Dextral shear, terrane accretion and basin formation in the Northern Andes: best explained by interaction with a Pacific-derived Caribbean Plate?

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Abstract: The structure, stratigraphy and magmatic history of northern Peru, Ecuador and Colombia are only adequately explained by Pacific-origin models for the Caribbean Plate. Inter-American models for the origin of the Caribbean Plate cannot explain the contrasts between the Northern Andes and the Central Andes. Persistent large magnitude subduction, arc magmatism and compressional deformation typify the Central Andes, while the Northern Andes shows back-arc basin and passive margin formation followed by dextral oblique accretion of oceanic plateau basalt and island arc terranes with Caribbean affinity. Cretaceous separation between the Americas resulted in the development of a NNE-trending dextral–transpressive boundary between the Caribbean and northwestern South America, becoming more compressional when spreading in the Proto-Caribbean Seaway slowed towards the end of the Cretaceous. Dextral transpression started at 120–100 Ma, when the Caribbean Arc formed at the leading edge of the Caribbean Plate as a result of subduction zone polarity reversal at the site of the pre-existing Trans-American Arc, which had linked to Central America to South America in the vicinity of the present-day Peru–Ecuador border. Subsequent closure of the Andean Back-Arc Basin resulted in accretion of Caribbean terranes to western Colombia. Initiation of flat-slab subduction of the Caribbean Plate beneath Colombia at about 100 Ma is associated with limited magmatism, with no subsequent development of a magmatic arc. This was followed by northward-younging Maastrichtian to Eocene collision of the trailing edge Panama Arc. The triple junction where the Panama Arc joined the Peru–Chile trench was located west of present-day Ecuador as late as Eocene time, and the Talara, Tumbes and Manabi pull-apart basins directly relate to its northward migration. Features associated with the subduction of the Nazca Plate, such as active calc-alkaline volcanic arcs built on South American crust, only became established in Ecuador, and then Colombia, as the triple junction migrated to the north. Our model provides a comprehensive, regional and testable framework for analysing the as yet poorly understood collage of arc remnants, basement blocks and basins in the Northern Andes.

Supplementary material: A detailed geological map is available at http://www.geolsoc.org.uk/SUP18364

The geology of the Northern Andes, from their southern end in northernmost Peru to their northern end in northern Colombia and westernmost Venezuela, provides numerous tests of whether the Caribbean Plate was formed more or less in situ and has migrated only a short distance to its present position (e.g. James 2006) or originated in the eastern Pacific and is relatively far-travelled (e.g. Pindell 1993; Pindell et al. 1988, 2005, 2006; Pindell & Kennan 2001, 2009).

These two classes of model for the origin of the Caribbean have very different implications for the geology of northern South America, the subject of this paper, and for southern Mexico and the Chortís Block of Guatemala and Honduras. In particular, Pacific-origin and Inter-American models for Caribbean models have different implications for relationships between active and fossil plate boundaries, predicted ‘stacking order’ of terranes and arcs, spatial relations between terrane boundaries, and expected magmatic history and geochemistry. Geological data strongly support an eastern Pacific origin for the Caribbean Plate; although there are variations in detail between the predictions of different Pacific-origin models, these are of second-order significance compared with the differences in situ-origin models for the Caribbean oceanic lithosphere. Below, we interpret the geology of the Northern Andes showing how it supports the case for a Pacific-origin for the Caribbean, and also highlight the role of some faults and shear zones which extend south of the ‘traditional’ view of the Northern Andes into northern Peru, and have not been incorporated into models
published to date. The analysis presented here is based on some tectonic first principles, dissection of geological maps and integration of geochemical and geochronological data with palinspastic restorations of Andean deformation (e.g. Pindell et al. 1998). We attempt to clarify and resolve some of the problems raised by our previous models and derivatives (e.g. the synthesis of Moreno & Pardo 2003) and anchor the geology of the Northern Andes in the context of the entire circum-Caribbean region, including Mexico and the Central Andes.

We focus on the Aptian to Middle Eocene in this paper. The pre-Aptian history of the region is reviewed briefly below since it provides the starting template for subsequent deformation. Significant new geochronological data have become available for this interval but there are as yet, to our knowledge, few if any regional quantitative structural studies of Cretaceous and older deformation. The new data have not previously been integrated into regional-scale tectonic models of the Caribbean region. The Maastrichtian and Cenozoic has been the subject of numerous recently published quantitative structural and stratigraphic studies (e.g. Montes et al. 2003, 2005; Gómez et al. 2003, 2005; Restrepo-Pace et al. 2004) and interactions between the Caribbean, Farallon and South American Plates for this period are relatively well-understood and there is little significant disagreement between models for Eocene and younger time. Many of the structures active since the Paleocene were also active during the Cretaceous and this paper aims to tie together structures mapped in Peru, Ecuador and Colombia, show how they accommodated Caribbean–South America relative motion. The model presented here provides a comprehensive, regional and testable framework for analysing the collage of arc remnants and associated basement fragments and basins in the Northern Andes which can be tested with future geological observations.

Overview of regional context

Pacific-origin models for the Caribbean Plate imply strong Cretaceous interaction with the Northern Andes, and this is reflected in the structure, stratigraphy, uplift and magmatic history of northern Peru, Ecuador and Colombia. In contrast, inter-American models for the origin of the Caribbean Plate do not imply this interaction and cannot adequately explain the dramatic contrasts in Cretaceous orogenesis and magmatism between the Northern Andes and the Central Andes (central Peru, Bolivia, northern Chile and northern Argentina). The Central Andes show evidence of persistent large magnitude east-directed subduction of the Farallon Plate or its precursors, associated more or less continuous arc magmatism and dominantly compressional or extensional deformation, without significant strike–slip offsets in the arc or forearc. In contrast, the Northern Andes has a protracted history of back-arc basin and passive margin formation followed by accretion of oceanic plateau basalt and island arc terranes, combined with large magnitude dextral shear. Regional plate reconstructions (see Pindell & Kennan 2009) show that the Caribbean Plate originated in the easternmost Pacific and in the Indo-Atlantic hot spot reference frame has moved slowly to the NNW since the Middle Cretaceous. Relative motion between the Caribbean Plate and southern Mexico was ENE-directed. Ongoing separation between the Americas, however, resulted in the NNE-trending boundary between the Caribbean and northwestern South America being dominated by almost pure dextral strike–slip until spreading in the Proto-Caribbean Seaway slowed at about 84 Ma and stopped at about 71 Ma. Dextral shearing between the Caribbean and northwestern South America started at about 120 Ma, when the Caribbean Arc (sometimes referred to as the ‘Great Arc of the Caribbean’) formed at the leading edge of the Caribbean Plate as a result of subduction zone polarity reversal at the site of the pre-existing Trans-American Arc (see Pindell & Kennan 2009), which had linked to Central America to South America in the vicinity of the present-day Peru–Ecuador border. This was followed by oblique closure of the Andean Back-Arc Basin and accretion of Caribbean terranes to western Colombia. Remnants of the Caribbean Arc are found immediately west of the Central Cordillera in Colombia and appear to be of pre-Albian age, as also seen in Cuba, Hispaniola and Margarita. The oldest 40Ar/39Ar plateau ages in the Northern Andes suggest that cooling associated with dextral shear initiated no later than Middle Albian time, in agreement with cooling ages in Caribbean Arc fragments throughout the Caribbean region. However, most cooling ages in the accreted Caribbean Arc terranes in the Western Cordillera, and in the Cordillera Real, Central Cordillera shear zone to the east, are Santonian or younger and probably reflect enhanced uplift as Caribbean–South American motion became more compressional following the end of spreading in the Proto-Caribbean Seaway. This resulted in South America over-riding the Caribbean Plate above a low angle subduction zone, driving accretion of the Western Cordillera. Limited magmatism is associated only with the onset of subduction; subsequent magmatism in the region was driven by subduction of the Farallon Plate or Nazca Plate (after c. 23 Ma, Meschede & Barckhausen 2000).

Dextral shearing continued during the diachronous collision of the Panama Arc with Ecuador
and Colombia between Maastrichtian and Eocene time, and has continued at a slower rate since then as a result of oblique subduction of the Farallon Plate and Miocene and younger Nazca Plate. Regional plate reconstructions suggest that the Caribbean Arc at the leading edge of the Caribbean spanned the gap between southern Yucatán and northwest Colombia by Maastrichtian time, and thus we propose (see below) that all the Late Cretaceous arc fragments accreted in Ecuador during and after Maastrichtian time pertain to the trailing edge (Costa Rica–Panama Arc) of the Caribbean Plate rather than to its leading edge (Caribbean Arc). As late as Eocene time, the triple junction between South America, the Caribbean, and the Farallon Plate, where the Greater Panama Arc joined western South America, was located west of present-day Ecuador, and strike–slip pull-apart basins such as the Talara, Tumbes and Manabi Basins directly relate to the northward migration of the triple junction. Features associated with the subduction of the Nazca Plate, such as active calc-alkaline volcanic arcs built on South American crust, only became established in Ecuador, and then Colombia, as the triple junction migrated to the north.

Plate boundaries and the importance of terrane stacking order in the Northern Andes

The relationships between the major plates and active plate boundaries in the Northern Andes (Fig. 1a) are key to assessing whether the Northern Andes were deformed by a Caribbean Plate that arrived in its present position from the SW during the Cretaceous and Palaeogene, or were driven by oblique subduction of the Farallon Plate or Nazca Plate, as they have been since at least Neogene time. The Lesser Antilles Arc forms the eastern boundary of the Caribbean Plate, where it overrides Atlantic lithosphere, and the Panama Arc forms its western boundary, where the Cocos and Nazca Plates (which formed from the Farallon Plate at about 23 Ma, Meschede & Barckhausen 2000) are subducting under the Americas roughly toward the NE and ENE, respectively. The southern end of the Panama Arc is a particular focus of this paper, and we propose below that related terranes extend south of westernmost Colombia into Ecuador and possibly offshore northernmost Peru. The southern edge of the Caribbean Plate is complex, defined by both anastomosing dextral shear zones and subduction beneath northern South America (e.g. Pindell et al. 1998). The Western Cordillera terranes in the Northern Andes comprise slivers of oceanic plateau basalt and island arc volcanic rocks (e.g. Kerr et al. 2003) and associated sedimentary

Fig. 1. (a) Sketch map of the northern Andes and Caribbean showing the major plates and plate boundaries. (b) Sketch map of terrane ‘stacking order’ predicted by Inter-American models for the origin of the Caribbean. (c) Sketch map of terrane ‘stacking order’ predicted by Pacific-origin models, and which best fits the geological maps.
rocks, accreted to South American basement and then subjected to large magnitude dextral shear. Active dextral shear (e.g. Trenkamp et al. 2002) is being driven by oblique ENE-directed subduction of the Nazca Plate, and many papers (e.g. Moberly et al. 1982) explicitly assume that oblique subduction of the Farallon Plate also explains dextral shear and terrane accretion as far back as the Cretaceous. The detailed relationships between these Western Cordillera terranes, the Panama Arc, and other terranes in the area are, however, more consistent with a Caribbean origin.

The terrane stacking order predicted by Inter-American models for the origin of the Caribbean, in which the Caribbean Plate and Panama Arc are restored only c. 300–400 km to the west relative to South America, implies that the Colombian Western Cordillera terranes should lie outboard of the meeting point of Panama and South America (Fig. 1b). There should be a Farallon-related calc-alkaline volcanic arc of Early Cretaceous and younger age along the Northern Andes as far north as Panama. Furthermore, because the Northern Andes in this view would have been subject to a protracted history (>100 Ma) of oblique Farallon Plate subduction beneath South America, there should be an Alaska-style terrane graveyard outboard of Panama.

In contrast, Pacific-origin models, in which the Caribbean and Panama have both moved >1500 km from west to east with respect to the Americas, predict that the dextral shear in the Northern Andes is the result of relative northeastward migration of the Caribbean Plate and the Caribbean–Andes–Farallon triple junction (trailing edge) relative to South America. Thus, the Panama Arc, and any slivers derived from Panama which were stranded farther south, should lie outboard of accreted Northern Andes terranes (Fig. 1c). Farallon Plate influence (for instance, establishing a calc-alkaline volcanic arc which persists to the present) would only be established as the triple junction migrates to the north and thus should be diachronous from south to north and much younger than predicted by Inter-American models.

Interpretative outline of key geological elements of the Northern Andes

The purpose of this brief outline of key terranes and faults is to introduce geological elements (Fig. 2) and the terrane-origin classification and terrane boundary nomenclature (Fig. 3 and Table 1) used in the plate reconstructions presented below, to outline their relationships to each other, and to justify some of our novel interpretations of those elements. Features younger than Eocene obscure many of the inferred relationships and are not shown on these maps. The lateral and cross-strike relationships between key geological elements are somewhat clearer on an expanded, dissected geological map (Fig. 4).

Boundary B1: Sub-Andean Fault, Cimarrona Fault

The Sub-Andean and Cosanga Faults in Ecuador (Litherland et al. 1994) and the Cimarrona Fault in Colombia separate the para-autochthonous and allochthonous Cordillera Real (Ecuador) and Central Cordillera (Colombia) to the west from the Magdalena Basin, Eastern Cordillera and Subandean terranes to the east. The latter have not undergone significant northward lateral displacement with respect to in situ South American basement. Palinspastic reconstructions (see below) suggest that the non-Caribbean portions of the Santa Marta and Guajira peninsulas should also be considered as more or less in situ South America, in addition to the Perijá Range, Santander Massif and Eastern Cordillera. Shortening within the Perijá Range (Kellogg 1984), the Eastern Cordillera, Cordillera Real and Subandes as far south as Peru is essentially east-directed, involving thin-skinned shortening (e.g. Dengo & Covey 1993; Roeder & Chamberlain 1995) and inversion of basement-cored pre-existing Mesozoic rifts (e.g. Cooper et al. 1995; Baby et al. 2004). Cenozoic uplift in the Santander Massif is due to sinistral transpressive, and links the Perijá and Mérida Andes to the north with the Eastern Cordillera to the south across the Santa Marta–Bucaramanga Fault. Granitoid plutons in these terranes range in age from Triassic to Middle Jurassic (e.g. Tschanz et al. 1974; Dörre et al. 1995).

Terranes T1a and T1b: para-autochthonous terranes

The eastern part of the Colombian Central Cordillera (Maya-Sánchez 2001; Maya-Sánchez & Vásquez-Arroyave 2001) and most of the Ecuadorian Cordillera Real (Litherland et al. 1994) comprise para-autochthonous terranes with affinity to the basement of the Magdalena Basin. They include Neoproterozoic, Grenvillian gneisses and schists, unmetamorphosed to low-grade metamorphic Palaeozoic sedimentary rocks (Restrepo-Pace 1992; Restrepo-Pace et al. 1997) with a thin Cretaceous cover section comparable to Colombian Cordillera Oriental and to the foreland east of the Andes, intruded by plutons ranging in age from c. 235 Ma to 160 Ma, latest Triassic to Middle Jurassic. In Colombia, these include the Segovia, San Lucas, Sonsón and Ibagué batholiths of Colombia
(e.g. González 2001; Villagómez et al. 2008) and the Abitagua and Zamora plutons of Ecuador (e.g. Litherland et al. 1994). In Ecuador, the western part of this belt (Terrane T1b) comprises laterally discontinuous belts of moderately to highly sheared rocks including the southern Loja Terrane Palaeozoic sedimentary rocks, Jurassic Salado volcanic rocks and metasedimentary rocks, intruded by the 143 Ma Azafrán Granitoids (Noble et al. 1997), the youngest pre-Caribbean pluton. Palaeozoic components of this belt were formed during the assembly of Pangea, and the younger granitoids, volcanic rocks and associated red beds were formed in two distinct but gradational tectonic contexts: (1) during rifting within and behind a Triassic–Jurassic volcanic arc formed on the west side of the Americas and (2) during the Middle Jurassic opening of the western end of Tethys between the Americas, in which the Colombian margin formed as the conjugate to southeastern Chortís. The composite arc was broad, extending into the present-day Subandes and foreland, and included the volcanic rocks of La Leche, Oyotún, Colán and Sarayaquillo Formations of northern Peru (e.g. Rosas et al. 2007) and the Santiago, Misahualli, Chapiza and Yaupi Formations of Ecuador (e.g. Jaillard et al. 1990; Gaibor et al. 2008). Middle Jurassic to Cretaceous stratigraphy east of the Central Cordillera and Cordillera Real shows no indication of any adjacent arc from Latest Jurassic until Maastrichtian time (although thin distal tuff bands characterize the Turonian–Campanian Upper Villeta Formation), and is inferred to have been deposited east of a wide
back-arc basin referred to herein as the Colombian Marginal Seaway (as defined by Pindell 1993 and discussed further below), which linked to the Proto-Caribbean Seaway and western Tethys.

Boundary B2: Huancabamba–Palestina Fault Zone

The boundary between moderately and intensely sheared portions of the Central Cordillera and Cordillera Real is marked by an anastomosing zone of brittle faulting which can be traced more or less continuously from northern Peru to the Lower Magdalena Valley, northeast of Medellín (Fig. 5). This zone is well exposed in much of Colombia, where a narrow zone of large magnitude dextral brittle faults, the Palestina Fault Zone (Fig. 3. Simplified terrane map of the Northern Andes. Analysis of terrane affinity suggests four major groupings from east to west: (1) para-autochthonous to allochthonous continental margin fragments; (2) ‘Caribbean Arc’ fragments derived from the leading edge of the Caribbean Plate, associated back-arc basin volcanic basement and sedimentary fill, and HP/LT rocks; (3) plateau basalts episodically accreted from the interior of the Caribbean Plate; and (4) ‘Greater Panama’ island arc fragments derived from the trailing edge of the Caribbean Plate.

Feininger (1970), can be traced from east of Medellín, where it separates the Antioquia Terrane and the para-autochthonous Serranía San Lucas. North of 6°30’N, there are four significant strands which all merge to the south: the Otú–Pericos, Nus, Bagre and Palestina Faults. These are probably kinematically related. The Otú–Pericos Fault defines the eastern edge of a ductile shear zone which is the precursor to the brittle fault zone. There is a pronounced jump in metamorphic grade across the Otú–Pericos Fault from greenschist (with lenses of much older granulites) on the east side to amphibolite on the west side (Maya-Sánchez 2001). Feininger (1970) mapped a c. 27 km displacement on one major strand of the Palestina Fault Zone, but we suspect the total offset across the fault zone is much larger. Towards Ibague farther south, it merges with the San Jeronimo Fault and can be traced south towards Pasto before disappearing beneath an extensive Palaeogene and younger ignimbrite cover (Gómez et al. 2007a, b). In Ecuador it is more difficult to track the fault precisely because the young cover is more widespread than in Colombia and there are multiple candidate fault strands with brittle fault breccias and mylonites in a narrow belt of the Cordillera Real some 25 km wide. In Ecuador, we suggest the equivalent fault trend in the north includes the La Sofia Fault and associated mylonite zones within and on the east side of the Azafrán Granite, the Baños Fault (although this is cross-cut by c. 60 Ma granitoids) and the lineaments which separate the Alao–Paute Terrane from the Guamote Terrane to the west. Dextral brittle faulting is still active (e.g. Machette et al. 2003) along the western margin of the Cordillera Real and strands of the Huancabamba–Palestina Fault Zone within the Cordillera, defining the eastern boundary of a zone of pull-apart and ramp basin formation of which the Inter-Andean Depression near Quito and the Loja, Nabo and Cuenca Basins are parts (e.g. Winkler et al. 2005). Here the fault zone is loosely synonymous with the eastern limit of the ‘Dolores–Guayaquil Megashear’ (e.g. Moberly et al. 1982), which is usually inferred to link to the Peru–Chile Trench in the vicinity of the Gulf of Guayaquil (e.g. Jaillard et al. 1995).

