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Late Cretaceous-Paleogene orogenic build-up of the Ecuadorian Andes: Review and discussion

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A R T I C L E I N F O

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A B S T R A C T

A review of the tectonic events recorded by sediments on the Andean continental margin of northern Peru and Ecuador and on the accreted oceanic terranes of Ecuador, allows to identify three tectonic events of late Campanian to late Paleocene age (~75 to ~55 Ma). Each tectonic event resulted in the arrival of quartz-rich deposits on the oceanic units and in a sedimentary hiatus in the backarc zone (Oriente basin), which both indicate an uplift of the South-American continental margin. This is interpreted as the underplating of oceanic terranes beneath the Andean continental margin. After the Incaic contractional phase (~40 Ma), the Oriente Basin recorded a sharp increase in the subsidence rate, the westward migration of the depocenters and a drastic change in the detrital source around 25 Ma, which indicate the onset of its foreland basin evolution, driven by flexural subsidence. It is therefore proposed that the Ecuadorian Andes resulted first from the evolution of a western, west-verging orogenic wedge, made of accreted oceanic material (~75–40 Ma). Once this western wedge overthickened and submitted to strong vertical body forces, the strain related to ocean-continent convergence was transmitted to the continental plate, where a second, eastern, east-verging orogenic wedge formed about 25 Ma ago. This scenario accounts for the tectonic and sedimentary evolution of the Ecuadorian-north Peruvian margin, and explains why, in spite of a moderate elevation, the partly oceanic crustal root of the Ecuadorian Andes, is almost as thick as beneath the high-altitude Altiplano of southern Peru and Bolivia, where the crustal root is mainly of continental nature.

1. Introduction

The Central Andes (Peru, Bolivia, northern Chile and Argentina) are considered a typical mountain range related to the subduction of an oceanic plate beneath the South-American continental margin (James, 1971; Mégard, 1987; Allmendinger et al., 1997). The northern Andes (Ecuador, Colombia) are marked by the presence of oceanic terranes (late Cretaceous oceanic plateau and island arcs) accreted to the South-American continental margin in Late Cretaceous-Paleocene times (Gansser, 1973; Reynaud et al., 1999; Kerr et al., 2002; Jaillard et al., 2009; Vallejo et al., 2019). In both Andean segments, the contraction induced by the plate convergence is assumed to have triggered tectonic shortening, crustal thickening of the upper plate and eastward propagation of the deformation front. Some peculiarities, however, remain unexplained or poorly understood.

One of these, is the fact that the tectonic shortening assessed in the Central Andes does not explain the whole volume of the observed crustal root. Some additional processes have been invoked to explain the lacking volume, such as magmatic addition, crustal underplating, lateral migration of ductile material, removal of dense lithosphere or presence of hydrated mantle (e.g. Allmendinger et al., 1997; Giese et al., 1999; Garzione et al., 2008). Even more intriguing is the case of Ecuador, where the observed tectonic shortening of the continental plate is especially low (Vega Torres, 1998; Baby et al., 2013), although the observed thickness of the crustal root (Guillier et al., 2001; Araujo et al., 2021; Koch et al., 2021) is almost as high as that of the Bolivian Altiplano, despite the fact that the average elevation of the Ecuadorian Andes is significantly lower than that of southern Peru and Bolivia. Another peculiarity is the presence of oceanic material accreted to the western edge of the Ecuadorian continental margin. The nature, age and number of these “terranes”, as well as the chronology and modalities of their emplacement have been extensively debated over the last few decades (Jaillard et al., 2009; Vallejo et al., 2019 and references therein). Whereas a consensus has been reached regarding the oceanic plateau nature and the late Cretaceous age of this oceanic material, the processes of accretion remains a matter of debate. Some authors proposed that the oceanic terranes entered the subduction zone before jamming the subduction process because of low average density of the

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terrane (Cloos, 1993), whereas others assume that the oceanic material has been obducted onto the continental Ecuadorian margin. Additionally, some workers have suggested multiple accretionary event, whereas others advocate a single collision. In this text, the term collision refers to the initial addition of oceanic material to the continental margin, while we use accretion (or accretionary event) to refer to the thickening of the accretionary wedge that forms the Ecuadorian Andes.

In this paper, the available data regarding the sedimentary evolution and tectonic behaviour of both the continental plate and the oceanic units are reviewed. Based on these data, their consequences are exposed and analysed, and a tectonic model for the evolution of the Ecuadorian Andes is proposed, which explains both the apparent mild shortening

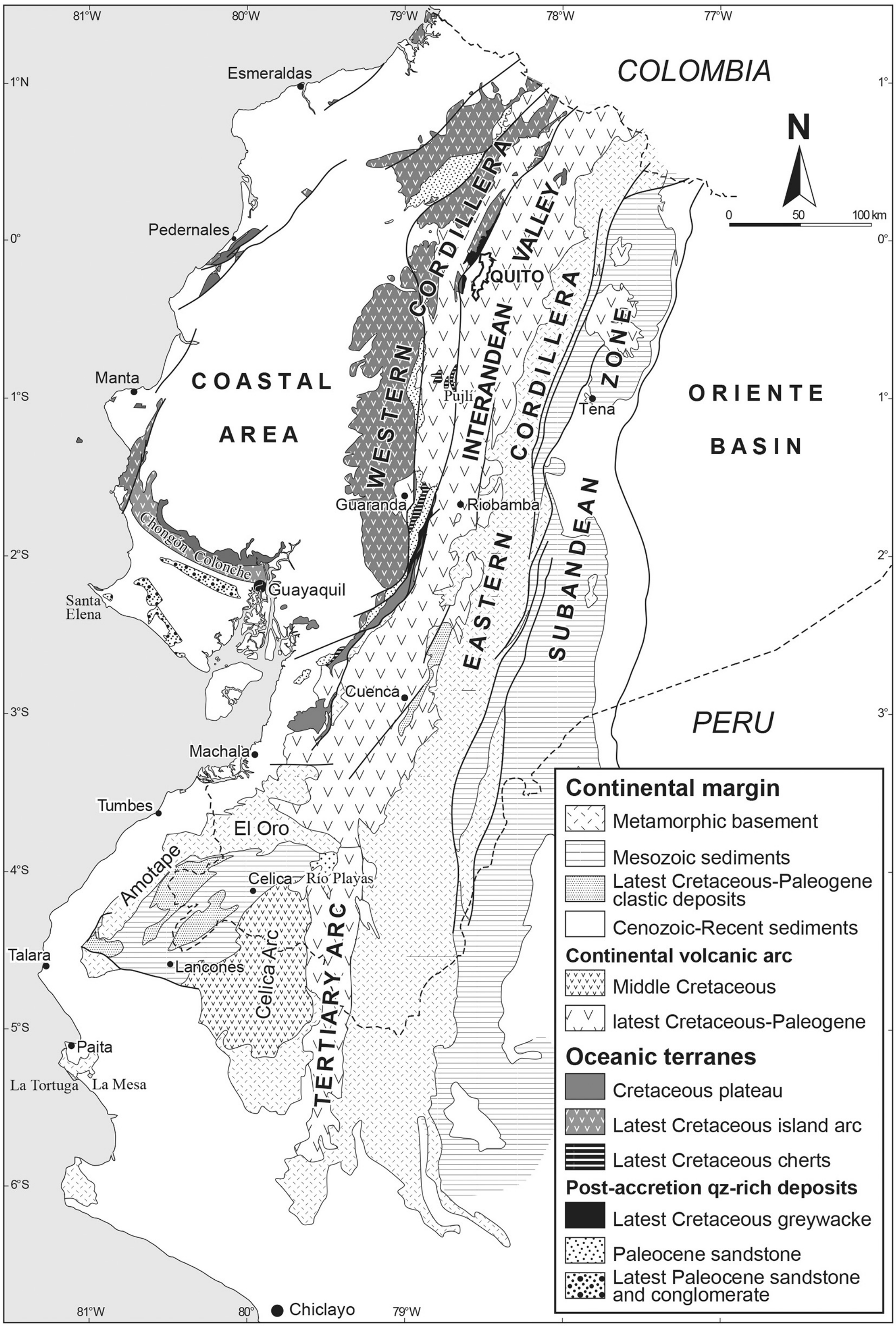

Fig. 1. Geological sketch of northern Peru and Ecuador, showing the main areas and localities cited in the text.

experienced by the continental crust, the overthickened crustal root assessed beneath the Andes of Ecuador, as well as the relatively low elevation of the latter. It is finally proposed that this model may not be restricted to the Ecuadorian Andes, and may explain part of the volume of the crustal root in other parts of the Andean chain.

2. Geological setting

Southern Ecuador and northern Peru mark the transition between the Central Andes and Northern Andes. Both segments comprise a late Cretaceous-Neogene continental volcanic arc, which allows the classic subdivisions of the Andean margin into forearc, arc, and backarc zones.

In northernmost Peru, the forearc zone comprises Cretaceous-Tertiary forearc basins (Lancones, Talara, Tumbes, Sechura) and a coastal range (Amotape and El Oro massifs) (Fig. 1). The arc zone migrated eastward since the Cretaceous, and is presently located on the western part of the Andean range(Mourier, 1988). The eastern part of the latter is made of deformed Paleozoic-Tertiary sediments resting on a metamorphic basement (Eude et al., 2015; Miskovic et al., 2009). The backarc zone comprises the Subandean zone made of folded Meso-Cenozoic sediments, and the Amazonian Basin infilled by Mesozoic-Quaternary sediments.

In Ecuador, the forearc zone comprises forearc basins resting on the oceanic accreted basement (Aizprua et al., 2020; Hernández et al., 2020) and constitutes the coastal zone (Fig. 1). The arc zone comprises the Western Cordillera made of an uplifted part of the accreted oceanic terranes, the Inter-Andean Valley infilled by the products of the Tertiary-Recent volcanic arc (Lavenu et al., 1992; Hungerbühler et al., 2002), and the Eastern Cordillera mainly composed of metamorphic rocks (Litherland et al., 1994; Pratt et al., 2005). The backarc zone comprises the Subandean zone made of mainly Meso-Cenozoic, folded sedimentary and volcaniclastic rocks, and the Oriente Basin infilled by Mesozoic-Quaternary deposits (Jaillard, 1997; Highley, 2001) (Fig. 1).

In order to reconstruct the tectonic evolution of the Andean orogeny in Ecuador, we analyse thereafter representative and well-dated sedimentary sections of the various zones of Ecuador and North-Peru.

3. Cretaceous-Eocene sedimentary record of the continental margin

3.1. Oriente Basin (Albian-Paleocene)

The Oriente Basin has been studied for a long time (e.g. Wasson and Sinclair, 1927; Tschopp, 1953; Faucher et al., 1971; Dashwood and Abbotts, 1990; Balkwill et al., 1995; Jaillard, 1997; Vallejo et al., 2017, 2021, and references therein). After deposition of Aptian-early Albian tidal to fluvial sandstones, the Oriente Basin recorded the Albian marine transgression, and its evolution was mainly controlled by sea-level eustatic fluctuations. These allowed deposition of alternating transgressive sandstones, outer shelf marls and shallow marine shelf carbonates until the Santonian (Napo Fm, Jaillard, 1997; Fig. 2).

A first sedimentary hiatus occurred after the Santonian and is followed by the appearance of mainly clastic deposits of middle Campanian age (M1 Sandstone; Raynaud et al., 1993). A second hiatus separates the shallow marine Campanian sandstones from thick, fine-grained red beds (Tena Fm), the base of which comprises a short marine incursion of early Maastrichtian age (Jaillard et al., 2005). A third sedimentary hiatus occurred in the Late Maastrichtian, and separates fine-grained, partly marine red beds (Lower Tena Fm), from thicker and coarser-grained, continental red beds of Paleocene age (Upper Tena Fm; Jaillard, 1997). A new hiatus separates the latter from alluvial sandstone and conglomerates of early to middle Eocene age (Tiyuyacu Fm; Christophoul et al., 2002; Fig. 2).

Heavy minerals studies show that Cretaceous sandstones were sourced from the Brazilian shield until the Campanian, and from the Ecuadorian Eastern Cordillera from the Maastrichtian onwards (Ruiz

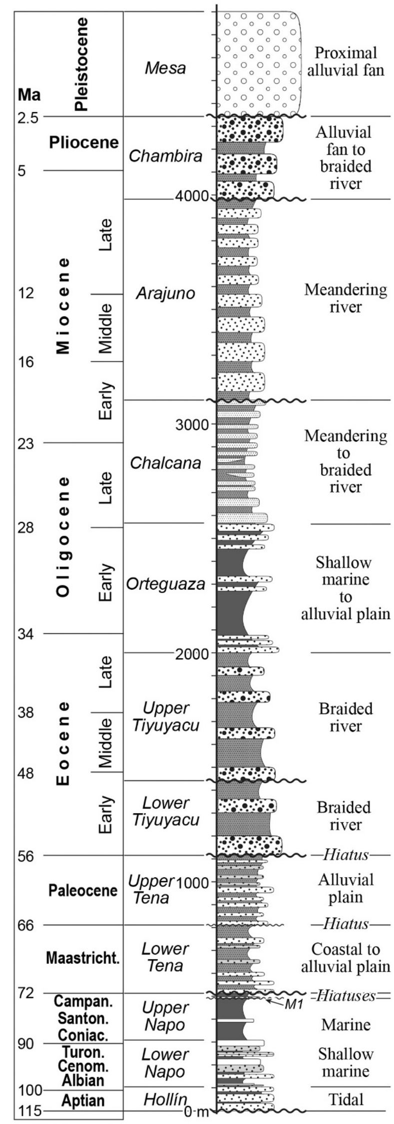

Fig. 2. Composite and simplified series of the Oriente Basin, Ecuador (compiled from Jaillard et al., 1997; Christophoul et al., 2004; Vallejo et al., 2021).

et al., 2004; Martin-Gombojav and Winkler, 2008; Gutierrez Tamayo, 2018; Vallejo et al., 2021), thus expressing a significant uplift of the Ecuadorian active margin in the middle to late Campanian. The subsidence of the Oriente Basin is mild between Albian and Eocene times (Thomas et al., 1995), and drastically increased from the late Oligocene onwards (~25 Ma; Dashwood and Abbotts, 1990), which coincides with a abrupt change in the heavy mineral assemblages (Chalcana Fm; Ruiz et al., 2004; Martin-Gombojav and Winkler, 2008).

