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Palaeomagnetism of the central Cuban Cretaceous Arc sequences and geodynamic implications

J. Tait [a,*], Y. Rojas-Agramonte [b,c], D. García-Delgado [d], A. Kröner [b], R. Pérez-Aragón [e]

[a] School of Geosciences, University of Edinburgh, EH9 3JW, UK
[b] Institut für Geowissenschaften, Universität Mainz, D-55099 Mainz, Germany
[c] Instituto Superior Minero-Metalúrgico, Departamento de Geología, Las Coloradas s/n, Moa 83329, Holguín, Cuba
[d] Centro de Investigaciones del Petróleo, Washington 169, Habana 12000, Cuba
[e] Instituto de Geología y Paleontología, Vía Blanca y Línea del Ferrocarril s/n, San Miguel del Padrón 11000, La Habana, Cuba

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ABSTRACT

A detailed palaeomagnetic study of Cretaceous age volcanic and sedimentary arc rocks from central Cuba has been carried out. Samples from 32 sites (12 localities) were subjected to detailed demagnetisation experiments. Nineteen sites from the Los Paso, Mataguá, Provincial and Cabaiguán Formations yielded high unblocking temperature, dual polarity directions of magnetisation which pass the fold tests with confidence levels of 95% or more and are considered to be primary in origin. The palaeomagnetic inclinations are equivalent to palaeolatitudes of 9°N for the Aptian, 18°N for the Albian. A synfolding remanence identified in 5 sites from the younger Hilario Formation indicates a late Cretaceous remagnetisation at a palaeolatitude of 16°N. Our results are in good agreement with previous palaeogeographic models and provide the first high quality palaeomagnetic data demonstrating the gradual northward movement of the Cretaceous Volcanic Arc throughout the Cretaceous. The declination values obtained all indicate significant and similar amounts of anticlockwise rotation from the oldest sequences studied through to the late Cretaceous remagnetisation. This rotation is most likely related to collision of the arc with the North American plate and transpressional strike slip movement along the northern margin of the Caribbean plate as it progressed eastwards into the large Proto-Caribbean basin.

1. Introduction

The Caribbean region is tectonically complex (Fig. 1), and its geological evolution remains vigorously debated. Today, the eastern margin of the Caribbean plate is bounded by the Antilles islands which can be divided into two regions: the northern Greater Antilles and the more southerly Lesser Antilles. The Greater Antilles were formed due to Cretaceous and Tertiary tectonic activity along the leading edge of the Caribbean plate with accretion of oceanic and continental terranes ranging in age from Jurassic to late Eocene (Iturralde-Vinent, 1996, 1998; Pindell and Kennan, 2001). This segment of the Greater Antilles includes the islands of Cuba, Hispaniola, Jamaica, Puerto Rico and the Virgin Islands, of which Cuba is the largest. The Lesser Antilles is an active volcanic arc marking the leading edge of the Caribbean plate over the westward-subducting Atlantic plate. It comprises subduction related volcanics of the Leeward and Windward Islands and was active from at least late Cretaceous times onwards.

The Caribbean is now part of a geographically diverse region, extending from southern North America to northern South America. Whereas the movements of these two continents bounding the region are fairly well constrained for post-Palaeozoic times, their interaction with the Caribbean plate and the geodynamic evolution of the Caribbean domain remains poorly understood. As a result, many different models concerning plate movements, major block rotations, island arc development, subduction polarities and the opening of oceanic basins have been proposed (Malfait and Dinkleman, 1972; Ross and Scotese, 1988; Pindell and Barrett, 1990; Pindell, 1994; Marton and Buffler, 1994; Meschede and Frisch, 1998; Kerr et al., 1999; Pindell and Kennan, 2001; Iturralde-Vinent, 1994, 1998, 2006; James, 2003, Pindell et al., 2006).

