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Cretaceous and Tertiary terrane accretion in the Cordillera Occidental of the Andes of Ecuador

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Abstract

New field, geochronological, geochemical and biostratigraphical data indicate that the central and northern parts of the Cordillera Occidental of the Andes of Ecuador comprise two terranes. The older (Pallatanga) terrane consists of an early to late (?) Cretaceous oceanic plateau suite, late Cretaceous marine turbidites derived from an unknown basaltic to andesitic volcanic source, and a tectonic mélange of probable late Cretaceous age. The younger (Macuchi) terrane consists of a volcanosedimentary island arc sequence, derived from a basaltic to andesitic source. A previously unidentified, regionally important dextral shear zone named the Chimbo-Toachi shear zone separates the two terranes. Regional evidence suggests that the Pallatanga terrane was accreted to the continental margin (the already accreted Cordillera Real) in Campanian times, producing a tectonic mélange in the suture zone. The Macuchi terrane was accreted to the Pallatanga terrane along the Chimbo-Toachi shear zone during the late Eocene, probably in a dextral shear regime. The correlation of Cretaceous rocks and accretionary events in the Cordillera Occidental of Ecuador and Colombia remains problematical, but the late Eocene event is recognised along the northern Andean margin. © 2002 Published by Elsevier Science B.V.

Keywords: Ecuador; Colombia; Cretaceous; Tertiary; Terrane; Accretion; Shear zone

1. Introduction

The Cordillera Occidental (Western Cordillera) of Ecuador forms part of the Northern Andes segment (Gansser, 1973), and is characterised by the presence of allochthonous terranes, including ophiolitic and oceanic crustal fragments (Feininger and Bristow, 1980; McCourt et al., 1984), accreted to the South American margin since the mid Cretaceous (Goossens and Rose, 1973). There is a broad consensus that accretionary processes and events played a leading role in the Cretaceous and Tertiary history of the northern Andean margin. However, the timing and processes of accretion of the Cordillera Occidental in Ecuador and Colombia are poorly understood (Kellogg and Vega, 1995). Existing models for the Cordillera Occidental of Ecuador include, for example, early Cretaceous to Eocene subduction (Lebrat et al., 1987), late Cretaceous Alpine style thrusting and Oligocene collision events (Bourgois et al., 1990), accretionary events in the Palaeocene–early Eocene and late Eocene–early Oligocene (Van Thournout et al., 1992), and late Cretaceous to late Palaeocene

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accretionary events (Cosma et al., 1998; Pecora et al., 1999). The geodynamic evolution of the Cordillera Occidental of Ecuador remains controversial, but its understanding is critical to the Cretaceous and Tertiary history of the northern Andes.

Between September 1995 and March 2000, the British Geological Survey, in conjunction with the Ministry of Mines and Energy of the Government of Ecuador, undertook the first comprehensive, systematic geological mapping programme of the Cordillera Occidental of Ecuador (Fig. 1). The survey area stretches from approximately 4°S to the Colombian frontier (ca. 1°N), and covers approximately 35,000 km^2. Field mapping was supported by a major analytical programme that included micro- and macropalaeontology, rock geochemistry, and geochronology (K–Ar mineral separate, zircon and apatite fission-track). Collectively, these programmes have produced a very large new data set, enabling major advances to be made in understanding the timing and processes of accretion in this little known part of the northern Andes. The model presented here is relevant not just to Ecuador, but is a paradigm for the entire northern Andean margin.

This paper focuses on the central part of the Cordillera Occidental, between 2°30′S and 0°00′ (Fig. 1). The area is depicted and described in three, newly published, 1:200,000 scale geological maps (BGS-CODIGEM, 1997a,b, 1999; see also references therein).

Previous studies of the Cordillera Occidental of Ecuador have been seriously hampered by the lack of a reliable, regional stratigraphical and structural framework. Some regional syntheses have presented very misleading interpretations, but nevertheless, many important contributions have been made. Biostratigraphical work by geologists of the 'Institut Francais du Petrole' in the late 1960s (e.g., Sigal, 1968; Faucher and Savoyat, 1973) successfully established the ages of two important Cretaceous turbidite sequences (the Yunguilla and Pilatón units — see below). From the mid-1970s onwards, a number of workers (Henderson, 1979, 1981; Kehrer and Van der Kaaden, 1979; Lebrat et al., 1985, 1987; Van Thournout et al., 1992) attempted to identify the geotectonic settings and ages of a series of Cretaceous and Tertiary magmatic and volcanic sequences within the cordillera (most notably the Macuchi and Piñon units — see below). Their efforts were held back by the lack of a regional stratigraphical framework, but important progress was made (through rock geochemistry) in constraining the probable geotectonic settings. Major stratigraphical advances were made by Eguez (1986) and Eguez and Bourgois (1986), who demonstrated that turbiditic rocks previously believed to be entirely of Maastrichtian age consisted in fact of two separate units, one Maastrichtian and the other Eocene (Yunguilla and Angamarca units, respectively — see below).

2. Regional setting

Ecuador can be divided into three main physiographic regions that reflect fundamentally different geological provinces (Fig. 1, inset map). The Andean region separates the Amazon Basin or 'Oriente' in the east from the coastal plain or 'Costa' to the west. The Oriente is a Mesozoic to Cenozoic, hydrocarbon-rich sedimentary foreland basin that includes a platform carbonate sequence, overlying an older cratonic basement. Basement and cover sequences are both intruded by large granitoid batholiths, mainly along the complex sub-Andean zone of folding and thrusting that lies along the boundary between the Oriente and the Andes. The Costa is the low-lying, Pacific coastal region west of the Andes and comprises a series of hydrocarbon-bearing Cretaceous to Cenozoic basins, underlain by oceanic crustal rocks that are exposed locally in the coastal cordilleras. At the present day, essentially orthogonal subduction of the Nazca Plate beneath continental South America is occurring along the Ecuadorian portion of this active margin. Young oceanic crust (<20 Ma) produced at the Nazca-Cocos spreading centre of the Galapagos Rift Zone is being subducted in the Ecuadorian trench at an angle of 25–35° (Lonsdale, 1978; Freymuller et al., 1993).

Throughout most of Ecuador the Andes consist of two parallel ranges, the cordilleras Occidental (Western Cordillera) and Real (Eastern Cordillera), separated by a central graben that is filled by Pliocene and Quaternary volcanosedimentary rocks (Fig. 1, inset map). The basement to the inter-Andean graben is poorly known, but gravity data (Feininger and Seguin, 1983) suggest a concealed extension of Cordillera Real rocks (Fig. 2). The Cordillera Real itself consists mostly of sub-linear

