (Kerr, 1977). This organic matter was identified as opaque grains, which do not present characters of metallic oxydes or sulphurs under reflected light.

4. Results of the petrographic study of the Upper Cretaceous-upper Eocene sandstones

The relative proportions of detrital grains, namely quartz (Q), feldspars (F), and rock fragments (L), combined with the percent of matrix (Mx) or very fine grains, allow the detrital rocks to be formally named (Dott, 1964; Folk et al., 1970; Pettijohn et al., 1987). According to these classifications, (1) the latest Cretaceous Yunguilla Formation deposits are mainly fine-grained feldspathic greywackes (Fig. 4); (2) the sandstones of the Paleocene Saquisilí Formation are mainly lithic greywackes, litharenites, and feldspathic litharenites, with subordinate sublitharenites; (3) the turbidites of the mid-Eocene Apagua Formation are mainly sublitharenites, litharenites, and to a minor extent, lithic greywackes; and (4) the sandstones of the upper Eocene Rumi Cruz Formation are mainly litharenites, arkosic litharenites, and to a minor extent, lithic and feldspathic greywackes (Fig. 4).

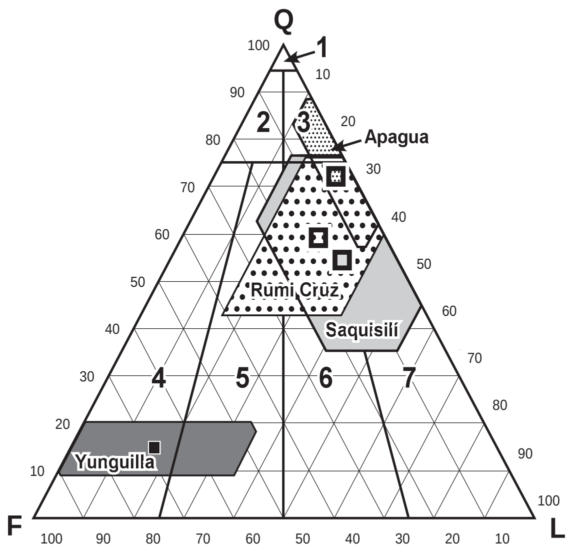

Fig. 4. Classification of the Upper Cretaceous–Eocene deposits of the Western Cordillera of Central Ecuador. 1: quartzarenite; 2: subarkose; 3: sublitharenite; 4: arkose; 5: lithic arkose; 6: arkosic litharenite; 7: litharenite.

4.1. Latest Cretaceous (Yunguilla formation)

Plotted on the Qt–F–L diagram (Dickinson, 1985; Fig. 5A), which emphasizes the maturity of the sediment (Tucker, 2001), the samples of the Yunguilla Formation indicate that the latter probably derived from the erosion of a partly dissected magmatic arc, and to a lesser extent, from uplifted continental basement rocks. In the Qm–P–K diagram (Dickinson and Suczek, 1979; Fig. 5B), which only takes into account single mineral grains (Tucker, 2001), these samples plot very close to the plagioclase edge, indicating that the volcanic component dominated within the magmatic source area. In the Qp–Lv–Ls diagram (Dickinson and Suczek, 1979), the Yunguilla Formation is rich in plagioclase, included in volcanic lithics and in fine-grained siliceous cherts (Fig. 5C), among which some are of diagenetic origin. In the F–Lv–Ls diagram (Fig. 5D), the fine-grained deposits of the Yunguilla Formation are virtually devoid of volcanic or sedimentary fragments, thus suggesting that the magmatic arc was located far from the depositional area, and that no deformed sedimentary areas were subjected to erosion at this time.

4.2. Paleocene (Saquisilí formation)

Between the Maastrichtian and the Paleocene, the source area changed dramatically. In the Qt–F–L diagram (Fig. 5A), the Paleocene Saquisilí Formation, rich in both quartz grains and lithic fragments, falls within the recycled orogen area. Thus, in contrast to the latest Cretaceous deposits, Paleocene times are characterized by the erosion of deformed, supracrustal rocks. In the Qm–P–K diagram (Fig. 5B), the sandstones show a clear increase in monocrystalline quartz, suggesting an increase of the plutonic/volcanic ratio with respect to the latest Cretaceous deposits, evolving from a distal volcanic arc source to a circumpacific VP suite (defined as the