However, faults which were active during the Late Cretaceous to Palaeogene extend farther south. Recently published geological maps suggest that close to the Peru border the Huancabamba–Palestina Fault Zone includes the southern end of the Las Aradas Fault, between the southern Loja and Alao–Paute terranes (Litherland et al. 1994). The sharply defined Palanda Fault, between the southern Loja Terrane and the Zumba Basin, may also accommodate some Palaeogene brittle faulting. There is often a significant mismatch between older and newer maps and between
Peruvian and Ecuadorian maps. However, the most recent maps (e.g. León et al. 1999) show that north–south-trending brittle faults also extend as far south as the city of Trujillo in northern Peru. The fault zone bounds north–south-trending slivers of Palaeozoic, Cretaceous and Paleocene rocks exposed where erosional windows cut through younger Late Palaeogene ignimbrites (possibly also reflecting Andean reactivation of the north–south-trending faults). The easternmost faults, near Huancabamba, are south of the Palanda Fault, and the westernmost faults, which define the eastern truncation of the Celica–Chignia volcanic arc near Morropón, are south of the Las Aradas Fault.

South of Olmos, the brittle fault zone swings towards the SW and merges with the Perú Trench south of the Sechura Basin. Basement depth maps (Wine et al. 2001) show that the Peruvian forearc is markedly different either side of this fault zone; to the north, the Talara, Tumbes and Progreso Basins have a distinctive dextral pull-apart structural character, while the forearc basins to the south are bounded by simple thrust-related anticlines parallel to the Peru Trench, with little or no indication of strike–slip. On its SE side, the brittle fault zone abruptly truncates the Jurassic La Leche volcanic arc and the Cretaceous Casma arc. On its NW side, the fault zone truncates the Palaeozoic rocks of the Amotape Block, and isolates the Cretaceous Celica–Chignia volcanic rocks close to the Peru–Ecuador border. Analysis of relations between fault strands, Palaeogene arc volcanic rocks, and older rocks beneath indicate that dextral strike–slip offset of about 300 km, perhaps 350 km, dismembered the NW end of the central Andean Cretaceous arc and forearc prior to 30 million years ago.

### Table 1. Nomenclature and geological summary for key terranes and their boundaries

| Feature | Geological summary |
|---------|--------------------|
| **B1** Sub-Andean Fault, Cimarrona Fault | Moderately sheared terranes including South Loja Terrane (Palaeozoic sedimentary rocks), Salado Terrane (Jurassic volcanic rocks) and the 144 Ma Azafrán granite |
| **T1a** Para-autochthonous South America fragments. Middle Jurassic (c. 160 Ma) San Lucas, Ibagué, Abitagua, and Zamora granitoids, Palaeozoic and Neoproterozoic metasedimentary rocks, unconformable Cretaceous cover |
| **T1b** Displaced South American terranes: Antioquia (Palaeozoic sedimentary rocks, c. 95–85 Ma Cretaceous granitoids), North Loja Terrane (Palaeozoic sedimentary rocks), Triassic Tres Lagunas granite |
| **B2** Huancabamba–Palestina Fault, which can be traced offshore south of the Talara Basin in Peru (Cenozoic, brittle, anastomosing with trace of B3 San Jerónimo, Baños Faults) | South of Olmos, the brittle fault zone swings towards the SW and merges with the Perú Trench south of the Sechura Basin. Basement depth maps (Wine et al. 2001) show that the Peruvian forearc |
| **T2a** Displaced South American terranes: Antioquia (Palaeozoic sedimentary rocks, c. 95–85 Ma Cretaceous granitoids), North Loja Terrane (Palaeozoic sedimentary rocks), Triassic Tres Lagunas granite |
| **B3** San Jerónimo Fault, Baños Fault, associated with slivers of ultramafic rock | Caucá–Almaguer (Romeral) Fault Zone (east side of Cauca–Patía Basin), Pujili melange (?) |
| **T3** Blueschists (including Jambalo), Arquia-Chaucha (Metasedimentary rocks with Palaeozoic–Cretaceous protoliths), Quebradagrande (mixed metasedimentary rocks and Cretaceous Caribbean Arc volcanic rocks), Guamote (Jurassic back-arc basin fill sediment), Alao (Jurassic volcanic rocks, possible back-arc basin basement), Chaucha (possible older continental basement to Cretaceous arc) |
| **B4a** Caucá–Almaguer (Romeral) Fault Zone (east side of Cauca–Patía Basin), Pujili melange (?) |
| **T4a** Amaime high-pressure metabasic rocks, 91 Ma Buga Batholith, Bolivar Complex, San Juan terrane, Caribbean Large Igneous Province oceanic plateau basalts extruded at 88–95 Ma. |
| **B4b** Caucá–Patía Fault Zone (east side of Western Cordillera, west side of Cauca–Patía Basin) | Amaime high-pressure metabasic rocks, 91 Ma Buga Batholith, Bolivar Complex, San Juan terrane, Caribbean Large Igneous Province oceanic plateau basalts extruded at 88–95 Ma. |
| **B4c** Western Cordillera, Volcanic and Barroso Formations, Guaranda terrane (Late Cretaceous volcaniclastic rocks and lavas), San Jacinto and Simu accretionary prisms |
| **B5a** Atrato, Urumita Suture, parts of Pallatanga Fault Zone | Macuchi (Palaeogene) arc and underlying Piñoñon basement (88 Ma Caribbean Plateau) |
| **B5b** Mulaute, Toachi and Chimbo Fault Zones | Puerto Ventura, Canande, Buenaventura Faults (parallel faults breaking up forearc into sub-terranes) |
| **T5b** Macuchi (Palaeogene) arc and underlying Piñoñon basement (88 Ma Caribbean Plateau) | Naranjal, San Lorenzo Arcs (Island-arc lavas 86–65 Ma) and overlying volcaniclastic sedimentary rocks. Timbiquí Arc (Paleocene, previously accreted Caribbean LIP basement). Eocene and younger forearc basins |
| **B5c** Mulaute, Toachi and Chimbo Fault Zones | Gorgona (?88 Ma far-travelled plateau, originated c. 26°S) |
| **B5d** Puerto Ventura, Canande, Buenaventura Faults (parallel faults breaking up forearc into sub-terranes) | Naranjal, San Lorenzo Arcs (Island-arc lavas 86–65 Ma) and overlying volcaniclastic sedimentary rocks. Timbiquí Arc (Paleocene, previously accreted Caribbean LIP basement). Eocene and younger forearc basins |
| **B5e** Mulaute, Toachi and Chimbo Fault Zones | Gorgona (?88 Ma far-travelled plateau, originated c. 26°S) |
the Late Eocene. Restoration of these inferred offsets allows a new and relatively simple interpretation of the geology and tectonic role of metamorphic belts in Ecuador during the Cretaceous. Only since the Eocene has the eastern limit of significant Northern Andes shearing been linked to the Peru–Chile trench at the Gulf of Guayaquil; prior to then the ‘Northern Andes’ geological province is considered to have extended into northwestern Peru.

Terranes T2a and 2b: Displaced, sheared terranes west of the Huancabamba–Palestina Fault

The western parts of the Central Cordillera and Cordillera Real are commonly more intensely sheared than their eastern parts, and individual rock units are more laterally discontinuous and much narrower (a few kilometres wide). T2a rocks include slivers of sheared Triassic granitoid (Tres Lagunas, 227 Ma, Noble et al. 1997), sheared Palaeozoic sedimentary rocks and schists (northern Loja terrane, which we infer to have been separated from similar rocks to the south) and the Middle Jurassic and possibly younger Alao–Paute metavolcanic rocks. The latter may be slightly younger (c. 160 Ma) than the granites of Terrane 1 (c. 170–190 Ma) and show no indication of granitoid intrusion. Geochemical data indicate a supra-subduction zone character (see Fig. 14 below), and there are some associated volcaniclastic turbidite sediments, which led Moreno & Pardo (2003) to explicitly tie them to the previously proposed Andean Back-Arc
Basin (e.g. Pindell 1993; Pindell & Erikson 1994; Pindell & Tabbutt 1995). K–Ar dates (Litherland et al. 1994) for Terrane 1 and Terrane 2 rocks are typically bimodal, being either Late Jurassic or older (probably protolith ages) or Albian or younger (probably exhumation and cooling ages).

The largest of the T2 terranes is the c. 100 km wide teardrop-shaped Antioquia Terrane in the northern Central Cordillera of Colombia, cored by the Antioquia Batholith, and bounded to the NE by the Otú–Pericos Fault. It is probably continuous with ‘Tahami Terrane’ basement of the floor of the Lower Magdalena Basin to the north, in which Jurassic thermal and magmatic events appear to be absent (Cardona et al. 2006), in contrast to the eastern parts of the Central Cordillera, east of the Otú–Pericos Fault and southern part of the Palestina Fault. The basement to the terrane comprises Neoproterozoic to Palaeozoic schists identical to the SW it is transitional with forearc sediments. Metamorphic conditions in the Antioquia Batholith are relatively undeformed, unlike older Terrane 2 granitoids, and has recently been dated at 88–95 Ma (U–Pb zircon, Villagómez et al. 2008). Similar ages have also been obtained from the Altavista Stock and San Diego Gabbro (Correa et al. 2003), the Aruba Batholith (White et al. 1999) and the Pujili granite in Ecuador (Vallejo et al. 2006). Only the last two of these have a close association with oceanic plateau basalts, but granites of this age appear to be restricted to close to the ductile boundary between the Caribbean and South American Plates, suggesting a Caribbean connection and separate origin from the older Jurassic plutons to the east. Furthermore, this plutonic episode appears in isolation. No further plutonism is recorded in the area until latest Cretaceous or Paleocene time. Detailed geological maps (e.g. González 2001; Maya-Sánchez 2001; Maya-Sánchez & Vásquez-Arroyave 2001) reveal a complex internal structure of north–south-trending, steeply dipping, sheared lozenge of interleaved Cretaceous sediments and schists with Palaeozoic and Mesozoic protoliths and ages of initial metamorphism. There is a central zone of sheared Mesozoic ultramafic rocks and gabbros, suggesting that the terrane was assembled during the Cretaceous and then intruded by the Antioquia Batholith after which shearing was concentrated around the terrane margins. At the western margin of the Antioquia Terrane, the Late Triassic Medellín Dunites were emplaced onto Neoproterozoic–Palaeozoic rocks above a low-angle thrust, possibly associated with the closure of the Andean Back-Arc Basin during Aptian–Albian time, prior to being intruded by the Antioquia Batholith.

The Antioquia Terrane is the only T2 terrane with associated internal slivers of ultramafic rocks, which elsewhere always lie west of T2 rocks. This may be a result of strike–slip duplexing of T2 and T3 rocks prior to intrusion of the Antioquia Batholith. Otherwise, there are no ultramafic rocks stranded between various components of T2 or between T2 and T1 rocks and no indication of associated subduction–accretion complexes. We think it unlikely that discrete subduction zones (as shown by Litherland et al. 1994; Chiaradia & Paladines 2004) separated, for instance, the Late Jurassic Alao and earlier Jurassic Salado metavolcanic rocks of Ecuador.

The southwesternmost portion of Terrane 2 comprises a basement of possibly Precambrian (Olmos Massif) to Palaeozoic metasedimentary rocks which appear to underlie a fragmentary Aptian–Albian volcanic arc and Palaeogene forearc basins (from south to north, Sechura, Talara and Tumbes). Close to the coast at the Peru–Ecuador border, Carboniferous rocks show a gradation from relatively undeformed in a landward or southern position (Amotape Massif of Peru, parts of the Tahuín Group of Ecuador) to highly sheared and exhumed garnet–biotite–Al-silicate schists of the Tahuín Group in the north, adjacent to Terrane 3 (Aspden et al. 1995). Metamorphic conditions in the Tahuín schists were of low-pressure Abukuma type. The age of initial metamorphism is pre-Aptian. The Aptian–Albian Celica volcanic arc overlies these Palaeozoic rocks and is sharply truncated by the Huancabamba–Palestina Fault Zone to the east and the ductile shear zones of the El Oro Metamorphic Belt of Ecuador to the north. To the SW it is transitional with forearc sediments deposited on low-grade Palaeozoic strata in the Amotape Hills. All these southwestern Terrane 2 rocks share a clear affinity with those of the more or less in situ Peruvian continental margin to the south. We classify T1 and T2 rocks together as ‘sheared continental margin’ (Fig. 3).

B3 San Jeronimo Fault, Baños Fault Zone, Zanjón–Naranjo Fault Zone

West of Medellín, the San Jeronimo Fault separates the Antioquia Terrane from Terrane 3 Quebrada-grande Complex and Arquia Complex rocks. To the north the San Jeronimo Fault merges with the Romeral Fault, and south of Ibagué, it merges with the Huancabamba–Palestina Fault Zone.
In Ecuador, we tentatively place this boundary along the Baños Fault, east of the ‘Peltetec Ophiolite’ and Alao Terrane. In northernmost Ecuador, the boundary may follow the neotectonically active El Angél Fault and pass east of Ibarra, where a narrow ‘Peltetec Ophiolite’ inlier lies west of Loja Terrane para-autochthonous rocks. We caution that a range of whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 53–1300 Ma suggest that unrelated rock suites along this fault zone may have been unjustifiably mapped together (Richard Spikings, pers. comm. 2008).

In southwestern Ecuador, we trace this terrane boundary as the Zanjón–Naranjo Fault Zone (Aspden et al. 1995) which separates a mixed terrane of Cretaceous metavolcanic rocks and high-pressure, low-temperature (HP/LT) schists to the north from the Las Piedras amphibolites (with Late Triassic volcanic protoliths) and the Tahuín schists with Paleozoic protoliths to the south.

The key to identifying this terrane boundary is the sharp separation between variably deformed rocks to the east which show no indication of volcanic arc influence later than Middle Jurassic, and very heterogeneous, highly sheared rocks to the west which include Cretaceous arc volcanic rocks, back-arc basin metavolcanic rocks and HP/LT schists. We suggest (see maps presented below) that this boundary and associated slivers of ultramafic rock mark the site of the former Colombian Marginal Seaway back-arc basin, which did not start to close until c. 120 Ma.

**Terrane T3: mixed blueschists, back-arc basin floor and Cretaceous volcanic arc fragments**

Terrane 3 comprises rocks found on the western side of the Colombian Central Cordillera, east of the Cauca–Almaguer Fault, and as scattered outcrops within the floor of the Inter-Andean Depression of Ecuador between the Pallatanga Fault (Ecuadorian equivalent to the Cauca–Almaguer Fault) and Peltetec Fault and may include the Alao Terrane rocks of the westernmost Cordillera Real. In Colombia, Terrane 3 is well defined on recent maps (González 2001; Maya-Sánchez 2001; Maya-Sánchez & Vásquez-Arroyave 2001; Gómez et al. 2007a, b) and can be subdivided into the Arquia Complex in the west (graphitic schists, garnet schists and amphibolites, with Paleozoic and Mesozoic mixed protoliths) and the Quebradagrande Complex in the east (metatuffs, pillow basalts and volcanioclastic sediments, all of Early Cretaceous age), separated by the Silvia–Pijao Fault. These rocks can be traced to Pasto, within 75 km of the Ecuadorian border, where they are buried beneath the Cenozoic volcanic cover.

Geochemical data on volcanic components of the Quebradagrande Complex suggest a tholeiitic to andesitic island arc to back-arc origin with some influence of underlying continental crust (e.g. Nivia et al. 2006), consistent with the interpretation of Moreno & Pardo (2003). Depositional ages from fauna range from Berriasian to Aptian. The protoliths of the Arquia Complex schists include continental and ultramafic rocks which may be the basement to the Quebradagrande arc with K–Ar whole rocks ages suggesting a range of protolith ages from Neo-proterozoic to Late Palaeozoic. Both these packages of rock underwent Barrovian metamorphism no earlier than Aptian time (McCourt et al. 1984). K–Ar ages and $^{40}\text{Ar}/^{39}\text{Ar}$ ages both suggest the onset of subsequent cooling between 120 and 100 Ma (Maya-Sánchez 2001; Maya-Sánchez & Vásquez-Arroyave 2001; Vinasco-Vallejo et al. 2003). The oldest $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages are 102–115 Ma in the Arquia Complex and 90–100 Ma in the Quebradagrande Complex. Most reported $^{40}\text{Ar}/^{39}\text{Ar}$ ages are somewhat younger, typically less than 85–90 Ma and often as young as Late Cretaceous or Cenozoic, suggesting a protracted deformation and exhumation event starting at about Albian time.

Also present in T3 are numerous, separate and laterally discontinuous packages of HP/LT rocks, including blueschists and eclogites (see Pindell et al. 2005 for a more detailed review) with both volcanic and continental (Palaeozoic schist) protoliths. These are tectonically interleaved with the Arquia Complex (e.g. at Pijao and Barragán) or form larger massifs isolated between the Quebradagrande in the west and para-autochthonous T2 terranes (e.g. at Jambaló). Mafic protoliths of possible Early Cretaceous age appear to have reached peak metamorphism not later than Aptian time, based on reported K–Ar ages (McCourt et al. 1984; Maya-Sánchez 2001; Maya-Sánchez & Vásquez-Arroyave 2001) from separate localities of 125 ± 15, 110 ± 10, 120 ± 5 (whole rock) and 104 ± 14 Ma (hornblende). As elsewhere in the Central Cordillera, associated structures appear dominantly vertical to steeply east-dipping. We consider it unlikely that the Jambaló HP/LT rocks were once a nappe thrust over the Quebradagrande and suggest that the protolith for the HP/LT rocks may have formed in a back-arc basin to the east of (relative, present-day coordinates) the Quebradagrande arc and west of the Cordillera Central continental margin. There are no arc or back-arc rocks mapped between the Jambaló HP/LT rocks and the Proterozoic Quintero Gneiss in the Central Cordillera to the east.

The continuation of T3 rocks into Ecuador may comprise the Alao Terrane metavolcanic rocks and the ‘Peltetec Ophiolite’. Geochemical data from
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Mourier wise rotation during the Late Cretaceous (e.g. metamorphic rock within a forearc subduction commonly assumed to comprise slices of low-grade Fault Zone (see below) associated with translation along the Huancabamba–Palestina canic cover and by significant northward dextral rotation is made difficult by widespread Cenozoic volcanics. Contextual interpretation of metamorphic terranes and volcanism evolving (summarized in Pindell et al. 2005). Exhumation of metamorphic terranes and volcanism evolving towards a more calc-alkaline character has been continuous since then. The relatively simple geologic history points to the existence of a west-dipping subduction zone which has persisted since c. 120 Ma.

Boundary B4 Cauca–Almaguer Fault Zone, Pujili mélangé–Pallatanga Fault Zone, Jubones Fault Zone

The Cauca–Almaguer Fault Zone in Colombia (broadly synonymous with ‘Romeral Fault’, a term...
Terrane 4: parts of the Western Cordilleras of Colombia and Ecuador, basement of Cauca–Patiá Valley and western foot of Central Cordillera

Stratigraphic terminology and geological maps for of Terrane 4 are in a state of flux, and recently published high precision isotopic ages are leading to substantial revisions. Among recent reviews and syntheses we note Kerr et al. (1997, 2002a, 2003), Hughes & Pilatasig (2002), Mamberti et al. (2003, 2004), Jaillard et al. (2004), Vallejo et al. (2006) and Vallejo (2007). In Colombia, this terrane comprises all but the southwesternmost parts of the Western Cordillera in addition to parts of the western foot of the Central Cordillera. It corresponds to the eastern parts of the Dagua–Piñón Terrane (Cediel et al. 2003) or Calima Terrane (Toussaint & Restrepo 1994). The terrane comprises fault-bounded slivers of oceanic plateau basalts and associated ultramafic rocks and sediments which originated as part of the Caribbean Large Igneous Province (or CLIP). In Colombia, the Amaime basalts in the westernmost part of the Central Cordillera (Terrane T4a) are separated from the Bolivarian Complex and the Western Cordillera (Terrane T4b) by the Cauca–Piñón Fault, but this appears not to correspond to a fundamental Mesozoic feature. In Ecuador, this terrane is equivalent to the ‘Pallatanga Terrane’ and ‘San Juan Terrane’ (sensu Vallejo 2007) and possibly the ‘Guaranda Terrane’ (sensu Jaillard et al. 2004). Terrane 4 rocks are much less areally extensive in Ecuador than in Colombia, and are limited to discontinuous outliers immediately west of the Pallatanga Fault.