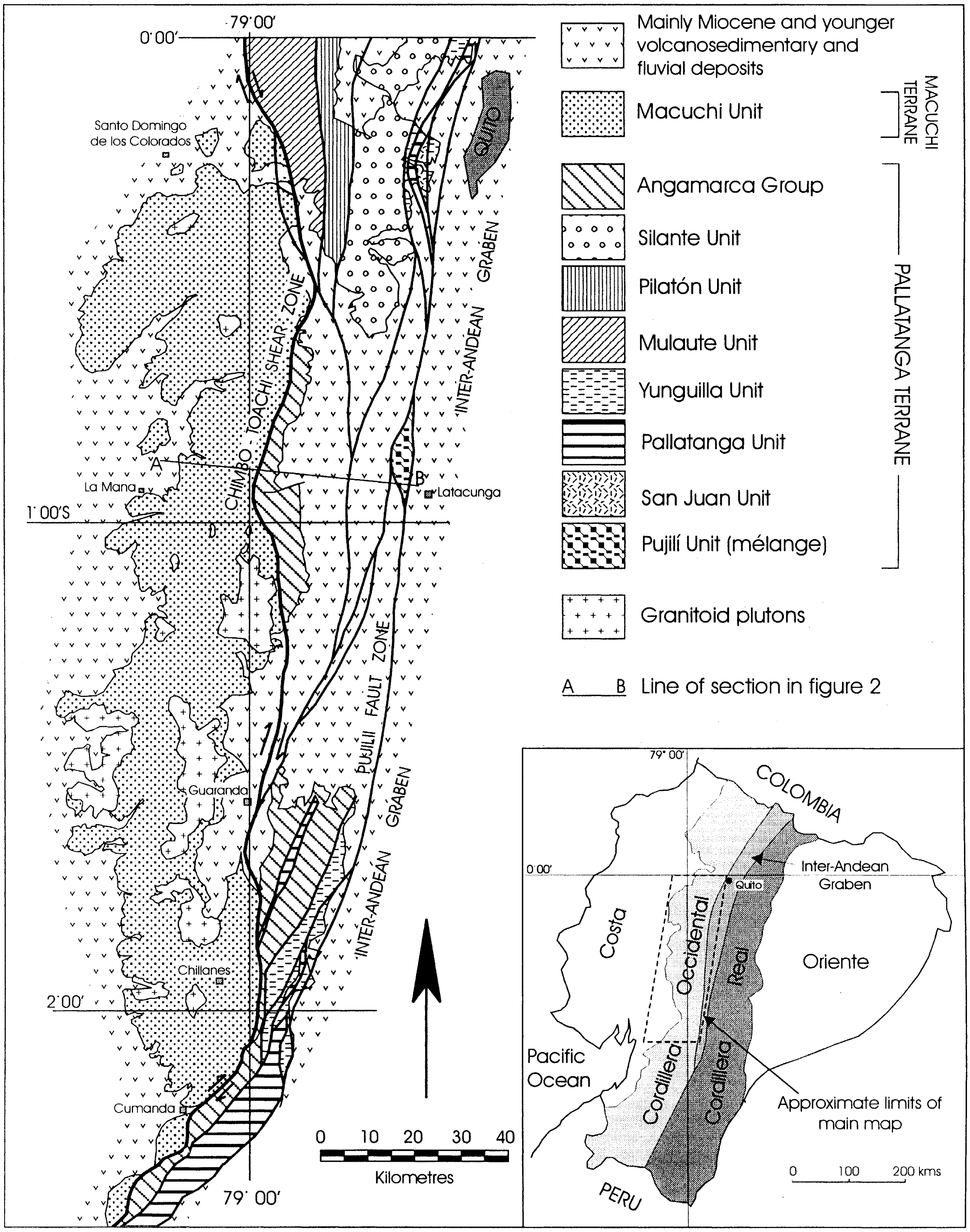


Fig. 1. Location of study area (inset), and simplified geological map of the Cordillera Occidental between 0°00′ and approximately 2°30′S. A_B is the line of section of Fig. 2.

belts of Palaeozoic to Mesozoic metamorphic rocks, intruded by S- and I-type granitoids, and capped by Cenozoic to modern volcanics (Litherland et al., 1994). The Cordillera Occidental consists almost entirely of non-metamorphic (sub-greenschist facies), early to late Cretaceous oceanic plateau basalts and ultramafic rocks, late Cretaceous marine turbidites, an early Eocene basaltic to andesitic oceanic island arc sequence, a Palaeocene to Eocene marine turbidite basin fill sequence, and a late Eocene–Oligocene terrestrial sequence. These are intruded by late Eocene and younger I-type granitoids. Major mid Eocene to Miocene and younger sub-aerial, calc-alkaline continental margin volcanic sequences occur in the south.

Structurally, the eastern limit of the Cordillera Occidental is the active Pujilí Fault zone (Figs. 1 and 2), this being the southern extension of the Cauca–Patía Fault that can be traced through Colombia towards the Caribbean (Litherland and Aspden, 1992). The western limit of the Cordillera Occidental, for the purposes of this paper, is the strong topographical feature that separates the steep slopes of the cordillera from the flat-lying alluvial sequences of the coastal plain.

One of the most important advances made during the BGS-led geological mapping programme is the recognition that the central and northern parts of the Cordillera Occidental of Ecuador comprise two major terranes, separated by a previously unknown, regionally important shear zone, named the Chimbo-Toachi shear zone (Figs. 1 and 2). The older Pallatanga terrane consists mostly of late Cretaceous turbidites, with small but significant fault-bounded slivers of basalts and ultramafic rocks interpreted formerly as a MORB sequence (e.g., Juteau et al., 1977; Lebrat et al., 1987) and more recently as an oceanic plateau sequence (Cosma et al., 1998; Reynaud et al., 1999; Lapierre et al., 2000), and a tectonic mélange. The younger Macuchi terrane consists predominantly of an early Eocene (and possibly late Palaeocene) volcanosedimentary sequence of basaltic to andesitic composition, the Macuchi Unit.

The lithostratigraphic sequences of these two terranes are summarised in Fig. 3, and the key features of their principal rock units are described below. With the exception of the Silante Unit (described briefly to clarify the significance of its lavas), post-accretionary volcanosedimentary sequences are not described in this paper. For further details of these, the reader is referred to BGS-CODIGEM (1997a,b, 1999 and references therein).

3. The Pallatanga terrane

The Pallatanga terrane is delimited by the Chimbo-Toachi shear zone to the west, and to the east by the suture with the Cordillera Real, namely the Pujilí Fault zone (Figs. 1 and 2). In contrast to the Macuchi terrane, the Pallatanga terrane comprises several lithostratigraphic units, described briefly below. An assemblage

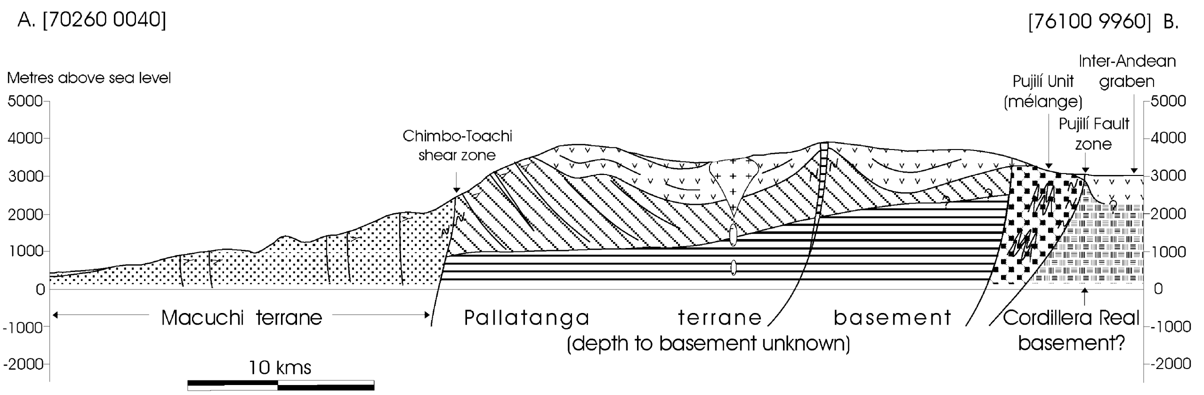


Fig. 2. Simplified cross-section along line A–B indicated in Fig. 1. Ornaments of main lithostratigraphic units as for Fig. 1; chevrons indicate evidence of ductile shearing. Vertical exaggeration × 2.