The autochthonous (in situ) models consider the Caribbean plate as an intra-American feature which formed along the Caribbean spreading centre during Jurassic and early Cretaceous times and is Proto-Caribbean in origin (Meschede and Frisch 1998). The allochthonous models as proposed by Pindell and Dewey (1982), Pindell and Barrett (1990), Pindell (1994), Iturralde-Vinent (1994, 1998); Pindell et al. (2006) are more generally accepted. According to these models the Caribbean region began to develop in latest Triassic–Jurassic times as a system of rift valleys during the break-up of Pangaea and opening

* Corresponding author.
E-mail address: jenny.tait@ed.ac.uk (J. Tait).

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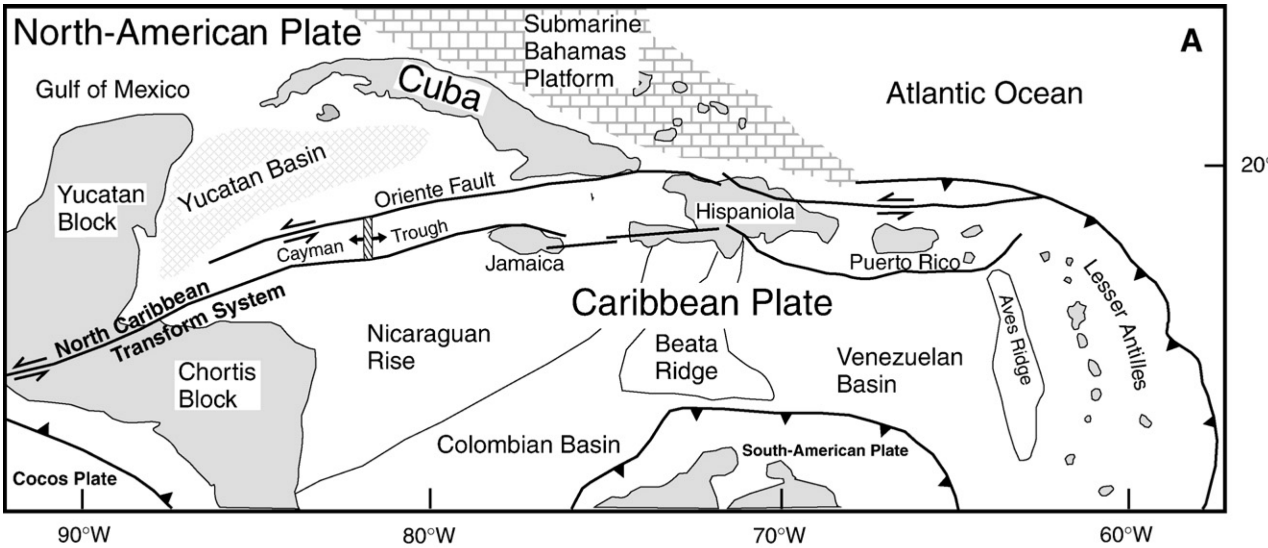

Fig. 1. Simplified map of the Caribbean realm.

of the Proto-Caribbean oceanic basin (Pindell and Kennan, 2001; Pindell et al., 2006). Sea floor spreading in the Proto-Caribbean continued probably into the earliest Cretaceous, forming passive margins along the bounding edges of the North and South American plates and intervening ocean. As these two continents moved westwards around Euler poles indistinguishable from the geographic spin axis in response to the opening of the Atlantic, an east-dipping subduction zone which erupted island arc tholeiites (the Primitive Island Arc) developed along the western margin of N and S America (Donnelly and Rogers 1980; Lebron and Perfit, 1993; Iturralde-Vinent, 1998, 2006; Pindell et al., 2006; Kerr and Tarney, 2005). By Aptian times (125–112 Ma) it has been proposed that a subduction polarity reversal occurred, establishing a new southwest-dipping subduction zone accompanied by a switch from primitive, tholeiitic to more mature, calc-alkaline island arc magmatism. Following the polarity reversal, a younger (late Cretaceous to Paleogene) arc was built upon the older primitive arc. One theory suggests that the polarity reversal was triggered when thickened, buoyant Pacific seafloor entered the trench but could not subduct, and west-directed subduction of the Atlantic Ocean began (Burke et al., 1978; Burke, 1988; Lebron and Perfit, 1993; Meschede and Frisch, 1998). On the other hand, Pindell and Kennan (2001), Pindell et al. (2006) and Draper and Pindell (2006) suggested that the reversal was triggered by a strong westward acceleration of the Americas relative to the mantle when the Chortis Block in Mexico and northern South America finally drifted clear of each other during the break-up of the Americas. It should be mentioned, however, that there is no final agreement regarding subduction polarities and whether or not there was a "flip". Continued westward movement caused subduction of Proto-Caribbean lithosphere beneath the Pacific-derived Caribbean lithosphere. The allochthonous model of Pindell et al. (2006) predicts longitudinal motion in equatorial regions of up to 1000 km (10°) for the early Cretaceous volcanic rocks in Cuba (e.g. Fig. 5 of Pindell et al., 2006).