3.2. Southernmost Ecuador-Northernmost Peru

3.2.1. The Paita area (Campanian-Paleocene)

The Paita area (northwesternmost Peru, Fig. 1) presents two interesting, isolated outcrops.

The Cerro La Mesa exhibits a 350 m-thick succession of marl, limestone and sandstone (La Mesa Fm, Iddings and Olsson, 1928; Olsson, 1948; Fischer, 1956; Taipe et al., 2004; Jaillard et al., 2005). The lower transgressive member is made of marl and sandstones that seem to overly the Paleozoic basement (Fig. 3). It contains a shallow marine, Late Campanian fauna associated with vertebrates and wood fragments. The Middle calcareous member (*Actaonella* limestone) consists of a

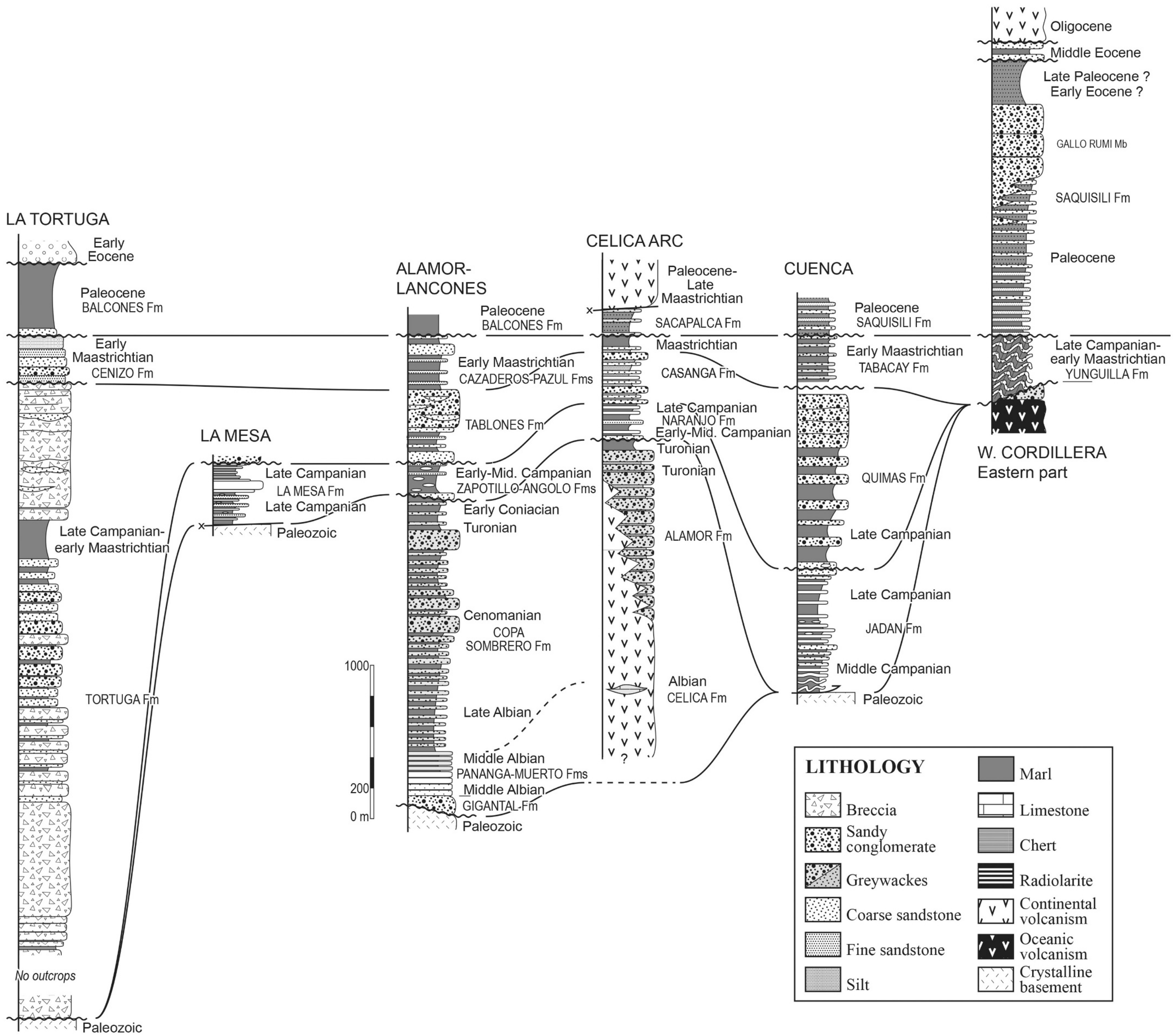

Fig. 3. Simplified stratigraphic succession of late Cretaceous-Paleogene age from the forearc zones of northwestern Peru (left) to central Ecuador (right) (from Jaillard et al., 1996, 1999, 2004, 2005).

shallow marine, rudistids- and gastropod-bearing carbonate shelf. The upper member is a transgressive-regressive sequence rich in shallow marine (ostreids, rudistids) to pelagic fauna (inoceramids, ammonites) of Late Campanian age (Taipe et al., 2004; Jaillard et al., 2005). The overlying subaerial conglomerates are undated, and express a sharp regression and a tectonic event.

South of the La Tortuga village (Fig. 1), the beaches offers good outcrops. There, a 3500 m-thick succession of coarse-grained breccia rests on the Paleozoic basement, and is interrupted by a marine intercalation (Fig. 3). The latter contains a shallow marine fauna, wood fragments and late Campanian-early Maastrichtian ammonites (Jaillard et al., 2005). The breccia of the La Tortuga Fm is overlain by transgressive sandstones (Cenizo Fm) with a coarse-grained intercalation. The lower member (*Baculites* sandstones) consists of shallow marine sandstones rich in shallow marine fauna and plant remains. Inoceramids and ammonites allow to date it as early Maastrichtian. The upper part of the coarse-grained middle member yielded an early Maastrichtian ammonite. The upper member (*Radiolites* sandstone) is made of very shallow marine sandstones that contain both scarce early Maastrichtian ammonites, giant rudistids (Philip and Jaillard, 2004) and a rich vertebrate fauna (Jaillard et al., 2005; Daillie, 2008; Martinez et al., 2018).

This unit is unconformably overlain by marine dark micaceous shales, ascribed to the Paleocene Balcones Fm (Fischer, 1956; Morales, 1993). Near its base, the latter unit includes a clastic unit, and/or intercalations of breccias reworking Maastrichtian sandstones and Albian limestones (Fischer, 1956), expressing a significant tectonic event that led to the reworking of Late Cretaceous to Early Cretaceous rocks. In the Talara Basin located farther North, the Balcones Fm is unconformably overlain by quartz-rich conglomerates of lower Eocene age (Basal Salina or Mogollón Fms; Séranne, 1987; Morales, 1993).

3.2.2. *The Alamor-Lancones forearc basin (Albian-Paleocene)*

The Cretaceous Alamor-Lancones forearc Basin is located immediately West of the Cretaceous Celica Arc (Fig. 1). Its northern part belongs to Ecuador, while its southern part lies in northern Peru. It is bounded to the West by the Paleozoic Amotape Massif, to the South by a major normal fault that separates it from the Miocene-Quaternary Sechura plain (Dunbar et al., 1990), and to the North by the *E*-W trending metamorphic El Oro Massif (Aspden et al., 1995; Bosch et al., 2002). The latter exhibits a striking section of the forearc crust, including remnants of a subducted plate (Raspas Complex, Aspden et al., 1995; Gabriele, 2002; John et al., 2010; Riel et al., 2013, 2014).

The initial opening of the Alamor-Lancones Basin is marked by undated transgressive fluvial conglomerates, bearing locally numerous silicified trees (Jaillard et al., 1999), overlain by shallow marine shelf limestone of Early Albian age and outer shelf black limestone of Middle to early Late Albian age (Pananga and Muerto Fms; Fischer, 1956; Reyes and Vergara, 1987) (Fig. 3). The latter are locally interbedded in the Celica Fm, partially of Albian age (105–100 Ma, Winter et al., 2010).

These carbonates are abruptly overlain by a thick series (2000–3000 m) of turbidites (Copa Sombrero Gp, Iddings and Olsson, 1928; Morris and Alemán, 1975; Chávez and Nuñez del Prado, 1991) of Late Albian to early Coniacian age (Petersen, 1949; Reyes and Vergara, 1987; Jaillard et al., 2005). Paleocurrents measurements indicate a NE-ward direction, i.e. parallel to the trough axes (Morris and Alemán, 1975; Jaillard et al., 1999). This succession is then overlain by a first sequence of quartz-rich, lens-shaped arkosic sandstone, overlain by dark shales of Early to Middle Campanian age (Zapotillo or Angolo Fms, Jaillard et al., 2005; Palacios et al., 2015) (Fig. 3). Then, an up to 800 m-thick series of quartz-rich conglomerate (Tablones Fm, Chalco, 1955) rest unconformably on Albian to Coniacian rocks. The overlying dark shales are of Campanian-Maastrichtian age (Pazul Fm of Chalco, 1955; Reyes and Vergara, 1987; Redondo Shale of Fischer, 1956; Cazaderos Fm of Jaillard et al., 1999). The onshore Cretaceous succession ends up with a new conglomeratic deposit of Maastrichtian age rich in nearshore molluscs and dated by the ammonite "*Turrilites peruvianus*" (Monte Grande Fm, Fischer, 1956). In the Talara basin, the series, known in subsurface, continues with marine shales dated as Maastrichtian by the planktic foraminifer *Rugoglobigerina rugosa* (Petacas Fm), overlain by beach sandstones (Mesa Fm) of Maastrichtian age (Fischer, 1956). It is not clear, however, if the Monte Grande and Mesa Fms are equivalent or not. A hiatus separates this succession from overlying Paleocene marine shales (Balcones Fm; Fischer, 1956; Morales, 1993) (Fig. 3).

In the southern part of the Alamor-Lancones Basin, numerous mafic intrusions (gabbros, diorites) intrude the Copa Sombrero Gp and are therefore, of pre-Campanian age (Chalco, 1955; Fischer, 1956). Fischer (1956) correlates them with the gabbro of the Morro de Eten near Chiclayo, in coastal northern Peru, which gave a K/Ar whole rock age of 82 Ma (Santonian; Mourier, 1988).

3.2.3. *The Celica-Lancones volcanic arc (Albian-Maastrichtian)*

The Celica (Ecuador) or Lancones (Peru) volcanic arc comprises two areas. To the East, the magmatic belt comprises basalts with subordinate felsic volcanic rocks of Albian age (105–100 Ma), overlain by bimodal volcaniclastic rocks of volcanic arc affinity, dated as Cenomanian-Turonian (99–91 Ma; Winter et al., 2010; Jaimes et al., 2012). To the West, these magmatic rocks grade to massive volcaniclastic accumulations referred to as the Alamor Fm (Kennerley, 1973; Valarezo et al., 2019; Quillosara Fm of Jaillard et al., 1999) (Fig. 3). The latter is made of thick-bedded high density turbidites, made of volcaniclastic material, interpreted as reworking the Celica-Lancones magmatic arc (Jaillard et al., 1999; Valarezo et al., 2019). Although no intermediate facies have been observed, they are considered grading laterally to the turbiditic greywacke and shales of the Copa Sombrero Fm of the Alamor-Lancones Basin. Scarce paleontological data suggest a Turonian age for the upper part of the unit (Jaillard et al., 1996). In the northern part of the arc zone, black shales yielded a Late Cenomanian-Turonian inoceramid (Carmelo Fm, Jaillard et al., 1999), which suggests that the volcanic activity was reduced by that time.

In the Río Playas area, the deformed Celica-Lancones volcanic arc (Valarezo et al., 2019) is unconformably overlain by marine marls and sandstone that yielded Santonian to Middle Campanian ammonites and microfauna (Naranjo Fm; Jaillard et al., 1996, 2005) (Fig. 3). They are overlain by a succession of shales, sandstones and conglomerates rich in bivalves and plant remains, interpreted either as marine turbidites to fan-delta deposits (Casanga Fm; Jaillard et al., 1996), or as deep-sea fan deposits (Valarezo et al., 2019). The last unit of this succession is represented by fine-grained shales of Maastrichtian age that crop out North of Casanga and West of Río Playas (Bristow and Hoffstetter, 1977, p. 360–361). The Casanga conglomerates are, therefore, of late Campanian to early Maastrichtian age (Fig. 3).