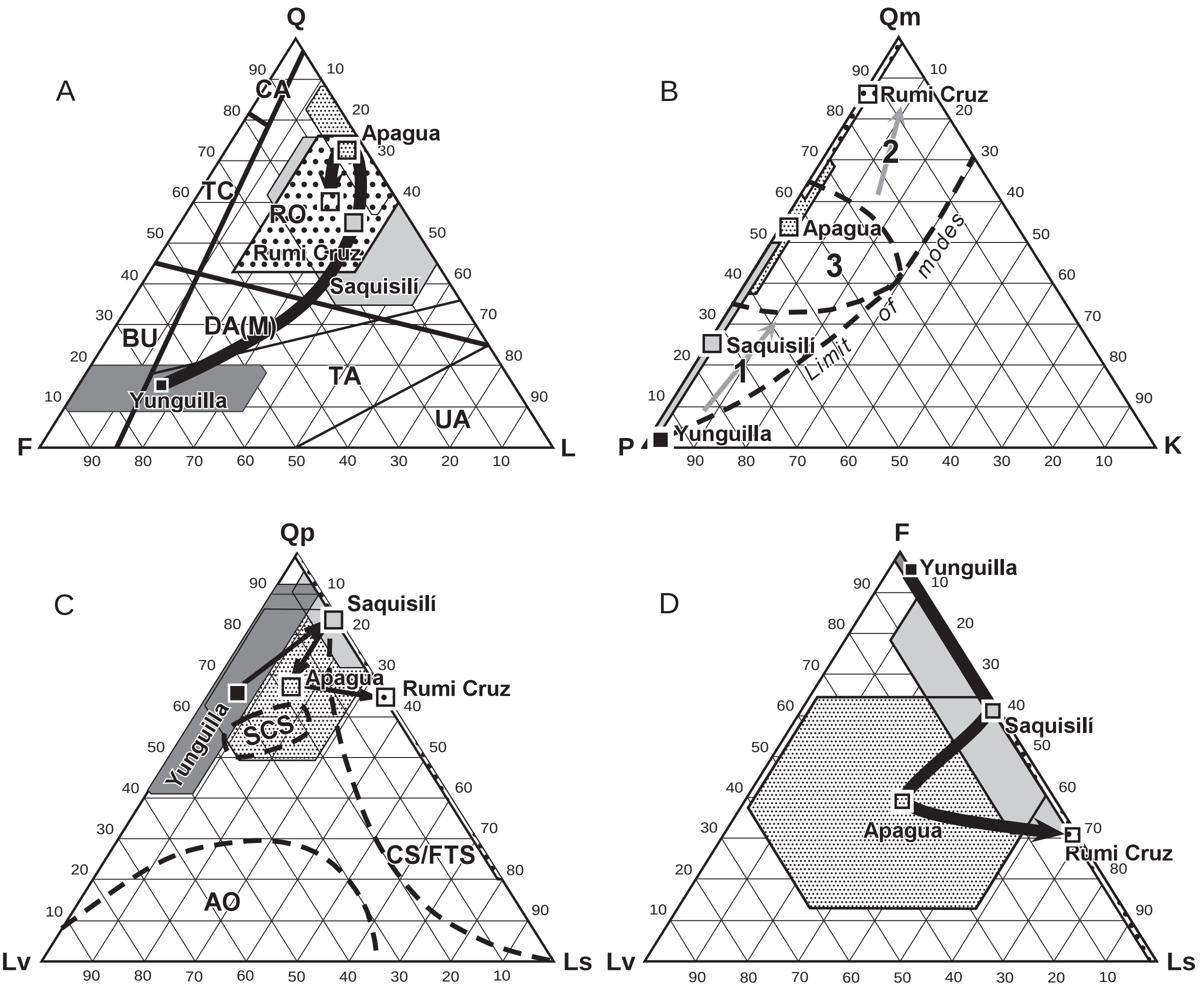

Fig. 5. Provenance diagrams of the Upper Cretaceous–upper Eocene clastic deposits of the Western Cordillera of Central Ecuador. (A) Q–F–L diagram. CA: craton interior, TC: transitional continental, BU: basement uplift, RO: recycled orogen, DA (M): dissected arc (magmatic), TA: transitional arc, UA: undissected arc. (B) Q–P–K diagram. 1: increasing ratio of P to V ratio in magmatic arc sources, 2: increasing maturity/stability from continental block sources, 3: Circumpacific VP suites. (C) Qp–Lv–Ls diagram. SCS: Subduction complex sources, CS/FTB: collision suture and fold-thrust belt sources, AO: arc orogen. (D) F–Lv–Ls diagram.