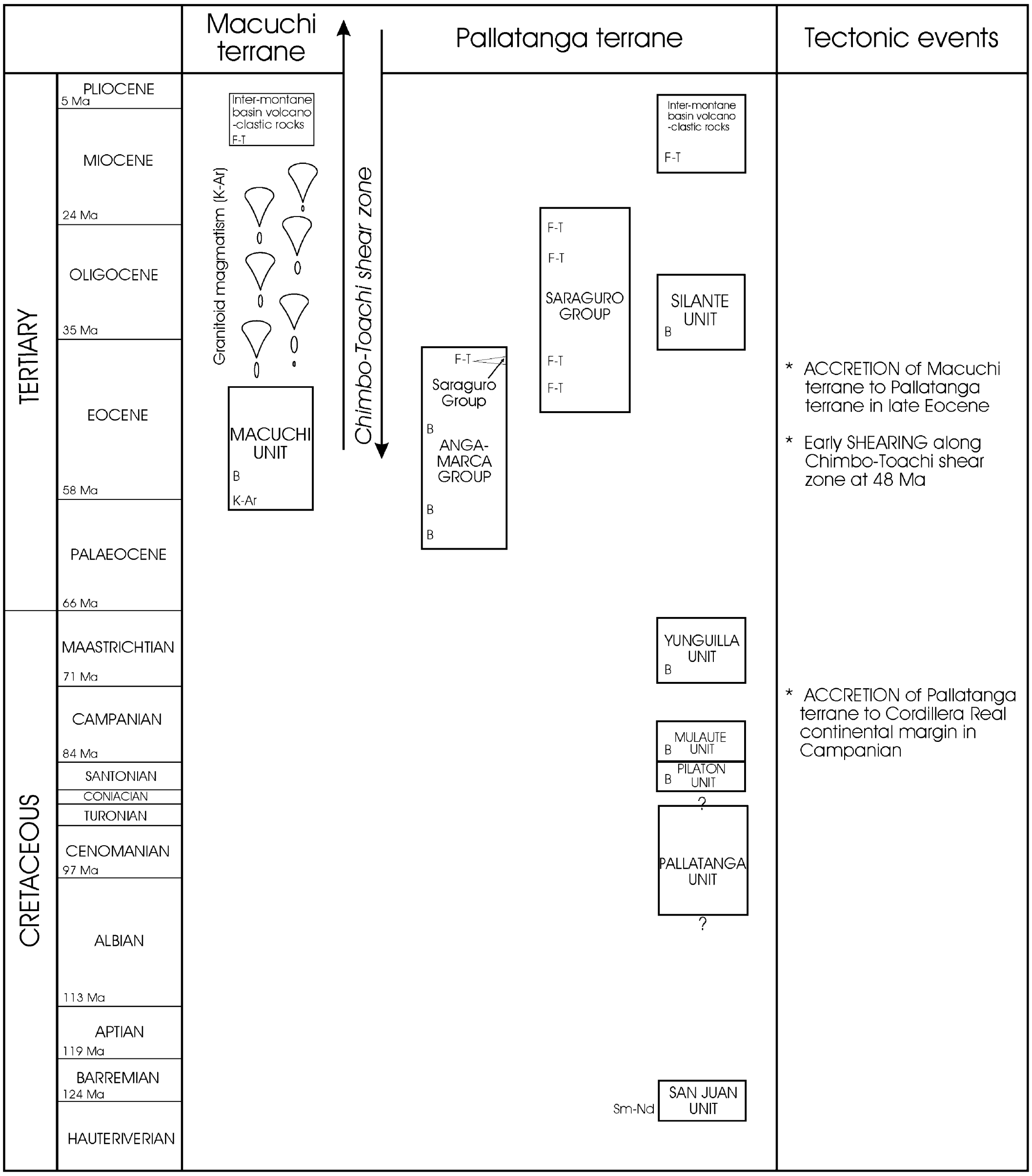


Fig. 3. Simplified stratigraphy of the Macuchi and Pallatanga terranes, showing key Cretaceous and Tertiary events. B — biostratigraphical age; K–Ar — Potassium–Argon age; F-T — fission-track age; Sm–Nd — Samarium–Neodymium age.

of oceanic plateau basalts and ultramafic rocks with related fine-grained turbidites (the Pallatanga Unit as defined in BGS-CODIGEM, 1997b) represents an oceanic suite. A locally exposed tectonic mélange (the Pujilí Unit) occupies a structural position along the suture at the eastern margin of the cordillera between 0° and 1°S. Areally, a large part of the terrane consists of late Cretaceous marine turbidites, the Mulaute, Pilatón and Yunguilla units. Also present within the terrane is a post-accretionary, terrestrial sedimentary sequence of late Eocene–early Oligocene age (the Silante Unit), derived from a sub-aerial andesitic volcanic source.

3.1. Pallatanga and San Juan units

Between the equator and 2°S, the Pallatanga Unit is exposed mainly in fault-bounded slivers along the eastern margin of the cordillera, but south of 2°S, it forms a broader belt consisting almost entirely of pillow lavas with minor hyaloclastites. It consists mainly of basalts (known formerly as the 'Piñon de la Sierra'), hyaloclastites, and fine-grained deep marine sediments, though ultramafic rocks are present locally (BGS-CODIGEM, 1997b; Mamberti et al., 1999a,b; Lapierre et al., 2000). It is commonly found in association with Maastrichtian turbidites of the Yunguilla Unit.

Lebrat et al. (1985, 1987) and Van Thournout et al. (1992) interpreted the Pallatanga basalts (Fig. 4a) to be of MORB composition. The oceanic affinities of these rocks (data presented in Table 1) are shown clearly in Fig. 4b (Ti vs. Zr, Pearce and Cann 1973), Fig. 5a (Ti vs. Cr, Pearce, 1975), and Fig. 5b (V vs. Ti/1000, Shervais, 1982). However, their full compositional range (Table 1) extends from N-MORB to oceanic plateau basalt (Neal et al., 1999). Olivine and clinopyroxene-rich basalts form part of the Pallatanga Unit in the Guaranda area (Mamberti et al., 1999a), and from San Jose de Minas [UTM coordinates 7880 00192] northwards towards the Colombian border (BGS field observations 1998, Mamberti et al., 1999a). The major trace element and isotope geochemistry of these rocks has been studied in detail by Mamberti et al. (1999a), Reynaud et al. (1999), and Lapierre et al. (2000), who conclude that they are typical of an oceanic plateau setting, and note close geochemical similarities between the Pallatanga rocks and the basalts of the Colombia–Caribbean Oceanic Plateau (ca. 90 Ma).

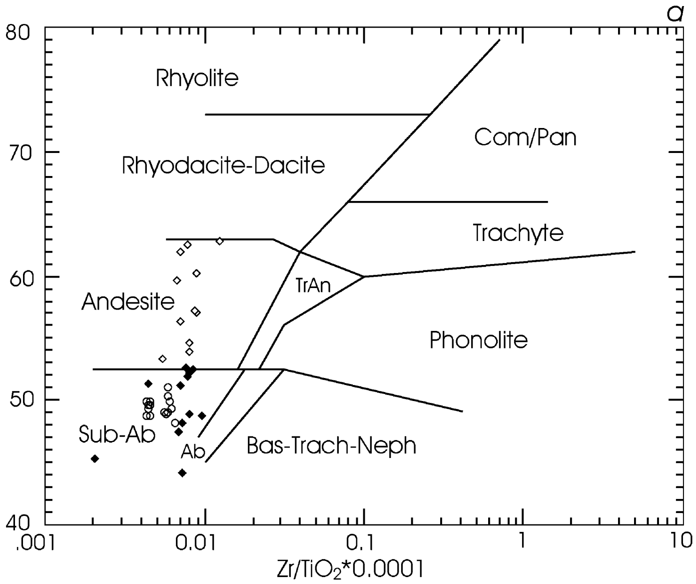
In faulted contact with the Pallatanga Unit to the west of Quito [761 9967] are the serpentinised ultramafics, anorthosites and gabbros of the San Juan Unit (BGS-CODIGEM, 1999; Juteau et al., 1977; Lebrat et al., 1985, 1987; Van Thournout et al., 1992). Lapierre et al. (2000) presented a Sm–Nd age of 123 ± 12 Ma from gabbros within the San Juan Unit, and (in agreement with the interpretation of Cosma et al., 1998) interpreted it as part of a mafic–ultramafic root zone to an oceanic plateau sequence.

In summary, the evidence suggests that oceanic plateau sequences of at least two distinct ages are present within the Pallatanga terrane. Multiple plume events are described from the coeval oceanic plateau basalt suites of the Caribbean (Lapierre et al., 2000), and the complexity of the mid to late Cretaceous oceanic plateau sequences of the Cordillera Occidental of Colombia has been described by McCourt et al. (1984), Nivia (1996), Kerr et al. (1996), and Sinton et al. (1998). It is possible, therefore, that further detailed work on the Pallatanga Unit basalts will reveal greater internal complexity of the Cretaceous plateau basalt sequences in Ecuador.

The contrasting trace element geochemistry of the basalts of the Pallatanga Unit and the basalts and andesites of the Macuchi Unit are clearly shown in Fig. 6a and b. The generally flat gradient of the normalised multi-element plot for the Pallatanga Unit (Fig. 6a) is typical of weakly evolved oceanic basalts, and contrasts strongly with the more highly evolved and enriched Macuchi basalts and andesites (Fig. 6b, data presented in Table 2).

3.2. Pujilí Unit

This is a chaotic and highly deformed tectonic mélange, present only along the eastern margin of the western cordillera (the Pujilí Fault zone, see Figs. 1 and 2), and exposed only in a small area to the north–west of Latacunga [75 980]. It was described by Litherland et al. (1994) as the 'Pujilí ophiolite'. Clast types within the mélange are derived from both oceanic and continental settings, and include foliated serpentinised ultramafic material containing chromite and magnesite, foliated muscovite-rich granitoids (similar to the Triassic (?) S-type Tres Lagunas granite of the Cordillera Real; Litherland et al., 1994), amphibolites with L-tectonite fabrics (similar to the Triassic (?) Piedras Unit of the El Oro complex; Aspden et al., 1995), phyllites, possible basaltic pillow lavas, and siliceous red siltstones/mudstones. Most of these exotic rock types are not known to occur elsewhere in the Cordillera Occidental. Shear fabrics are common in the matrix, and include S–C mylonites that consistently indicate dextral movement.