The discovery of a dinosaur in fluvial sandstones and conglomerates (Río Playas Fm), located immediately East of the Casanga Fm, indicates a Campanian to Maastrichtian age for the unit (Apesteguía et al., 2020). The latter can be thus considered equivalent to the conglomeratic Casanga Fm, since the heavy mineral assemblages of both units do not differ significantly (Valarezo et al., 2019). A shallow marine to fan-delta depositional environment is, therefore, more probable for the Casanga Fm. The Río Playas Fm seems to be overlain by subaerial volcanics and red beds, ascribed to the Paleocene (Sacapalca Fm; Valarezo et al., 2019). However, the Sacapalca Fm has been dated by a zircon F-T age at 67 ± 6 Ma (Hungerbühler, 1997) and subaerial volcanism yielded Ar/Ar ages of 67–35 Ma in northern Ecuador (Tandapí facies of Silante Fm; Vallejo et al., 2009, 2020), indicating that a continental arc volcanism was active during the late Maastrichtian and Paleogene (Fig. 3). This explains the volcano-clastic content (Vallejo, 2007) and volcanic intercalations (Dunkley and Gaibor, 1998; McCourt et al., 1998) in the well-dated Maastrichtian sediments of southern and central Ecuador (Yunguilla Fm), as well as in the more distal Maastrichtian-Paleocene cherts of the coastal area (Guayaquil Fm; Witt et al., 2019).

3.2.4. *Andean forearc zone of the Cuenca area (Middle Campanian-Paleocene)*

The Cretaceous sediments of this area are considered resting on the Paleozoic basement (Faucher et al., 1971; Bristow, 1980; Dunkley and Gaibor, 1998; Jaillard et al., 2008). The succession begins with transgressive, prograding sequences of outer shelf marine shales, limestones, calciturbidites and sandstones, yielding middle and late Campanian ammonites and inoceramids (Jadán Fm, Jaillard et al., 2008) (Fig. 3). They are overlain by ~1000 m of a thickening-upward succession of quartz-rich sandstones, conglomerates and coarse-grained conglomerates of outer shelf to fan delta environment (Quimas Fm). The latter seal, at least locally, the mild deformation of previous deposits. Ammonites at the base of this unit indicate a late Campanian age (Jaillard et al., 2008). The overlying deposits (Tabacay Fm, Fig. 3) consist of dark shales and lithic sandstone beds interpreted as turbidites, locally deformed by gravitational processes and admitting sparse volcanic or volcaniclastic intercalations (Dunkley and Gaibor, 1998). They contain scarce ammonites, inoceramids and microfauna, which indicate an early Maastrichtian age (Faucher et al., 1971; Bristow, 1973; Jaillard et al., 2008).

North of Cuenca, the Tabacay Fm is unconformably overlain by dark shales and siltstones, with sandstone and micaceous arkosic sandstone beds, deposited in a clastic shelf environment (Jaillard et al., 2008). Since palynomorphs and foraminifers indicate a Paleocene age, they are correlated with similar and coeval deposits known farther North (Saquisilí Fm of Hughes et al., 1998). These are unconformably overlain by Eocene subaerial volcanic rocks.

3.3. *Synthesis*

The continental margin of Ecuador and northernmost Peru recorded a first tectonic event of late Santonian-early Campanian age (85–80 Ma), responsible for hiatuses (Oriente, Alamor-Lancones Basin, Celica Arc) and probable deformation expressed by unconformities (Celica arc). This event represents the Peruvian tectonic phase of Steinmann (1929) (see also Mégard, 1984, 1987; Jaillard et al., 2000). A major marine transgression occurred in middle Campanian times (Jaillard et al., 2005), which is recorded in all areas (La Mesa, Zapotillo, and Jadan Fms, M1 sandstone). A second, major tectonic event of late Campanian age (~75 Ma) is associated or, more frequently, followed by the deposition of thick, coarse-grained, quartz-rich conglomerates or breccias in all forearc zones (La Tortuga, Tablones, Casanga, Quimas Fms), and by the transition to continental deposits in the Arc zone and Oriente Basin (lower Tena Fm). A third, important tectonic event of late Maastrichtian age (~68 Ma) was marked in all areas by hiatuses followed by unconformities (Balcones, Saquisilí, upper Tena Fms), by a shallowing up in the sedimentary environments (Oriente, Cuenca), and by the local deposition of quartz-rich conglomerates. A fourth tectonic event of late Paleocene age (~58 Ma) is expressed by Paleocene-Eocene hiatuses and unconformities, followed by quartz-rich, coarse-grained deposits in the Talara (Mogollón Fm) and Oriente basins (Tiyuyacu Fm). No Eocene sedimentary deposits are known in other areas of the continental margin.

4. Cretaceous-Paleocene sedimentary record of the accreted oceanic terranes

4.1. Coastal area

The coastal area of Ecuador presents several types of successions according to the location.

4.1.1. Chongón-Colonche Cordillera

The basement of this classical series was considered Albian in age (Goossens and Rose, 1973; Jaillard et al., 1995; Reynaud et al., 1999), but is now dated as Turonian-Coniacian (87–89 Ma; Gamber et al., 1990; Luzieux et al., 2006; Vanmelle et al., 2008; Seyler et al., 2021). It consists of basalts originated from a mantle plume (Reynaud et al., 1999; Mamberti et al., 2003, 2004; Jaillard et al., 2009) and is considered part of the Caribbean Oceanic Plateau (Lapierre et al., 2000; Kerr et al., 2002; Luzieux et al., 2006). It is overlain by the Calentura Fm (Fig. 4), which is made of acidic volcanic breccias and tuffs interbedded with black siliceous limestones of early to middle Coniacian age (50–150 m), red radiolarians of Santonian age (30 m), and marls, tuffs and litharenites of early(?) Campanian age (100–300 m), which mark the transition to the overlying Cayo Fm (Vanmelle et al., 2008) (Fig. 4). The Cayo Fm is made of 2000–3000 m of volcanoclastic turbidites, interpreted as derived from the activity of a volcanic arc (San Lorenzo Fm; Benítez, 1995; Reynaud et al., 1999; Luzieux et al., 2006). The latter, of Campanian to Maastrichtian age (Jaillard et al., 1995), is located farther West and extends to the North of the Western Cordillera (Río Cala or Naranjal Fm; Boland et al., 2000; Vallejo, 2007) and to Colombia (Ricaurte Fm; Spadea and Espinosa, 1996). The Cayo Fm is overlain by black pelagic cherts of middle Maastrichtian-Late Paleocene age (Guayaquil Fm; Benítez, 1995; Jaillard et al., 1995; Keller et al., 1997; Ordóñez et al., 2006; Vanmelle et al., 2008).

This Cretaceous to Paleocene series is unconformably overlain by a 1000 to 1500 m-thick transgressive-regressive sequence of middle Eocene age (San Mateo Fm, Fig. 4). It begins with local, lens-shaped shelf limestones (50 m), continues with quartz-rich turbidites (500 m) and marls and sandstones (500 m), both deposited in an outer shelf environment, and ends up with shoreface to foreshore, coarse-grained quartz-sandstones (200 m) (Jaillard et al., 1995). An unconformity emphasizes the deposition of terrestrial to marginal marine greywackes and conglomerates of Oligocene age (Zapotal Fm; Ordoñez et al., 2006; Witt et al., 2019).

4.1.2. Santa Elena Peninsula

South of the Chongón-Colonche Cordillera, the base of the succession is similar to that of the Chongón-Colonche Cordillera, but is highly deformed (Jaillard et al., 1995, 1997; Aizprua et al., 2019). Overlying the deformed remnants of the Cayo Fm, pelagic, radiolarian-rich black cherts of Maastrichtian age exhibit isoclinal folds and penetrative cleavage (Santa Elena Fm) and are considered equivalent to the Guayaquil Fm (Fig. 4). They are unconformably overlain by thick, coarse-grained, high-density, quartz-rich turbidites of latest Paleocene age (Azúcar Fm), thus expressing a major tectonic event of late Paleocene age (Jaillard et al., 1995; Witt et al., 2019). The latter are in turn deformed and unconformably overlain by a Middle Eocene sequence comparable to that of the Chongón-Colonche Cordillera (Ancón Gp; Ordoñez et al., 2006; Witt et al., 2019). The Eocene sequence, therefore, postdates the late Paleocene deformation and early Eocene hiatus (Fig. 4). Eocene paleocurrent measurements indicate a NW-ward transport (Jaillard et al., 1995), supporting the Amotape Massif as a detritus source (Witt et al., 2019).

4.2. Western Cordillera

Two distinct stratigraphic successions can be identified in the Western Cordillera of Ecuador (Fig. 4).

4.2.1. Eastern succession, with Maastrichtian quartz-rich turbidites

In the Pallatanga area, dark mudstones and siltstones, interbedded with fine-grained sandy turbidites (Yunguilla Fm) exhibit soft-sediment deformation and scarce volcanic intercalations (McCourt et al., 1998). Although mafic minerals dominate, quartz and plagioclase are present, indicating the erosion of a crystalline basement (Toro and Jaillard, 2005). Foraminifers indicate a Maastrichtian age (Thalmann, 1946; Faucher et al., 1971; McCourt et al., 1998). This unit is highly deformed, and is usually in tectonic contact with magmatic rocks of the accreted oceanic terranes; it is thus interpreted as deposited on the latter (Bristow and Hoffstetter, 1977; McCourt et al., 1998; Jaillard et al., 2004; Vallejo et al., 2019) (Fig. 4).

West of Riobamba, the same unit is locally intercalated with calciturbidites (San Juan Fm of Kehrer and Kehrer, 1969; Vallejo, 2007) and presents dispersed fold axes (Jaillard et al., 2004; Vallejo, 2007). It yielded ammonites, radiolarians and foraminifers of late Campanian-early Maastrichtian age (Jaillard et al., 2004). Petrographic analysis indicates a mainly metamorphic detrital source (Toro and Jaillard, 2005; Vallejo et al., 2019). It is in fault contact with quartz-rich siltstones, sandy turbidites and conglomerates of Paleocene age (Saquisilí Fm; Hughes et al., 1998; Jaillard et al., 2004).

West and North of Quito, heavy mineral assemblages of the Yunguilla Fm indicate a source rich in granitoids and metamorphic rocks, most probably represented by the Eastern Cordillera (Vallejo, 2007). However, Maastrichtian zircons suggest a coeval volcanic activity (Vallejo et al., 2009), confirmed by the mafic minerals observed farther South. In spite of the high deformation and although it is systematically in tectonic contact with surrounding volcanic rocks, the Yunguilla Fm is considered deposited on the eastern part of the accreted terranes (Vallejo, 2007). As a matter of fact, it is restricted to the eastern margin of the Western Cordillera, and is mainly sourced by the continental margin. Because of similar ages, lithologies and facies, the Yunguilla Fm is considered equivalent to the Maastrichtian Tabacay Fm of the Cuenca area. Therefore, the Maastrichtian sedimentary basin that received both the quartz-rich turbidites of the Tabacay and Yunguilla Fms crosscut the contact between the continental margin and the accreted oceanic terranes, and therefore, seals the collision of the western oceanic terrane.

In all studied area, the Yunguilla Fm is unconformably overlain by Paleocene and Eocene, quartz-rich deposits (Angamarca Gp, Hughes et al., 1998). Paleocene deposits (Saquisilí Fm; Hughes et al., 1998) consist of a 2000–3000 m-thick series of thickening-upward dark shales, siltstones, turbiditic sandstones and conglomerates (Gallo Rumi Mb; Bristow and Hoffstetter, 1977) (Fig. 4). The base contains blocks and olistoliths of the latter, whereas the upper part comprises finer-grained siltstones and sandstones. The Eocene sequence unconformably overlies the Paleocene deposits. It begins with local shelf to reef limestones of middle to late Eocene age (Unacota Fm; Bourgois et al., 1990) and continues with a thickening upward series of siltstone, turbiditic