Most crystallization ages from the plateau basalts are close to 90 Ma as elsewhere in the Caribbean. Geochemistry indicates an intra-oceanic plateau origin without subduction zone influence (Kerr et al. 1997). Small granitoids intruding the plateau basalts which pre-date terrane accretion include the c. 90 Ma Buga tonalite (Richard Spikings, pers. comm. 2008) and Buritica Tonalite (González & Londoño 2000) in Colombia, and the c. 86 Ma Pujili granite of Ecuador (Vallejo et al. 2006). Older ages include a poor 99 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age (Mamberti et al. 2004) and a 123 ± 13 Ma Sm–Nd internal isochron age, but recent U–Pb zircon crystallization ages from these sites confirm the c. 90 Ma age of eruption (Vallejo 2007).

Within the Western Cordillera of Colombia, dominant structure is top to the west thrusting, interleaving volcanic rocks and sediments, with an overprint of dextral transtensive shear. Structures are cross-cut by numerous, but volumetrically minor, latest Maastrichtian to Early Eocene
plutons which post-date accretion of Caribbean basalts west of the Central Cordillera (e.g. González 2002). Both Caribbean rocks (including fragments of the Caribbean Arc) and South American rocks are intruded by suites of identical plutons as far north as Santa Marta and Guajira, indicating that the leading edge of the Caribbean Plate was located close to the Venezuela border by that time (e.g. Cardona et al. 2008). The thrust fabric is cut by ENE-trending dextral strike-slip faults which truncate individual thrust sheets and Palaeogene intrusive and extrusive rocks, and appear to allow north–south lengthening of the Cordillera during and since Palaeogene time. In Ecuador and Colombia, there are numerous sub-terrane boundary en-echelon strike-slip faults which trend slightly clockwise of the overall north–south-trend of the major terrane bounding faults, also consistent with an overall dextral transpressional structural context. The accretion ages summarized above are somewhat younger than the oldest $^{40}\text{Ar} / ^{39}\text{Ar}$ plateau and K–Ar ages from schists and deformed igneous rocks in Terranes 2 and 3, which range from c. 105–89 Ma.

**Boundary B5: Atrato and Urumita Sutures, parts of Pallatanga Fault Zone**

There is a sharp morphologic break between the Western Cordillera and present-day forearc terranes. The boundary is clearest in the north as the Atrato and Urumita sutures east of the Panama and Baudó blocks, where terranes to the west comprise plateau basalts (some possibly as young as 78 Ma) but with overlying intra-oceanic island arc volcanic rocks, unlike Terrane 4 where plateau basalts and sediments show no arc influence. A traverse across the Western Cordillera near Cali (Kerr et al. 1997) shows that the boundary lies west of the Cordillera. In the Rio Timbiquí, the boundary coincides with a belt of Cretaceous ultramafic rocks which separate the Palaeogene Timbiquí Arc to the west from the plateau basalts to the east. South of 2°S, the boundary between the Cretaceous Ricuarte arc (Spadea & Espinosa 1986) and plateau basalts is defined by the north–south-trending Falla de Cuercuel (Gómez et al. 2007a, b), which approximately coincides with the northern limit of the Mulaute, Toachi and Chimbo Fault Zones (e.g. Hughes & Pilatasig 2002; Kerr et al. 2002a, b) to the east of the Campanian–Maastrichtian Naranjal Arc (Kerr et al. 2002a, b) and the Palaeogene Macuchi Arc. However, recent mapping in Ecuador (Boland et al. 1998; Vallejo 2007) shows that intra-oceanic island arc rocks, albeit with Caribbean Plateau basement extend as far east as the Pallatanga Fault Zone in northernmost Ecuador, raising the possibility that island arc rocks may be more widespread in the southern Colombian portion of the Western Cordillera than currently mapped.

Several north–south- to ENE-trending strike-slip faults also cut the forearc and Western Cordillera terranes, such as the Buenaventura, Garrapata and Ibagué Faults in Colombia and the Puerto Cayo and Canande Faults in Ecuador, which appear to accommodate north–south lengthening, east–west thinning, and rotation of these terranes since Late Cretaceous time. The Mulaute–Toachi–Chimbo Fault Zone is a steeply dipping reverse fault separating the Eocene Macuchi Arc from Terrane 5 arc rocks in the Western Cordillera. The presence of sheared Eocene granitoids and fission track data (Richard Spikings, pers. comm. 2008) indicates that the feature may be a Miocene or younger fault zone rather than a significant terrane suture.

**Terrane 5: ‘Greater Panama Arc’ and forearc trailing edge Caribbean terranes**

Since Pindell & Dewey (1982), the majority of evolutionary models for Panama have considered the Buenaventura Fault at about 4°N as the southern limit of the Caribbean lithosphere from which the far-travelled Panama Arc terrane (trailing edge of Caribbean Plate) has been accreted to western Colombia, with the suture lying on the east side of Dabeiba Arch. Panama Arc crust has been indenting Colombia since the Eocene at the latitude of the Upper Magdalena Basin, driving the Oligocene development of the Chusma thrustbelt along the western Upper Magdalena Valley (Butler & Schannel 1988; Pindell et al. 1998). Seismic tomography (Van der Hilst & Mann 1994) supports the view that Caribbean lithosphere now reaches the Buenaventura Fault but not farther south. Here, we explore and develop the idea that additional buoyant parts of an originally longer Panama Arc were clipped off from their underlying lithosphere and accreted to the Northern Andes well south of Buenaventura, and we refer to the collective group of such additional terranes as the ‘Greater Panama Arc’ (Fig. 3).

The western parts of the Western Cordillera and the forearc of the present-day Andes of Ecuador and central and southern Colombia makes up Terrane 5. Here, boninites, tholeiites and calc-alkaline basalts of intra-oceanic island arc origin overlie oceanic plateau basalts. Outcrops are relatively limited, comprising fault slices in the Western Cordillera and forearc. Most of this terrane is buried by Palaeogene and younger forearc basin sediments, such as those of the Progreso, Santa Elena and Manabi forearc.
basins in Ecuador (e.g. Jaillard et al. 1995) and the Pacífico forearc basin in Colombia. The oceanic plateau basement is particularly well developed in the Pinón Formation of Ecuador and in the Serranía de Baudó in northwestern Colombia. The latter appears conspicuously younger than other plateau fragments, dated at 73–78 Ma, in contrast to typical CLIP ages of 88–93 Ma elsewhere (e.g. $^{40}$Ar/$^{39}$Ar ages reported in Kerr et al. 1997), indicating a protracted history of plateau basalt eruption in the Caribbean. The young age, however, may be coincident with the passage of the rear of the Caribbean Plate over the Galapagos Hotspot (Pindeell & Kennan 2009). The age of the Piñon basement has previously been considered as Aptian, but is now considered to be earliest Coniacian on the basis of identical c. 88 Ma crystallization ages from the forearc (Luzieux 2007) and Western Cordillera near Quito (Vallejo 2007).

Numerous fragments of oceanic island arc volcanic rocks and associated volcanoclastic sediments are associated with the Piñon basement. However, outcrop is poor and often only exposed briefly, and field relationships are thus not clear. Recent fieldwork, palaeomagnetism and biostratigraphy have led to substantial revisions and simplifications (Vallejo et al. 2006; Luzieux 2007; Vallejo 2007). The oldest island arc elements in Terrane 5 are found in the La Portada Formation (Vallejo 2007), in which primitive island arc boninites are associated with sediments from which Santonian to Campanian foraminifera have been recovered. These volcanic rocks are broadly coeval with the volcanoclastic Calentura Formation, which overlies the Piñon basement of the forearc. Younger arc elements include the San Lorenzo and Naranjal Formations in Ecuador and the Ricaurte Formation of southernmost Colombia. All yield low-precision Maastrichtian radiometric ages and all are associated with volcanoclastic sediments with well-constrained Campanian–Maastrichtian faunal ages, including the Mulaute and Natividad Formations in the Western Cordillera and the Cayo Formation in the forearc.

The geochemistry of these rocks is consistent with formation above an intra-oceanic subduction zone with no continental influence. Proximity to the South American margin is indicated by the first appearance of terrane-linking quartz-rich sediments which derive from the unroofing of the Cordillera Real in latest Campanian or Maastrichtian time in the Western Cordillera (e.g. Jaillard et al. 2004). In Ecuador, accretion of Terrane 5 rocks appears to be in the form of large thrust east-dipping sheets subcreted to the South American continental margin during discrete Late Campanian and Late Maastrichtian events, predating the Yunguilla and Saquisili Formations, respectively (Jaillard et al. 2008). However, field relationships are not always clear, and ‘basement’ and ‘cover’ rocks are usually found in adjacent fault slivers without clear unconformable contacts. In our view they do indicate palaeogeographic proximity, but not necessarily final terrane accretion, nor do they indicate the end of dextral strike–slip motion between now adjacent blocks. Eocene tuff-bearing quartzose strata coeval with the Saraguro Ignimbrites do overlap and post-date plateau basalt accretion, but not the end of dextral strike–slip.

Paleocene–Middle Eocene arc fragments are also found in Terrane 5 at the foot of the Western Cordillera, including the Macuchi arc (Terrane 5a in Fig. 3), the Timbiqui arc of southwestern Colombia, and the Dabeiba arc of northwestern Colombia and Panama. The structure of the forearc portion of Terrane 5 appears to be much simpler than the subduction complex in the Western Cordillera. There is relatively little internal shortening, and the dominant features on geological maps are an array of north–south-trending to SW–NE-trending dextral strike–slip faults which may link with those which cut across the Western Cordillera (the largest of these are distinguished on Fig. 4). Forearc narrowing as a result of strike–slip on these faults brings Cretaceous arc fragments to within 75 km to the present-day trench, and Palaeogene arc fragments step east to the foot of the Western Cordillera about 200 km east of the trench.

We introduce and clarify the concept of a ‘Greater Panama’ terrane (Fig. 3). This comprises the Panama Arc (defined as reaching the Buenaventura Fault by Pindeell & Dewey 1982), and the Santonion to Maastrichtian Rio Cala, Ricaurte, Naranjal, and San Lorenzo arc remnants in Colombia and Ecuador. Together with the associated Piñon basement we propose that these rocks as having formed above a single northeast-dipping subduction zone at the trailing edge of the Caribbean Plate. The presently fragmented outcrop of these arcs reflects the post-accretion faulting and block rotation after accretion of this terrane to the South American margin from latest Cretaceous to Palaeogene time. We suggest that mainly the buoyant upper crustal parts of the lithosphere were clipped off and accreted, while the deeper upper mantle lithosphere continued to be obliquely subducted, such that the accreted terranes now lie far south of their parental lithospheric root, which now lies north of the Buenaventura Fault. Previous models, which assumed that a triple junction at the end of the Panama Arc migrated northwards outside the Piñon forearc block, would not explain the presence of Cretaceous arc rocks on the Piñon block unless those arcs had formed at the leading edge of the Caribbean Plate. However, the Caribbean Arc appears to have initiated at about 120 Ma, about 35 Ma before the
boundaries but also show breaks and offsets that.
oldest of these ignimbrites cross the major terrane
underlying South American continental crust. The
of Terrane 5, but which show a strong influence of
Ecuador, which erupted during and after accretion
ignimbrites of northernmost Peru and southernmost
arcs contrasts with the Paleocene and Eocene
increased coupling with the subducting Farallon
(2005) thus does not indicate the accretion of an far-
exhumation event identified by Spikings
et al. 2008) shows that locally the Macuchi
clastic sediments, and that the Angamarca contains
mostly continent-derived Angamarca Formation
arc is overlain by, rather than faulted against, the
comm. 2008) shows that locally the Macuchi
chemistry, superficially suggesting an intra-oceanic
margin. These arcs have tholeiitic to calc-alkaline
that had already accreted to the South American
margin. These arcs have tholeiitic to calc-alkaline
chemistry, superficially suggesting an intra-oceanic
island arc origin, but this is inconsistent with their
position inboard of forearc terranes that were already adjacent to South America and receiving
continent-derived sediment. New field and labora-
dory data (Vallejo 2007; Richard Spikings, pers.
comm. 2008) shows that locally the Macuchi
arc is overlain by, rather than faulted against, the
mostly continent-derived Angamarca Formation
clastic sediments, and that the Angamarca contains
some detritus of Macuchi origin. Thus these rocks
were adjacent during the Eocene. The c. 40 Ma
exhumation event identified by Spikings et al.
(2005) thus does not indicate the accretion of an far-travelled terrane but is probably a reflection of
increased coupling with the subducting Farallon
Plate. The chemistry of the Macuchi and Timbiqui
arcs contrasts with the Paleocene and Eocene
ignimbrites of northernmost Peru and southernmost
Ecuador, which erupted during and after accretion
of Terrane 5, but which show a strong influence of
underlying South American continental crust. The
oldest of these ignimbrites cross the major terrane
boundaries but also show breaks and offsets that
indicate that substantial strike–slip was yet to
occur. The youngest of these formations overlap
the terrane boundaries south of the Gulf of Guaya-
quil, indicating that Late Eocene and younger
strike–slip was confined to Colombia and Ecuador
and did not affect Peru.

A note on the pre-Cretaceous history of the
Northern Andes and its influence on
subsequent deformation
Granulite-grade metamorphic rocks as old as at least Neoproterozoic (c. 1 Ga), and greenschist to amphi-
bolite facies Early to Late Palaeozoic metamorphic
rocks and arc volcanic rocks are common elements
of the Central and Eastern Cordilleras of Colombia
(e.g. Restrepo-Pace 1992; Restrepo-Pace et al.
1997). However, the history of this part of South
America is not one of a long-lived proto-Andean
subducting margin which extended as far north as
the Guajira Peninsula. During the Late Precambrian,
following Grenvillian orogeny, Colombia lay adja-
cent to eastern North America and Greenland
in the core of the Rodinia super-continent (e.g. Li
et al. 2008). Subsequently, Rodinia broke up,
leaving western South America facing the Iapetus Ocean during the Early Palaeozoic. Terranes now
in Mexico and Central America, such as Chortís,
Yucatán and Oaxaquia rimmed northern South
America. The evolution of the Iapetus Ocean and
younger Rheic Ocean is complex and subject to
ongoing controversy (e.g. contrast Dalziel 1997;
MacNiocaill et al. 1997; Van Staal et al. 1998;
Keppie & Ramos 1999; Cocks & Torsvik 2006,
among many). Laterally discontinuous, sometimes
short-lived, subduction zones were established
along both Gondwanan and Laurentian margins of
Iapetus at various times, and some peri-Gondwanan
terranes (the best understood is Avalonia) were
detached from Gondwana during the opening of
the Rheic Ocean, and accreted to Laurentia prior
to the onset of Rheic Ocean closure. Chortís,
Yucatán and Oaxaquia are thought to have remained
on the South American side of the Rheic Ocean
and the Palaeozoic volcanic arcs and metamorphic
rocks in the Central Cordillera of Colombia
(Restrepo-Pace 1992) probably reflect poorly under-
stood arc accretion or back-arc basin opening
and closure events between the southern end of
Chortís and the proto-Peruvian trench which faced
Iapetus and/or Rheic Oceans. Final closure of
the Rheic Ocean during the Permian resulted in
the assembly of Pangaea, with the Acatlan and
Ouachita deformed belts representing the suture
between Laurentia and Chortís/Oaxaquia and
Yucatán, respectively.
Prior to the breakup of Pangaea during the Triassic to Early Jurassic, a single Pacific-facing arc became established along the west side of the Americas (Fig. 6). Breakup of Pangaea occurred between Colombia–Venezuela and Chortis–Yucatán, along a line south of the Rheic suture and possibly following an older back-arc basin trend. Motion of South America away from North America was towards the SE, resulting in the opening of an oceanic tract between the Americas by Late Jurassic time. This was separated from the Pacific domain by a lengthening Trans-American arc (see additional maps in Pindell & Kennan 2009), whose position is approximately defined by a flowline of South America away from southernmost Chortis (Fig. 6). Critically, it is kinematically impossible for the spreading centres in the Proto-Caribbean Seaway and Colombian Marginal Seaway (see Fig. 7) to cross the Inter-American trench (in contrast to the model of Jaillard et al. 1990) and for subduction of Pacific Plates beneath South America to have occurred beneath central or northern Colombia after about 160 Ma, which is the age of the youngest Colombian supra-subduction rift-related granitoids. Only in Ecuador are younger granitoids and arc volcanic rocks found on undisputed para-autochthonous South American crust. The Colombian magmatic record after 160 Ma is very sparse and does not indicate the persistence of subduction immediately west of the Colombian margin.

The future Northern Andean margin of Ecuador and Colombia is defined by the continent–ocean boundary which formed as a result of Pangaea break up and is quite distinct from the trend of slightly older proto-Andean and Cordilleran Permian to Early Jurassic margins of the Americas. Subsequently, the western end of the Proto-Caribbean Seaway was modified by the Late Jurassic and Early Cretaceous opening of oceanic back-arc basins which extended the areas of oceanic crust into Mexico and towards the Peru–Ecuador border (Fig. 7). The ages of these back-arc basin seaways are poorly constrained. The oldest reasonably well-dated arc or back-arc volcanic rocks (K–Ar ages only) and sediments

Fig. 6. A 190 Ma reconstruction of South America (after Pindell & Kennan 2009) against a fixed North America, closing the Equatorial and Central Atlantic oceans. Present-day coastlines are shown in grey. Pangaea started to break up shortly before this time, causing the lengthening of the subduction zone to the west. The 190–130 Ma flowline for South America away from North America defines the approximate boundary between a Proto-Caribbean realm of spreading between the Americas, and a zone of subduction or strike-slip between Pacific plates and both North and South America. It is kinematically impossible for the Proto-Caribbean spreading centre to extend into the Pacific across this subduction zone or for long-lived subduction to occur on the Colombian margin northeast of the palaeoposition of Antioquia shown.
are earliest Cretaceous (Nivia 1996). The Aburra Ophiolite (which includes the Medellin Dunites) has also been proposed as part of the floor of the Andean Back-arc Basin (Correa 2007). However, the well-constrained 217–228 Ma age (U–Pb on zircons extracted from associated plagiogranites) of these rocks is c. 90 Ma older than any other Andean Back-Arc Basin rocks, and some 30 Ma older than basalt associated with ocean floor formation between the Americas (Sabalos Basalt, Cuba: Pszczolkowski 1999; Pszczolkowski & Myczynski 2003). If a back-arc basin rock, it must have formed in a basin parallel to the Trans-American arc. However, the lack of arc rocks of this age to the west suggests to us an alternative origin as an accreted ocean crust fragment in the Trans-American subduction zone. Only much later was it thrust west onto the Antioquia Terrane, which we suggest lay close to the trench in Triassic–Early Jurassic time, seaward of a broad zone of subduction influenced granitoid intrusion and arc magmatism that stretched from northern Mexico to Ecuador. The geochemistry of the Aburra Ophiolite is consistent with MORB subsequently mixed with subduction related magmas, and its age is strikingly similar to accreted ophiolites and fossiliferous sediments in the forearc Cochimi Terrane (Viscaino Peninsula) of Baja California (Rangin et al. 1983; Sedlock 2003). Baja California lay not more than c. 1000–1500 km to the north at that time (Fig. 6), and may be a good analogue for the Aburra Ophiolite.