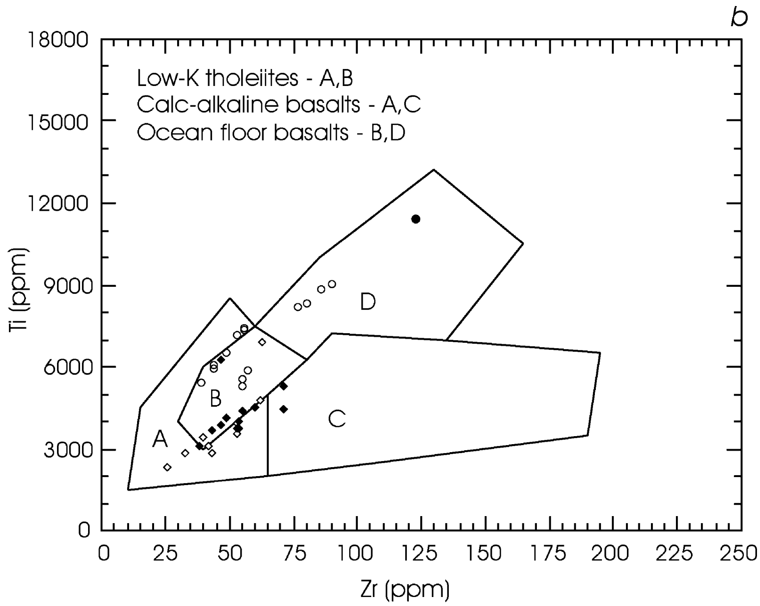


Fig. 4. (a) SiO_2 vs. $Zr/TiO_2 * 0.0001$ (Winchester and Floyd, 1977) for Pallatanga Unit basalts (circles), Macuchi Unit basalts (filled diamonds) and Macuchi andesites (open diamonds). (b) Ti vs. Zr (Pearce and Cann, 1973) for Pallatanga Unit basalts (circles), Macuchi Unit basalts (filled diamonds) and Macuchi Unit andesites (open diamonds).

The mélange is interpreted to be of tectonic origin, and is believed to have formed in the suture zone (Fig. 2) during the accretion of the Pallatanga oceanic terrane to the South American continental margin (the Chaucha terrane of the Cordillera Real; Litherland et al., 1994), during the late Cretaceous (further discussion below). Metamorphic xenoliths reported by Bruet (1987) in lavas from Pichincha volcano near Quito

Table 1
Major and trace element geochemical data for basalts of the Pallatanga Unit

Sample	M3-312C	M3-312D	M3-542C	P0 1441	P0 1476	P0 1482	P0 1508	P0 196	P0 198	P0 199	P0 208	P0 224	P0 225
UTM coordinates	7337 97932	7337 97932	7385 98546	6706 97028	6906 97225	7023 97332	6696 97012	6170 97061	6723 97061	6725 97058	6725 97072	6722 97100	6720 97103
SiO_2	49.08	48.92	51.01	49.87	50.33	48.14	49.11	49.39	49.87	49.93	49.59	48.81	49.64
TiO_2	1.37	1.39	1.48	1.51	0.93	1.91	0.98	0.99	1.01	1.23	1.09	0.90	1.20
Al_2O_3	13.61	14.59	13.44	13.97	14.54	13.79	13.27	13.67	13.72	13.32	14.11	14.07	13.25
Fe_2O_3	12.15	11.83	13.78	13.49	11.28	15.01	11.26	11.53	11.87	13.48	11.49	10.58	13.40
MnO	0.18	0.20	0.21	0.21	0.18	0.21	0.18	0.19	0.18	0.21	0.17	0.17	0.21
MgO	6.73	7.27	6.64	7.09	8.13	5.68	10.16	7.47	7.50	6.82	7.44	8.28	6.96
CaO	8.54	8.34	10.19	9.50	10.40	11.10	12.80	10.90	10.02	8.84	8.99	12.09	10.31
Na_2O	3.80	3.26	1.43	2.59	2.24	1.79	1.58	2.58	2.29	3.26	3.57	2.63	2.37
K_2O	0.06	0.10	0.12	0.23	0.34	0.22	0.07	0.09	0.29	0.15	0.48	0.11	0.14
P_2O_5	0.12	0.12	0.12	0.13	0.08	0.18	0.08	0.07	0.07	0.09	0.07	0.06	0.08
LOI	4.13	3.40	1.20	1.81	1.47	1.63	0.54	2.97	2.98	2.56	2.22	1.82	2.01
Cr	100	120	74	55	202	116	490	179	159	94	156	319	85
Ni	72	99	70	63	82	75	142	81	77	73	87	103	66
Co	47	51	49	57	45	66	53	42	42	45	42	41	43
Sc	31	44	48	46	42	45	51	36	37	38	35	35	39
V	345	358	387	346	289	473	293	268	275	326	270	234	312
K	473	863	980	0	0	0	0	0	0	0	0	0	0
Rb	0	0	0	6	4	2	2	1	5	4	7	1	2
Cs	0.00	0.00	0.00	2.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	49	75	19	28	55	20	57	0	21	0	0	0	0
Sr	47	120	97	116	173	107	114	65	101	100	146	122	93
Nb	6.0	6.0	5.0	7.0	5.0	11.0	4.0	3.0	2.0	4.0	3.0	3.0	3.0
Hf	0.00	0.00	7.00	7.00	3.00	5.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr	77	80	86	90	55	123	57	44	44	56	49	39	53
Ti	8219	8339	8885	0	0	0	0	0	0	0	0	0	0
Y	27	28	33	29	19	44	21	17	19	23	21	16	23
Th	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
U	1.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
La	5.00	0.00	7.00	0.00	6.00	7.00	0.00	0.00	7.00	6.00	4.00	0.00	4.00
Ce	22.00	12.00	16.00	10.00	16.00	55.00	35.00	8.00	9.00	10.00	9.00	8.00	12.00
Nd	8.00	8.00	11.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sm	0.00	9.00	21.00	0.00	0.00	0.00	6.00	0.00	0.00	0.00	0.00	0.00	0.00

LOI — loss on ignition.

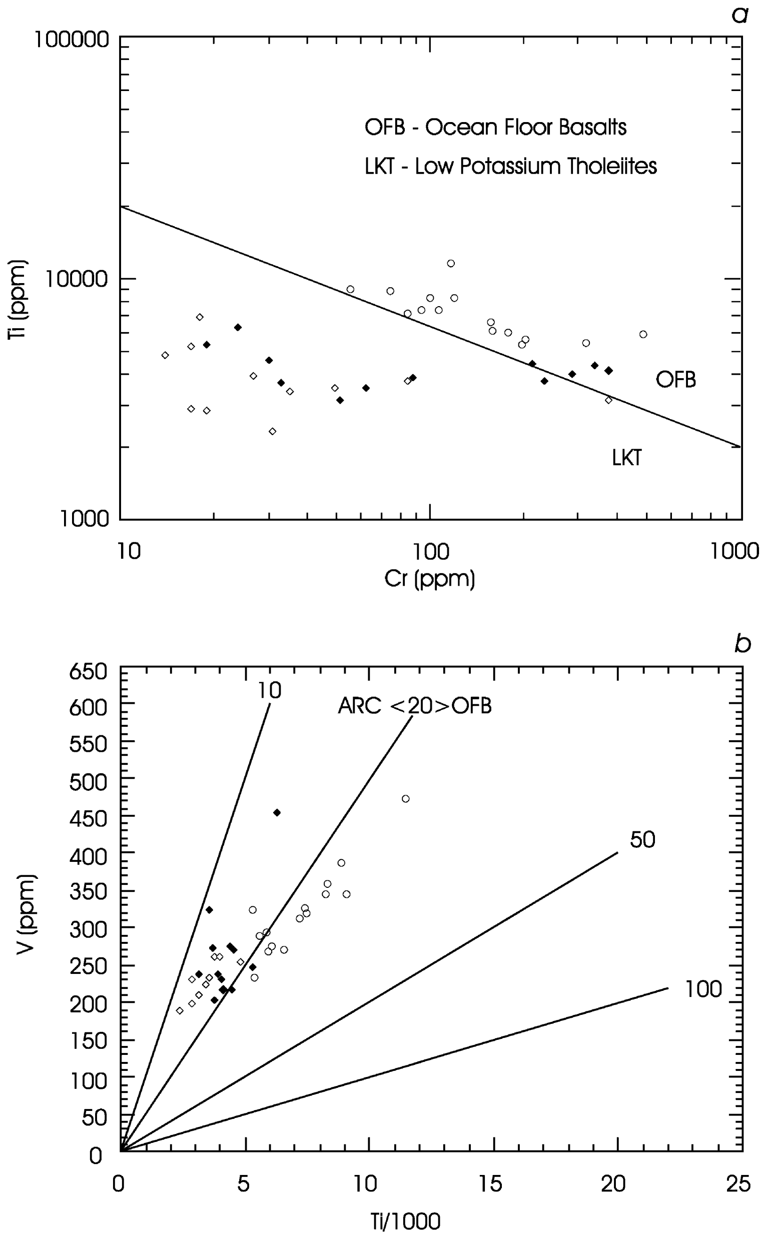


Fig. 5. (a) Ti vs. Cr (Pearce, 1975) for Pallatanga Unit basalts (circles), Macuchi Unit basalts (filled diamonds) and Macuchi andesites (open diamonds). (b) V vs. Ti/1000 (Shervais, 1982) for Pallatanga Unit basalts (circles), Macuchi Unit basalts (filled diamonds) and Macuchi Unit andesites (open diamonds).

indicate the presence of metamorphic rocks within the magmatic plumbing system. It is probable therefore that the mélange is present at depth along other parts of the eastern margin of the cordillera.