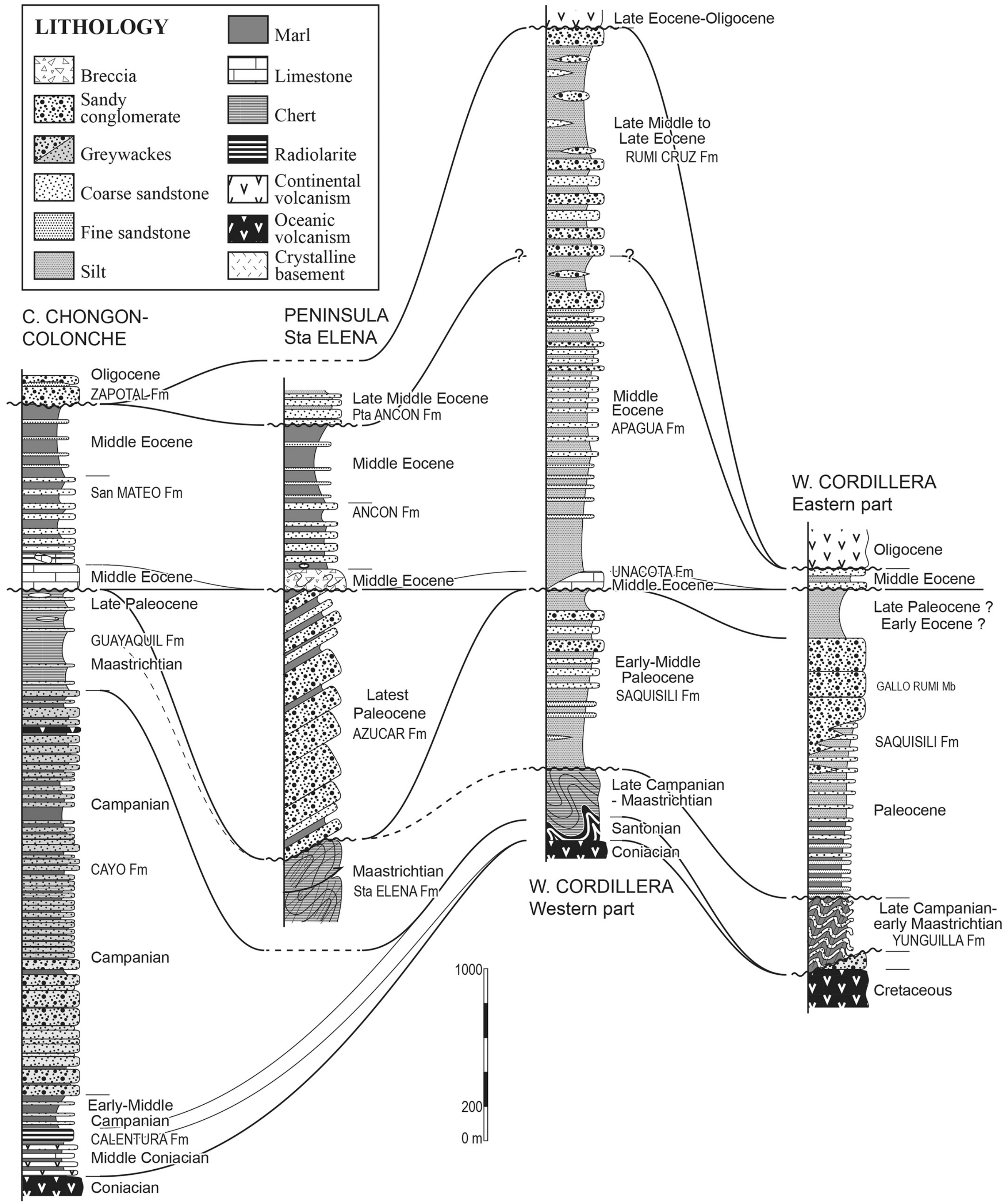

Fig. 4. Cretaceous-Paleogene successions of the accreted oceanic terranes, from Southwest Ecuador (left) to central Ecuador (right) (from Jaillard et al., 1995, 2004; 2009).

sandstone and scarce conglomerates (Apagua Fm; Santos et al., 1986; Egüez and Bourgois, 1986). It ends up with a thinning-upward series of mainly fluvial shales, sandstones and conglomerates (Rumi Cruz Fm; McCourt et al., 1998; Hughes et al., 1998). Therefore, the Eocene sequence displays a deepening-, then shallowing-upward succession. It is then unconformably overlain by Oligocene subaerial volcanic rocks (McCourt et al., 1998).

4.2.2. *Western succession, with Maastrichtian oceanic cherts*

Remnants of a distinct series have been mainly observed West of Riobamba and Pujilí (Fig. 1). There, deformed bituminous black limestones, red radiolarites and black pelagic shales and cherts are observed, locally in stratigraphic contact with the oceanic volcanic rocks (Jaillard et al., 2004) (Fig. 4). Boland et al. (2000) reported a Santonian age for the radiolarites. Therefore, the black limestones and red radiolarites can be correlated with similar deposits of the coastal area, of Coniacian and Santonian age, respectively (Vanmelle et al., 2008; see Section 4.1.1). The black, quartz-free pelagic cherts yielded a microfauna of radiolarians and foraminifers of middle-late Campanian to Maastrichtian age (Jaillard et al., 2004) and are, therefore, coeval with the quartz-rich Yunguilla-Tabacay Fms located farther East (Fig. 3), and partly with the quartz-free Guayaquil Fm of the coastal area (Fig. 4).

The Cretaceous rocks are then unconformably overlain by a Paleocene-Eocene series comparable to that observed on the eastern succession. However, it is thinner and displays a finer-grained and thinner-bedded lithology, that leads to interpret it as a distal facies of the eastern coeval sequence (Jaillard et al., 2004; 2009). Furthermore, the Eocene sequence locally overlies paleosoils that indicate a period of subaerial exposure and erosion, likely of early Eocene age (Jaillard et al., 2004).

Vallejo et al. (2009, 2019) consider that both the Yunguilla and oceanic cherts belong to the same unit. However, the fact that the pelagic oceanic cherts of the western unit are free of detrital quartz, and are associated with black limestones and radiolarites contradicts this interpretation. In my view, the presence of the quartz-rich Yunguilla Fm on the easternmost oceanic accreted tectonic unit indicates that it was already accreted to the continental margin in the Maastrichtian, whereas the western unit was still in a distal oceanic setting at that time. The occurrence of Paleocene quartz-rich sandstone and conglomerates resting unconformably on both the eastern Yunguilla Fm and western oceanic cherts indicates that the western unit has been accreted during the late Maastrichtian-early Paleocene time-span, i.e. after the eastern unit (Jaillard et al., 2009).

4.3. *Synthesis*

The coastal area recorded the Campanian-Maastrichtian activity of an island arc, developed on top of a Turonian-early Coniacian Caribbean Oceanic Plateau. A first important tectonic event (~75 Ma) provoked the deposition of quartz-bearing, late Campanian-early Maastrichtian turbidites (Yunguilla Fm) on the easternmost part of the area. A second major tectonic event of late Maastrichtian age (~70 Ma) is recorded in the coastal area by the end of the island arc activity, and elsewhere by the deformation of the Maastrichtian deposits (Sant Elena, Yunguilla Fms) and the unconformity below the thick, quartz-rich, Paleocene succession (Saquisilí Fm). A third, major tectonic event of late Paleocene age (~58 Ma) was responsible for the deposition of thick, quartz-rich, coarse-grained conglomerates of latest Paleocene age on the coastal area (Azúcar Fm), and by a hiatus in the present-day Western Cordillera. In all oceanic terranes, deposition locally resumed with local, transgressive shelf limestone of middle Eocene age (Santos et al., 1986), thus demonstrating first, that the whole area became emergent about the Paleocene-Eocene boundary, and second, that the Eocene sedimentary evolution was common to the coastal area and the Western Cordillera (Jaillard et al., 2009). Finally, clastic, quartz-rich deposits progressively invaded the oceanic terranes, in late Campanian times in the eastern Western Cordillera (Yunguilla Fm), in the Paleocene in the western part of the Western Cordillera (Saquisilí Fm), and in latest Paleocene to Eocene times in the coastal area (Azúcar, Ancón, San Mateo Fms). This indicates that, even though these areas may belong to a same oceanic plateau, their accretionary history differs, and that quartz-rich syntectonic deposits migrated westward through time.

5. Discussion of the orogenic build-up of the Ecuadorian Andes

5.1. *One or several oceanic terranes?*

A debate still exists about the collision of a single, or of various, oceanic terranes (Kerr and Tarney, 2005; Jaillard et al., 2009; Vallejo et al., 2009, 2019; Witt et al., 2017, and references therein). Our data do not permit a resolution of this question. As a matter of fact, on one hand, geochemical data all point to an oceanic plateau origin for these terranes, and radiometric ages (123 to 85 Ma; Lapierre et al., 2000; Luzieux et al., 2006; Vallejo et al., 2019) show that they most probably belonged to the Caribbean Oceanic Plateau. On the other hand, the lavas of the latter yielded a wide range of ages (~130 to 70 Ma; Sinton et al., 1998; Hoernle et al., 2004; Buchs et al., 2010; Whattam and Stern, 2015), which does not allow to distinguish between oceanic terranes of distinct ages. Therefore, we will consider, whatever the number of oceanic plateaus, that an oceanic "terrane" is defined by its stratigraphic cover that expresses a distinct and peculiar tectonic, paleogeographic and sedimentary evolution (see Coney et al., 1980; Jaillard et al., 2009). In that sense, three distinct terranes can be distinguished, defined by the three successive quartz-rich deposits invading the oceanic plateau (Jaillard et al., 2009). These are, from East to West, (1) the eastern San Juan Plateau (eastern Western Cordillera) accreted in the late Campanian, (2) the Guaranda terrane (western Western Cordillera) accreted in the late Maastrichtian, and (3) the western Piñón terrane (coastal area) accreted in the late Paleocene.

Therefore, if a single oceanic plateau, i.e. the Caribbean Oceanic Plateau, the latter was progressively splitted, during the accretion process, into (at least) three terranes, the sedimentary cover of which recorded their own tectonic evolution. Each collision or accretion pulse (1) created, on the recently formed suture, a foredeep basin infilled by the erosion of the uplifted continental margin (Yunguilla, Saquisilí and Apagua basins), and (2) provoked in the Oriente basin a long-lasting hiatus, followed there (3) by the arrival of progressively coarser-grained clastic deposits (Lower Tena, Upper Tena and Tiyuyacu Fms).

5.2. *Timing of collision(s) and accretion*

Vallejo et al. (2009, 2019) assumed that a single collision occurred at ~75–65 Ma (Late Campanian to Maastrichtian), while Spikings et al. (2010) proposed a single, but oblique and diachronous collision at the same time. The analysis of the sedimentary record highlighted the occurrence of four tectonic events of Late Cretaceous-Paleocene age (see Jaillard et al., 2009; Witt et al., 2019).

The Santonian event is well-known in the central Andes (Steinmann, 1929; Mégard, 1984; Jaillard et al., 2000). In Ecuador, it is mainly responsible for hiatuses, without evidence of collision. On the southern coastal area, the Santonian radiolarites are overlain by thick-bedded volcaniclastic turbidites of Campanian-Maastrichtian age (Cayo Fm) that rework an active island arc.

The late Campanian event (~75–80 Ma) is a major tectonic event in Ecuador. Because of poor age data at that time, Steinmann (1929) and Mégard (1984) did not differentiate the Santonian and late Campanian events, and merged them in the "Peruvian tectonic phase". Since the easternmost part of the oceanic terranes recorded the first arrival of detrital quartz, the late Campanian event is thought to represent a first collision event, postdated by the deposition of quartz-bearing turbidites of late Campanian-early Maastrichtian age (Yunguilla Fm) (Fig. 5). The location of the latter, and the fact that no quartz-rich deposits are known

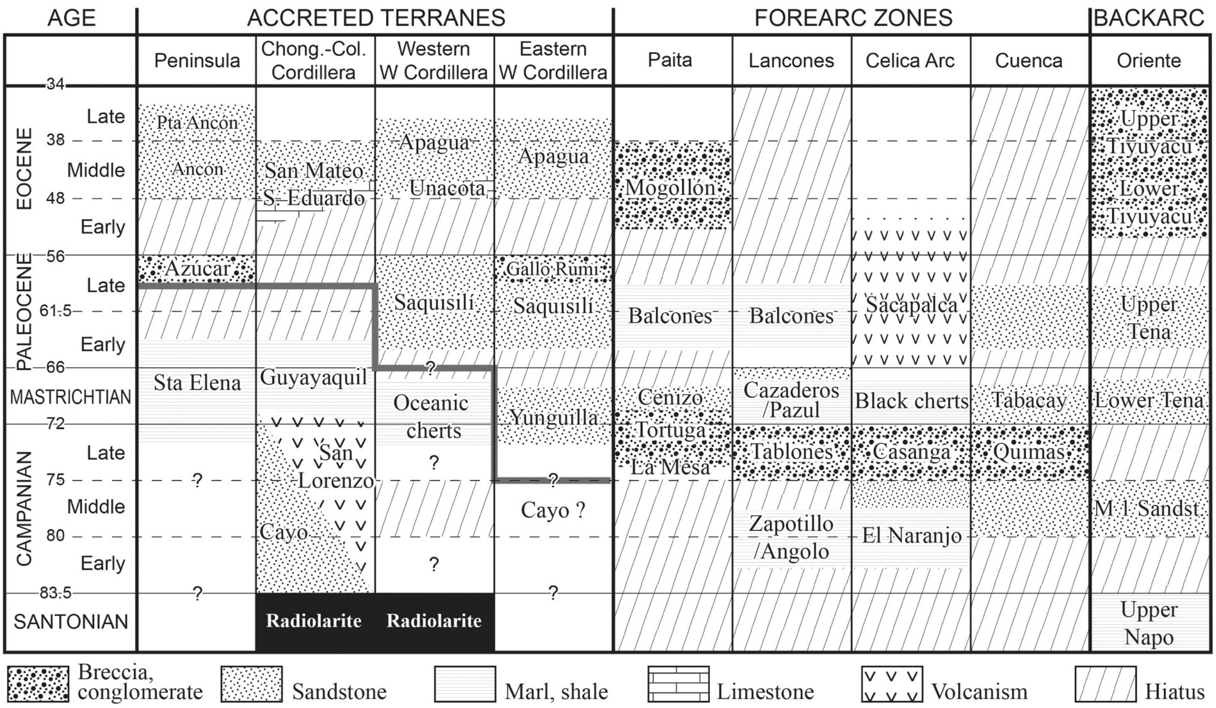

Fig. 5. Chronostratigraphic chart of the Late Cretaceous-Paleogene sediments deposited on the Ecuadorian margin. The grey bold line underlines the appearance of detrital quartz, and thus the accretion date of the described unit.

on the other oceanic terranes, indicate that the Yunguilla basin was a narrow and elongated trough, located on the easternmost part of the oceanic terranes to the North (Riobamba, Quito), and on the continental margin to the South (Cuenca, Tabacay Fm). The thick, coarse-grained, quartz-rich late Campanian-Maastrichtian conglomerates deposited in the Paita, Lancones, Celica and Cuenca areas (Fig. 3) indicate that the late Campanian event provoked the abrupt uplift and erosion of the continental margin. In the Oriente Basin, this event is responsible for the lack of late Campanian sediments and for the unconformity below the early Maastrichtian clastic deposits (Lower Tena Fm), thus indicating that the uplift of the continental margin also involved at least the western part of the Oriente basin.