products of a calcalkaline arc associated with subduction complexes). Plotted on the Qp–Lv–Ls and F–Lv–Ls diagrams (Fig. 5C and D), the Paleocene sandstones appear to be rich in chert fragments of chemical to biochemical origin. This, together with the abundance of polycrystalline (metamorphic) quartz, indicates the erosion of a collisional orogen. The F–Lv–Ls diagram shows that the sandstones of the Saquisilí Formation have a high Ls/Lv ratio, supporting the idea that they result from the recycling of an orogenic belt.

4.3. Middle Eocene (Apagua formation)

The petrography of the middle Eocene Apagua Formation suggests that it recycled an uplifted orogen marked by abundant metamorphic rocks and cherts (Qt–F–L diagram, Fig. 5A). In the Qm–P–K diagram (Dickinson and Suczek, 1979), the composition of the Apagua Formation and the increasing maturity and stability of its clastic components indicate the evolution from a magmatic arc provenance to a dominantly crystalline continental block source area.

However, as evidenced by the Qp–Lv–Ls diagram (Fig. 5C), the sandstones of the Apagua Formation are rich in polycrystalline quartz and cherts, suggesting the recycling of both a collisional orogenic belt (rich in Qp and cherts) and subduction complexes (rich in Lv and Ls fragments). This apparent discrepancy is most likely due to the fact that the Apagua Formation reworked the deformed margin, including the uplifted quartz-rich Paleocene sandstones and conglomerates, thus explaining the maturity and stability of the rocks. The actual tectonic setting was that of a recycled orogen involving accreted terranes, thus resembling a subduction complex. According to the F–Lv–Ls diagram (Fig. 5D) the Apagua Formation is characterized by roughly equal proportions of the three modal components: F, Lv, and Ls. The lower Paleocene–middle Eocene interval records an increase in volcanic fragments, suggesting that the Apagua Formation was deposited in a composite tectonic setting, including a collisional orogenic belt and a subduction complex.

4.4. Upper Eocene (Rumi Cruz formation)

The petrography of the upper Eocene Rumi Cruz Formation suggests that it also derived from a recycled orogen. The sandstones of the Rumi Cruz Formation are mainly feldspathic litharenites (Fig. 4). With respect to the Apagua Formation, however, the content of quartz grains decreased, whereas that of lithic fragments increased (Fig. 5A). In the Qm–P–K diagram (Dickinson and Suczek, 1979), the composition of the mature Rumi Cruz Formation would indicate the evolution from a circumpacific magmatic arc provenance to a dominantly crystalline, continental source area. This suggests that the orogen was more deeply eroded and uplifted than during the middle Eocene. However, in the Qp–Lv–Ls diagram (Fig. 5C), the sandstones of the Rumi Cruz Formation contrast markedly with those of the Apagua Formation, in that Lv fragments are nearly absent. This observation is confirmed by the F–Lv–Ls diagram (Fig. 5D), which indicates that the sandstones of the Rumi Cruz Formation are marked by a high content of sedimentary fragments and feldspar grains and a lack of volcanic fragments. Therefore, in comparison with the middle Eocene, the upper Eocene deposits derived clearly from an uplifted and a more deeply eroded orogenic belt.

In summary, the evolution of the source areas between the Maastrichtian and Paleocene–Eocene times, from uplifted basement rocks and/or magmatic arcs, to uplifted, deformed and deeply eroded orogenic belts, correlates with variations in the matrix content and grain size. In the Q–Mx–OM diagram (Fig. 6A), the Yunguilla Formation is rich in matrix and organic matter, the Saquisilí Formation shows low to medium contents in matrix and organic matter,