3.3. Pilatón, Mulaute and Yunguilla units

The Pilatón Unit (formerly known as the 'Cayo de la Sierra', re-named Pilatón Unit by Eguez, 1986)

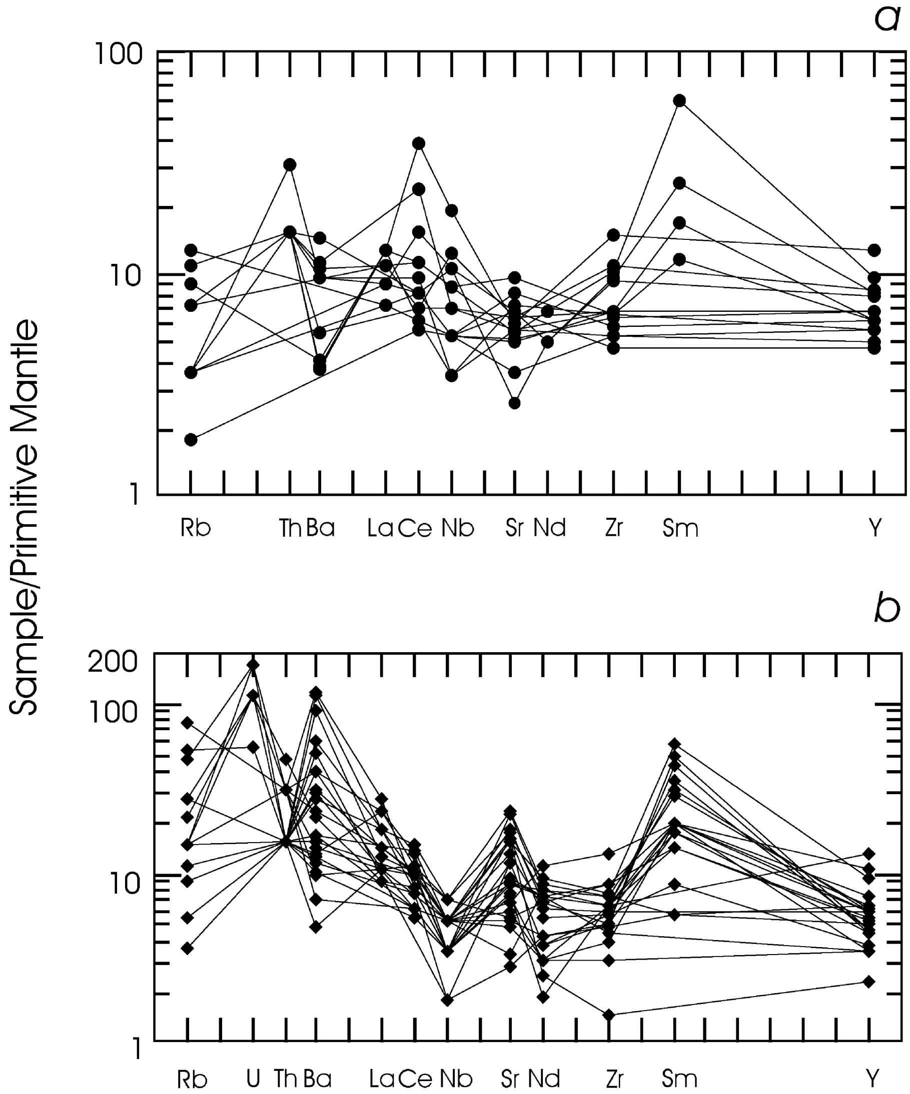


Fig. 6. (a) Pallatanga Unit basalts normalised against primitive mantle composition (mantle data from Sun and McDonough, 1989). (b) Macuchi Unit basalts and andesites normalised against primitive mantle composition (mantle data from Sun and McDonough, 1989).

and the Mulaute Unit (a previously undiscovered sequence, first named in BGS-CODIGEM, 1999) collectively comprise thick sequences of crystal-and lithic-rich debrites, turbidite sandstones and turbidite mudstones, derived from a submarine, basaltic to andesitic volcanic source. The turbidite facies (Bouma T_{abc} units) indicate deposition at proximal to medial positions on a submarine turbidite fan, and an as yet unidentified island arc system is the probable source. Fossil evidence (Sigal, 1968; Faucher and Savoyat, 1973; BGS-CODIGEM, 1997b, 1999) indicates Senonian and Campanian ages respectively for the Pilatón and Mulaute units.

The Yunguilla Unit consists of fine-grained turbidite sandstones, siltstones and mudstones (T_{bde} units), and was probably deposited upon the oceanic crust basalts of the Pallatanga Unit (see below) following accretion of the Pallatanga terrane. The age of the

Table 2
Major and trace element geochemical data for basaltic and andesitic extrusive rocks of the Macuchi Unit

Sample	M3-201	M3-485	M3-485D	M3-518	M3-761	RH 5	RH 122A	RH 122B	RH 130A	RH 258A	RH 258B	RH 258C	RH 274	RH 276	RH 278B	RH 279B	RH 280B	RH 282B	RH 297	RH 299
UTM coordinates	7002 97847	7128 98730	7128 98730	7056 98713	7044 98729	7164 99024	7171 99675	7171 99675	7305 99657	7096 99432	7096 99432	7096 99432	6886 99314	7200 99685	7249 99654	7261 99655	7277 99653	7219 99650	7313 99439	7219 99428
SiO_2	51.40	47.51	48.20	52.18	53.29	60.17	61.90	59.61	62.77	57.13	56.31	57.26	53.87	48.97	48.74	51.13	54.65	52.52	52.69	62.58
TiO_2	1.05	0.62	0.65	0.88	1.15	0.48	0.47	0.39	0.87	0.59	0.57	0.63	0.66	0.67	0.74	0.69	0.52	0.63	0.73	0.80
Al_2O_3	15.12	18.42	19.19	18.59	17.08	11.76	11.59	12.26	14.85	15.96	15.22	15.42	15.75	15.57	17.73	15.41	14.34	15.96	16.65	13.19
Fe_2O_3	13.78	9.97	9.67	9.70	11.80	6.38	7.46	7.42	7.51	6.96	6.95	8.16	9.53	8.31	7.91	8.46	7.28	8.07	12.10	9.18
MnO	0.19	0.13	0.13	0.18	0.30	0.20	0.20	0.24	0.17	0.17	0.17	0.21	0.17	0.20	0.17	0.16	0.19	0.16	0.13	0.09
MgO	4.43	9.14	8.37	3.29	4.43	2.50	3.67	5.30	3.75	4.57	5.41	6.24	3.78	7.05	8.45	11.00	10.30	7.60	4.54	6.19
CaO	8.01	5.10	6.43	9.02	5.48	11.47	8.23	9.48	1.86	6.32	6.41	5.47	7.91	9.99	8.99	7.42	5.26	8.40	5.89	1.08
Na_2O	2.81	1.73	1.12	2.42	3.57	3.60	4.26	4.01	4.39	3.47	4.32	3.31	2.75	3.79	2.38	1.90	3.12	3.63	3.94	2.77
K_2O	0.46	0.82	0.71	0.74	0.34	0.11	0.05	0.10	1.08	1.63	0.50	1.03	0.67	0.08	1.32	0.50	0.04	0.15	0.07	0.75
P_2O_5	0.13	0.07	0.02	0.17	0.20	0.12	0.10	0.12	0.24	0.18	0.19	0.19	0.10	0.12	0.14	0.12	0.09	0.09	0.41	0.20
LOI	2.36	6.15	5.08	3.03	2.30	3.37	1.73	1.02	2.70	2.63	3.98	2.28	4.47	4.91	3.38	2.98	4.14	2.77	2.38	3.54
Cr	24	33	88	19	18	17	19	31	17	49	35	85	27	286	213	374	374	235	339	14
Ni	11	27	27	9	12	11	11	14	5	19	23	40	21	200	132	243	176	149	78	7
Co	42	38	35	22	31	21	34	32	18	22	26	28	38	37	38	41	36	37	51	26
Sc	49	33	32	29	42	28	37	28	25	30	25	27	32	34	34	39	34	32	40	28
V	454	272	239	248	331	199	232	189	127	233	225	260	261	232	217	217	210	203	274	253
K	3810	6815	5935	6151	2864	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rb	5	8	5	12	2	0	0	0	8	26	8	15	29	0	43	8	0	3	0	6
Cs	1.00	2.00	1.00	0.00	0.00	1.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00
Ba	154	204	264	161	85	50	25	36	591	313	108	200	455	53	119	73	59	64	66	570
Sr	283	210	204	313	274	97	86	131	121	156	94	157	397	138	322	231	51	105	161	60
Li	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ta	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.00
Nb	3.0	2.0	1.0	4.0	3.0	4.0	3.0	2.0	3.0	2.0	3.0	3.0	2.0	2.0	3.0	3.0	1.0	3.0	2.0	3.0
Hf	9.00	0.00	0.00	6.00	9.00	0.00	6.00	4.00	0.00	0.00	0.00	8.00	4.00	6.00	6.00	4.00	0.00	7.00	14.00	6.00
Zr	47	43	47	71	63	43	33	26	107	53	40	54	53	54	71	49	42	53	55	62
Ti	6319	3711	3927	5294	6912	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Y	25	15	13	22	32	15	12	12	36	20	17	20	20	18	19	20	16	16	44	22
Th	1.00	1.00	1.00	1.00	1.00	2.00	1.00	2.00	2.00	1.00	3.00	2.00	1.00	1.00	2.00	2.00	1.00	1.00	1.00	1.00
U	0.00	0.00	0.00	2.00	0.00	2.00	2.00	0.00	3.00	3.00	2.00	2.00	1.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00
La	0.00	6.00	0.00	8.00	0.00	0.00	6.00	0.00	15.00	10.00	5.00	13.00	7.00	0.00	8.00	6.00	0.00	0.00	13.00	10.00
Ce	9.00	14.00	0.00	0.00	20.00	16.00	0.00	9.00	12.00	0.00	12.00	16.00	15.00	8.00	15.00	0.00	11.00	9.00	19.00	0.00
Nd	9.00	6.00	6.00	12.00	15.00	11.00	5.00	5.00	18.00	12.00	7.00	13.00	13.00	3.00	11.00	10.00	7.00	5.00	12.00	13.00
Sm	7.00	6.00	3.00	7.00	20.00	15.00	7.00	0.00	7.00	7.00	2.00	6.00	11.00	5.00	5.00	0.00	17.00	12.00	0.00	2.00