The late Maastrichtian tectonic event (~70 Ma) is marked both by the end of the San Lorenzo island arc activity, and by the arrival of detrital quartz on the eastern part of the oceanic terranes (present-day Western Cordillera), and by a sedimentary hiatus on the continental margin, followed during the Paleocene by a change in the depositional environments (Fig. 5). Quartz-rich Paleocene deposits (Saquisilí Fm) are known both on the oceanic terranes to the North (Western Cordillera) and on the continental margin to the South (Cuenca area), but are unknown on the western part of the oceanic terranes and the coastal area (Fig. 5), where detrital quartz-free oceanic cherts deposited (Guayaquil Fm). This indicates that the Saquisilí basin was also a narrow and elongated through, located on the eastern part of the oceanic terranes and crossed the terrane-margin tectonic contact. In the Western Cordillera, the thick Paleocene quartz-rich clastic succession indicates that the continental margin (Eastern Cordillera) was again significantly uplifted at that time. In the Oriente Basin, it corresponds to the unconformity between the Lower and Upper Tena Fms (Fig. 5), indicating that at least part of the Oriente basin was also uplifted. This event may coincide with the resumption of arc volcanism on the westernmost part of the continental margin in late Maastrichtian times (Sacapalca, Silante-Tandapi; Vallejo et al., 2019, 2020); this can be related to the arrival, at depth of magma generation, of the oceanic plate subducted beneath the oceanic terranes accreted in the late Campanian.

The late Paleocene event (~58 Ma) is the last accretionary event recorded in the oceanic terranes, since it recorded the local arrival of late Paleocene coarse-grained, quartz-rich deposits (Azúcar Gp) on the detrital quartz-free Paleocene oceanic cherts (Guayaquil Fm) of the Coastal area (Fig. 5) (Witt et al., 2019). On the continental margin, it is marked by coarse-grained deposits (Gallo Rumi Mb), but no Eocene deposits are known, except in the Talara Basin of northwestern Peru (e. g. Mogollón, Verdún Fms) and in the Oriente basin, where coarse-grained fluvial sandstones and conglomerates of Eocene age unconformably overly older rocks (Tiyuyacu Fm, Christophoul et al., 2002; Gutierrez Tamayo, 2018). This indicates that the western part of the margin have been again significantly uplifted.

The subsequent middle Eocene sedimentary sequence, where present, is comparable in all the oceanic terranes (Fig. 5). It consists of local, lens-shaped transgressive shelf limestones, likely related to the Eocene eustatic sea-level rise (Haq et al., 1987; Hardenbol et al., 1998), overlain by middle Eocene turbidites and shelf sandstones (Apagua, Ancón, San Mateo Fms), and late Eocene (?) fluvial sandstones and conglomerates (Rumi Cruz Fm). This common evolution indicates that, from then on, the accreted terranes were incorporated to the Ecuadorian margin, and that they formed a same marine sedimentary domain, although presenting an irregular topography that explains local variations and diachronous transgressions.

5.3. Location of collision(s)

Latest Cretaceous collision seems to have occurred in northern Peru or southern Ecuador. As a matter of fact, coarse-grained, syntectonic forearc deposits are more developed, thicker and coarser-grained in these areas (Fig. 3), and emergence may have occurred earlier there, and involved a larger area than farther North (Fig. 7). However, this observation may result from better outcrop conditions, from the existence of a wider continental forearc zone, or from a milder tectonic deformation and a subsequent less erosion amount. Nevertheless, on one hand, Pécora et al. (1999) mention large mafic boulder bearing an island arc geochemical affinity in a conglomerate ascribed to the late Paleocene-early Eocene in Northwest Peru, and Spikings et al. (2010)

mention a rapid uplift of the Amotape Massif of southern Ecuador around 75 Ma ago (Late Campanian), interpreted as resulting from the collision of an oceanic terrane. On the other hand, it is widely admitted that the opening of the Gulf of Guayaquil in the Miocene separated the oceanic terranes of the coastal area of southern Ecuador from the continental margin of northern Peru (Deniaud et al., 1999; Witt and Bourgois, 2010; Aizprua et al., 2020). Finally, the source of the Paleocene-Miocene clastic sequences of southern coastal Ecuador is probably represented by the crystalline basement of northern Peru (Witt et al., 2017, 2019). The latter interpretation is further supported first, by the northward fining and thinning of the late Paleocene clastic deposits (Azúcar Fm) that do not exist in the Chongón-Colonche Cordillera, and second, by the dominantly Northward paleocurrents measured in the Paleocene-Eocene sequences (Jaillard et al., 1995). These observations strongly suggest that northwesternmost Peru was in contact with the oceanic terranes in latest Cretaceous to Miocene times. Note that thermochronological (Spikings et al., 2010) and geochemical data (George et al., 2021) both suggest that collision occurred earlier in the South of the Northern Andes.

5.4. Obduction vs subduction jam

Two interpretations have been proposed regarding the tectonic process of accretion. Vallejo et al. (2009, 2019); see also Aizprua et al., 2020; Siravo et al., 2021; George et al., 2021) proposed that collision provoked the obduction of the oceanic terrane (Fig. 6), following the westward subduction of an oceanic space located between the Ecuadorian margin and the oceanic plateau. In this case, the continental plate is underthrust beneath the oceanic terranes (Fig. 6). Conversely, Lebrat et al. (1987), Mégard (1987, 1989) and Jaillard et al. (2000; 2009) proposed that collision occurred through subduction jam, due to the arrival of buoyant oceanic plateau in the eastward subduction zone beneath the Ecuadorian margin. In this interpretation, the oceanic terranes are underthrust beneath the continental plate. Feininger and Bristow (1980) proposed a process involving first docking, then oceanic terrane subduction and underplating. We discuss thereafter the obduction interpretation.

5.4.1. Evidences from the Western Cordillera

If obducted, the H-T metamorphosed base of the oceanic plateau should crop out somewhere along the contact between oceanic terranes and continental margin, as in Oman (e.g. Duretz et al., 2016). However, the only Cretaceous high-grade H-T metamorphic oceanic rocks known so far in the Western Cordillera of Ecuador (granulites, garnet-bearing amphibolites) were exhumed thanks to a large-scale flower structure (Jaillard et al., 2004; Beaudon et al., 2005). They yielded a 85 Ma crystallisation age suggesting that they were formed at the base of the accreted oceanic plateau (Vallejo, 2007). Moreover, this structure only exhumed mafic material of oceanic origin (Beaudon et al., 2005), thus indicating that the deep parts of the Western Cordillera are made mainly -if not exclusively- of oceanic material. Farther North, Bruet (1949) described xenoliths of pyroxenites, associated with diorites, in a volcanic flow near Quito. This shows that even the basement of the Inter-Andean Valley comprises ultramafic oceanic rocks. Studying crustal and mantle xenoliths exhumed by a volcano on the western flank of the Central Cordillera of southern Colombia, Weber et al. (2002) concluded that the deep crust is mainly formed by basaltic components with minor sediment, thus supporting the observation by Beaudon et al. (2005). Additionally, obducting an oceanic lithosphere is likely to have triggered the obduction of pieces of the underlying lithospheric mantle. However, outcrops of peridotites or serpentinites are extremely rare among the accreted oceanic rocks of the Western Cordillera. The lack of outcrops of the deep parts of the oceanic plateau does not support the obduction model.

From a sedimentary point of view, sediments on oceanic terranes in the Western Cordillera remained continuously deposited in a marine environment until the Middle Eocene (Apagua Fm), i.e. long after collision. This is hardly compatible with the obduction of the oceanic terranes that would have provoked the uplift and emergence of the eastern part of the oceanic terranes above a west-dipping thrust plane, and above the buoyant continental margin. Additionally, if obduction occurred, mafic detrital material would have invaded the Oriente Basin as early as the latest Cretaceous. However, provenance studies of the latest Cretaceous deposits of the Oriente Basin indicate that they were fed by the metamorphic basement of the continental margin, i.e. the Eastern Cordillera (Gutierrez Tamayo, 2018; Vallejo et al., 2021). Significant mafic detrital material only arrived in the Oriente basin in the Late Oligocene-Early Miocene (Ruiz et al., 2004, 2007; Vallejo et al., 2021).

Furthermore, the fact that the oceanic terranes of the Western Cordillera received marine quartz-rich sediments of Maastrichtian to middle Eocene age, and then continental quartz-rich deposits from late Eocene onwards, implies that the Ecuadorian continental margin was higher that the oceanic terranes, and was submitted to subaerial erosion, whereas the oceanic terranes were still located below sea-level. Therefore, the uplifted part of the orogenic wedge was the continental margin, not the oceanic terranes, which suggests that the oceanic terranes were underthrust beneath the continental margin, thus provoking exhumation of the upper plate. This is illustrated by the location of the sea shore during Late Cretaceous to Paleocene times (Fig. 7), which illustrates the westward migration of the shoreline and the disappearance of marine deposits in the Oriente Basin (Toro and Jaillard, 2005). This shows the progressive uplift of the Eastern Cordillera and of the Oriente Basin, i.e. of the whole continental margin. The slow, continuous sea level fall recorded in the Late Cretaceous and Paleocene (Haq et al., 1987; Haq, 2014) may have contributed to the sea shore retreat. However, such a sea level lowering cannot explain neither the abrupt transition from turbidites to shelf or subaerial deposits in the Celica-Lancones Basin and in the Celica arc, nor the appearance of coarse-grained, quartz-rich Paleocene deposits onto Maastrichtian turbidites and oceanic cherts in the Western Cordillera. Moreover, as mentioned earlier, the relative homogeneity of the middle Eocene sedimentation throughout the

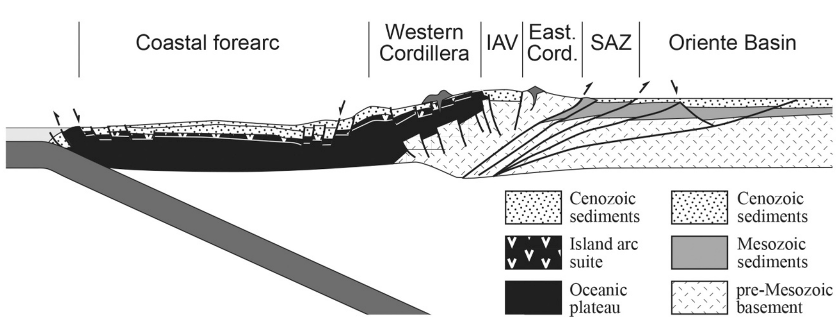

Fig. 6. Schematic cross section of the Ecuadorian Andes assuming the obduction of a single accreted terrane (simplified from Vallejo et al., 2019). Compare with Figs. 11 and 13. IAV: Inter-Andean Valley; SAZ: Sub-Andean Zone.

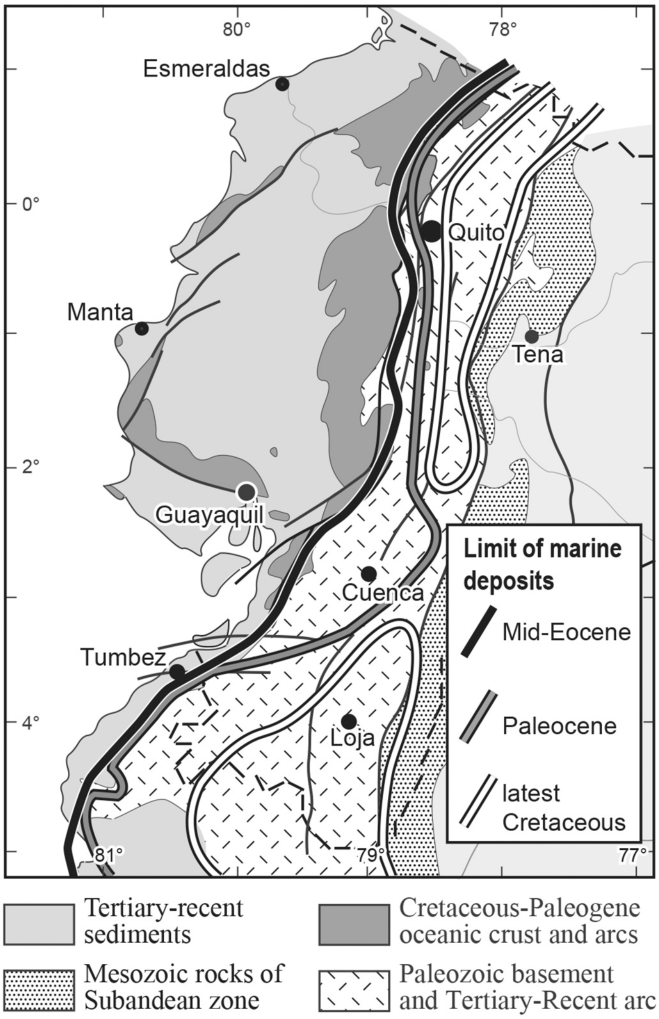

Fig. 7. Evolution of the marine shoreline from Maastrichtian to Late Eocene times (from Toro and Jaillard, 2005). Marine environment persisted on the oceanic terranes during this whole time-span, whereas most of the forearc zones and the Oriente Basin became emergent in latest Cretaceous and Paleocene times, respectively.

accreted terranes (Santos et al., 1986; Jaillard et al., 2009) indicates that the whole oceanic terranes (Coast and Western Cordillera) were grossly at the same elevation at that time, and therefore, that none of them was thrusted onto the continental margin.