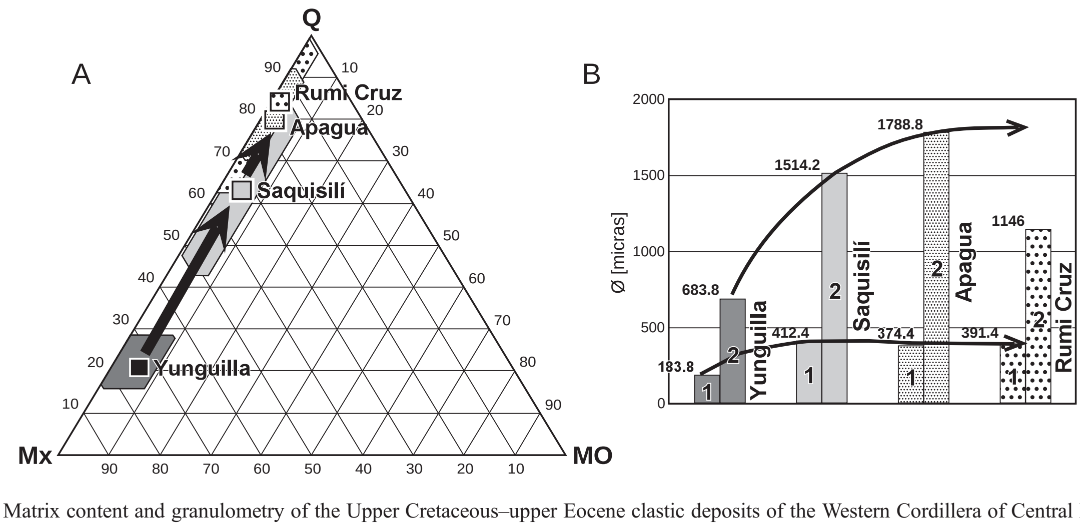

Fig. 6. Matrix content and granulometry of the Upper Cretaceous–upper Eocene clastic deposits of the Western Cordillera of Central Ecuador. (A) Quartz–matrix–organic matter diagram. (B) Grain size variation. 1: phi median; 2: phi max.

whereas the Apagua and Rumi Cruz formations evidence low contents. This indicates increasing energy conditions and/or decreasing transport distances, and correlative increasing instability of the nearby emergent source areas between latest Cretaceous and late Eocene times.

The average grain size (Fig. 6B) significantly increases from the Yunguilla Formation (184), to the Saquisilí and Apagua formations (412 μ and 374 μ, respectively). In the same way, the maximum grain size increases from the Yunguilla Formation (684 μ) to the Saquisilí and Apagua formations (1514 μ and 1789 μ, respectively). However, this diagram (Fig. 6B) does not take into account the Gallo Rumi and Rumi Cruz conglomerates, where clasts reach diameters of 180 and 130 mm, respectively.

5. Paleogeographic and tectonic evolution

A study of the paleogeography of the successive depositional sequences of latest Cretaceous–Eocene age suggests that the petrographic evolution of these deposits is related to the progressive uplift of the Cordillera Real.

5.1. Late Campanian–Maastrichtian

During late Campanian–Maastrichtian times, pelagic black cherts were deposited in the Guaranda Terrane, indicating that the latter still belonged to the oceanic realm. Meanwhile, clastic marine deposits were deposited in the Subandean Zone (Tena Fm, Jaillard, 1997), below part of the present-day Inter-Andean Valley, and on the San Juan–Multitud Terrane of the Western Cordillera of Ecuador (Yunguilla Fm). From east to west, the depositional environments evolved from shallow marine to a coastal alluvial plain in the Sub-Andean Zone, to basinal turbidites in the Western Cordillera. Intermediate facies, probably of a shelf environment, have been mentioned on the eastern slope of the southern part of the Cordillera Real ("Limón Flysch"; Faucher et al., 1971). This indicates that the Yunguilla Basin was connected to the eastern basins, and that the Cordillera Real was not totally emergent (Fig. 7) at this time. On the other hand, the Yunguilla Formation results mainly from the erosion of uplifted basement