LOI — loss on ignition.

Yunguilla Unit was stated originally by Savoyat et al. (1970) and by Faucher et al. (1971) to be Maastrichtian to early Palaeocene, on the basis of foraminiferan evidence. However, these authors' faunal lists have been reassessed, and are believed to indicate an age no younger than Maastrichtian (BGS-CODIGEM, 1997a,b, 1999). Thin sections from the Yunguilla Unit between 0°00′ and 1°S contain strained quartz aggregates and serpentinised amphibole grains, indicating a metamorphic source in part, while vitriclastic textures indicate contemporaneous volcanism (BGS-CODIGEM, 1999). South of 1°S the Yunguilla Unit contains mafic minerals that also suggest a volcanic input from the source area.

3.4. The Silante Unit

This is a sequence of terrestrial sediments, dominated by fluvial and possibly lacustrine sequences, of late Eocene–early Oligocene age (BGS-CODIGEM, 1999), derived from a relatively proximal, probably sub-aerial andesitic volcanic source. Rocks of similar composition and probably similar age (the Puñay Unit of the Saraguro Group, Dunkley et al., in preparation) occur just east of the Pallatanga terrane in the southern part of the cordillera. The Silante Unit and its possible correlatives were formed after the accretion of the Macuchi terrane, but are apparently absent from the Macuchi terrane. The reason for this is unclear, but it seems probable that the calc-alkaline volcanic source of the Silante rocks was geographically restricted to the already accreted crust of the Pallatanga (and older) terranes to the east.

At the western end of the Silante succession in the northern part of the cordillera, near the village of Tandapi [746 9953] between Quito and Santo Domingo de los Colorados, is a sequence of andesites and andesitic breccias. These rocks were named the 'Tandapi Beds' by Kehrer and Van der Kaaden (1979), and the 'Tandapi Unit' by Eguez (1986), Van Thournout et al. (1992), Cosma et al. (1998), and Reynaud et al. (1999). These authors demonstrated the calc-alkaline nature of these andesites, and believed that they represented a volcanic arc sequence of late Palaeocene to Eocene age (or late Oligocene by Van Thournout). Eguez believed the unit to be a sequence of andesitic lavas and breccias in 'transitional' contact with the Silante Unit. However, the breccias of the 'Tandapi Unit' were reinterpreted (BGS-CODIGEM, 1999 and references therein) as peperites, produced by explosive hydromagmatic reactions that occurred when hot andesite magmas intruded wet sediments (red sandstones and mudstones) of the Silante Unit. The 'Tandapi Unit' is therefore interpreted as a magmatic sequence within the late Eocene–early Oligocene Silante Unit, and probably represents part of a larger (continental margin?) magmatic episode that supplied the Silante depositional basin.

3.5. Angamarca group

This is a turbidite-dominated sedimentary sequence of early–mid Palaeocene (BGS-CODIGEM, 1997a,b, 1999) to late Eocene age (Eguez and Bourgois, 1986; Bourgois et al., 1990), containing a mid to late Eocene limestone unit (the Unacota Limestone; Eguez and Bourgois, 1986) (Fig. 3), and includes the former Apagua and Gallo Rumi units. In the Cumanda area (e.g., along the Cumanda–Pallatanga road between [172 97627] and [7174 97632]), Angamarca Group turbidites commonly contain silicic ash-flow tuffs that are correlatives of the Saraguro Group (BGS-CODIGEM, 1997a). One such tuff (from [7215 97692]) was dated at 37.8 ± 3.5 Ma (BGS-CODIGEM, 1997a), indicating that clastic deposition in the Angamarca basin continued until at least late Eocene times.

In the central part of the cordillera, the succession is a coarsening-upward basin fill sequence, and shows progradation from submarine fan to fan-delta (BGS-CODIGEM, 1999). The Unacota Limestone contains in situ stromatolite mounds, indicating a water depth of < 200 m. The limestone probably represents a significant shallowing of the Angamarca depositional basin, with the development of Waulsortian-type reef mounds, and possible temporary emergence. The presence of limestones of the same age within the Tertiary basins of the Costa (Progreso, Manabí and Borbón basins; Santos et al., 1986) suggests a regional eustatic low sea-level stand in the mid Eocene.

Angamarca sandstones are typically feldspathic, rich in sericite, and contain virtually no mafic minerals. The conglomerates are polymictic but of generally uniform composition, containing abundant white quartz of probable metamorphic origin, black chert, rare foliated muscovitic granitoids, and some meta-sedimentary(?) clasts.

Stratigraphical evidence clearly indicates that the Macuchi island arc was active during the deposition of the Angamarca Group. Provenance studies show that the Angamarca Group sediment was supplied from a partly metamorphic source area. If this source area was the Cordillera Real, it would imply at least partial emergence of that area by Eocene times. Also present within the Angamarca Group in the Cumanda area are acid ash-flow tuffs derived from the continental margin Saraguro Group (BGS-CODIGEM, 1997a). Collectively, this evidence strongly suggests that the Angamarca Group depositional basin occupied a fore-arc setting, between the early Tertiary continental margin and the seaward Macuchi island arc, on crust belonging to the Pallatanga terrane. This interpretation is supported by the geographical distribution of the Angamarca Group (Fig. 1), which is consistently along or about the suture between the Macuchi and Pallatanga terranes.

4. The Macuchi terrane

Excluding post-accretionary cover sequences, this terrane comprises just one lithostratigraphic unit, the eponymous Macuchi Unit. It forms a substantial proportion of the cordillera between 2°30′S and the equator, but is found only to the west of the Chimbo-Toachi shear zone (Figs. 1 and 2). The sequence is predominantly (up to 90%) volcanosedimentary, with the remainder comprising pillow lavas and probable high level diabase intrusions. It also contains at least two economically important volcanogenic massive sulphide mineral deposits (at Macuchi [716 9997] and La Plata [7292 99567]).

As defined by Henderson (1979, 1981), the Macuchi Unit was believed to be of late Cretaceous to Eocene age. The interpretation was based in part upon the inclusion within his Macuchi Unit of late Cretaceous marine turbidites, now known to be part of the Pilatón Unit (Fig. 3). Henderson's late Cretaceous to Eocene age range for the Macuchi was accepted by Lebrat et al. (1985, 1987) and Aguirre and Atherton (1987), and has resulted in some very misleading interpretations of the late Cretaceous to Tertiary evolution of the Ecuadorian margin. Bourgois et al. (1990) stated that the Macuchi island arc was active during Palaeocene, Eocene and Oligocene times, but presented biostratigraphical evidence that support only an Eocene age.

In fact, all available biostratigraphical and geochronological evidence for the age of the Macuchi Unit in the present area indicates an Eocene age. Henderson (1979) reported Eocene foraminifera from the 'Macuchi Formation' west of Latacunga, but no locality details were provided. More reliably, Eguez (1986) reported an early to mid Eocene radiolarian fauna from a turbidite sequence a few kilometres west of the type area at Macuchi village [716 9997], and early Eocene foraminifera from a nearby limestone [7152 99020] within the sequence.