These observations are in accordance with the exhumation rates computed for the same period in the Ecuadorian Andes (Spikings et al., 2001, 2005), which specify the age of the uplift stages (Fig. 8). A rapid exhumation of the continental margin (Eastern Cordillera) is observed between 75 and 55 Ma (late Campanian-latest Paleocene) that correspond to the three accretion stages of the oceanic terranes. Note that, while most samples of the Eastern Cordillera record the latest Cretaceous uplift period, the Western Cordillera recorded only locally this exhumation event (Fig. 8). A second period of rapid exhumation occurred between 45 and 35 Ma (middle to late Eocene), which corresponds to the contractional Incaic tectonic phase, known in the whole Andean realm (Steinmann, 1929; Mégard, 1984), even in areas where no collision occurred. A last exhumation period is recorded from 25 to 20 Ma onward (Fig. 8). High exhumation rates observed since ~10 Ma are related to the rapid uplift observed in the late Miocene in southern Ecuador (Steinmann et al., 1999; Hungerbühler et al., 2002) and northern Peru (Neser et al., 1991; Eude et al., 2015; Moreno et al., 2020).

5.4.2. *Evidences from the continental margin*

From a geodynamic point of view, the obduction of the oceanic terranes onto the Ecuadorian continental margin (Fig. 6) would have provoked, in addition to the uplift of the oceanic material, the flexure of the continental lithosphere due to tectonic loading (Beaumont, 1981; Molnar and Lyon-Caen, 1988), and therefore, the subsidence of the Ecuadorian margin and the Oriente Basin (e.g. Xie and Heller, 2009) However, as exposed before, late Cretaceous and Paleocene times are marked in the Oriente Basin by repeated sedimentary hiatuses, of Late Santonian-early Campanian, Late Campanian, Late Maastrichtian and Late Paleocene-early Eocene age (Fig. 2). Because of the shallow marine depositional environment and the transgressive character of the subsequent deposits (e.g. Jaillard, 1997; Vallejo et al., 2021), these hiatuses are interpreted as related to uplift events, that coincide with the identified accretionary events (Fig. 5). The contrary would be expected in a basin controlled by flexural subsidence. Thomas et al. (1995) computed a mild, jerky subsidence rate in the Maastrichtian-Eocene time span, and showed that the thickness of Neogene deposits exceeds that of the whole Cretaceous-Paleogene succession, thus demonstrating that high subsidence began in the early Neogene. In the same way, Dashwood and Abbotts (1990) showed that a high subsidence rate is not recorded before the Late Oligocene or Early Miocene (Fig. 9; see also Fig. 2). This period coincides with a rapid and drastic change in the heavy mineral assemblages recorded in the late Oligocene-early Miocene (Chalcana Fm; Ruiz et al., 2004; Martin-Gombojav and Winkler, 2008).

Additionally, the depocenters of the Cretaceous deposits in the Oriente Basin (Fig. 10) were located in the central or eastern parts of the basin (Dashwood and Abbotts, 1990), and the depocenter of the Eocene and early Oligocene deposits is located in the centre of the Basin (Christophoul et al., 2004), the proximal western part of the basin being relatively starved, and thus submitted to relative uplift and/or erosion. Only from the late Oligocene onwards, did the depocenter migrate to the foot of the Andean Chain, as expected for a flexural foreland basin (Fig. 10). Moreover, Christophoul et al. (2004) mention that the Pliocene average sedimentation rate (336 m/Ma) is twice as much as that of the middle and late Miocene (162 m/Ma), the latter being twice as much as the late Oligocene-earliest Miocene mean sedimentation rate (86 m/Ma) (see Figs. 2 and 9), which is typical of a subsidence controlled by the flexure of the lithosphere beneath the advancing orogenic front (e.g. Jordan, 1981).

These data indicate that the evolution of the Oriente Basin as a flexural foreland basin did not start before late Oligocene times (~25 Ma). This accelerated subsidence may explain the marine ingression recorded in the Oriente Basin in the Miocene (Hoorn, 1993; Hoorn et al., 2010; Boonstra et al., 2015; Gross and Piller, 2020), which shows that subsidence rate exceeded the sedimentation rate at that time, even though the middle Miocene global sea level rise (Haq et al., 1987; Hardenbol et al., 1998) may have contributed. Note that, based on sedimentary and thermochronological data, respectively, Parra et al. (2009) and Mora et al. (2010) also dated the beginning of the foreland evolution of the Llanos Basin, Colombia, as early to latest Oligocene (~30–25 Ma). A comparable age is also proposed for the initiation of the eastward propagation of the thrust wedge in northern Peru (30 to 24 Ma; Eude et al., 2015) and of the foreland basin evolution in eastern Bolivia (~27 Ma; Sempéré et al., 1990; Allmendinger et al., 1997).

Finally, clastic sediments of the Oriente Basin are mainly sourced by the Western and Eastern Cordilleras since the Oligocene (Roddaz et al., 2006, 2012), thus showing that erosion of the accreted oceanic terrain began at that time. Age refinement of the Oligocene and Miocene units by Gutierrez Tamayo (2018) allow to revise the actual age of the beginning of the high subsidence as early Oligocene (~30 Ma, base of Chalcana Fm).

5.4.3. *Geophysical and geodynamic evidences*

On another hand, the crustal root of the Ecuadorian Andes (~70 km; Guillier et al., 2001; Araujo, 2016; Araujo et al., 2021) appears to be

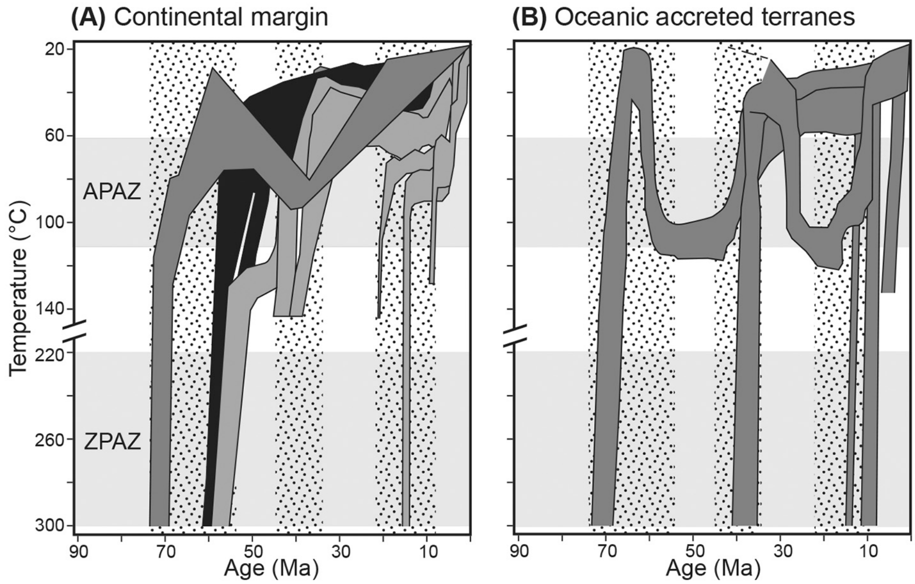

Fig. 8. Thermal history of the Ecuadorian Andes (after Spikings et al., 2010). Dotted areas: inferred exhumation periods. (A): Continental margin. Light grey: northern Eastern Cordillera; black: southern Eastern Cordillera; dark grey: Amotape Massif. (B) Oceanic accreted terranes (Western Cordillera). APAZ and ZPAZ: Apatite and Zircon partial annealing zone, respectively.

almost as thick as that of the Peruvian-Bolivian Altiplano (Fukao et al., 1989; Ward et al., 2016; Ryan et al., 2016), although the average elevation of the Ecuadorian Andes is 1000 to 1500 m less than the Altiplano. Moreover, Koch et al. (2021) assume that the crustal root is 5 to 10 km thicker beneath the Western Cordillera than below the Eastern one, in spite of a lower elevation. This strongly suggests that the crustal root of the Ecuadorian Andes has a significantly higher density than that of the Altiplano. This interpretation is supported by the high P-wave (Prévot et al., 1996) and S-wave velocity observed below the Western Cordillera, which suggests the presence of mafic material at depth (Lynner et al., 2020; Koch et al., 2021). Although Allmendinger et al. (1997) noted that the observed tectonic shortening only accounts for 70 to 80% of the observed crustal thickness of the Bolivian Andes, it is widely admitted that the crustal root of the Altiplano mainly results from the shortening of the South American continental crust (e.g., Lyon-Caen et al., 1983; Baby et al., 1997; Anderson et al., 2017), and is, therefore, chiefly of continental nature.

In Ecuador, tectonic shortening of the Oriente Basin is especially low (Vega Torres, 1998; Baby et al., 2013) and cannot explain the observed crustal thickness. Therefore, it is likely that accreted oceanic terranes form a large part of the crustal root of the western Ecuadorian Andes (Weber et al., 2002; Beaudon et al., 2005). Supporting this assumption, Chiaradia (2009) proposed that the thick pile of oceanic plateau basalts and superimposed Cretaceous and Tertiary volcanic arc suites is responsible for the generation of adakite-like magmas in the Western Cordillera. This would imply that, rather than obducted onto the Ecuadorian margin (Vallejo et al., 2009, 2019), the oceanic terranes have been first subducted, then jammed the subduction zone and eventually were underplated beneath the active margin, thus creating its crustal root (Feininger and Bristow, 1980; Lebrat et al., 1987; Mégard, 1989; Jaillard et al., 2000; 2002; 2009) (Fig. 11). This underthrusting process along the east-dipping subduction plane is consistent with the geometry of crustal earthquakes grossly aligned along east-dipping planes (Guillier et al., 2001).

Finally, the obduction model (Vallejo et al., 2009, 2019) raises an additional difficulty. Obducting the oceanic terrane(s) would imply that, during the Late Cretaceous, subduction occurred beneath the oceanic plateau, i.e. along a west-dipping Wadati-Benioff zone. However, arc volcanism on the North-Andean continental margin is known during the whole Jurassic in Ecuador and Colombia, until Late Cretaceous times in Colombia (Aspden et al., 1987; Cardona et al., 2020; Rodríguez-García et al., 2020; López-Isaza and Zuluaga, 2020), and until 90 Ma in southernmost Ecuador (Celica arc, Winter, 2010; Jaimes et al., 2012), implying that an east-dipping subduction zone existed North and South of Ecuador, at least until Middle Cretaceous times. Therefore, assuming a west-dipping subduction zone beneath the Caribbean plateau at the time it collided the Ecuadorian margin (Late Cretaceous), would imply, either that trench-normal transform faults existed North and South of Ecuador, allowing a change in subduction vergence on either side of these faults, or that the oceanic domain separating the continent and the Caribbean plateau disappeared through a double subduction, as proposed by Cardona et al. (2020) or Pardo-Trujillo et al. (2020). The first interpretation is unlikely, since the northern transform fault would have cut the oceanic plateau, which is assumed to be continuous from Ecuador to the Caribbean realm, although most probably splitted or teared during the accretion process. Moreover, since an Eastward subduction zone already existed beneath the South American margin, there was no mechanical necessity to create a new subduction zone beneath the oceanic plateau in order to consume the oceanic space separating the plateau and the margin. The latter observation also applies to the second interpretation, which fails to explain the location of island arcs on the western border of the oceanic plateau (e.g. San Lorenzo arc), all along the north Andean margin.