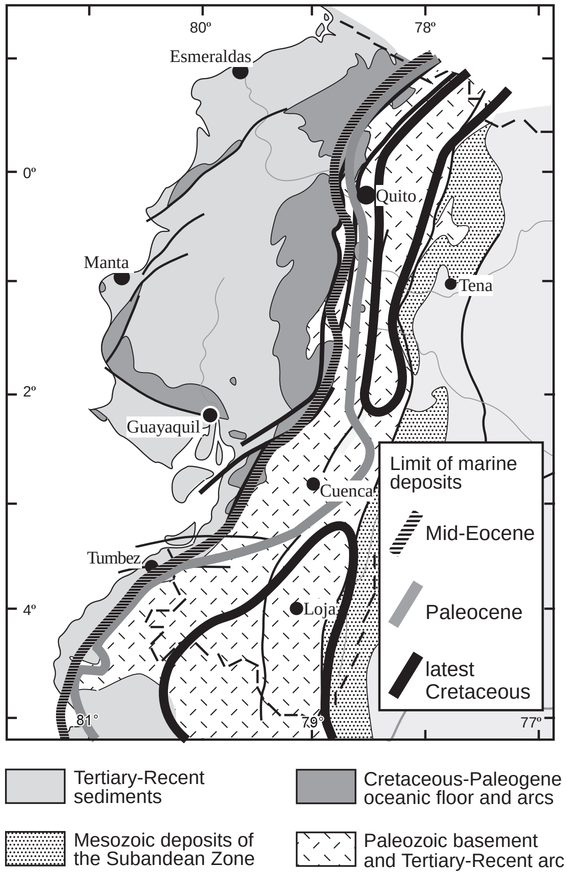

Fig. 7. Paleogeographic sketch of Ecuador, showing the westward retreat of the coastline between ≈80 and 40 Ma.

rocks probably represented by the Cordillera Real, and of a partly dissected volcanic arc. Although minor contributions from the Cretaceous volcanic arc of southernmost Ecuador, or from volcanic suites identified along the western edge of the Cordillera Real (Peltetec Suture, Litherland et al., 1994) cannot be ruled out, this volcanic source might be a newly accreted oceanic terrane. As already proposed (Lebrat et al., 1987; Reynaud et al., 1999; Hughes and Pilatasig, 2002; Kerr et al., 2002), we interpret the Yunguilla Formation as a response to the accretion of the San Juan–Multitud Terrane during the Campanian (Fig. 8).

5.2. Lower to middle Paleocene

The lower to middle Paleocene Saquisilí Formation is chiefly composed of medium- to coarse-grained

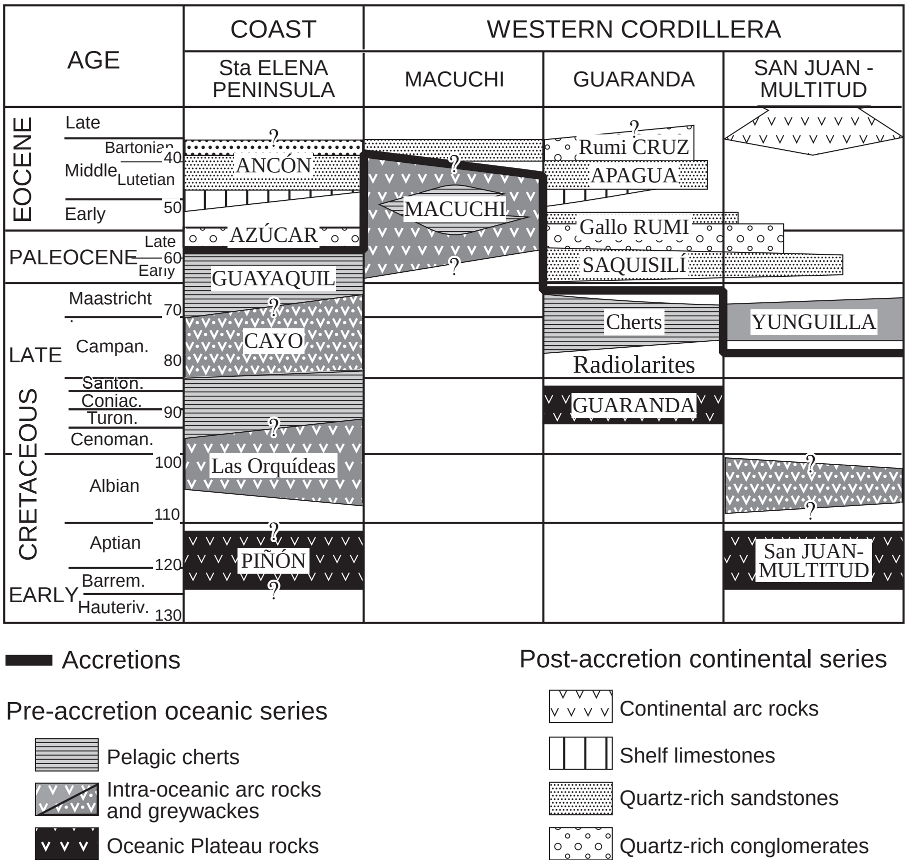

Fig. 8. Chronostratigraphic chart of the oceanic terranes and their sedimentary cover of western Central Ecuador. The heavy line separates the lower oceanic rocks from unconformable Qz-rich deposits, and is interpreted as the accretion date of each oceanic terrane.