Eguez (1986) also reported two K–Ar whole-rock ages of 41.6 ± 2.1 and 35.8 ± 1.8 Ma (mid- to late-Eocene) from basaltic andesite sheets that intrude Eocene limestones in the same area. A suite of granitoid plutons (discussed further below), the oldest of which (from results obtained to date) has a K–Ar hornblende age of 38.1 ± 0.39 Ma (late Eocene), also intrudes the Macuchi Unit. Though evidence is far from abundant, it consistently points to an early to mid Eocene age for the Macuchi Unit. The youngest parts of the sequence can be no younger than late Eocene, but it is possible (though as yet unproven) that the oldest parts extend into the Palaeocene.

The Macuchi Unit between the equator and 2°30′S (including the type area around Macuchi mine) is redefined here as an early to mid Eocene, submarine, volcanosedimentary sequence, with pillow lavas and related intrusive bodies, derived from an oceanic island arc of basaltic to andesitic composition.

4.1. Macuchi unit facies

The sedimentary facies of the Macuchi Unit consist predominantly of poorly sorted debrites, coarse-grained turbidite sandstones and hyaloclastites, but thin, discontinuous limestones are also present. Debrites are very common, and comprise unsorted, coarse, matrix-supported breccias containing clasts of broken pillows up to 1 m across. They are normally associated with pillow lavas and hyaloclastites. Analysed clasts have the same composition as the pillow lavas within the Macuchi sequence (see discussion of Macuchi geochemistry below), and consist of basaltic andesites or andesites, commonly pyroxene-phyric, with vesicular rims. The sandstones are of quartz-feldspathic (plagioclase) composition and lithic-rich, with abundant clasts of highly vesicular, fine-grained, pyroxene-phyric andesite/basaltic andesite. Poor exposure and intense recrystallisation of the limestones make their interpretation difficult; they could be discontinuous, lenticular limestone beds, or olistoliths derived from a foundered fringing reef system.

Pillow basalt sheets, up to 50 m thick, are commonly intercalated with lesser thicknesses of matrix-supported pillow breccias, coarse-grained poorly sorted sandstones of basaltic composition, and hyaloclastites. The sedimentary intercalations commonly contain detached pillows, and were clearly derived from the same submarine effusive sources that produced the pillows. The lavas are typically fine-grained, plagioclase-rich, and commonly pyroxene-phyric, with highly vesicular rims. Diabase bodies, in the form of dykes and small intrusions, probably represent high-level intrusions. Dr. Arturo Eguez (personal communication, March 1997) reports acid ash-flow tuffs from the La Mana area [79 989], a few kilometres from the Macuchi type area.

With the exception of the limestones, all the sedimentary facies of the Macuchi Unit are the products of submarine eruptions, and the deposition of the eruptive products by gravity flow processes. The pillow lavas, pillow breccias and diabase intrusions represent the near-vent effusive products, high level intrusions, and possible magma conduits.

The reported presence of silicic ash-flow tuffs within the Macuchi Unit is significant to the interpretation of the sequence, possibly indicating subaerial eruption and an island-arc setting. The development of fringing reefs, possibly represented by locally developed limestones within the Macuchi sequence, would be expected in a low latitude island-arc setting. This island-arc interpretation, based upon facies and mineralisation style alone, is strongly supported by rock geochemistry.

4.2. Macuchi unit geochemistry

Previous geochemical studies (e.g., Henderson, 1979; Lebrat et al., 1985, 1987; Aguirre and Atherton, 1987; Cosma et al., 1998) have interpreted the sequence as a suite of volcanic island arc tholeiites. Lebrat et al. (1987) believed that the Macuchi unit contains slivers of MORB rocks and ultramafic rocks, but this conclusion was based on incorrect interpretation of stratigraphical relationships. Aguirre and Atherton (1987) interpreted the low-grade metamorphism of the Macuchi Unit as indicative of an ‘oceanic island arc generated contemporaneously with a marginal basin’.

In terms of their whole-rock composition, the lavas of the Macuchi Unit are sub-alkaline basalts and andesites (Fig. 4a; Winchester and Floyd, 1977), and predominantly are basaltic andesites and andesites. The Macuchi data (Table 2) fall into the low-potassium tholeiite field of the Ti vs. Zr plot (Fig. 4b) of Pearce and Cann (1973) and the Ti vs. Cr plot (Fig. 5a) of Pearce (1975), and fall clearly into the arc field of the V vs. Ti/1000 plot (Fig. 5b) of Shervais (1982). However, a group of Macuchi basalt samples (from the Río Toachi at La Unión del Toachi [7277 99645]) contains anomalously high Cr concentrations, causing them to fall into the ocean floor basalt field (Fig. 5a). These samples also contain abnormally high concentrations of MgO, Sr and Ni. Their unusual geochemistry is more typical of primitive arc basalts, but the presence of large amounts of pyroxene (from the crystallisation of cumulates) could also explain the high values of Cr, Ni and Mg.

When normalised against a primitive mantle composition (Fig. 6b), the Macuchi rocks are characterised by relative enrichment in low field strength and light rare earth elements such as Rb, Ba, K and Sr, and relative depletion in high field strength elements such as Nb, Zr, and Y. The strongly negative gradient of the curve is typical of island arc assemblages, and clearly contrasts with the much flatter curve of the Pallatanga basalts (Fig. 6a).

In summary, the data indicates an island arc setting for the basalts and andesites of the Macuchi Unit, though a marginal basin setting is possible. These conclusions are in broad agreement with the previous interpretations of Henderson (1979), Lebrat et al. (1985, 1987), Aguirre and Atherton (1987), and Cosma et al. (1998).

5. The Chimbo-Toachi shear zone

This previously unknown, low grade ductile shear zone, is the suture between the Macuchi and Pallatanga terranes. Its trace is shown in Fig. 1, and its structural position within the cordillera in Fig. 2. Along its length, kinematic indicators (S–C mylonite fabrics, deformed clasts and strain shadows) consistently indicate dextral movement.

The shear zone is best exposed (albeit poorly) between Santo Domingo de los Colorados and San Miguel de los Bancos, in the area of the ríos Macas [7279 99956] and Mulaute [7224 99882] (details in BGS-CODIGEM, 1999 and references therein). Here, it is at least 12 km wide, and consists of a high strain zone of penetrative cleavage development, within which there are at least five, and possibly more, narrow zones of ductile deformation. It has an approximately north–south trend and is moderately to steeply dipping (45–80°) to the east and west. Gently inclined stretching lineations (plunging up to 35°), indicative of a component of strike–slip movement, are commonly visible on S_1 planes. Zones of ductile deformation are visible in the Río Mulaute at [7293 99799] where the sense of movement is indeterminate, and in the Río Macas at [99261 7890] and [7270 99925], where S–C mylonite fabrics indicate dextral movement.

6. Timing and nature of accretionary events

6.1. Pallatanga terrane accretion

The basement to the Pallatanga terrane consists of oceanic plateau basalts and ultramafics, locally exposed as the Pallatanga and San Juan units. The unusual thickness and resultant buoyancy of oceanic plateau basalt crust means that such rocks are commonly obducted or accreted, rather than being subducted at convergent margins (e.g., Saunders et al., 1996). The very nature of the Pallatanga terrane crust is the probable reason for its accretion. If the inferred correlation (Mamberti et al., 1999a; Reynaud et al., 1999; Lapierre et al., 2000) of the Pallatanga Unit with the ca. 90 Ma basalts of the Colombia–Caribbean Oceanic Plateau proves to be correct, the accretion of the Pallatanga terrane must have occurred after ca. 90 Ma; that is, in Coniacian or younger times.

Aspden et al. (1992) proposed that the widespread resetting of isotopic ages in the Cordillera Real of Ecuador at 85–65 Ma was caused by uplift resulting from the earliest stages of accretion of the Cordillera Occidental. This is supported by evidence of the deposition of very different sedimentary facies in Maastrichtian times on either side of the Cordillera Real, with marine turbidites of the Yunguilla Unit to the west, and the red-beds of the Tena Formation to the east. This evidence implies emergence of the proto-cordillera by the Maastrichtian (Baldock, 1982), and suggests that accretion and uplift took place in pre-Maastrichtian times, probably during the Campanian. Fission-track studies in the Cordillera Real indicate an important phase of rapid crustal cooling, possibly related to a regional uplift event, at 65–60 Ma (Dr. Richard Spikings, ETH-Zurich, personal communication, February 2000). The exact cause of this crustal cooling event in unknown at present, but it is tempting to speculate that the event was related to Maastrichtian uplift following the accretion of the Pallatanga terrane in the Campanian.

The Pallatanga and San Juan units are early to late Cretaceous oceanic plateau fragments, accreted during the Campanian event. The Campanian and Senonian Mulaute and Pilatón units were deposited upon this oceanic crust, and were accreted during the same event. The Yunguilla Unit is believed to be the marine turbidite system that developed in the fore-arc region, derived in part from the Cordillera Real. This interpretation is supported by the petrography of the Yunguilla sandstones, which contain metamorphic and some fresh, subaerial volcanic input. The Pujilí Unit tectonic mélange formed in the suture zone (now marked by the Pujilí Fault zone, see Fig. 2) between the Pallatanga terrane and the Chaucha terrane of the Cordillera Real (Litherland et al., 1994) during the Campanian accretion event.