6. Kinematics of the Andean build-up of Ecuador

6.1. The orogenic wedges

The location of the quartz-rich sediments that post-dated the collision or accretion pulses supports the play of east-dipping crustal-scale thrust planes. Assuming that the oceanic terranes were blocked in the subduction zone implies that they were bent and acquired an eastward dip, thus creating a narrow trough above the thrust plane. The first collision (Late Campanian) involved the eastern part of the oceanic plateau, thus explaining that deposition of the first quartz-rich deposit (Yunguilla Fm) was restricted to the easternmost part of the oceanic terranes. As explained above, a second collision or accretion pulse involved part of the oceanic terranes located farther west, provoking the creation of a new, westward shifted narrow trough filled up by quartz-rich deposits (Paleocene Saquisilí Fm). Finally, a last accretion pulse

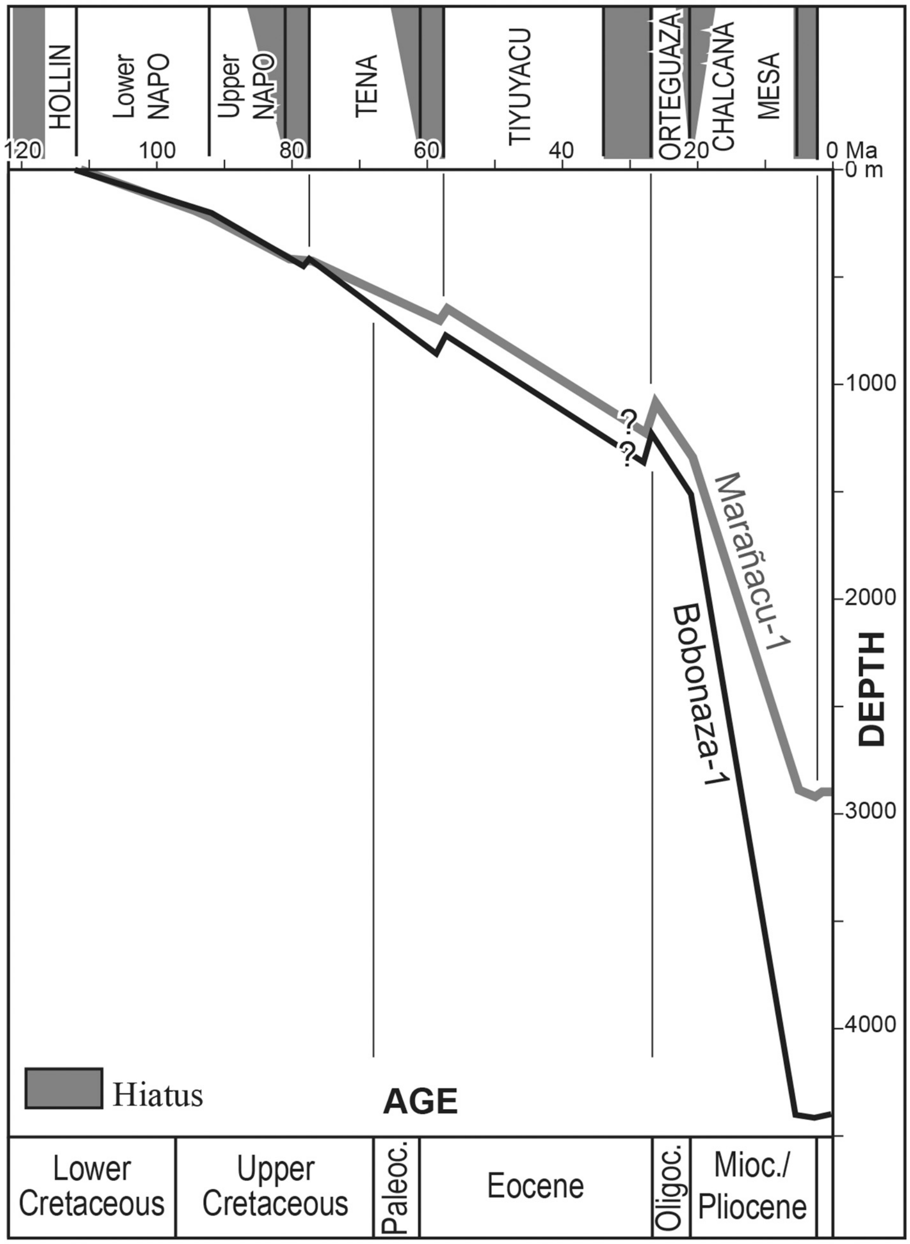

Fig. 9. Sedimentary accumulation in the Oriente Basin since the base of the Napo Fm (from Dashwood and Abbotts, 1990, simplified).

involved the coastal part of the oceanic terranes, which may have created a third trough that received deposits (late Paleocene Azúcar Gp) derived from the continental margin (Witt et al., 2019). The localized nature of these deposits, however, may lead to alternative interpretations (see Aizprua et al., 2019).

This chronological and geographical succession of narrow troughs is well-known in collision chains and illustrates the progressive advance of the orogenic front onto the lower plate. In the Western Alps for example, a first foredeep basin of Eocene age in the internal alpine zones (Flysch briançonnais) is followed by a second foredeep basin of late Eocene-early Oligocene age along the Penninic Front (Grès du Champsaur, flysch des aiguilles d'Arves, Grès de Taveyannaz…), and is belayed by a last foredeep basin of Miocene age on the external zones (Molasse of France and Switzerland) (e.g. Kerckhove et al., 1980; Allen et al., 1986; Pfiffner, 1986; Schlunegger et al., 1997; Ford and Lickorish, 2004; Dumont et al., 2012). This observation strongly suggests that the accreted oceanic terranes of Ecuador were underplated eastward beneath the continental margin, and that the thrust front progressed westward through time, as expected in any typical orogenic wedge.

This interpretation is furthermore supported by observations on the sedimentary basin (Manabí basin) located at the western foot of the Western Cordillera. There, the Tertiary infill of the sedimentary basin thickens toward the East, and wedges out toward the West (Hernández, 2020), thus suggesting that the oceanic lithosphere of coastal Ecuador was bent, as a result of the westward thrust of the Western Cordillera and continental margin. This assumption is supported by the play of East-dipping reverse faults affecting the oceanic substrate of the basin and its Cretaceous cover (Hernández, 2020).

In both Ecuadorian and west Alpine examples, the west-ward progradation of main thrust planes is associated with the creation of successive foredeep basins that are younger and younger westward. Therefore, we may assume that the successive collisions or accretion pulses of the oceanic terrane(s) created a crustal-scale accretionary prism. The evolution of the latter is mainly governed by the basal shear surface, and the angle of the wedge tip, the latter controlling the maximum thickness of the wedge, and thus, the body force exerted by

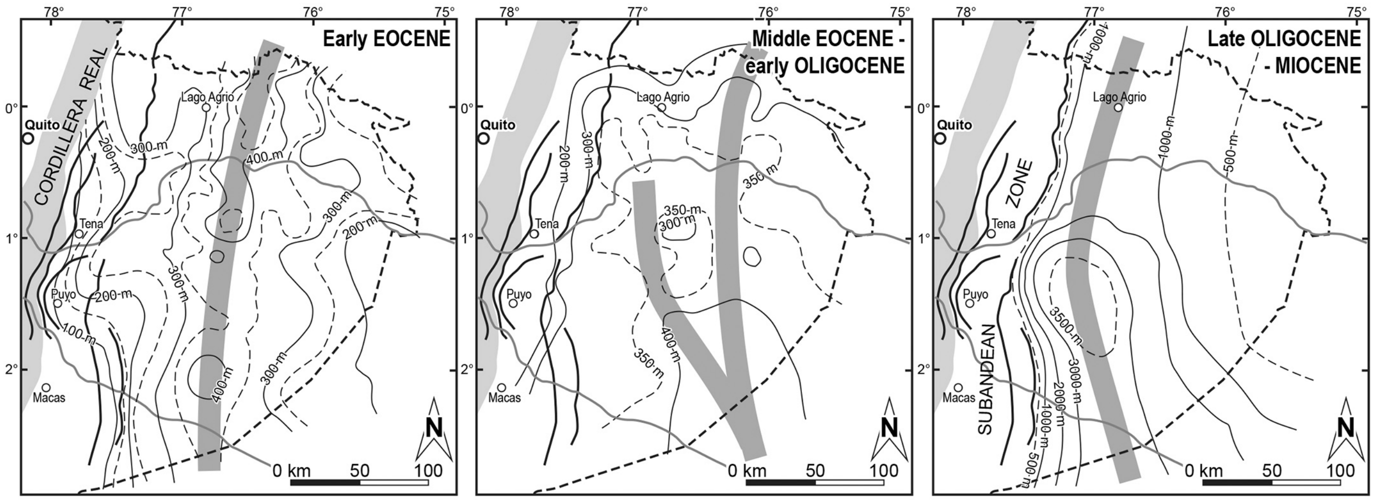

Fig. 10. Isopach maps of the Oriente Basin for various Tertiary periods (simplified from Christophoul et al., 2004). Grey line: depocenter axis.

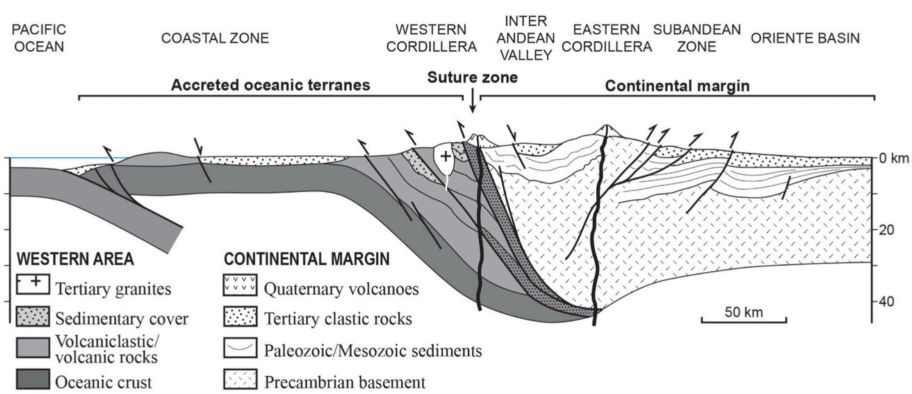

Fig. 11. Schematic cross section of the Ecuadorian Andes (adapted from Mégard, 1989). Note the western, west-verging wedge made of oceanic terranes, and the eastern, east-verging wedge, made of continental rocks. Compare with Fig. 6.

the weight of the accreted material, depending on the density of the material involved (e.g., Platt, 1986; Molnar and Lyon-Caen, 1988; Ball et al., 2019). As the wedge thickens, the cumulated strain of the balanced, downward directed body force (wedge weight) and upward directed buoyancy (Archimedes force) may exceed the lateral strain exerted by subduction; at this point, the wedge ceases to thicken and extensional stress appears on top of the wedge, as known for a long time in the Central Andes (e.g. Dalmayrac and Molnar, 1981; Mercier et al., 1992). Then, lateral contraction must be accommodated by the lateral progradation of thrust planes toward the free border of the wedge (Suárez et al., 1983). In the case of the Ecuadorian Andes, the free border of the system is the continental margin, including the Oriente Basin. Therefore, as foreseen by Mégard (1987, 1989)) (Fig. 11), the build-up of the Ecuadorian Andes can be seen as resulting from the play of a first, western, West-verging wedge made of accreted terranes, followed by a subsequent, eastern, East-verging wedge made of continental basement and sedimentary cover and represented by the Eastern Cordillera and the Subandean zone.

According to thermochronological data of Spikings et al. (2001, 2005) (Fig. 8), the western accretionary wedge formed and grew between 75 and 55 Ma, as indicated by the stratigraphic data. It was then probably deformed and thickened by the Incaic phase (middle-late Eocene), without new identified accretion or collision event. The last exhumation stage of the continental margin since 25–20 Ma (Fig. 8) corresponds to the beginning of the evolution of the Oriente Basin as a flexural, foreland basin (Section 5.4.2). It is, therefore, interpreted as the onset of the eastern, east-verging accretionary wedge, made of the Eastern Cordillera and Subandean zone.

6.2. *A model for the build-up of the Ecuadorian Andes*

Based on this hypothesis, Bonnardot (2003) carried out very simple 2D finite element numerical modelling (Hassani and Jongmans, 1997) of the collision of an oceanic terrane. She used density parameters given by Cloos (1993), and various values for lithosphere thickness and elastic thickness, and for friction forces along faults and plate interface. Note that this model implies that the single oceanic plateau presents pre-existing faults or weakened zones that may be hot island arc zones, transform faults or other crustal heterogeneities. Fig. 11 shows a summary of the experiment using a 40 km-thick oceanic lithosphere (plateau) and a 60 km-thick, homogeneous, continental plate, and friction forces of 0,25 and 0,18 along the subduction plane and intra-oceanic faults, respectively. In the initial stage, the oceanic plateau is horizontal, located between the continental crust and the oceanic slab, and is divided by oblique faults (Bonnardot, 2003). After convergence begins, the experience shows two main stages. In a first stage, convergence is accommodated by subduction of the oceanic crust, the trench migrates rapidly toward the upper plate, and the western accretionary wedge made of the oceanic plateau fragments shortens and thickens (Fig. 12a, b). Deformation is concentrated within the latter, especially close to the subduction zone, and in the proximal forearc zone of the upper continental plate. In a second stage (Fig. 12c, d), the highly