feldspathic litharenites and litharenites, rich in feldspars and volcanic rock fragments. It was deposited in a collisional setting, and probably recycled a metamorphic and partly plutonic uplifted basement. In the Inter-Andean Valley and Western Cordillera, the Paleocene coastline apparently shifted westwards, since strong fluvial influences are recorded in the Riobamba area (Fig. 7). The change in the clastic supply, the increase in grain size, and the uplift of the eastern source areas are due to the accretion of the Guaranda Terrane in the late Maastrichtian (Jaillard et al., 2004), which represents a major tectonic event in the evolution of the Ecuadorian Andes (Jaillard et al., in press). Paleocene deposits are unknown so far in the Sub-Andean Zone, but in the Oriente Basin, Late Cretaceous, marine to continental rocks are unconformably overlain by fluvial Paleocene deposits.

5.3. Late Paleocene

The Gallo Rumi conglomerates, probably of late Paleocene age, exhibit westward paleocurrents (Santos, 1986). They reflect a significant resumption of the erosion in the eastern source areas, without a change in the detrital supply, and thus indicate an important uplift of the Cordillera Real. These conglomerates seem to be coeval with the conglomeratic turbidites of the Azúcar Group of southern coastal Ecuador, which seal the accretion of the Piñón Terrane in the late Paleocene (Fig. 8; Benítez, 1995; Jaillard et al., 1997). The Gallo Rumi conglomerates are thus interpreted as a distal consequence of the accretion of the Piñón Terrane to the Andean margin, and/or of the late Paleocene major compressional event (e.g. Daly, 1989; Pécora et al., 1999; Spikings et al., 2001).

5.4. Middle Eocene

The deposition of the middle Eocene, mature sublitharenites and litharenites of the Apagua Formation, resulted from the recycling of a collision belt involving deformed and uplifted sedimentary, plutonic, and metamorphic areas. In the Western Cordillera of Central Ecuador, marine sediments of middle Eocene age were deposited in restricted, fault-bounded basins, located in the western part of the Guaranda Terrane (Fig. 7). This suggests that the middle Eocene basins were pull-apart basins related to dextral movements affecting the Andean margin (Pécora et al., 1999; Hughes and Pilatasig, 2002). The Eocene sequence of the Guaranda Terrane, composed of transgressive limestones, deep marine shales and turbidites, and coarse-grained shallow marine sandstones or conglomerates, is comparable to the coeval sequences recognized in the coastal forearc basins (Faucher and Savoyat, 1973; Evans and Whittaker, 1982; Benítez, 1995), thus suggesting that this part of the Western Cordillera was connected to the Coastal Zone (Fig. 8). Further south, coarse-grained, subaerial volcanogenic red beds of middle Eocene age were deposited in the Cuenca area (Quingeo Fm, Steinmann, 1997; Hungerbühler et al., 2002), thus documenting the uplift of the Cordillera Real. Therefore, the Eocene coastline shifted westwards with respect to the Paleocene, indicating a new uplift stage of the Cordillera Real about 50 Ma ago (Spikings et al., 2001). In the whole eastern zones, Eocene deposits are composed of fluvial conglomerates (Christophoul et al., 2002; Ruiz et al., 2002).

5.5. Late Eocene (?)

The undated sandstones and conglomerates of the Rumi Cruz Formation indicate a drastic change in the paleogeography of the Western Cordillera of Central Ecuador. In contrast to the Apagua Formation, these deposits are coarse-grained, partly subaerial, and contain very abundant clasts of black cherts. West of Latacunga, the transition between the Apagua and Rumi Cruz formations is marked by a succession of fine- to medium-grained alluvial sandstones, alternating with shallow marine siltstones and fine- to medium-grained sandstones. This transition most probably correlates with that observed in the southern forearc basins near the Lutetian–Bartonian boundary ($\approx$41 Ma), which is also marked by the arrival of conglomerates, a change in the detrital supply, and by the transition from marine to subaerial or coastal environments (Jaillard et al., 1997). This regional event may coincide with the accretion of the Macuchi Island Arc Terrane (Fig. 8) in the late middle Eocene to late Eocene (Hughes and Pilatasig, 2002; Kerr et al., 2002).