In previous papers (e.g. Pindell & Erikson 1994; Pindell & Tabbutt 1995), the Colombian margin...
east of the Palestina Fault has been characterized as essentially a passive or Atlantic-type margin (all rocks to the west are to greater or lesser degree allochthonous and 'suspect'). However, it is clear that some rifting did remain active in the Eastern Cordillera rifts of Colombia until about Albian time (Sarmiento-Rojas et al. 2006), possibly kinematically linked to the nearby Proto-Caribbean spreading centre which lay to the north of the Maracaibo Transform (Fig. 7), and there is low volume, rift-related (no supra-subduction zone geochemical signature) associated mafic magmatism (e.g. Vásquez & Altenberger 2005). Thus, we consider the 'passive margin' approximation still more or less valid, in the sense that the Colombia and Ecuador margins were not associated with adjacent subduction and have no volcanic arc built on them in the interval 160–50 Ma. The Colombian Marginal Seaway and Andean Back-arc Basin appears to have been wide enough to isolate the margin from the influence of the Trans-American Arc and the younger Caribbean Arc. Some thin foreland tuffs could be derived from hot spot volcanism within the coeval Napo Formation of Ecuador (Baby et al. 2004). A 130 Ma reconstruction (Fig. 7) is the starting point for subsequent Caribbean evolution involving subduction polarity reversal and closure of the Andean Back-arc Basin followed by eastward advance of the Caribbean Plate relative to the Americas.

Summary of critical contrasts between the Northern Andes and the Central Andes

In the northern Andean autochthonous continental basement, Jurassic magmatism can be plausibly related to eastward subduction of the Farallon Plate or its precursors beneath South America. However, Cretaceous magmatism is absent and a magmatic arc only became well established during Eocene time, after a c. 100 Ma hiatus. The only exceptions are the c. 95–85 Ma intrusions along the boundary between Western Cordillera and Central Cordillera rocks. All these rocks lie west of major dextral strike–slip faults and ductile shear zones and were not in their current positions when intruded. All are associated with remnants of the Caribbean Arc or the Andean Back-Arc Basin and are more plausibly related to the Aptian and younger Caribbean subduction zone which consumed the Proto-Caribbean Seaway or to the slightly younger onset of low-angle subduction of Caribbean crust beneath the Colombian margin (see maps and discussion below). There are no arc-associated intrusive or proximal extrusive rocks on the continental margin inboard of the Huancabamba–Palestina Fault Zone.

Only a single dismembered 'Greater Panama' arc terrane, built on Caribbean-like crust, is present outside the Western Cordilleras. Eastward subduction associated with Late Cretaceous to Palaeogene accretion of this terrane from the Caribbean crust did not form an associated volcanic arc on the continental crust to the east; the subduction was probably of low-angle geometry as it remains today in the north (Van der Hilst & Mann 1994; Pindell & Kennan 2009). The terrane has been dismembered by block faulting and rotation but there is no evidence of sutures, which would indicate that it comprises separate subterranes formed at multiple plate boundaries.

In contrast to the Northern Andes, in Peru (south of 7°S), Cretaceous intrusive and extrusive magmatism appears to be more or less spatially continuous and persisted into and through the Cenozoic (e.g. Pitcher & Cobbing 1985; Mukasa 1986; Jaillard & Soler 1996). Lava flows and tuffs are found to the east of the arc in the Cretaceous section, in contrast to the Northern Andes. Granite emplacement and andesite extrusion during the Cretaceous gave way to intrusion of smaller stocks and widespread ignimbrite volcanism during the Early Cenozoic. There are no known accreted Caribbean-type plateau or volcanic arc terranes in the forearc, which comprises mostly Palaeozoic rocks, accreted trench fill and cover sediments (e.g. von Huene et al. 1988; von Huene & Lallemand 1990; Wine et al. 2001). South of the boundary between the Talara and Salaverry forearc basins there are no major strike–slip fault zones within the forearc or arc.

Regional structural styles are very different. The Northern Andes shows both subduction complex formation and dextral strike–slip deformation of Late Cretaceous to Palaeogene age, evolving from ductile to brittle, and there is evidence of significant north–south lengthening of accreted terranes and northward terrane migration. In contrast, in the Central Andes a back-arc basin started to close at about 100–120 Ma (e.g. Cobbing et al. 1977) and east-directed thrusting progressing from west to east from Late Cretaceous to the present-day, which no indication of regional-scale strike–slip deformation and terrane migration south of Trujillo.

The boundary between autochthonous South America and allochthonous terranes

Central Cordillera–Cordillera Real Cretaceous dextral shear zone

The Central Cordillera of Colombia and the Cordillera Real of Ecuador are interpreted here to form a continuous major ductile shear zone, about 50–100 km wide, which separates mixed mafic, volcanic
and high-grade metamorphic terranes with Caribbean affinity from the former South American passive margin. Protolith ages range from Neo-Proterozoic through Palaeozoic to Jurassic, but these rocks were all strongly deformed (or reformed) and exhumed starting at about 120–100 Ma. Structure, regardless of protolith, is dominated by steep to vertical cleavages and more or less horizontal stretching lineations (e.g. Litherland et al. 1994), oriented parallel to the more or less north-south trend of the shear zone. There is also evidence of significant cross-strike shortening in some areas (e.g. Pratt et al. 2005). The offset on the shear zone during Middle to Late Cretaceous is not directly known but can be inferred from internally consistent sequential palaeotectonic maps (see below). The Antioquia Batholith lies on the west side of this shear zone and has a similar age and host rock to a batholith trend on autochthonous South American crust which terminates against the east side of this ductile shear zone close to the Peru–Ecuador border, suggesting a total offset of several hundred kilometres is possible.

The age of onset of shearing is difficult to constrain precisely, in part because of the dating methods used, and because it is not clear whether the ages record partial resetting due to Ar loss, synmetamorphic (peak or retrogressive) mineral growth, or cooling of older mineral grains below closure temperature. In Colombia, K–Ar cooling ages of schists with a variety of protolith and types range from c. 120 to 90 Ma (e.g. McCourt et al. 1984; Maya-Sánchez 2001; Maya-Sánchez & Vásquez-Arroyave 2001). HP/LT rocks at Jambaló and Pijao have yielded ages of 125–104 Ma. 40Ar/39Ar ages from Central Cordillera schists are generally no older than c. 85 Ma (e.g. Maya-Sánchez 2001; Maya-Sánchez & Vásquez-Arroyave 2001), but some samples give plateau ages as old as 106 Ma (e.g. Sabanalarga Batholith, Vinasco-Vallejo et al. 2003). Together with the Aptian–Albian ages, the youngest faunal ages from associated sediments, the ages suggest that metamorphism and shearing starting at about 120–100 Ma. In Ecuador, most protolith ages are recorded by Rb–Sr (Litherland et al. 1994) and appear to be no younger than c. 145–150 Ma. K–Ar ages show a spread from c. 145 Ma into the Cenozoic but are strikingly bimodal, with most older than 145 Ma or falling between 100 and 60 Ma. There are no reported ages from 100 to 115 Ma, and only a single hornblende age in the interval 115–120 Ma. A few hornblende and biotite ages fall in the range 125–145 Ma and have been used to define an earliest Cretaceous ‘Peltetec Event’ for which there is little other evidence. These ages may be partially reset. To date there are few 40Ar/39Ar plateau ages in Ecuador older than c. 80 Ma (Richard Spikings, pers. comm. 2008). We know of no U–Pb ages which could constrain the age of growth of higher-grade metamorphic minerals, and which might more precisely date the Aptian–Albian event.

We suggest that unroofing during dextral shearing resulted in the c. 120–60 Ma spread of ages in Colombia, and 100–60 Ma ages in Ecuador. The paucity of ages between cooling ages of 100–120 Ma and protolith ages of >145 Ma suggests that the Aptian–Abian ages are not simply partial resets (the interpretation of Vallejo et al. 2006), particularly since both K–Ar and 40Ar/39Ar ages from the accreted arc (Quebradagrande) and blueschist (Jambaló) fragments to the west also show evidence for an exhumation event starting at c. 120 Ma, as do terranes throughout the circum-Caribbean region (e.g. Pindell et al. 2005). Recently published zircon and apatite fission track dates (Spikings et al. 2001, 2005) show that unroofing became more clearly established in Ecuador in the interval 85–60 Ma, but regional palaeotectonic modelling suggests that it would be difficult to justify delaying the onset of cooling or shearing in Ecuador until 20 Ma after it apparently started in Colombia. The dominance of younger age in Ecuador may reflect the interaction between regional scale plate kinematics and subtle differences in palaeogeographic configuration between Colombia and Ecuador prior to 85 Ma (see below).

To our knowledge, this dextral shear zone has not previously been explicitly traced into Peru, where many of the rocks adjacent to those mapped as Mesozoic metamorphic rocks in Ecuador are commonly mapped as Precambrian. South of the border, rocks of the Ecuadorian Cordillera Real can be followed to about 6°S near Olmos, where they terminate abruptly against the north-south-trending brittle faults of the Huancabamba–Palestina Fault Zone and are juxtaposed with Cretaceous carbonate and elastic back-arc basin strata in Coastal batholith intrusions. Cordillera Real rocks appear to have near-identical origin and geological history, including dextral ductile shearing and juxtaposition with HP/LT rocks, to those in the east–west-trending El Oro Metamorphic Belt of Ecuador. The El Oro Belt must have formed at a significant plate boundary but today comprises a plate boundary fragment only 300 km long (Fig. 2), truncated against the Huancabamba–Palestina Fault Zone at 3.5°S.

Brittle faulting on the Huancabamba–Palestina Fault Zone

During the latest Cretaceous and Early Cenozoic, shearing along the Central Cordillera–Cordillera
Real Cretaceous dextral shear zone became brittle, as recorded in the youngest K–Ar ages and the oldest zircon and apatite fission track ages. The brittle Huancabamba–Palestina Fault Zone (Fig. 5) follows the older ductile shear zone along most of its length in Colombia and Ecuador, except in the far north, where brittle faulting stepped about 25 km to the east (from the Otú–Pericos Fault onto the northern Palestina Fault). In Peru, brittle faulting cuts south and east of the El Oro Metamorphic Belt, into the formerly more or less in situ Coastal Batholith rocks of the northernmost Central Andes and adjacent forearc and back-arc. Rocks now on the west side of the brittle fault zone include the Amotape basement of the Talarà Basin, the Celica Cretaceous volcanic arc, and the basement of the Sechura forearc basins. We propose that this block was translated north and rotated clockwise to bring the El Oro Metamorphic Belt into its present position relative to the Cordillera Real. If the El Oro Belt is restored to the southern end of the Cordillera Real shear zone, all the major ductile shear zones plausibly link to a single major plate boundary.

Paleocene–Eocene dextral brittle faulting on the Huancabamba–Palestina Fault Zone resulted in the opening of the Talarà pull-apart basin in northernmost Peru, creating accommodation space for several kilometres of delta and slope sediments (e.g. Jaillard & Soler 1996) which unconformably overlie Albian to Maastrichtian forearc carbonates and turbidites (Jaillard et al. 1999) with mixed volcaniclastic (from uplifted Celica Arc) and continental (from erosion of Cordillera Real ductile shear zone) provenance. Paleocene and Early Eocene volcanic rocks (Llamas and Sacapalca Formations) show offsets smaller than those of Cretaceous rocks, and the faults are covered by widespread late Middle Eocene ignimbrites which show essentially no fault offset (Porculla and Saraguro Formations). The point where this dextral brittle shear has linked to the Peru–Ecuador trench has migrated north and west of the Talarà area since the Eocene, through the Tumbes Basin in the Oligocene, into the Gulf of Guayaquil and Buenaventura Bay areas at present, leaving formerly migrating terranes south of Guayaquil docked to western South America. Since the Eocene, most of the dextral shear in Colombia seems to have stepped east of the Palestina Fault, into the Upper Magdalena Valley and across the Eastern Cordillera and Llanos Foothills. Neotectonic fault offsets are relatively small on both Cauca–Almaguer and Palestina Faults but significantly larger within the Eastern Cordillera (Paris et al. 2000; Trenkamp et al. 2002).

Summary of offset estimates and rates of Eocene and older dextral shear

There are several direct independent estimates for the amount of offset during latest Cretaceous to Eocene phase of brittle faulting on the Huancabamba–Palestina Fault Zone:

- Restoring the El Oro Metamorphic Belt to the southern end of the Cordillera Real, to define a single continuous ductile dextral shear zone which links to the Peru Trench, indicates an offset of 250–300 km.
- The Celica volcanic arc, straddling the Peru–Ecuador border and lying immediately south of the El Oro Metamorphic Belt, is similarly offset by approximately 300 km from the similar Casma arc of north-central Peru.
- Cretaceous carbonates and clastic rocks derived from a volcanic arc found on continental crust cover both of these arc fragments, with a 300 km gap between them where Palaeozoic strata are found on either side of the brittle fault zone.
- An elongate sliver of Palaeozoic strata south of Talarà (Paita area) may match similar Palaeozoic basement in the Salaverry forearc basin. These are separated by approximately 250–300 km across a prominent oblique tear bounding the southern edge of the Talarà and Sechura pull-apart basins.

These estimates collectively suggest a dextral shear rate of c. 7–10 km/Ma between forearc terranes and the interior of South America during the earlier latest Cretaceous to Eocene brittle phase. Fault patterns in Colombia suggest that much of this brittle shear passed east of the Antioquia Terrane. The Cauca–Almaguer Fault between Cali and Medellín is dominated by a subduction accretion structural style reflecting east-directed underthrusting of Western Cordillera rocks beneath the Central Cordillera. In contrast, anastomosing patterns of brittle, high-angle faults characterize the Silvia–Pijao and San Jeromino Fault Zones in southern Colombia. North of Armenia (c. 4.5°N), this brittle faulting and associated pull-apart basins (the largest is near Manizales) and restraining bend pop-ups swing to the NE and follow the Palestina and Otú–Pericos faults and other north–south-trending fault strands between Antioquia and the Serranía San Lucas.

Eocene to present Nazca–South America relative plate motion history is well known (e.g. Pardo-Casas & Molnar 1987). The strike–slip component of this plate motion matches the rates of post-glacial (c. 10 000 years) moraine offsets, seismicity and present-day GPS fault slip measurements (Trenkamp et al. 2002), indicating about
250–350 km dextral offset at a rate of c. 5–7 km/Ma since 50 Ma. In northern Peru, this displacement probably occurred entirely seaward of Talara Basin, and is consistent with the observation of fragments of Piñon Block ultramafic fragments in conglomerates at Paita (Pecora et al. 1999), about 300 km south of the Piñon Block today. In Ecuador, this offset occurred on either of both of the Mulaute–Toachi–Chimbo Fault Zone, between the Macuchi Terrane and Pallatanga Terrane, or within the Central Andean Depression. Maastrichtian and younger total brittle offset of the Piñon forearc of Ecuador relative to South America is thus estimated to be up to 650 km and Antioquia must have moved north relative to the Llanos Basin by a similar amount. The slightly higher estimated offset rate from Maastrichtian to Eocene time is consistent with faster and more oblique subduction of the Farallon Plate beneath South America prior to Early Eocene time (Pardo-Casas & Molnar 1987; our own calculations based on the results of Doubrovine & Tarduno 2008).

Total offset must be significantly greater than the post-Maastrichtian brittle offset, but cannot be easily constrained. Relative plate motion data suggests that the dextral component of Farallón–South America motion was even higher during Aptian–Campanian time than since the Maastrichtian (Engebretson et al. 1985), and thus, the rate of ductile shearing could have been higher than 7–10 km/Ma. This is qualitatively consistent with the intense internal dextral ductile shear fabric. Most of the dextral offset since c. 120 Ma has occurred east of the Antioquia Terrane, or within it prior to the intrusion of the Antioquia Batholith.

Palinspastic palaeotectonic reconstructions of northwestern South America

Eocene palinspastic map

Reconstruction of the relationships between the Caribbean Plate and northwestern South America, and the testing the interpretations made above, requires the construction of palinspastic palaeotectonic maps which are based as far as possible on reliable estimates of strike–slip fault offset and shortening or extension measurements derived from the analysis of geological maps, balanced or semi-balanced cross-sections and other data sources which are independent of the Pacific-origin Caribbean model. We have constructed palinspastic maps of the Colombian region, progressively restoring the effects of Neogene and later Palaeogene deformation to produce a palinspastic map of Colombia during the Middle Eocene (Fig. 8, modified from Pindell et al. 1998, 2000). The map accounts for post-Eocene strike–slip fault offsets, shortening in the Eastern Cordillera, Perijá and Mérida Andes, and northward expulsion of the Maracaibo Block towards the Caribbean. Terranes that were accreted after the Eocene are also removed. The map-view process is analogous to balancing a structural cross-section. No input to this map was derived from larger-scale plate models. The same basic process (and same offset estimates) can be applied semi-schematically to the dissected geological map (Fig. 4). The resulting 42 Ma map (Fig. 9) restores post-Eocene dextral motion of the Ecuador and Colombia forearc terranes and the Central Cordillera. This shear linked the trench north of the Talara Basin, was distributed from the Gulf of Guayaquil through the Cauca–Almaguer and San Jeronimo Fault Zones and stepped across the Eastern Cordillera towards the Llanos Basin. The map shows the Macuchi Arc (Eocene) and the Piñon Block (Cretaceous) adjacent to the Western Cordillera in Ecuador, south of their present positions. The Panama Arc has not yet accreted to the Colombian Margin, but trends more or less east–west and lies west of the Chusma thrust belt of the Upper Magdalena Valley. The Urutemi Suture has not yet formed and there is a v-shaped tract of Caribbean Plate still visible between the Panama Arc and the Sinú accretionary prism in NW Colombia where Caribbean crust is subducting beneath South American continental crust and already-accreted terranes (San Jacinto Belt and northernmost Western Cordillera). Subsidence is coming to an end in the Talara Basin (e.g. Jaillard & Soler 1996) and brittle dextral faulting is stepping out to the west and initiating opening of the Tumbes and Progreso forearc basins.

Late Cretaceous palinspastic map

This in turn provides the basis for a semi-schematic restoration of the region to its 71 Ma configuration (Fig. 10). The proposed 250–300 km Late Cretaceous to Eocene dextral strike–slip offset on the Huancabamba–Palestina Fault Zone has been restored, restoring a continuous Aptian Celica–Casma Arc. We also restore a continuous ‘Greater Panama’ arc at the rear of the Caribbean Plate, which meets the Peru Trench near Paita in the Sechura Basin. The Talu̇n–El Oro Metamorphic Belt is shown at the southern end of the Cordillera Real ductile shear zone, which until this time defined the eastern edge of the Caribbean Plate. The map also restores some of the clockwise rotations and northward terrane migration indicated by palaeomagnetic data (e.g. Roperch et al. 1987).
We infer the existence of a broader tract of Caribbean crust west of southern Colombia and Ecuador, between the Piñon–Panama Arc and the Cordillera Real shear zone. We do not draw the ‘Greater Panama’ arc and associated back-arc basin parallel to the present-day Peru–Colombia trench. At this time, the leading edge of the Caribbean (the Lesser Antilles Arc) lay to the north, and slices cut from the eastern end this arc had already been incorporated into the Cordillera Real–Central Cordillera shear zone (T2 ‘slivers’ and T3 ‘Caribbean Arc’ on Fig. 10). The only truly far-travelled terrane in this view is the Gorgona Island Terrane, which may originate far to the south of northern Peru (MacDonald et al. 1997; Kerr & Tarney 2005). This is perhaps the earliest reconstruction that we can confidently generate from local geological data, without constraint coming in part from the Pacific-origin Caribbean model presented below (which links together data drawn from far beyond the Northern Andes). This reconstruction is broadly similar to that of Montes et al. (2005); although we accounted for some block rotations in different ways, they also place the Antioquia Terrane opposite the Ecuador–Colombia border west of the present-day coastline. However, our maps do differ (e.g. contrast our Fig. 14 with Montes et al. 2005, fig. 16a) in the Late Cretaceous placement of the northern Maracaibo and Santa Marta areas.