6.2. Macuchi terrane accretion

The age of accretion of the younger Macuchi terrane is better constrained. Evidence from the area between the equator and 1°S suggests that the Macuchi terrane was accreted in, or before, the late Eocene (BGS-CODIGEM, 1999). Here, the steeply inclined rocks of the Macuchi Unit and the Angamarca Group are unconformably overlain by the gently dipping Zumbagua Group, of Miocene age. The evidence indicates that a major tectonic event occurred at some stage in latest Eocene to early Miocene times.

In the southern parts of the Cordillera Occidental, a local late Eocene to early Oligocene deformation event, a hiatus in Saraguro Group volcanism, and a subsequent marked change in the composition and style of volcanism are attributed to the docking of the Macuchi terrane in the late Eocene (BGS-CODIGEM, 1997a; Dunkley et al., in preparation) The presence within the Angamarca Group fore-arc sedimentary sequence here of ash-fall tuffs derived from the Saraguro Group, and dated at 37.8 ± 3.5 Ma (BGS-CODIGEM, 1997a), implies that the fore-arc basin between the Pallatanga terrane and the approaching Macuchi arc remained open until late Eocene times.

The age of shearing along the Chimbo-Toachi shear zone remains uncertain. However, strongly foliated diorites within the shear zone east of Santo Domingo de los Colorados contain amphibole aggregates comprising hornblende cores and actinolite overgrowths. K–Ar analysis of a hornblende mineral separate from one intrusion gave an age of 48.28 ± 0.55 Ma (early to mid Eocene). This age is almost certainly reset, and may represent the earliest stages of dextral shearing during the accretion of the Macuchi terrane.

Though there is abundant kinematic evidence of dextral shear in the suture zone between the Pallatanga and Macuchi terranes, the initial convergence of the Macuchi island arc and the continental margin was probably by subduction of the oceanic crust upon which the Macuchi arc was founded. The oldest (mid Eocene) parts of the Saraguro Group represent the continental volcanism generated by this subduction event (BGS-CODIGEM, 1997a). It is not known whether subduction was orthogonal or oblique, but it is reasonable to suggest that initially oblique convergence of the Macuchi island arc and the continental margin culminated in dextral shearing along the suture, now represented by the Chimbo-Toachi shear zone.

7. Discussion

7.1. Correlation with coastal ecuador

Palaeogene deformation events are described from the fore-arc sedimentary sequences of the Ecuadorian ‘Costa’, but here the situation appears to be more complex than in the cordillera. Jaillard et al. (1995), for example, describe late Palaeocene, earliest Eocene and ‘early late Eocene’ tectonic events in southern coastal Ecuador. Indeed, the late Cretaceous and Tertiary sequences described by Jaillard et al. (1995) appear superficially to be quite different to their coeval correlatives in the cordillera, and it is tempting to speculate that their depositional and accretionary histories are unrelated.

Nevertheless, there are some significant similarities between the two areas. Of particular interest is the mid to late Eocene sedimentary record from coastal Ecuador, in which transgressive shelf limestones are overlain by shallowing upward turbidites and conglomerates (Jaillard et al., 1995). In general terms, the main events within this sequence are very similar to those of the coeval Angamarca Group in the cordillera. If these two sequences are indeed part of the same sedimentary basin fill, it might imply accretion of the Macuchi terrane by middle Eocene times (slightly earlier than deduced from other evidence presented above). Detailed sedimentary provenance studies are required to advance this hypothesis.

The late Eocene tectonic phase described from coastal Ecuador as ‘the result of the definitive collision of southern Ecuador with the Andean continental margin’ (Jaillard et al., 1995) may be part of the event during which the Macuchi terrane was accreted to the continental margin. It is also worthy of note that an early to mid Eocene transpressive inversion episode is described from the Oriente basin (Baby et al., 1999).

7.2. Correlation with the Cordillera Occidental of Colombia

The rocks of the Cordillera Occidental in Ecuador and Colombia are generally believed to share a similar Cretaceous and Tertiary accretionary history (e.g., McCourt et al., 1984). Although there is broad agreement that oceanic rocks were accreted to the continental margin in late Cretaceous times in both areas (e.g., Bourgois et al., 1990; Kellogg and Vega, 1995), in practice, detailed correlation of lithostratigraphic units and accretionary events between the two areas remains difficult (see, for example, the discussion in Reynaud et al., 1999).

In general terms, the mafic–ultramafic rocks of the Pallatanga Unit in Ecuador can be correlated with the Cretaceous plateau basalts of the ‘Diabase Group’ of the Cordillera Occidental of Colombia (described by Millward et al., 1984). Bourgois et al. (1990), for example, ‘assumed’ that the Piñon Formation of the Cordillera Occidental of Ecuador (the Pallatanga Unit of this paper) was the 'southward prolongation of the western cordillera ophiolites of Colombia'. Although the general correlation remains valid, new data published in the past decade (Nivia, 1996; Kerr et al., 1996; Sinton et al., 1998; Reynaud et al., 1999; Lapierre et al., 2000) have highlighted important differences between the two areas. Summarising other work, Reynaud et al. (1999) believe that at least three suites of Cretaceous oceanic plateau basalts to are present in the Cordillera Occidental of Colombia. These authors state further that the oceanic plateau sequences of the Cordillera Occidental of Ecuador (the Pallatanga and San Juan units of this paper) are distinct from those of the Colombian Cordillera Occidental, and therefore cannot be considered part of the late Cretaceous Colombian–Caribbean oceanic plateau.

Furthermore, although at the regional scale the two areas share common major crustal structures (e.g., the Cauca–Patía and Romeral faults), in detail there appear to be differences in structural style between the two areas. Bourgois et al. (1982, 1987) for example, describe a series of south–east verging 'alpine-style nappes' from the Buga-Buenaventura traverse of the Cordillera Occidental in central Colombia. Later workers (e.g., Millward et al., 1984; Kerr et al., 1998) refuted these interpretations (Bourgois et al., 1982, 1987). Nevertheless, the structural interpretations of Kerr et al. (1998) for the eastern margin of the Cordillera Occidental of Colombia include eastward dipping thrust faults and intense folding of the Cretaceous sequences. They indicate a degree of structural complexity simply not seen in the Cordillera Occidental of Ecuador.

Relatively little attention has been paid to the Tertiary rocks of the Cordillera Occidental of Colombia, which therefore remain poorly understood. Nevertheless, a mid to late Eocene accretionary event has been described from the Cordillera Occidental of south–west Colombia by McCourt et al. (1991). In this event, the Palaeocene–Eocene Timbiqui andesitic volcanosedimentary sequence was accreted against the Cretaceous 'Diabase Group' plateau basalt sequence. The similarities with the Macuchi accretionary event in Ecuador are striking, and the recognition of a late Eocene accretionary event in both Colombia and Ecuador suggests that the event may have affected much of the northern Andean segment.

8. Conclusions

(1) The Cordillera Occidental of Ecuador between 0° and 2°30′S comprises two terranes. The older Pallatanga terrane consists predominantly of early to late Cretaceous oceanic plateau rocks, a probable late Cretaceous tectonic mélange, and late Cretaceous marine turbidites. The younger Macuchi terrane consists of an early Eocene (and possibly late Palaeocene), basaltic to andesitic, volcanosedimentary island arc sequence.

(2) Regional evidence, including widespread resetting of Rb–Sr ages in the Cordillera Real of Ecuador and in Colombia, and differing Maastrichtian depositional environments on either side of the Cordillera Real in Ecuador, indicates the accretion of the Pallatanga terrane in late Cretaceous (Campanian) times.

(3) Regional stratigraphical and geochronological evidence indicates accretion of the Macuchi terrane to the Pallatanga terrane during late Eocene times. The Angamarca Group is a mid-late Palaeocene to late Eocene, mainly turbiditic, basin fill sequence that accumulated in the fore-arc region between the Pallatanga terrane and the encroaching Macuchi island arc.

(4) Convergence of the Macuchi island arc and the continental margin took place initially through oblique, dextral subduction of oceanic crust. Subduction (and related volcanism) ceased when the Angamarca fore-arc basin closed due to the arrival of the Macuchi island arc at the continental margin in the late Eocene. Continued dextral motion produced dextral shear along the Chimbo-Toachi shear zone, displacing the Macuchi terrane an unknown distance parallel to the continental margin.

(5) Accretion of basaltic–andesitic volcanosedimentary sequences during the late Eocene is recognised in the Cordillera Occidental of both Ecuador and Colombia. This event appears, therefore, to have affected much of the northern Andean margin.

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