Therefore, between the latest Cretaceous and the Eocene, the depositional areas of the clastic deposits of the Western Cordillera shifted significantly westward (Fig. 7).

The uplift of the Cordillera Real is further documented by a sedimentological study of the Late Cretaceous–Eocene deposits of the Western Cordillera. Preliminary results indicate that the Yunguilla Formation is of deep marine environment, the Paleocene succession was deposited in a mainly clastic shelf to continental-floored basin environments, the middle Eocene is marked by deposition in relatively small-scale turbiditic marine basins, whereas late Eocene deposits are either alluvial to shallow marine sediments (Apagua area), or continental volcanogenic deposits (Cuenca area). Therefore, the latest Cretaceous to late Eocene deposits exhibit a clear shallowing upward evolution, which supports the interpretation of a progressive, although jerky, uplift and erosion of the Cordillera Real, related to the successive accretions of oceanic terranes to the continental margin. Ruiz (2002) and Ruiz et al. (2004) proposed a comparable conclusion, using fission track and heavy mineral analysis on the Upper Cretaceous–Tertiary rocks of the Cordillera Real and Subandean Zone of Ecuador.

6. Conclusions

The fine-grained feldspathic greywackes of the late Campanian–early Maastrichtian Yunguilla Formation seem to result from the erosion of both the uplifted Cordillera Real and a volcanic basement. Paleogeographic reconstructions indicate that the Cordillera Real was not totally emergent. The deposition of the Yunguilla Formation on the Andean margin and in the San Juan–Multitud Terrane is interpreted as a response to the accretion of the latter during the Campanian (Fig. 8).

The lithic greywackes, litharenites, and sublitharenites of the lower to middle Paleocene Saquisilí Formation were deposited in both the San Juan–Multitud and Guaranda terranes, and recycled a metamorphic and partly plutonic uplifted basement, i.e. the Cordillera Real. With respect to Maastrichtian times, the change of the source areas, the increase of clastic grain size, and the westward shift of the depositional areas indicate a significant uplift of the Cordillera Real. We interpret this uplift as related to the accretion of the Guaranda Terrane in the late Maastrichtian (Fig. 8).

The Gallo Rumi conglomerates, likely of late Paleocene age, reflect a significant uplift of the source areas, which is interpreted as a consequence of the accretion of the Piñón Terrane of southern coastal Ecuador (Fig. 8).

The middle Eocene litharenites and feldspathic litharenites of the Apagua Formation result from the erosion of both the Paleocene deposits, and a collisional belt, involving uplifted sedimentary, volcanic, plutonic, and metamorphic areas. They are restricted to the western part of the Guaranda Terrane, and were deposited in a belt of fault-bounded marine basins, interpreted as pull-apart basins related to significant dextral wrench-movements.

The upper Eocene Rumi Cruz Formation consists of litharenites, feldspathic litharenites, lithic arkoses, and chert-rich conglomerates, which reflect a new significant uplift of the source areas. These deposits result from the erosion of a collisional belt involving crystalline rocks and deformed sedimentary rocks (cherts and Tertiary deposits). They are restricted to the central Western Cordillera of Ecuador. The transition to subaerial environments, the change in source areas, and the increase in grain size observed between the Apagua sandstones and the Rumi Cruz conglomerates may correlate with the accretion of the Macuchi Island Arc Terrane in the late middle Eocene ($\approx$41 Ma; Fig. 8).

The increasing occurrence of plutonic or metamorphic fragments in the Saquisilí, Apagua and Rumi Cruz formations indicates that the crystalline basement of the Cordillera Real was uplifted and increasingly eroded during the Paleocene–Eocene interval. Continuous, although jerky, uplift of the Cordillera Real during the Maastrichtian–late Eocene interval supports the idea that the accreted oceanic material contributed to the crustal thickening, and hence to the creation of the relief of the Ecuadorian Andes.

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