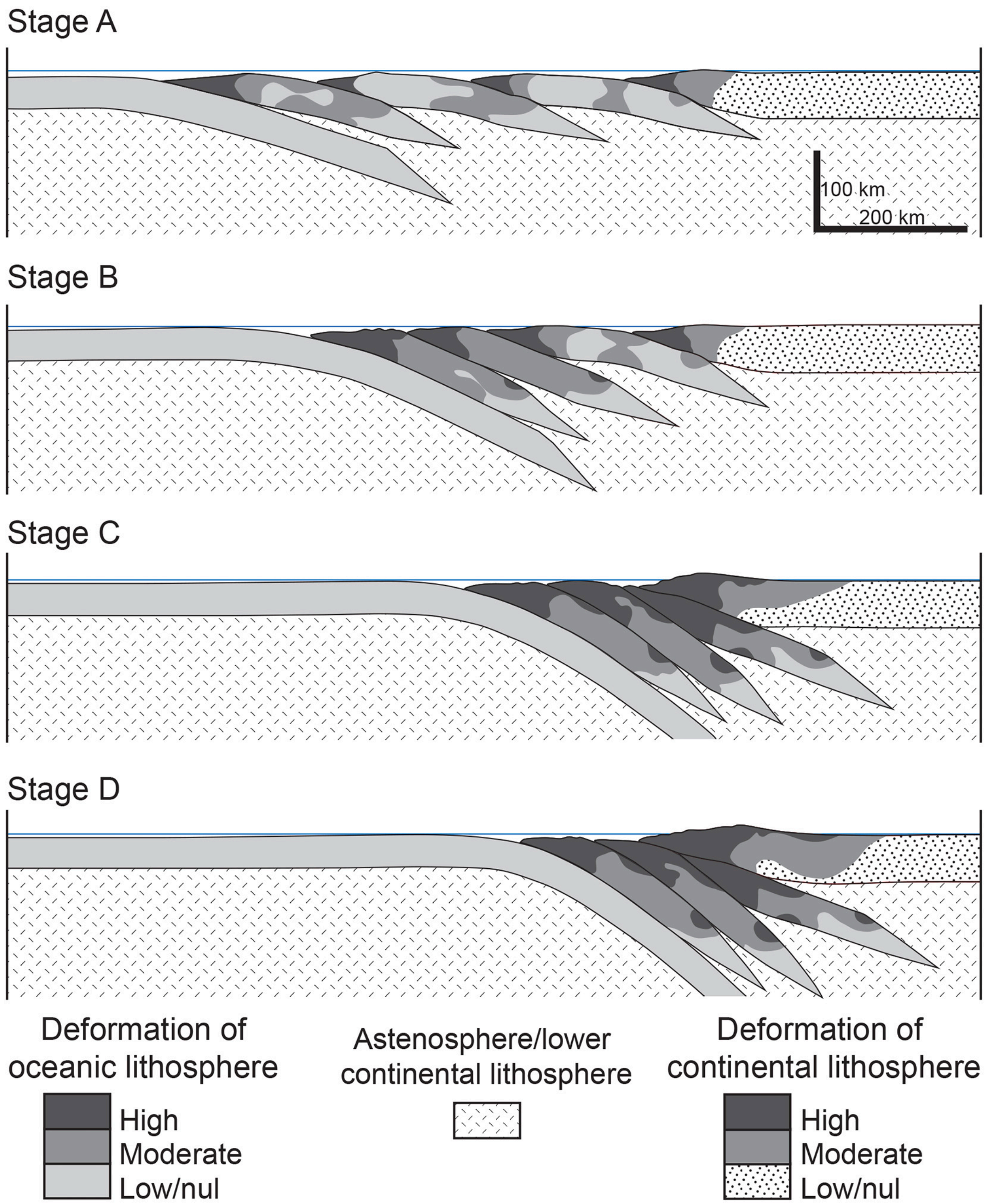

Fig. 12. 2D numerical modelling of the accretion of a low-density oceanic terrane divided by oblique, pre-existing faults (simplified from Bonnardot, 2003).

deformed western accretionary prism cannot be deformed and thickened anymore because of body forces, the trench migrates slowly continent-ward, and convergence is mainly accommodated by the subduction of the oceanic crust. As a consequence, the lateral stress related to convergence is transmitted to the upper continental plate that undergoes a landward migrating deformation, forming a second, eastern accretionary wedge made of continental material (Fig. 12d). In the same way, studying recent examples, Doglioni et al. (2007) observed that, when the rate of landward migration of the trench is much lower than the subduction rate, a significant part of the resulting convergence is accommodated by the deformation of the upper plate (see also Sébrier and Soler, 1991). Note that this simplified model overlooks the right-lateral movements that subsequently affected the accreted terranes, and probably re-used the major faults of the western wedge (see Ego et al., 1996; Alvarado et al., 2016).

Much more elaborated calculations or experiments have been performed regarding oceanic plateaus or island arc accretions (e.g. Cloos, 1993; Shemenda, 1994; Moresi et al., 2014; Vogt and Gerya, 2014; Tao et al., 2020). In these experiments, the oceanic plateau is usually subducted beneath the continental plate, except if the oceanic plateau is young (Vogt and Gerya, 2014; Yang et al., 2018) or significantly thick (Tao et al., 2020). In the latter cases, the plateau is incorporated to the margin, and a double vergency accretionary prism develops. Therefore, although oversimplified, the simple experience by Bonnardot (2003) makes likely the hypothesis of a double verging orogenesis, due to the functioning of two successive, and opposite-verging accretionary wedges (Fig. 11). Interestingly, this experience also shows that, the closer the terrane to the upper plate, the deeper it is under-thrusted, and thus, the less it crops out. This may explain why witnesses of the San Juan eastern oceanic terrane are rare, whereas the western Piñón oceanic terrane crops out extensively in the Coastal zone.

As a consequence, a model can be proposed for the accretion-related build-up of the Ecuadorian Andes (Fig. 13). In a first step, during Late Campanian times, the oceanic plateau collided with the Ecuadorian margin. The latter was uplifted, thus feeding the late Campanian conglomerates of the forearc zone (Tortuga, La Mesa, Tablones, Casanga Quimas Fms) and then provoking the deformation of the Campanian conglomerates and a hiatus of late Campanian age in the Oriente Basin. After this collision event, marine sedimentation resumed in both the forearc zone (Cenizo, Cazaderos, Tabacay, Yunguilla Fms), and the Oriente Basin (Lower Tena Fm) of the continental margin. In a second step (late Maastrichtian), the oceanic plateau was splitted, and the Guaranda terrane was driven like a wedge beneath the already accreted terrane, triggering the deformation of the Maastrichtian forearc sediments and a new uplift of the whole continental area. After this emergence-related hiatus, unconformable, transgressive marine (Saquisilí Fm) and subaerial clastic (Upper Tena Fm) sediments of Paleocene age were deposited in the forearc and eastern zones, respectively (Fig. 13). Note that at that time, the coastal area recorded the end of the island arc activity, but remained undeformed, and that volcanic activity resumed in the continental arc zone (Sacapalca Fm). During the

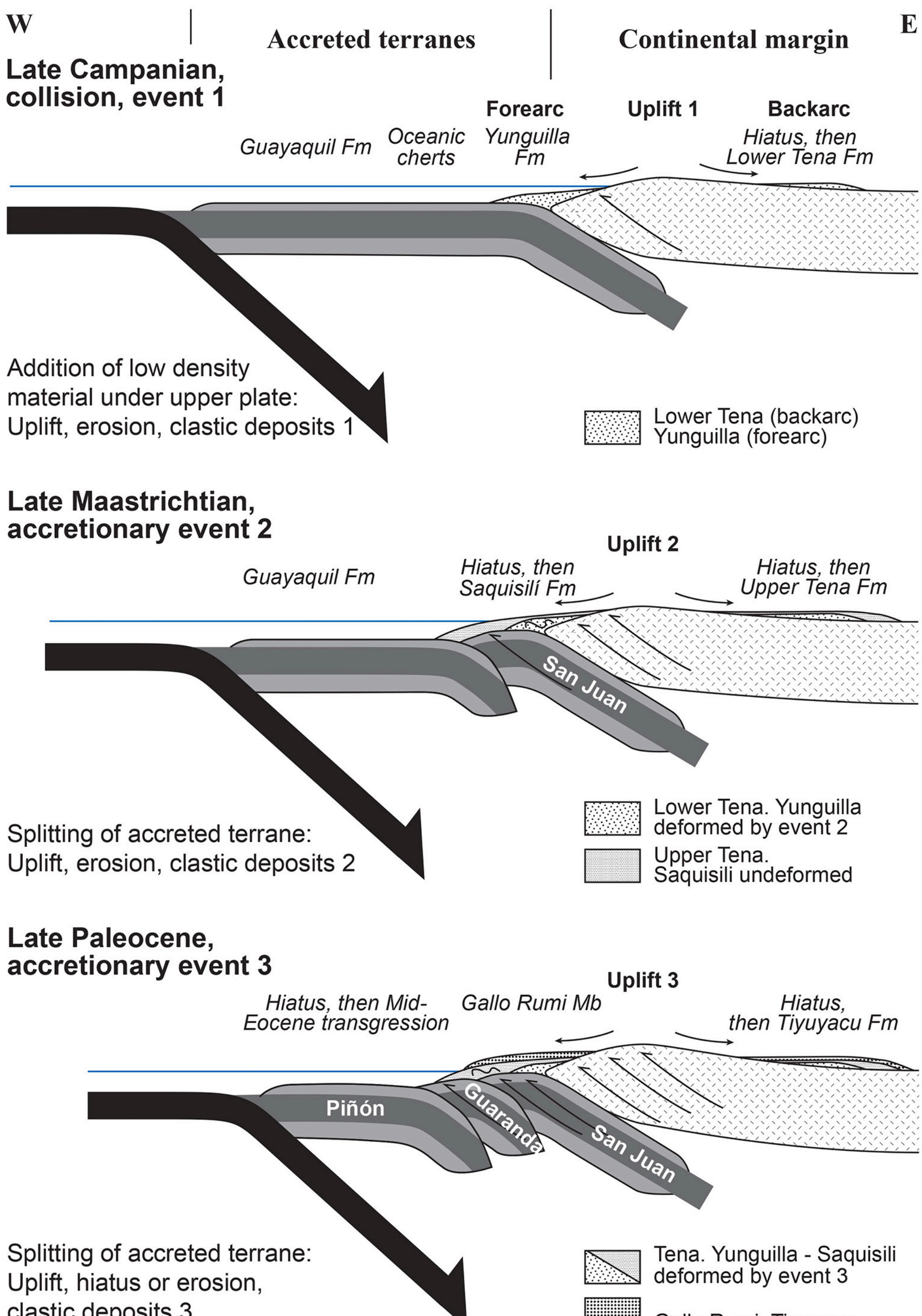

Fig. 13. Model for the accretion of oceanic terranes, accounting for the uplift, deformation, hiatuses and deposition observed in the forearc (accreted terranes) and backarc (Oriente Basin) areas of the Ecuadorian margin. The first accretionary event led to the end of the San Lorenzo island arc activity located on the accreted oceanic plateau. Arc volcanism resumed in latest Maastrichtian-Paleocene times, after accretionary event 2, on the continental margin.

last accretionary event of late Paleocene age, the oceanic plateau is again splitted, and the Piñón coastal terrane was under-thrusted beneath the Guaranda terrane of the Western Cordillera. This provoked the deformation of the Paleocene forearc sediments (Santa Elena, Saquisilí Fms), the uplift of the continental margin, and therefore, a hiatus of early late Paleocene-early Eocene age in the whole area, except the southern coastal zone (Azúcar Fm). Then, deposition resumed with deposition of marine deposits on the little deformed, newly accreted terranes (Apagua, San Mateo, Ancón Fms), and fluvial deposits in the uplifted Western Cordillera (Gallo Rumi) and Oriente Basin (Tiyuyacu Fm) (Fig. 13). This scenario accounts correctly for the sedimentary and tectonic events recorded by both the accreted terranes and continental margin.

7. Conclusions

The forearc zones are closest to the subduction zone and trench, and thus, accurately record the main tectonic events related to subduction, and thus, highlight the tectonic evolution of the active margin as a whole. Although they underwent significant and complex deformation and are commonly covered by younger volcanic rocks, their bio- or chrono-stratigraphic and sedimentological study is crucial to understand the early evolution of subduction orogens, such as the Ecuadorian Andes. Accurate dating of sedimentary series is also essential to specify the timing of the tectonic and paleogeographic evolution of the area, and therefore, the rate of the tectonic processes acting there.

The Ecuadorian Andes comprises accreted and uplifted oceanic material to the West, and the deformed continental margin to the East. The study of the age, nature and distribution of syn-orogenic sediments throughout the Ecuadorian Andes and margin allows to propose a scenario for the orogenic build-up of the Ecuadorian Andes. The study of forearc deposits reveals the occurrence of three successive accretionary events, which triggered the creation of three successive, west-migrating post-accretion basins infilled with syn-orogenic deposits. This period (~75–60 Ma) corresponds to the rapid uplift of Eastern Cordillera recorded by thermochronology. This period is interpreted as the creation of a western, west-verging, crustal-scale accretionary wedge (coastal zone and Western Cordillera), the evolution of which culminated with the mid- to late Eocene Incaic contractional phase. Because deformation of the western wedge became impossible due to excessive vertical body forces, deformation migrated eastward into the upper continental plate. Therefore, the western wedge was relayed by an eastern, east-verging accretionary wedge involving the upper, continental plate (Eastern Cordillera, Subandean zone and Oriente Basin). Subsidence curves, migration of depocenters and detrital source evolution indicate that the Subandean zone and Oriente Basin behaved as a foreland basin since ~25 Ma (late Oligocene-earliest Miocene), thus indicating a minimum age for the creation of the eastern accretionary wedge.

Simple numerical modelling based on the mechanical functioning of accretionary wedge reproduce consistently the proposed scenario. Additionally, the subaerial hiatuses observed in the Oriente Basin (late Campanian, late Maastrichtian-early Paleocene, late Paleocene-earliest Eocene), may be explained by the uplift of the whole continental margin due to the underplating of the buoyant oceanic material during the three identified accretionary events (late Campanian, late Maastrichtian, late Paleocene).

Although this Andean build-up scenario has been elaborated through the Ecuadorian particular example, marked by accretion of oceanic terranes it is not impossible that it may apply to Colombia and to other parts of the Andean chain. As a matter of fact, the play of west-verging thrusts affecting the western parts of the Andean chain have been recently emphasized also in Chile (Armijo et al., 2010; Riesner et al., 2018) and Peru (Prudhomme et al., 2019). Therefore, it is possible that early shortening and thickening of the western parts of the South-American margin have been underestimated so far, because of complex deformation and poor outcrop conditions due to extensive volcanic cover and tectonic erosion of the continental margin. Further studies of the deformation of the arc and forearc zones of the Andean chain would specify to which extent the latter areas contributed to the unexplained thickness of the central Andean crustal root.

Declaration of Competing Interest

No.

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