Fig. 8. Early Middle Eocene (c. 46 Ma) reconstruction of the Northern Andes, modified from Pindell et al. 1998), showing a palinspastic latitude-longitude grid which undoes the effect of subsequent deformation. Also shown are major blocks noted in the text. Black arrows summarize total 46–0 Ma displacement. The reconstruction differs from that of Montes et al. (2005) in applying lower magnitude post-46 Ma dextral shear, and interpreting palaeomagnetic rotations of blocks in northern Colombia and Venezuela as local, fault-related, rather than regional effects.
Reconstructions of the relationship between the Caribbean Plate and northwestern South America

Basic constraints on large-scale plate reconstructions

In building regional palaeotectonic maps, parts of which are presented below, we honour circum-Caribbean geological control such as ages, stratigraphy, geochemistry, incorporating data from Peru to Trinidad, Mexico to the Virgin Islands, the Lesser Antilles, Costa Rica to Panama and ODP/DSDP boreholes. We account for geophysical data such as tomography, palaeomagnetic rotations, palaeomagnetic latitudinal drift and seismicity patterns. This breadth of data helps us to avoid local ad hoc or non-unique explanations for geological features when data of adjacent geographic areas may lead us to larger-scale, geometrically simpler, explanations of the observations which have greater predictive value and testability.

We assume little or no Late Cretaceous shape change within the interior of the Caribbean oceanic lithosphere. Turonian–Coniacian oceanic plateau basalts were erupted at a sites of half graben formation in the interior of the plate, at its margins, onto possibly Early Aptian oceanic...
basement (Driscoll & Diebold 1999; Kerr et al. 2003). Since 90 Ma at least the assumption of no significant shape change is justified and prior to then it is as yet unquantifiable. The models presented also account for the entire area of the Caribbean Plate (Fig. 11), including areas subducted beneath Colombia and, possibly, the Nicaragua Rise, which are only visible with seismic tomography (van der Hilst 1990; van der Hilst & Mann 1994). This is a particularly important constraint on the origin of the Caribbean Plate because it shows that the plate is simply too large to have formed in the Early Cretaceous within the narrow gap between North America and South America that existed at that time (Pindell 1993).

Caribbean Plate motion in the hot spot reference frame

Pindell & Kennan (2009) analyse and update the Aptian–Eocene Caribbean evolutionary model of Pindell (1993) in the Müller et al. (1993) Indo-Atlantic hot spot reference frame, incorporating more recently published plate rotation parameters. Since 84 Ma, which is the period when the Caribbean lithosphere has had eastern and western inward-dipping subduction boundaries, the Caribbean oceanic lithosphere has moved less than 200 km east or west in the hot spot reference frame. Pindell & Kennan (2009) conclude that this is because of the anchoring effect of the Caribbean’s...
opposing Lesser Antilles/Aves Ridge and Middle American subduction zones in the mantle, which has been especially effective since the Eocene. However, according to the reconstructions, the Caribbean lithosphere moved northwards some 1100 km in the hot spot reference frame between 84 and 46 Ma. This motion is in good agreement with palaeomagnetic data and projection of the maps in other hot spot reference frames (e.g. Torsvik et al. 2008). Prior to about 90 Ma, there are significant differences between published reference frames, and the northward motion from 120 to 84 Ma shown in our maps is much reduced in palaeomagnetic-controlled reference frames. A key assumption in our new maps is that the total number of major plates and plate boundaries is similar to today, that major plate boundaries are ‘relatively long’ (i.e. 1000 km or more) and that subduction zones and substantial oceanic island arcs do not appear and disappear abruptly in space and time; the scale of this region is somewhat smaller than the western Pacific.

Excerpts of the new maps, covering only the Northern Andes area, are presented below (Figs 12–14, 16–18). We present the maps working backwards in time from the relatively well-constrained Eocene reconstruction through increasingly uncertain, but internally consistent, Cretaceous reconstructions.

46 Ma Northern Andes reconstruction

This map (Fig. 12) shows the Macuchi arc (Eocene) and Piñón Block (plateau basalt and overlying Late Cretaceous oceanic island arc) c. 300 km south of their present positions and about to be covered by Eocene continent-derived, volcaniclastic terrane-linking sequences (e.g. Jaillard et al. 2004). By this time, the southern part of the Panama Arc had been accreted to the Ecuadorian margin as a result of a

Fig. 11. The entire area of the Caribbean Plate (heavy line), including portions subducted beneath the Nicaragua Rise and Colombia, is much larger than the area at the surface today. A minimum 1500 km dextral offset between the southern Caribbean and northern South America is needed to restore the Caribbean crust which has been subducted beneath Colombia to the surface. Note that at c. 125 Ma, before formation of the basement to the Caribbean Plateau basalts, the inter-American gap was a fraction of the total width of known Caribbean crust (South America position calculated with respect to a fixed North America). In the Late Cretaceous, South America was at its farthest from North America; even at that time there was insufficient space to accommodate known Caribbean crust within the inter-American gap.
250% higher rate of subduction of the Caribbean beneath Ecuador and then Colombia compared to the Late Cretaceous (up from 11 to 23–30 km/Ma). The Pin˜on Block and overlying Late Cretaceous volcanic arc was clipped off from its underlying Caribbean lithosphere, which continued to move towards the north, and became part of the hanging wall of the Peru trench. Following the accretion of the Pin˜on Block, the Ecuadorian margin was exposed to rapid, c. 100 km/Ma, east-directed subduction of the Farallon Plate (Pardo-Casas & Molnar 1987; our own calculations based on the results of Doubrovine & Tarduno 2008), resulting in stronger inter-plate coupling at the subduction interface. This resulted in a widespread c. 40 Ma cooling and exhumation event in Ecuador revealed by fission track studies (Spikings et al. 2005). This event has previously been interpreted as the accretion of an intra-oceanic Macuchi arc (Hughes & Pilatasig 2002). However, here we show the Macuchi arc as built on the edge of South America, on a basement of Caribbean Plateau basalt slices (consistent with field observations, Richard Spikings, pers. comm. 2008; following the interpretation of Jaillard et al. 2008) that had already been accreted by Eocene time.

Rapid Palaeogene subduction of the Farallon Plate also resulted in the development of a bimodal volcanic arc on the continental margin in the latest Eocene, but only to the south of the triple junction. North of the triple junction, the Dabeiba calc-alkaline oceanic island arc of Panama had not yet accreted to the Colombian margin. No Farallon-related arc had yet developed on the Colombian margin.

Fig. 12. A 46 Ma Caribbean reconstruction in the Müller et al. (1993) hotspot reference frame (as are all subsequent reconstructions). Present day coastlines are shown in light grey in the background. The hatched area is present day surface Caribbean Plate in its position at the time of this map. The grey area NW of Colombia is Caribbean Plate subducted between 46 and 33 Ma. Black arrows show relative plate motions for this interval (Abbreviations: NA, North America; SA, South America; CA, Caribbean; FA, Farallon; HS, Indo-Atlantic Hotspots). Note that Caribbean–South America motion is c. 23 km/Ma, more or less orthogonal to the Northern Andes, resulting in little dextral shear on the Huancabamba–Palestina Fault Zone. Oligocene and Early Miocene relative motions become more dextral oblique, resulting in renewed dextral shearing at that time. South of the Panama triple junction, the Farallon Plate was subducting at a high angle to the South American margin at about 110 km/Ma.
margin north of the Panama triple junction; subduction of the Caribbean Plate since the Maastrichtian was too slow and too low-angle to drive a volcanic arc but was sufficient to build the San Jacinto accretionary prism (Pindell & Tabbutt 1995). This reconstruction shows up to 1500 km of Caribbean crust yet to subducted beneath the South American Margin (see also Fig. 11); south of the Caribbean–South America–Farallon triple junction, subduction of Farallon lithosphere beneath South America was far faster, with correspondingly high volumes of arc volcanism (Pindell & Tabbutt 1995).

The direction of subduction beneath Ecuador and Colombia, first of the Caribbean Plate and then of the Farallon Plate, was almost orthogonal to the margin; with little dextral component to subduction, dextral strike-slip on the Huancabamba–Palestina Fault appears to have slowed and stopped at about this time. East-directed underthrusting of Colombia at this time culminated in the regional development of a Late Eocene unconformity, the most spectacular manifestation of which is the consistent eastward tilting of the Central Cordillera and basement to the Middle Magdalena Valley east of the Palestina Fault. The same event seals the Eocene wrench structures of the Cimitarra–Opón area of the Middle Magdalena Valley. This tilting event may have led to the erosion of much of any earlier Paleocene–Eocene proximal foredeep section adjacent to the Palestina Fault. However, overall there is little evidence of significant east-directed shortening and accommodation space formation associated with Palaeogene underthrusting of the Caribbean Plate, and Central Cordillera detritus may have been transported farther to the east (for instance, as low-gradient Pepino Formation conglomerate...
fans in the Putumayo Basin) and ultimately fed the sandy Misoa shelf to the north (Pindell et al. 1998).

At the same time, ongoing opening of the Grenada intra-arc basin was allowing the Villa de Cura portion of the Caribbean forearc to impinge towards the SE onto the central Venezuelan margin, driving foredeep subsidence first in the Maracaibo area and then in the Guárico Basin.

**A 56 Ma Northern Andes reconstruction**

An earliest Eocene reconstruction (Fig. 13) restores about 40% of the total dextral slip on the brittle Huancabamba–Palestina Fault, still active and accommodating at least 50% of the dextral trench-parallel component of Caribbean oblique subduction beneath Colombia. North of Ibagué we also show an eastern splay from the Palestina Fault along the Cimitarra–Opón–Perijá trend linking to the leading edge of the Caribbean Plate north of Maracaibo. The southern end of the dextral strike-slip fault system is defined by the active pull-aparts of the Talara–Tumbes area on the Peru–Ecuador border. The dextral component of Farallon–South America subduction in this area was lower than that of Caribbean–South America subduction farther north (about 5–10 km/Ma compared with about 15 km/Ma) and this resulted in north–south stretching of the Ecuador–Colombia forearc, and creation of accommodation space in the Manabi, Manglares and other forearc basins.

Following emplacement of Caribbean thrust sheets in the Guajira area, post-thrust granitoids were intruded which probably represent the southernmost magmatism associated with the Caribbean (Lesser Antilles) subduction zone. The map also shows the Piñon Block at the former trailing edge of the Caribbean essentially accreted to the Ecuadorian margin. Forearc basins on the Piñon Block were, for the first time, adjacent to areas of
eroding quartz-rich rocks of the Cordillera Real on the South American margin and became the site of continental clastic deposition (such as the Angamaqucha Group and Azúcar Formation, Jaillard et al. 1995, 2004). Inboard of the forearc basins, the Sitante, Timbiqui (and later Macuchi) volcanic arcs were established, driven by subduction of the Farallon Plate. The apparently intra-oceanic island arc geochemical character of these rocks reflects, in our opinion, the nature of the underlying basement (accreted Caribbean oceanic plateau basalt) through which subduction zone melts rose and the contribution of melted subducted oceanic sediment. The arc was not allochthonous to South America (in contrast to the model of Hughes & Pilatasig 2002). On adjacent South American continental crust to the east and south of the Huancabamba–Palestina Fault Zone volcanic rocks of this age are typically laterally extensive ignimbrite shields (Sacapalca, Saraguro and Llamas Formations). The Western Cordillera of Colombia was essentially accreted by this time and is overlain by Eocene clastic sediments (Chimborazo Formation, Nivia 2001) and intruded by Eocene and younger Farallón-related stocks.

A 71 Ma Northern Andes Reconstruction

A Late Campanian reconstruction (Fig. 14) shows the southern part of the ‘Greater Panama’ Terrane, including the Rio Cala Arc and its Caribbean oceanic plateau basement, yet to be accreted to the Western Cordillera of Ecuador. Volcaniclastic flysch was being deposited in the narrow trough between the arc and the trench at the foot of the western Cordillera. To the east, in the Western Cordillera, the earliest accreted Caribbean Plateau basalt terranes were overlapped by quartz-bearing continent-derived Yunguilla Formation flysch at about this time (Jaillard et al. 2008). Jaillard et al. (1999) distinguished this basin as the ‘Paita–Yunguilla’ basin because its fill unformly overlies the fill of the earlier Lancones Basin (see below), although its trend is broadly similar. Field relationships in the western Cordillera suggest that there may have been several discrete events during the Campanian and Maastrichtian in which separate sheets of Caribbean Plateau basalt underthrust and uplifted the South American margin. Fission track data suggest that terrane accretion and exhumation was diachronous, and younged from c. 75 Ma in the south to c. 65 Ma in the north of Ecuador (Spikings et al. 2005; Richard Spikings, pers. comm. 2008). However, in distinction, we interpret this diachronity as being a result of northward-younging oblique accretion of the trailing edge of the Caribbean to South America, not its leading edge.

The San Lorenzo volcanic arc of westernmost Ecuador is interpreted here as a minor fault-bounded remnant of the Greater Panama Arc. Dextral slip on the Canande Fault Zone during the Palaeogene stripped the forearc from the San Lorenzo area and carried it to the NE, bringing the present-day trench much closer to the San Lorenzo outcrop, and causing the Palaeogene Timbiqui arc to form inboard of the older San Lorenzo and Naranjal Arc fragments and causing the Macuchi Arc to form just west of the accreted Rio Cala Arc. As the Piñon Block migrated north during the latest Cretaceous and Palaeogene, the Peru forearc was exposed to the Peru Trench above the subducting Farallon Plate, leading to transtensional collapse of the margin and to initial subsidence of the Talara pull-apart basin and subsequent development of the Tumbes and Progreso Basins to the north. The dextral component of both Farallon–South America and Caribbean–South America relative motion was significantly higher during Late Campanian–Palaeocene time than during the Eocene.

We have suggested that the Cordillera Real was continuous with the Tahuín–El Oro belt prior to the onset of brittle faulting on the Huancabamba–Palestina Fault Zone. At this scale, its position at the eastern edge of the Caribbean Plate is clear, as is its role in linking the leading edge of the Caribbean, which was overthrusting the Santa Marta Massif in Northern Colombia, to its trailing edge in the Talara area. We show the Antioquia Terrane about 300 km south of its present position, an absolute minimum for the brittle dextral shear that passes east of it. The role of the ductile Cordillera Real Shear Zone and younger brittle Huancabamba–Palestina Fault Zone in partitioning oblique Caribbean Plate subduction is shown schematically in Figure 15.

The overall position and orientation of the Caribbean Plate at this time is constrained by the need to initiate overthrusting of ophiolites onto the Yucatán Block in Guatemala (Rosenfeld 1993), to drive

![Fig. 15. Schematic cross section through Ecuador, highlighting the partitioning of oblique subduction of the Caribbean Plate into more or less orthogonal subduction and terrane accretion in the Western Cordillera, and inboard dextral shear. The latter was becoming brittle by the end of the Cretaceous and becoming more focused towards the western edge of the Cordillera Real.](image-url)
accretion of Caribbean arc and forearc rocks and uplift of metamorphic rocks in the northwestern Sierra de Santa Marta and Guajira areas of northernmost Colombia (Case et al. 1984; Stéphan 1985), to initiate Caribbean-driven subsidence in northernmost Colombia and in the Maracaibo Basin of westernmost Venezuela (Pindell & Kennan 2009), and intrude Palaeogene post-collisional granitoids (e.g. Cardona et al. 2008). The Cimarrona Formation clastic sediments in the Middle Magdalena Basin of Colombia (Villamil 1999) were derived from the Central Cordillera to the west, which was unroofing rapidly by 80 Ma (Villagómez et al. 2008). Thus, the accreting plateau basalt terranes west of Cauca–Almaguer Fault must have been derived from the interior of the Caribbean Plate and not from the floor of the Proto-Caribbean Seaway, and the accreted volcanic arc terranes outboard of the plateau basalts in Ecuador must have derived from the trailing edge of the Caribbean Plate. This stands in contrast to the model of Vallejo et al. (2006, fig. 4) which shows the leading edge of the Caribbean Plate interacting with Ecuador, and too far to the SW relative to the Americas to interact with Yucatán or Guajira.

Regional plate motions suggest why peak exhumation may be some 30–40 Ma later than our preferred onset of shearing between the Caribbean Plate and South America and why accretion of Caribbean oceanic plateau basalt terranes to the Ecuadorean margin occurred during the Maastrichtian. At c. 84 Ma, spreading between the Americas slowed dramatically and at c. 71 Ma it ceased. Until this time, South America had been moving southeast relative to North America, opening the Proto-Caribbean Seaway (e.g. Pindell et al. 2006). While Caribbean terranes were migrating east relative to North America, inter-American spreading more or less matched the eastward component of Caribbean–South America motion and Caribbean–South America motion was extremely oblique or essentially dextral strike–slip (Figs 14, 16–18). However, once spreading stopped, there must have been a marked increase in the coupling of the Caribbean and South American Plates, resulting in dextral oblique subduction with a very significant component of inter-plate compression. The area of Caribbean crust subducted by 71–46 Ma is significantly larger than that shown on earlier reconstructions (Figs 16, 17 & 18).

A 84 Ma Northern Andes reconstruction

Recent work (Bandini et al. 2008; P. Baumgartner & D. Buchs, pers. comm. 2008) has shown that arc volcanism in Costa Rica and Panama did not start before this time. Thus, this is the oldest map on which we show an active arc at the trailing edge of the Caribbean Plate. New dates on the Orquídeas, Río Cala and Naranjal volcanic rocks in Ecuador (Vallejo 2007) suggest that none are older than about 85 Ma on this intra-oceanic plate boundary.

This map (Fig. 16) fully restores the Celica and Casma arcs as a single continuous volcanic arc which was inactive and degrading at this time and shedding volcanoclastic detritus into the Lancones Basin. This basin is typically described as ‘forearc’ because of its position between the Celica arc to its east and the Amotape Hills to the west; the latter appears to have been a source for quartz-rich sediment. However, there is no indication of an active volcanic arc to the east of the basin at this time. Rather, it may have occupied a back-arc position relative to the northeast-migrating newly active Greater Panama Arc, which lay outboard of the inactive Celica arc. Volcanoclastic flysch on the Piñon Block is derived directly from the active Naranjal and San Lorenzo volcanic arcs (fragments of the eastern end of the Panama Arc), and there is no indication of continent-derived sediment input. We infer the existence of a complexly deforming back-arc basin between Piñon, autochthonous Ecuador and NW Peru, producing the fragmentary arc remnants we see today, and which was deep enough to isolate the Piñon Block from South American margin sediments until Palaeogene time.

Northwestward migration of the Caribbean Plate is partitioned into minor subduction and more or less vertical dextral ductile shear through the Cordillera Real–Central Cordillera shear zone. $^{40}$Ar/$^{39}$Ar ages indicate that unroofing had definitely begun by the time of this reconstruction. The position of the Caribbean Plate at this time is constrained by incipient interaction with Mexico and southern Yucatán. The positioning of the Caribbean Plate shown here (Fig. 16) exposes a part of the former Colombian margin which faced NW toward the Colombian Marginal Seaway. This is also consistent with apparent persistence of more or less passive margin conditions in the Middle Magdalena Basin until this time, with no west-derived sediment.

We restore the Antioquia Terrane to a position close to the Colombia–Ecuador border at the time of intrusion of the Antioquia Batholith (and Altavista Stock, Buga and Pujili Granites, see above), and speculate that it was intruded between 95 and 85 Ma as a result of the onset of subduction of the Caribbean Plate beneath South America (see Figs 16 & 17). The origin of the magma may be melting of the leading edge of the Caribbean slab early during subduction (e.g. Nikolaeva et al. 2008). The slow rate and low angle of subduction inhibit subsequent normal hydration melting of a
mantle wedge beneath Colombia, so there is no significant younger Caribbean-related arc in Colombia. Both deformed continental margin (Antioquia Terrane) and already-accreted Caribbean plateau basalts (Amaime Formation, Buga area) were intruded. The age and geochemistry of the Colombian batholiths and stocks are similar to the Aruba Batholith in the Leeward Antilles Arc (White et al. 1999) and the Salado granite of Margarita (Stöckhert et al. 1995; Maresch et al. 2009), both of which are shown not far west of the inferred palaeoposition of Antioquia. The Aruba Batholith is in a position where it may derive from either the same mechanism as the Antioquia Batholith, or may be the southernmost melt related to subduction of Proto-Caribbean Seaway oceanic crust and sediment beneath the leading edge of the Caribbean. The Salado Granite and the granitoids of Tobago are probably of the latter origin.

Note that this reconstruction puts the Leeward Antilles (or ABC Islands) adjacent to the Lower Magdalena Basin, in the position of the present-day San Jacinto and Sinú accretionary prisms. This portion of the margin was approximately parallel to Caribbean–South America motion at this time and may have been the site of a major lateral ramp that cut across the Western Cordillera, allowing a northern fragment (ABC Islands) to move northeast with the Caribbean, bringing the site of Caribbean subduction much closer to the edge of continental crust than it was farther south. Note that we show the leading edge of the Caribbean as not yet having reached the Guajira Peninsula.

In northwestern Peru, ongoing Caribbean or Farallon Plate motion relative to South America drove deformation of the fill of the Albian–Coniacian Lancones ‘forearc basin’ prior to the deposition of the Cazaderos Formation, which is broadly correlative to the Yunguilla Formation farther north (Jaillard et al. 1999).

The Caribbean Plateau basalts were erupted onto pre-existing Caribbean oceanic crust between
the Caribbean Arc (Antilles) to the east and the
Panama Arc to the west about 6 Ma before the
time shown on this map. The origin of these
basalts is discussed in more detail in a companion
paper (Pindell & Kennan 2009). Our calculations
of relative motions between Pacific and Indo-
Atlantic hot spots place the Galapagos hot spot in
the vicinity of the central or western Caribbean at
84 Ma. Thus, if it existed at this time, it may have
been the source of the Caribbean Large Igneous
Province.

A 100 Ma Northern Andes reconstruction

A 100 Ma reconstruction (Fig. 17) pre-dates the
onset of Middle American subduction in Panama
and Costa Rica, and restores the Caribbean farther
south with respect to northwestern South America.
The approximate position of the Caribbean Plate is
also controlled by early interaction of the north
end of Caribbean Arc in Cuba and Jamaica with
the Chortís Block (Siuna Terrane of Rogers et al.
2007), generally believed to have lain adjacent
to southern Mexico during the Late Albian. This,
and the estimated width of the Inter-American gap
(interpolated between 124 and 84 Ma reconstruc-
tions assuming a constant rate of spreading in
the Proto-Caribbean Seaway) places the eastern
end of the Caribbean Arc at the then NE end of
the Central Cordillera ductile shear zone close to
Pasto in southern Colombia. The lithosphere
behind (SW of) the Caribbean Arc was probably
that of the Farallon Plate, and the oldest parts of
the Caribbean layered igneous province or its under-
lying basement (95–100 Ma; Mamberti et al.
2004; Villagómez et al. 2008) pre-date the formation
of the Middle American plate boundary (see also
Pindell & Kennan 2009).

Geological maps of the Medellin area suggest
that the Palaeozoic core of the Antioquia Terrane
may comprise eastern and western parts, separated
by one or more fault-bounded slivers of gabbro

Fig. 17. A 100 Ma Caribbean reconstruction. The light grey area is Caribbean Plate subducted between 100 and 84 Ma.
Caribbean–South America motion is c. 25 km/Ma pure strike–slip in Ecuador, driving transpressive obduction of
back-arc rocks onto Antioquia in Colombia. Motion of the Farallon Plate relative to South America is very poorly
constrained, but is estimated to be about 100–120 km/Ma directed to the ESE.
and ultramafic rock. Thus, we speculate that eastern Antioquia may have lain close to the continent–ocean boundary on the Colombian passive margin, and that western Antioquia (including the Palaeozoic Cajamarca Complex and Sabanalarga Batholith) may have originated farther south in the vicinity of central Ecuador, and that they were juxtaposed by dextral shearing prior to the intrusion of the Antioquia Batholith.

The back-arc basin which once separated the Caribbean Arc and the passive margin in southern Colombia and Ecuador (see Fig. 7 above) is inferred to have been closed by this time, and its site is marked by a newly formed ductile shear zone of gabbroic, ultramafic (including parts of the Peltepec ‘ophiolite’) and blueschist (e.g. Jambaló) slivers which are all that remains of subducted and sheared ocean crust that formerly floored the back-arc. In the Medellín area, at least, Triassic mafic and ultra-mafic rocks (Aburra Ophiolite) found within the back-arc or arc to the west seem to have been thrust east over older metamorphic basement, consistent with the subduction polarity shown here (Fig. 18). We suggest that the short duration of subduction beneath the Caribbean Arc of the floor of the Andean Back-Arc Basin (c. 20–25 Ma) before its closure may be sufficient to produce the Jambaló and Pijao blueschists. Maresch & Gerya (2005) show that less than 5 Ma and 100 km of subduction can lead to production of both lawsonite and epidote blueschists. Exhumation in Colombia is almost certainly related to the dextral strike–slip superimposed on the closed back-arc.

On the west side of the back-arc suture, the Quebradagrande and Arquia Terranes of Colombia are inferred to be the sheared remains of the eastern end of the Caribbean Arc or the precursor Trans-American Arc, accreted to western Colombia as the Caribbean Arc passed to the NE. The youngest arc remains are slightly older than the age of onset of dextral shearing. This reconstruction also shows that following closure of the back-arc and thrusting of associated rocks onto the Antioquia Terrane, the Caribbean Plate started to subduct beneath...
Antioquia, reusing the pre-existing east-dipping subduction zone beneath the Quebradagrande and Arquia Terranes, leading to intrusion of the Antioquia Batholith and the onset of exhumation.

In order for large magnitude subduction of Caribbean lithosphere to be possible beneath Colombia, any subducted oceanic crust of the former back-arc basin must have torn away from the continental crust to the east. Such a tear is probably diachronous and northward-younging, driven by northward migration of the leading edge of the Caribbean along the Colombian margin (the STEP model of Govers & Wortel 2005). Such a tear greatly enhances the possibility of migration of melts related to subduction of the Proto-Caribbean Seaway, into the Cordillera Real, Cordillera Central ductile shear zone, in addition to facilitating the onset of subduction of Caribbean lithosphere beneath Colombia.

Outboard of northern Peru and Ecuador, the Costa Rica–Panama trench may have been a transform margin separating the Caribbean and Farallon Plates at this time. Relative plate motions are very uncertain prior to the Campanian. Our own calculations (based on the work of Doubrovine & Tarduno 2008) indicate that the Farallon Plate may have been moving to the SE (at a low angle to the Peru margin) while the Caribbean Plate was moving to the NE, and that there may in consequence have been a subduction zone bounding the northwest Caribbean (see Pindell & Kennan 2009).

By the time of this reconstruction, the contiguous Celica and Casma Arcs appear to have become inactive and starting to erode, resulting in deposition of the Alamor and Copa Sombrero Formation volcanioclastic rocks in the Lancones Basin. We suggest that the Pinón Block was close to the Peru Trench at this time, and that the future triple junction between the trench outboard of the Greater Panama Arc and the Peru Trench lay close to Chimborazo. The trench normal component of Farallon Plate sinistral-subduction may have increased between 110 and 100 Ma, driving the Albian metamorphism and deformation in the Peruvian back-arc basin north of Lima (Bussell 1983), and subsequently, the angle of subduction may have been too low to drive active arc volcanism during Cenomanian–Santonian time. The possible low rate of trench-normal subduction (about 50 km/ Ma compared with 80–100 km/Ma during the Campanian–Maastrichtian) may also have been a factor.

There is little evidence for strong coupling of the plates at this time from the subsidence history of the Marañón or Oriente Basins of northern Peru and Ecuador. Tectonic subsidence curves from northern Peru (Jaillard 1993) show no enhanced subsidence in the Late Cretaceous, while curves from the northern Oriente in Ecuador (Thomas et al. 1995) show no enhanced subsidence until about 72 Ma. It is possible that these areas were east of the flexural influence of the Caribbean deformation. The Late Cretaceous stratigraphic record in western areas is too poor to reconstruct subsidence history.

A 120 Ma Northern Andes reconstruction

So far our discussion has addressed the northward migration of Caribbean lithosphere once south-dipping subduction beneath the Great Arc had begun. However, this time is about when the Caribbean Arc and its SW-dipping subduction zone became active (Fig. 18). The evidence for this is four-fold: (1) arc plutonism and volcanism of the ‘Antillean Cycle’ began in the Albian, and needed some finite period (perhaps 10–15 Ma at our estimated subduction rate) to become well established; (2) nearly all circum-Caribbean HP/LT metamorphic complexes appear to have formed at about 110–125 Ma, suggesting that the associated west-dipping subduction zone itself began then but is not older; (3) there appears to have been an Aptian change in the direction of Farallon Plate motion with respect to North America, from SE to the east and the northeast (Engebretson et al. 1985; our own calculations based on the results of Doubrovine & Tarduno 2008), which could have made the early Caribbean boundary more compressional; and (4) the initial opening of the Equatorial Atlantic and westward drift of northern South America occurred during the Early Aptian, as well as a westward acceleration of North America (Pindell & Dewey 1982; Pindell 1993), which also could be expected to trigger plate boundary changes along the Cordilleran arc.

Two popular models for the advent of the Caribbean Arc are: (1) polarity reversal from SW-facing to NE-facing of an Trans-American Arc linking Chortis to Ecuador or northern Peru (Pindell 1993); and (2) onset of SW-dipping subduction at a transform/fracture zone plate boundary in the same position (Pindell et al. 2005, their figs 7c, d). In the transform model, slivers of arc, forearc and subduction complex from the west-facing, Late Jurassic–Early Cretaceous Mexico Arc (Baldwin & Harrison 1989, 1992; Sedlock et al. 1993; Sedlock 2003) may have been translated along the sinistral transform to the SE such that they were amalgamated into the Caribbean Arc when southward subduction began (Pindell & Kennan 2009). It is not the goal of this paper to resolve these ongoing uncertainties, but it may be helpful for the Northern Andes discussion if we can constrain where tectonic elements in these models may once have been located. A third model delays polarity reversal until about 85 Ma, calling on the
Caribbean Plateau to choke the SW-facing subduction zone (Burke 1988; Kerr et al. 2003). However, this model fails to explain the Aptian onset of Caribbean HP/LT metamorphism noted above, and we do not consider it further. If we can conceive of plausible models for the advent of the Caribbean Arc, then we can also generate a template for Early Aptian Caribbean palaeogeography.

We consider three ways of estimating where the Trans-American Arc or transform intersected South America. First, we can determine the northward limit of Early Cretaceous Central Andean arc magmatism, and the transition into a more or less passive Colombian margin. The Celica Arc is the northernmost known Early Cretaceous Central Andean magmatism, and hence the Early Cretaceous palinspastic position we estimate for that terrane should be about where the Trans-American Arc or transform intersected South America (e.g. Pindell & Tabbutt 1995). Second, we consider which blueschist complexes might have been formed by eastward dipping subduction on the outside of the Central Andean Early Cretaceous arc. The Raspas complex of southern Ecuador is the only HP/LT terrane that we estimate for that terrane should be about where the Trans-American Arc or transform intersected South America as shown, then the Caribbean Arc should be about where the Trans-American Arc or transform intersected South America in NW Peru as shown here (Fig. 18).

Figure 17 implies that the Andean shear zone at the southeastern end of the Trans-American Arc could have been dominated by sinistral transcurrent motion, or by oblique subduction. This trend incorporates various continental protoliths in its roots: at the northeastern portion of the arc (Cuba) Grenvillian age rocks (Renne et al. 1989) presumably derive and were carried south from Grenvillian terranes of Mexico/Chortis. At the southeastern end of the arc, we show the Celica–Casma Arc close to the Peru–Ecuador border, at the SE end of a thumb-like promontory of continental rock and associated arc volcanic rocks rifted away from the Ecuador–Colombia margin by probably Neocomian back arc spreading. This trend, possessing the western (continental) flank of the intra-arc rift, may include the precursors of the Arquia and Quebradagrande Complexes in Colombia, the Juan Griego Group of Margarita, and possibly the Tinaco Complex of Central Venezuela (Bellizzia 1985). We speculate that the high-pressure metavolcanic Rinconada Terrane of Margarita originated within the southern part of the Andean Back-Arc Basin and was then overthrust by the Caribbean Arc shortly after the subduction polarity reversal.

We are not aware of evidence in the Northern Andes (or elsewhere) which supports the collision of separate intra-oceanic island arc at the leading edge of the a very far-travelled Caribbean Plate (Mann 2007, modified from Dickinson & Lawton 2001) with the older Trans-American Arc. We speculate that the high-pressure metavolcanic Rinconada Terrane of Margarita originated within the southern part of the Andean Back-Arc Basin and was then overthrust by the Caribbean Arc shortly after the subduction polarity reversal.

If the Early Cretaceous plate boundary intersected South America as shown, then the Caribbean oceanic lithosphere must have originated from west of the Trans-American Arc or transform. In the Colombian and Venezuelan basins and the Beata Ridge, true oceanic basement (Diebold 2009) beneath the areas of Turonian–Coniacian basaltic extrusions has not been dated. Thus it is possible that Aptian–Albian constructional plate boundaries between unnamed plates/platelets were situated in the area to the SW of the Trans-American Arc, but it is just as likely that this region comprised a single swath of Farallon crust.

Prior to the onset of southwest-dipping subduction (Fig. 7) and after (Fig. 18), we show the inter-American plate boundary linking Chortís and NW Peru. Prior to about 120 Ma, this boundary could have been dominated by sinistral transcurrent motion, or by oblique subduction. This trend incorporates various continental protoliths in its roots: at the northwestern portion of the arc (Cuba) Grenvillian age rocks (Renne et al. 1989) presumably derive and were carried south from Grenvillian terranes of Mexico/Chortís. At the southeastern end of the arc, we show the Celica–Casma Arc close to the Peru–Ecuador border, at the SE end of a thumb-like promontory of continental rock and associated arc volcanic rocks rifted away from the Ecuador–Colombia margin by probable Neocomian back arc spreading. This trend, possessing the western (continental) flank of the intra-arc rift, may include the precursors of the Arquia and Quebradagrande Complexes in Colombia, the Juan Griego Group of Margarita, and possibly the Tinaco Complex of Central Venezuela (Bellizzia 1985). In Ecuador, it is possible that the opening of a narrow oceanic back-arc was younger and post-dated Middle to Late Jurassic deformation of Cordillera Real rocks and the formation of angular unconformities at the base of Haurterivian and younger foreland strata (Jura’a, ‘Nevadan’ and possibly ‘Peltetec’ events, all poorly dated). We speculate that the high-pressure metavolcanic Rinconada Terrane of Margarita originated within the southern part of the Andean Back-Arc Basin and was then overthrust by the Caribbean Arc shortly after the subduction polarity reversal.

We are not aware of evidence in the Northern Andes (or elsewhere) which supports the collision of separate intra-oceanic island arc at the leading edge of the a very far-travelled Caribbean Plate (Mann 2007, modified from Dickinson & Lawton 2001) with the older Trans-American Arc. We know of no examples of thrust slices of possible Trans-American Arc origin lying to the east of primitive island arc rocks which lie at the eastern edge of the Caribbean Plate.

Figure 17 implies that the Andean shear zone at the eastern end of the Great Arc should have become active in the Aptian and propagated and lengthened north along the Ecuadorian and Colombian margins through Middle and Late Cretaceous time. If the intersection of the nascent Caribbean Arc with the South American margin is as far south as shown,
the rocks now in Colombia which do show evidence for Aptian–Albian events (including the Arquia and Quebradagrande Complexes and the Sabanalarga Batholith) probably originated close to the Peru–Ecuador border. Rocks in a more inboard position or more northerly starting position within the Cordillera Real–Cordillera Central Shear Zone would only start to cool as they were entrained in the lengthening shear zone. Thus, the area from which we might expect to find cooling ages as old as 120 Ma will be much more limited than that for younger ages because the shear zone was relatively short at that time. Fragments of the 120 Ma shear zone may, however, now be preserved as areally limited tectonic lenses along the entire length of the Northern Andes from Amotape to Medellín and beyond.

There is independent evidence that a Proto-Cordillera Real was growing during the Early Cretaceous. First, palaeontological data indicates that the Napo Formation was isolated from the Pacific at this time (Vallejo et al. 2002) and, second, petrographic and detrital zircon U–Pb and fission track age data from the Hollín and Napo Formations support a partial western sediment source at that time (Ruiz et al. 2004; Winkler et al. 2008; Martin-Gombojav & Winkler 2008).

Discussion

The model presented here provides a comprehensive, regional and testable framework for analysing the collage of arc remnants and basins in the Northern Andes and explains many of the geological features of the Northern Andes. This paper places much of the progress that has been made in the understanding of the geology of the region into the general Pacific-origin Caribbean model of Pindell (1993), Pindell & Tabbutt (1995) and Pindell & Kennan (2009), improving in particular on the palinspastic restoration and subsequent motions, prior to Caribbean tectonism, of various blocks and terranes.

How many arcs are needed to explain the observations in northwestern South America?

Various regional syntheses have depicted the origin and evolution of Northern Andes arc fragments in two-dimensional cross-sections, rather than in map view, without addressing the issues of lateral continuity (e.g. Kerr et al. 2002a, b; Jaillard et al. 2005), subduction geometry (e.g. Hughes & Pilatasig 2002), or the effect of large strike–slip offsets on the cross-sections. In some models, every arc fragment is associated with a distinct subduction zone (e.g. Cediel et al. 2003), yet the map scale of the fragments is such that they could simply represent fault-bounded blocks of slightly different ages and geochemistry within a single larger arc. Furthermore, the cross-section depictions result in maps in which arcs and back-arc basins are shown parallel to their present orientations, which is not consistent with palaeomagnetic data or with present-day analogues. Thus, models often miss the possibility of arc migration from out of the plane of cross-section. Arc migration along a margin can easily result in, for example, contrasts in subduction polarity between discrete peri-continental arcs and dramatic temporal changes in subduction geometry in any given cross-section.

The western Pacific-like multiple arc scenario (Fig. 19) is implausible; the scale of individual subducting slabs is too small and short-lived to produce subduction zone magmatism and the westward drive of the Americas during the Late Cretaceous would tend to hinder the trench retreat.
necessary to form discrete back-arc basins and subduction zones. Is there a simpler model that can explain all the relevant observations? In contrast (Fig. 20), we suggest there may have only been three significant plates near the Northern Andes (South America, Caribbean and Farallon) and only two arcs (at the leading and trailing edges of the Caribbean Plate) during the Late Cretaceous to Middle Cenozoic. This simple model requires no more major plates or plate boundaries than exist today. The eastern side of the Caribbean was defined by a zone of slow subduction and accretion (Western Cordillera during and after Late Cretaceous time) without an associated volcanic arc. The ‘forearc-like’ subduction complex sliver was separated from South America by broad dextral shear zone (Cordillera Real and Central Cordillera). All the fragments of volcanic arc (Quebradagrande Complex) and continental basement (Arquia Complex) with sedimentary cover along the west side of the dextral shear zone could have been derived from the east end of the Caribbean Arc, at the leading edge of Caribbean. Blueschists and mafic rocks between the Caribbean Arc remnants and the shear zone could have derived from the back-arc basin (Colombian Marginal Seaway) that was being overridden by the Caribbean Arc as it migrated north.

Caribbean Plateau basalts in the Western Cordillera of Ecuador and Colombia were accreted during slow subduction of the Caribbean Plate beneath the Cordillera Real shear zone once the leading edge of the Caribbean had passed to the north. The rate of trench-orthogonal subduction became much higher during the Maastrichtian as the Americas stopped separating, leading to accretion of Caribbean terranes in both Ecuador and Colombia, and to enhanced exhumation in the Cordillera Real dextral shear zone. The subduction accretionary prism structural style is most clearly seen in the San Jacinto and Simi belts of Colombia because these areas have not yet been overprinted by a further accretion of Caribbean trailing edge terranes. Cretaceous arc slivers in the westernmost part of the Western Cordilleras of Ecuador and Colombia were derived from a single ‘Greater Panama Arc’ as it migrated with the Caribbean

![Fig. 20.](image.png)
Plate towards the north. Accretion started earlier in southern Ecuador (c. 75 Ma) than in northern Ecuador (c. 65 Ma) and Colombia (Palaeogene in the south, younging to Early Miocene in the north). Accretion of ‘Greater Panama’ was associated with fragmentation, strike-slip faulting and block rotation and resulted in the fragmented arc remains seen today beneath an extensive forearc cover. Accretion of the ‘Greater Panama’ terrane was also accompanied by northward younging of a volcanic arc on South America driven by subduction of the Farallon Plate (Pindell & Tabbutt 1995; Pindell et al. 1998).

**Fundamental problems with inter-American models for the origin of the Caribbean Plate**

‘In situ’ or ‘Inter-American’ models for the origin of the Caribbean Plate cannot account for:

- The c. 70 Ma hiatus in continental arc magmatism in Colombia and Ecuador, because in these models this margin lies south of the Trans-American Arc and is thus always exposed to subduction of ‘Pacific’ Plates from the west; unlike the thick, buoyant Caribbean Plate, the Farallon and Nazca Plates comprise normal oceanic crust and flat slab subduction zones and associated volcanic hiatuses are transient (<20 Ma) and on a shorter length scale than the Northern Andes.
- Terrane stacking order, with accreted Western Cordillera terranes always lying inboard of Panama terranes which are known to have formed at the trailing edge of the Caribbean Plate. A Farallon Plate origin for the accreted terranes would be expected were the inter-American Caribbean model correct.
- The accretion of plateau basalt fragments identical to those in the Caribbean. These fragments would have to originate west of the Costa Rica–Panama plate boundary, and therefore would not be of Caribbean origin.
- The accretion of multiple arc fragments to western Ecuador and Colombia. To do so requires the invention of multiple and arbitrary new ‘Pacific’ volcanic arcs and plate boundaries for which there is no independent evidence.
- The timing and magnitude of ductile and brittle shearing and associated blueschist metamorphism and accretion in Colombia and Ecuador, when nothing similar is seen in Peru and farther south.
- Palaeomagnetic data which places Caribbean-derived terranes near or south of the magnetic equator, when the gap between the Americas lay at least 10° north of the palaeo-equator at the time of Caribbean Plateau basalt eruption. Only a model in which the Caribbean Plate originated in the easternmost Pacific, immediately west of the Trans-American volcanic arc, satisfactorily explains all these observations.

**Uncertainties in this Pacific-origin Caribbean model and possible future research directions**

There remain many questions and uncertainties within this iteration of the Pacific-origin Caribbean model. Detailed integration of metamorphic petrology and geochronology from the wider circum-Caribbean region supports the c. 120 Ma differentiation of the Caribbean Plate from the Farallon Plate and generation of associated HP/LT rocks from protoliths derived from the Proto-Caribbean Seaway rather than from Pacific oceanic crust subducting towards the east. However:

- The c. 120 Ma age for the onset of shearing at the eastern edge of the Caribbean in the northern Andes is dependent mostly on relatively old and poorly documented K–Ar ages, with few modern 40Ar/39Ar (some are as old as Middle Albian) or fission track ages in critical areas (especially Colombia). The almost total lack of K-ages in the range 150–120 Ma suggests that the widespread post-120 Ma K–Ar ages may not simply be partial resets in Jurassic schists and plutons. Also suggestive is the lack of ages from the Quebradagrande sediments and volcanic rocks younger than about 120 Ma.
- It is not clear whether many of the ages in the literature reflect cooling of older minerals or growth of new metamorphic minerals. Better integration of updated geochronology with metamorphic petrography and microstructure is clearly required.
- Our model implies diachronous, northward-younging subduction of the oceanic crust of the Colombian Marginal Seaway beneath the leading edge arc. If this crust was coupled to the continental crust of the passive margin, there may be a northward migrating inflection in tectonic subsidence curves starting in northern Peru at c. 120 Ma (although areas with well-known stratigraphy may be beyond the influence of Caribbean-driven flexural subsidence). Robust flexural backstripping may allow better determination of the timing and rate of tectonic subsidence in adjacent foreland areas and may reveal something of the age and nature of Late Cretaceous tectonic events to the west.
Panama triple junction migration north along

We predict that all volcanic arc remnants in

We predict that the Peru Bank (offshore Tumbes

We expect to find no pre-Caribbean subduction-

Conclusions

We subtly redefine the ‘Northern Andes’ to include

Testable predictions of the Pacific origin

Caribbean model

Our plate reconstructions make the following pre-

dictions, supported by preliminary observations

of the geology of the northern Andes:

- We expect to find no pre-Caribbean subduction-

related magmatic rocks within or east of the

Cordillera Real–Cordillera Central shear zone that post-date westward rifting of the south end of

the Trans-American Arc from interior South

America during the Jurassic.

- We predict that the Peru Bank (offshore Tumbes

Basin) lies at the tail of the ‘Greater Panama

Terrane’ and comprises Caribbean plateau

basalt and overlying arc volcanic rocks rather than

continental crust similar to the onshore

Amotape Block (e.g. Martinez et al. 2005).

- We predict that all volcanic arc remnants in

Ecuador west of the Pallatanga Fault formed at

the trailing edge of the Caribbean Plate as part of

‘Greater Panama’, and that none predate c. 85 Ma or formed at the leading edge of the

Caribbean Plate as part of the older Caribbean Arc. We expect a belt of accreted interior Carib-

bean oceanic plateau basalts, reflecting sub-

duction of the Caribbean Plate under northern

South America, will always separate leading edge ‘Caribbean Arc’ (such as the Quebrada-

grande Complex) and trailing edge ‘Greater Panama’ fragments, and that evidence for pre-

existing Early Cretaceous Proto-Caribbean oceanic crust (in the form of ultramafic or basaltic

rocks) will be found between Caribbean Arc fragments and the Cordillera Real–Cordillera

Central Shear Zone.

- Panama triple junction migration north along the

Andes allowed the Farallon Plate to be sub-

ducted directly beneath parts of the Northern

Andes that were previously shielded by the

northward migrating Caribbean Plate. We expect all ages on associated volcanic rocks to show the same pattern of slow northward migration of the onset of volcanism. Ad hoc multi-platelet models (Fig. 19) would not produce smooth, predictable variations in features such as the age of terrane accretion or the onset of volcanism in the post-accretion arc.

References

ALFONZO, C. A., SACKS, P. E., SECOR, D. T., RINE, J. & PEREZ, V. 1994. A Tertiary fold and thrust belt in the Valle del Cauca Basin, Colombian Andes. Journal of South American Earth Sciences, 7, 387–402.

ASPDEN, J. A., BONILLA, W. & DUQUE, P. 1995. The El Oro Metamorphic Complex, Ecuador: Geology and Economic Mineral Deposits. British Geological Survey, Overseas Geology and Mineral Resources, 67.
Pacific Oceanic Plates and North America since the Late Cretaceous. *Journal of Geophysical Research*, 113, B12101.

Driscoll, N. W. & Diebold, J. B. 1999. Tectonic and stratigraphic development of the eastern Caribbean: new constraints from multichannel seismic data. In: Mann, P. (ed.) *Caribbean Basins*. Sedimentary Basins of the World, 4. Elsevier Science, Amsterdam, 591–626.

Dunkley, P. N. & Gaibor, A. 1997. *Mapa geológico de la Cordillera Occidental del Ecuador entre 2°–3°S (Scale 1:200000)*. Corporación de Desarrollo e Investigación Geológico, Minero, Metalúrgica (CODIGEM) – British Geological Survey.

Engelbreton, D. C., Cox, A. & Gordon, R. G. 1985. *Relative Motions between Oceanic and Continental Plates in the Pacific Basin*. Geological Society of America, Boulder, CO, Special Papers, 206.

Feininger, T. & Silberman, M. L. 1982. 82-206. Geological Society of America Bulletin, 93, 1201–1216.

Feininger, T. & Silberman, M. L. 1982. *K–Ar Geochronology of Basement Rocks on the Northern Flanks of the Huancabamba Depression, Ecuador*, United States Geological Survey, Open File Reports, 82-206.

Gaibor, J., Hochuli, J. P. A., Winkler, W. & Toro, J. 2008. Hydrocarbon source potential of the Santiago Oriente Basin, SE of Ecuador. *Journal of South American Earth Sciences*, 25, 145–156.

Gómez, E., Jordan, T. E., Allmendinger, R. W., Hegarty, K., Kelley, S. & Heizler, M. 2003. Controls on architecture of the Late Cretaceous to Cenozoic southern Middle Magdalena Valley Basin, Colombia. *Geological Society of America Bulletin*, 115, 131–147.

Gómez, E., Jordan, T. E., Allmendinger, R. W. & Cardozo, N. 2005. Development of the Colombian foreland-basin system as a consequence of diachronous exhumation of the northern Andes. *Geological Society America Bulletin*, 117, 1272–1292.

Gómez, J., Nivia, A. et al. 2007a. Atlas Geológico de Colombia (Scale 1:500 000). Instituto Colombiano de Minería y Geología (INGEOMINAS), Bogotá. World Wide Web Address: http://www.ingeominas.gov.co/content/view/761/316/lang.es/.

Gómez, J., Nivia, A. et al. 2007b. *Geological Map of Colombia* (Scale 1:1 000 000). Instituto Colombiano de Minería y Geología (INGEOMINAS), Bogotá. World Wide Web Address: http://www.ingeominas. gov.co/component?option=com_docman/task_doc_download/gid/5284/.

González, H. 2001. *Mapa geologico del departamento de Antioquia y memoria explicativa (Scale 1:400 000)*. Instituto Colombiano de Minería y Geología (INGEOMINAS), Bogotá. World Wide Web Address: http://productos.ingeominas.gov.co/products/.

González, H. 2002. Cuervodiorita de Mistrató, Catálogo de las unidades litostratigráficas de Colombia. Instituto Colombiano de Minería y Geología (INGEOMINAS), Bogotá. World Wide Web Address: http://productos.ingeominas.gov.co/products/.

González, H. & Londono, A. C. 2002. *Tonalita de Burtítica*, Catálogo de las unidades litostratigráficas de Colombia. Bogotá, Instituto Colombiano de Minería y Geología (INGEOMINAS), Bogotá. World Wide Web Address: http://productos.ingeominas.gov.co/products/.

Govers, R. & Wortel, M. J. R. 2005. Lithosphere tearing at STEP faults: response to edges of subduction zones. *Earth and Planetary Science Letters*, 236, 505–523.

Hughes, R. A. & Pilatasi, L. F. 2002. Cretaceous and Tertiary terrane accretion in the Cordillera Occidental of the Andes of Ecuador. *Tectonophysics*, 345, 29–48.

Jaillard, E. 1993. L’évolution tectonique de la marge péruvienne au Sénénien et Paléocène et ses relations avec la géodynamique. *Bulletin de la Société Géologique de France*, 164, 819–830.

Jaillard, E. & Soler, P. 1996. Cretaceous to Early Paleogene tectonic evolution of the northern Central Andes (0–18°S) and its relations to geodynamics. *Tectonophysics*, 259, 41–53.

Jaillard, E., Soler, P., Carlier, G. & Mouriére, T. 1990. Geodynamic evolution of the northern and central Andes during Early to Middle Mesozoic time: a Tethyan model. *Journal of the Geological Society, London*, 147, 1009–1022.

Jaillard, E., Ordóñez, M., Benítez, S., Berrones, G., Jimenez, N., Montenegro, G. & Zambrano, I. 1995. Basin development in an accretionary, oceanic-floored fore-arc setting: Southern coastal Ecuador during Late Cretaceous–Late Eocene time. In: Tanskard, A. J., Suárez-Soruco, R. & Welsink, H. J. (eds) *Petroleum Basins of South America*. American Association of Petroleum Geologists, Memoirs, 62, 615–631.

Jaillard, E., Laubacher, G., Bengtsson, P., Dhondt, A. V. & Bulot, L. G. 1999. Stratigraphy and evolution of the Cretaceous forearc Celica–Lancones basin of southwestern Ecuador. *Journal of South American Earth Sciences*, 12, 51–68.

Jaillard, E., Ordóñez, M., Suárez, J., Toro, J., Iza, D. & Lugo, W. 2004. Stratigraphy of the Late Cretaceous–Paleogene deposits of the cordillera occidental of central Ecuador: geodynamic implications. *Journal of South American Earth Sciences*, 17, 49–58.

Jaillard, E., Guiller, B., Bonnardot, M.-A., Hassani, R., Lapierre, H. & Toro, J. 2005. Orogenic buildup of the Ecuadorian Andes. 6th International Symposium on Andean Geodynamics, Barcelona, Spain, 12–14 September 2005, 404–407. World Wide Web Address: http://irdal.ird.fr/PDF/ISAG_2005/isag05_404-407.pdf.

Jaillard, E., Bengtsson, P., Ordóñez, M., Vaca, W., Dhondt, A., Suárez, J. & Toro, J. 2008. Sedimentary record of terminal Cretaceous accretions in Ecuador: the Yunguilla Group in the Cuenca area. *Journal of South American Earth Sciences*, 25, 133–144.

James, K. 2006. Arguments for and against the Pacific origin of the Caribbean Plate: discussion, finding for an inter-American origin. *Geological Acta*, 4, 279–302.

Kellogg, J. N. 1984. Cenozoic tectonic history of the Sierra de Perijá, Venezuela–Colombia, and adjacent basins. In: Bonini, W. E., Hargreaves, R. B. &...
SHAGAM, R. (eds) The Caribbean—South America Plate Boundary and Regional Tectonics. Geological Society of America, Boulder, CO, Memoir, 162, 239–261.

KEPPIE, J. D. & RAMOS, V. A. 1999. Odyssey of terranes in the Iapetus and Rhei oceans during the Paleozoic. In: RAMOS, V. A. & KEPPIE, J. D. (eds) Laurentia—Gondwana Connections before Pangaea. Geological Society of America, Boulder, CO, Special Papers, 336, 267–276.

KERR, A. C. & TARNEY, J. 2005. Tectonic evolution of the Caribbean and northwestern South America: the case for accretion of two Late Cretaceous oceanic plateaus. Geology, 33, 269–272.

KERR, A. C., MARRINER, G. F. ET AL. 1997. Cretaceous basaltic terranes in western Colombia: elemental, chronological and Sr–Nd isotopic constraints on petrogenesis. Journal of Petrology, 38, 677–702.

KERR, A. C., TARNEY, J., NIVIA, A., MARRINER, G. F. & SAUNDERS, A. D. 1998. The internal structure of oceanic plateaus: inferences from obducted Cretaceous terranes in western Colombia and the Caribbean. Tectonoophysics, 292, 173–188.

KERR, A. C., ASPDEN, J. A., TARNEY, J. & PILATASIG, L. F. 2002. The nature and provenance of accreted oceanic terranes in western Ecuador: geochemical and tectonic constraints. Journal of the Geological Society, 159, 577–594.

KERR, A. C., TARNEY, J. ET AL. 2002b. Pervasive mantle plume head heterogeneity: evidence from the Late Cretaceous Caribbean—Colombian oceanic plateau. Journal of Geophysical Research, 107, B7.

KERR, A. C., WHITE, R. V., THOMPSON, P. M. E., TARNEY, J. & SAUNDERS, A. D. 2003. No oceanic plateau – no Caribbean Plate? The seminal role of an oceanic plateau in Caribbean Plate evolution. In: BARTOLINI, C., BUFLER, R. T. & BLICKWEDE, J. F. (eds) The Circum-Gulf of Mexico and the Caribbean; Hydrocarbon Habitats, Basin Formation, and Plate Tectonics. American Association of Petroleum Geologists, Memoirs, 79, 126–168.

LEÓN, W., PALACIOS, O., SÁNCHEZ, A. & VARGAS, L. 1999. Memoria explicativa del mapa geologico del Peru (Scale 1:1 000 000). Instituto Geologico, Minero y Metalurgico (INGEMMET), Lima.

LI, Z. X., BOGDANOVA, S. V. ET AL. 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Research, 160, 179–210.

LITHERLAND, M., ASPDEN, J. A. & JAMILIELTA, R. A. 1994. The Metamorphic Belts of Ecuador. British Geological Survey Overseas, Memoirs, 11.

LUZIEUX, L. 2007. Origin and Late Cretaceous-Tertiary evolution of the Ecuadorian forearc. PhD thesis, ETH, Zurich.

MACDONALD, W. D., ESTRADA, J. J. & GONZALEZ, H. 1997. Paleoplate Affiliations of Volcanic Accretionary Terranes of the Northern Andes. Geological Society of America, Boulder, CO, Abstracts with Programs, 29, 245.

MACHETTE, M. N., EGUEZ, A., ALVARADO, A. & YEPES, H. 2003. Map of Quaternary Faults and Folds of Ecuador and its Offshore Regions (Scale 1:1 250 000). United States Geological Survey, Open File Reports, 03-289.

MACNIOCAILL, C., VAN DER PLUEM, B. A. & VAN DER VOO, R. 1997. Ordovician paleogeography and the evolution of the Iapetus ocean. Geology, 25, 159–162.

MAMBERTI, L., LAPIERRE, H., BOSCH, D., JAILLARD, E., ETHIEN, R., HERNANDEZ, J. & POLVE, M. 2003. Accreted fragments of the Late Cretaceous Caribbean—Colombian Plateau in Ecuador. Lithos, 66, 173–199.

MAMBERTI, L., LAPIERRE, H., BOSCH, D., JAILLARD, E., HERNANDEZ, J. & POLVE, M. 2004. The Early Cretaceous San Juan Plutonic Suite, Ecuador: a magma chamber in an oceanic plateau? Canadian Journal of Earth Sciences, 41, 1237–1258.

MANN, P. 2007. Overview of the tectonic history of northern Central America. In: MANN, P. (ed.) Geologic and Tectonic Development of the Caribbean Plate Boundary in Northern Central America. Geological Society of America, Boulder, CO, Special Papers, 428, 1–19.

MARESCH, W. V. & GERYA, T. V. 2005. Blueschists and blue amphiboles: how much subduction do they need? International Geology Review, 47, 688–702.

MARESCH, W. V., KLUGE, R., BAUMANN, A., PINDELL, J. L., KRUCKHANS-LUEDER, G. & STANEK, K. 2009. The occurrence and timing of high-pressure metamorphism on Margarita Island, Venezuela: a constraint on Caribbean—South America interaction. In: JAMES, K. H., LORENTE, M. A. & PINDELL, J. L. (eds) The Origin and Evolution of the Caribbean Plate. Geological Society, London, Special Publications, 328, 703–739.

MARTIN-GOMBBAJOV, N. & WINKLER, W. 2008. Recycling of Proterozoic crust in the Andean Amazon foreland of Ecuador: implications for orogenic development of the Northern Andes. Terra Nova, 20, 22–31.

MARTINEZ, E., FERNANDEZ, J., CALDERON, Y., HERMOZA, W. & GALDOS, C. 2005. Tumbes and Talara Basins Hydrocarbon Evaluation. Perupetro, Lima, Peru. World Wide Web Address: http://www.perupetro.com.pe/home-e.asp.

MAYA-SANCHEZ, M. 2001. Distribución, Facies y Edad de las Rocos Metamórficas en Colombia. Memoria Explicitiva: Mapa metamórfico de Colombia. Instituto Colombiano de Minería y Geología (INGEMINAS), Bogotá. World Wide Web Address: http://productos.ingeminas.gov.co/productos/MEMORIA/Memoria%20MMC.pdf.

MAYA-SANCHEZ, M. & VASQUEZ-ARROYAVE, E. 2001. Mapa metamórfico de Colombia (Scale 1:2 000 000). Instituto Colombiano de Minería y Geología (INGEMINAS), Bogotá. World Wide Web Address: http://productos.ingeminas.gov.co/productos/OFFICIAL/georecon/geologia/escmilin/pdf/Metamorfico.pdf.

MCCOURT, W. J., ASPDEN, J. A. & BROOK, M. 1984. New geological and geochronological data from the Colombian Andes: continental growth by multiple accretion. Journal of the Geological Society, London, 141, 831–845.

MESCHENDE, M. & BARCKHAUSEN, U. 2000. Plate tectonic evolution of the Cocos—Nazca spreading center. In: SILVER, E. A., KIMURA, G., BLUM, P. & SHIPLEY, T. H. (eds) Proceedings of the Ocean Drilling Program, Scientific Results, 170, 1–10. World Wide Web Address: http://www-odp.tamu.edu/publications/170_SR/chap_07/chap_07.htm.
CARIBBEAN PLATE–ANDEAN INTERACTIONS

MOBERLY, R., SHEPHERD, G. L. & COULBORN, W. T. 1982. Forearc and other basins, continental margin of northern and southern Peru and adjacent Ecuador and Chile. In: LEGGETT, J. K. (ed.) Trench—Forearc Geology: Sedimentation and Tectonics in Modern and Ancient Active Margins. Geological Society, London, Special Publications, 10, 171–189.

MONTES, C., RESTREPO-PAZ, P. A. & HATCHER, R. D. 2003. Three dimensional structure and kinematics of the Piedras–Girardot fold belt: surface expression of transpressional deformation in the northern Andes. In: BARTOLINI, C., BUFFLER, R. T. & BLICKWEDE, J. F. (eds) The Circum-Gulf of Mexico and the Caribbean; Hydrocarbon Habitats, Basin Formation, and Plate Tectonics. American Association of Petroleum Geologists, Memoirs, 82, 849–873.

MONTES, C., HATCHER, R. D. & RESTREPO-PAZ, P. A. 2005. Tectonic reconstruction of the Northern Andean blocks; oblique convergence and rotations derived from the kinematics of the Piedras–Girardot area, Colombia. Tectonophysics, 399, 221–250.

MORENO, M. & PARDO, A. 2003. Stratigraphical and sedimentological constraints on western Colombia: Implications on the evolution of the Caribbean Plate. In: BARTOLINI, C., BUFFLER, R. T. & BLICKWEDE, J. F. (eds) The Circum-Gulf of Mexico and the Caribbean; Hydrocarbon Habitats, Basin Formation, and Plate Tectonics. American Association of Petroleum Geologists, Memoirs, 79, 891–924.

MOUREIR, T., LAI, C., MEIGARD, F., ROPERCH, P., MITOUGAR, P. & FARFAN, A. 1988. An accreted continental terrane in northwestern Peru. Earth and Planetary Science Letters, 88, 182–192.

MUKASA, S. B. 1986. Zinc U–Pb ages of super-units in the Coastal batholith, Peru: implications for magmatic and tectonic processes. Geological Society of America Bulletin, 97, 241–254.

MULLER, R. D., ROYER, J.-Y. & LAWVER, L. A. 1993. Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. Geology, 21, 275–278.

NIKOLOAEVA, K., GERYA, T. V. & CONNOLLY, J. A. D. 2008. Numerical modelling of crustal growth in intra-oceanic volcanic arcs. Physics of the Earth and Planetary Interiors, 171, 336–356.

NIVIA, A. 1996. The Bolivar mafic–ultramafic complex, SW Colombia: the base of an obducted oceanic plateau. Journal of South American Earth Sciences, 9, 59–68.

NIVIA, A. 2001. Mapa geologico del departamento del Valle de Cauca y memoria explicita (Scale 1:250 000). Instituto Colombiano de Mineria y Geologia (INGEOMINAS), Bogotá. World Wide Web Address: http://productos.ingeominas.gov.co/productos/.

NIVIA, A., MARRiner, G. F., KERR, A. C. & TARNEY, J. 2006. The Quebradagrande Complex: a lower Cretaceous ophiolite in the Cordillera of the Colombian Andes. Journal of South American Earth Sciences, 21, 423–436.

NOBLE, S. R., ASPDEN, J. A. & JEMIELITA, R. 1997. Northern Andean crustal evolution: new U–Pb geochronological constraints from Ecuador. Geological Society of America Bulletin, 109, 789–798.

Pardo-Casas, F. & Molnár, P. 1987. Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time. Tectonics, 6, 233–248.

Paris, G., Machette, M. N., Dart, R. L. & Haller, K. M. 2000. Map and Database of Quaternary Faults and Folds in Colombia and its Offshore Regions (Scale 1:1 250 000). United States Geoogical Survey, Open File Reports, 00-0284.

Pecora, L., Jalillard, E. & Lapierre, H. 1999. Accretion paleogene and decroachment d’u’terrain oceanique dans le Nord du Perou. Comptes Rendus de l’Academie des Sciences, Serie Il, Sciences de la Terre et des Planetes, 329, 389–396.

Pindell, J. L. 1993. Regional synthesis of Gulf of Mexico and Caribbean evolution. In: Pindell, J. L. & Perkins, R. F. (eds) Transactions of the 13th Annual GCSESEP Research Conference: Mesozoic and Early Cenozoic Development of the Gulf of Mexico and Caribbean Region, 251–274.

Pindell, J. & Dewey, J. F. 1982. Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region. Tectonics, 1, 179–211.

Pindell, J. L. & Barrett, S. F. 1990. Geological evolution of the Caribbean region; a plate tectonic perspective. In: DengO, G. & Case, J. E. (eds) The Caribbean Region. Decade of North American Geology, H. Geological Society of America, Boulder, CO, 405–432.

Pindell, J. L. & Eriksen, J. P. 1994. Mesozoic passive margin of northern South America. In: SalFitI, J. A. (ed.) Cretaceous Tectonics of the Andes. Vieweg, Earth Evolution Sciences International Monograph Series, 1–60.

Pindell, J. L. & Tabbutt, K. D. 1995. Mesozoic–Cenozoic Andean paleogeography and regional controls on hydrocarbon systems. In: Tankard, A. J. R., Suarez-Soruco, R. & Welsink, H. J. (eds) Petroleum Basins of South America. American Association of Petroleum Geologists, Memoirs, 62, 101–128.

Pindell, J. L. & Kennan, L. 2001. Kinematic evolution of the Gulf of Mexico and Caribbean. In: Fillon, R. H., Rosen, N. C. et al. (eds) Transactions of the 21st GCSESEP Annual Bob F. Perkins Research Conference: Petroleum Systems of Deep-Water Basins, 193–220.

Pindell, J. L. & Kennan, L. 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. In: James, K. H., Lorente, M. A. & Pindell, J. L. (eds) The Origin and Evolution of the Caribbean Plate. Geological Society, London, Special Publications, 328, 1–55.

Pindell, J. L., Higgs, R. & Dewey, J. F. 1998. Cenozoic palinspastic reconstruction, paleogeographic evolution, and hydrocarbon setting of the northern margin of South America. In: Pindell, J. L. & Drake, C. L. (eds) Paleogeographic Evolution and Non-glacial Eustasy, northern South America. SEPM (Society for Sedimentary Geology), Special Publication, 58, 45–86.

Pindell, J. L., Kennan, L. & Barrett, S. F. 2000. Kinematics: a key to unlocking plays. Part 2 of a series: ‘Regional Plate Kinematics: Arm Waving, or
Underutilized Exploration Tool. American Association of Petroleum Geologists Explorer, July 2000. World Wide Web Address: http://www.aapg.org/explorer/geophysical_corner/2000/gep07.cfm.

Pindell, J. L., Kennan, L., Maresch, K. P., Draper, G., Higgs, R. 2005. Plate-kinematics and crustal dynamics of circum-Caribbean arc-continent interactions, and tectonic controls on basin development in Proto-Caribbean margins. In: Avé-Lallemant, H. G. & Siisson, V. B. (eds) Caribbean–South American Plate Interactions, Venezuela. Geological Society of America, Boulder, CO, Special Papers, 394, 7–52.

Pindell, J. L., Kennan, L., Maresch, K. P., Maresch, W. V. & Draper, G. 2006. Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved. Geologica Acta, 4, 89–128.

Pitcher, W. S. & Cobbing, E. J. 1985. Phanerozoic plutonism in the Peruvian Andes. In: Pitcher, W. S., Atherton, M. P., Cobbing, E. J. & Beckinsale, R. D. (eds) Magmatism at a Plate Edge. Blackie, Glasgow, 19–25.

Pratt, W. T., Duque, P. & Ponce, M. 2005. An autochthonous geological model for the eastern Andes of Ecuador. Tectonophysics, 399, 251–278.

Pszczolkowski, A. 1999. The exposed passive margin of north America in western Cuba. In: MANN, P. (ed.) Caribbean Basins. Sedimentary Basins of the World, 4, Elsevier Science, Amsterdam, 93–122.

Pszczolkowski, A. & Myczynski, R. 2003. Stratigraphic constraints on the Late Jurassic–Cretaceous paleotectonic interpretations of the Placetas Belt in Cuba. In: Bartolini, C., Buffler, R. T. & Blikwede, J. F. (eds) The Circum-Gulf of Mexico and the Caribbean; Hydrocarbon Habitats, Basin Formation, and Plate Tectonics. American Association of Petroleum Geologists, Memoirs, 79, 545–581.

Rangin, C., Girard, D. & Maury, R. 1983. Geodynamic significance of Late Triassic–Early Cretaceous volcanic sequences of Vizcaino Peninsula and Cedros Island, Baja California, Mexico. Geology, 11, 552–556.

Renne, P. R., Mattinson, J. M., Hatten, C. W., Somin, M. L., Onstott, T. C., Millan, G. & Linares, E. 1989. 40Ar/39Ar and U–Pb evidence for Late Proterozoic (Grenville-age) continental crust in north-central Cuba and regional tectonic implications. In: Onstott, T. C. (ed.) Recent Advances on the Precambrian Geology of South and Central America and the Caribbean, Precambrian Research, 42, 325–341.

Restrepo-Pace, P. A. 1992. Petrotectonic characterization of the Central Andean Terrane, Colombia. Journal of South American Earth Sciences, 5, 97–116.

Restrepo-Pace, P. A., Ruiz, J., Gehrels, G. E. & Cosca, M. 1997. Geochronology and Nd isotopic data of Grenville-age rocks in the Colombian Andes: New constraints for Late Proterozoic–Early Paleozoic paleocontinental reconstructions of the Americas. Earth and Planetary Science Letters, 150, 427–441.

Restrepo-Pace, P. A., Colmenares, F., Higuera, C. & Mayorga, M. 2004. A fold-and-thrust belt along the western flank of the Eastern Cordillera of Colombia; style, kinematics, and timing constraints derived from seismic data and detailed surface mapping. In: McCly, K. R. (ed.) Thrust Tectonics and Hydrocarbon Systems. American Association of Petroleum Geologists, Memoirs, 82, 598–613.

Roefer, D. & Chamberlain, R. L. 1995. Eastern Cordillera of Colombia: Jurassic–Neogene crustal evolution. In: Tankard, A. J., Suarez-Soruco, R. & Welsink, H. J. (eds) Petroleum Basins of South America. American Association of Petroleum Geologists, Memoirs, 62, 635–645.

Rogers, R. D., Mann, P. & Emmet, P. A. 2007. Tectonic terranes of the Chorrísl block based on integration of regional aeromagnetic and geologic data. In: MANN, P. (ed.) Geologic and Tectonic Development of the Caribbean Plate Boundary in Northern Central America. Geological Society of America, Special Papers, 428, 65–88.

Roperch, P., Megard, F., Laj, C., Mournier, T., Clube, T. & Noblet, C. 1987. Rotated oceanic blocks in Western Ecuador. Geophysical Research Letters, 14, 558–561.

Rosas, S., Fontbote, L. & Tankard, A. J. 2007. Tectonic evolution and paleogeography of the Mesozoic Pucará Basin, central Peru. Journal of South American Earth Sciences, 24, 1–24.

Rosenfeld, J. H. 1993. Sedimentary rocks of the Santa Cruz Ophiolite, Guatamala—a proto-Caribbean history. In: Pindell, J. L., Perkins, R. F. (eds) Transactions of the 13th Annual GCSSEPM Research Conference: Mesozoic and Early Cenozoic Development of the Gulf of Mexico and Caribbean Region, 173–180.

Ruiz, G. M. H., Seward, D. & Winkler, W. 2004. Detrital thermochronology—a new perspective on hinterland tectonics, an example from the Andean Amazon Basin, Ecuador. Basin Research, 16, 413–430.

Sarmiento-Rojas, L. F., Van Wees, J. D. & Cloetingh, S. 2006. Mesozoic transtensional basin history of the Eastern Cordillera, Colombian Andes: Inferences from tectonic models. Journal of South American Earth Sciences, 21, 383–411.

Schiebenschau, C. & Bellizzia, A. (coordinators) 2001. Geologic Map of South America (Scale 1:5 000 000). ECGMW-CPRM-DPNM-UNESCO, Brazilia. World Wide Web Address: http://ccgm.free.fr/.

Sedlock, R. L. 2003. Geology and tectonics of the Baja California peninsula and adjacent areas. In: Johnson, S. E., Paterson, S. R., Fletcher, J. M., Girty, G. H., Kimbrough, D. L. & Martín-Barajas, A. (eds) Tectonic Evolution of Northwestern Mexico and the Southwestern USA. Geological Society of America, Boulder, CO, Special Papers, 374, 1–42.

Sedlock, R. L., Ortega, G. F. & Speed, R. C. 1993. Tectonostratigraphic Terranes and Tectonic Evolution of Mexico. Geological Society of America, Boulder, CO, Special Papers, 278, 1–153.

Spadea, P. & Espinosa, A. 1996. Petrology and chemistry of Late Cretaceous volcanic rocks from the southemmost segment of the Western Cordillera of Colombia (south America). Journal of South American Earth Sciences, 9, 79–90.

Spikings, R. A., Winkler, W., Seward, D. & Handler, R. 2001. Along-strike variations in the thermal and tectonic response of the continental Ecuadorian Andes to the collision with heterogeneous oceanic crust. Earth and Planetary Science Letters, 186, 57–73.
SPIKINGS, R. A., WINKLER, W., HUGHES, R. A. & HANLDER, R. 2005. Thermochronology of allochthonous terranes in Ecuador: Unravelling the accretionary and post-accretionary history of the Northern Andes. Tectonophysics, 399, 195–220.

STÉPHAN, J. F. 1985. Andes et Chaîne Caribbe sur la transversale de Barquisimeto (Venezuela): Evolution Géo-dynamique. In: MASCLE, A. (ed.) Géodynamique des Caribes. Editions Technip, Paris, 505–529.

STOCKHEFT, B., MARESH, W. V. ET AL. 1995. Crustal history of Margarita Island (Venezuela) in detail: constraint on the Caribbean Plate tectonic scenario. Geology, 23, 787–790.

THOMAS, G., LAVENU, A. & BERRONES, G. 1995. Évolution de la subsidence dans le Nord du bassin de l’Oriente équatorial (Critacé supérieur à Actuel). Comptes Rendus de l’Académie des Sciences, 320, 617–624.

TORSVIK, T. H., MÜLLER, R. D., VAN DER VOO, R., STEINBERGER, B. & GAINA, C. 2008. Global plate motion frames: toward a unified model. Reviews of Geophysics, 46, RG004.

TOUSSAINT, J.-F. & RESTREPO, J. J. 1994. The Colombian Andes during Cretaceous times. In: SALTITY, J. A. (ed.) Cretaceous Tectonics of the Andes. Vieweg, Earth Evolution Sciences, International Monograph Series, 61–100.

TRENKAMP, R., KELLOGG, J. N., FREYMUeller, J. T. & MORA, H. P. 2002. Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. Journal of South American Earth Sciences, 15, 157–171.

TSCHANZ, C. M., MARVIN, R. F., CRUZ, B. J., MEHNERT, H. H. & CEBULA, G. T. 1974. Geologic evolution of the Sierra Nevada de Santa Marta, north-eastern Colombia. Geological Society of America Bulletin, 85, 273–284.

VALLEJO, C. 2007. Evolution of the Western Cordillera in the Andes of Ecuador (Late Cretaceous–Paleogene). PhD thesis, ETH, Zürich.

VALLEJO, C., HOCHEL, P. A., WINKLER, W. & VON SALIS, K. 2002. Palynological and sequence stratigraphic analysis of the Napo Group in the Pungarayacu 30 well, Sub-Andean Zone, Ecuador. Cretaceous Research, 23, 845–859.

VALLEJO, C., SPIKINGS, R., LUZIEUX, L., WINKLER, W., CHEW, D. & PAGE, L. 2006. The early interaction and southwest Pacific-type segment of Iapetus. In: BLUNDELL, D. J. & SCOTT, A. C. (eds) Lyell: Past is the Key to the Present. Geological Society, London, Special Publications, 143, 199–242.

VÁSQUEZ, M. & ALTENBERGER, U. 2005. Mid-Cretaceous extension-related magmatism in the eastern Colombian Andes. Journal of South American Earth Sciences, 20, 193–210.

VILLAGÓMEZ, D., SPIKINGS, R., SEWARD, D., MAGNA, T. & WINKLER, W. 2008. Thermotectonic history of the Northern Andes. 7th International Symposium on Andean Geodynamics, 2–4 September 2008, Nice, 573–576. World Wide Web Address: http://www.geoazur.unice.fr/ISAG08/Soumissions/PDF/573-576_Villagomez_et_al.pdf.

VILLAMIL, T. 1999. Campanian–Miocene tectonostratigraphy, depocenter evolution and basin development of Colombia and western Venezuela. Palaeogeography, Palaeoclimatology, Palaeoecology, 155, 239–275.

VINASCO-VALLEJO, C. J., CORDANI, U. & VASCONCELOS, P. 2003. Application of the 40Ar/39Ar methodology in the study of tectonic reactivations of shear zones: Romeral fault system in the Central cordillera of Colombia. IV South American Symposium on Isotope Geology, 24–27 August 2003, Salvador, Bahia, Brazil, 138–144. World Wide Web Address: http://www.brasil.ird.fr/symplisotope/Papers/ST1/ST1-29-Vinasco.pdf.

VON HUENE, R. & LALLEMAND, S. 1990. Tectonic erosion along the Japan and Peru convergent margins. Geological Society of America Bulletin, 102, 704–720.

VON HUENE, R., SUES, E. ET AL. 1988. Ocean Drilling Program Leg 112, Peru continental margin; Part 1. Tectonic history. Geology, 16, 934–938.

WHITE, R. V., TARNY, J. ET AL. 1999. Modification of an oceanic plateau, Aruba, Dutch Caribbean: Implications for the generation of continental crust. Lithos, 46, 43–68.

WINE, G., ARCURI, J., MARTINEZ, E., MONGES, C., CALDERON, Y. & GALDOS, C. 2001. A study on the remaining undiscovered hydrocarbon potential of the Trujillo offshore basin, Peru. Proyecto de asistencia para la reglamentacion del sector energetico del Peru (PARSEP), distributed by Perupetro, Lima, Peru. World Wide Web Address: http://www.perupetro.com.pe/home-e.asp.

WINKLER, W., VILLAGÓMEZ, D., SPIKINGS, R., ABEGLEND, P., TOBLERE, S. & EGUEZ, A. 2005. The Chota basin and its significance for the inception and tectonic setting of the inter-Andean depression in Ecuador. Journal of South American Earth Sciences, 19, 5–19.

WINKLER, W., VALLEJO, C., LUZIEUX, L., SPIKINGS, R. & MARTIN-GOMBAY, N. 2008. Timing and causes of the growth of the Ecuadorian cordilleras, as inferred from their detrital record. 7th International Symposium on Andean Geodynamics, 2–4 September 2008, Nice, France, 587–591. World Wide Web Address: http://www.geoazur.unice.fr/ISAG08/Soumissions/PDF/587-591_Winkler_et_al.pdf.

ZAMORA, A. & LITHERLAND, M. 1993. Mapa geologico de la Republica del Ecuador (Scale 1:1 000 000). Corporación de Desarrollo e Investigación Geológico, Minero, Metalúrgica (CODIGEM), British Geological Survey.