Westward subduction along the leading edge of the Caribbean plate continues today in the southerly Lesser Antilles, but was blocked in the Greater Antilles when this northerly segment of the arc collided, first with Caribeana – a sedimentary promontory to the Maya Block – in the latest Cretaceous-earliest Tertiary (García-Casco et al., in press) and again in the middle Eocene with the continental margin of the North American plate (Bahamas Platform; Hatten et al., 1988; Iturralde-Vinent, 1996; Millán-Trujillo et al., 1998; Pindell and Kennan 2001; Iturralde-Vincent, 2003, 2006; Schneider et al., 2004). The final collision resulted in left lateral displacement along the Oriente Transform Wrench Corridor, thus separating Cuba from the eastern part of the Arc (i.e. Hispaniola and Puerto Rico; Iturralde-Vinent, 1996; Rojas-Agramonte et al., 2005). The Oriente Transform Wrench Corridor now marks the boundary between the N American and Caribbean plates (Rojas-Agramonte et al., 2005). East-dipping subduction developed along the trailing edge of the Caribbean Plateau as the Farallón plate continued to subduct beneath the western Americas, thus forming the Central American Arc which today forms Guatemala, Costa Rica and Panamá.

The island of Cuba (Fig. 2A) is central to our understanding of the Caribbean evolution as the geology of this island reflects the accretion of various island arcs, closure of ocean basins of unknown width and collision of these arcs with Caribeana and the North American plate. Much of the uncertainty concerning the geological development of Cuba and the Caribbean region as a whole is due to the lack of reliable palaeomagnetic data with which to constrain the palaeogeographic evolution of the various tectonostratigraphic units. To help resolve these problems a detailed sampling of sediments and volcanic rocks from the Cretaceous volcanic arc in Central Cuba has been carried out for palaeomagnetic analysis.

2. Geological setting

Cuba is the largest island in the Greater Antilles and essentially comprises a series of Jurassic to middle Eocene accreted terranes of continental, mixed and oceanic affinity (Fig. 2A; Iturralde-Vinent, 1994, 1996, 1998). These are the continental Jurassic–Eocene sediments of the Bahamas margin in the north of the island (the Florida Strait Block of the North American plate), the Pinos terrane, the mixed Mesozoic metamorphic Guaniguanico and Escambray complexes, the oceanic units from the Northern Ophiolite belt, the Cretaceous Volcanic Arc, and the younger EW trending Palaeogene Sierra Maestra volcanic arc of south-eastern Cuba (Fig. 2A).

The tectonic elements of the Cuban foldbelt are all exposed in Central Cuba (Fig. 2B) and record a migration in time of the tectonic development and transport from the southwest to the northeast (Meyerhoff and Hatten, 1974; Iturralde-Vinent, 1994, 1998). From north to south the Cayo Coco, Remedios, Camajuaní and Placetas Belts have been identified within the autochthonous continental margin of the North American Plate and Proto-Caribbean basin (Florida Strait Block, Fig. 2), the Northern Ophiolite Belt, the Cretaceous Volcanic Arc (CVA), the Mabujina amphibolites and the Escambray Massif (or terrane sensu Iturralde-Vinent, 1994, 1998).

The Cuban foldbelt was consolidated in two phases, between latest Campanian and late Eocene times, with an eastward age migration

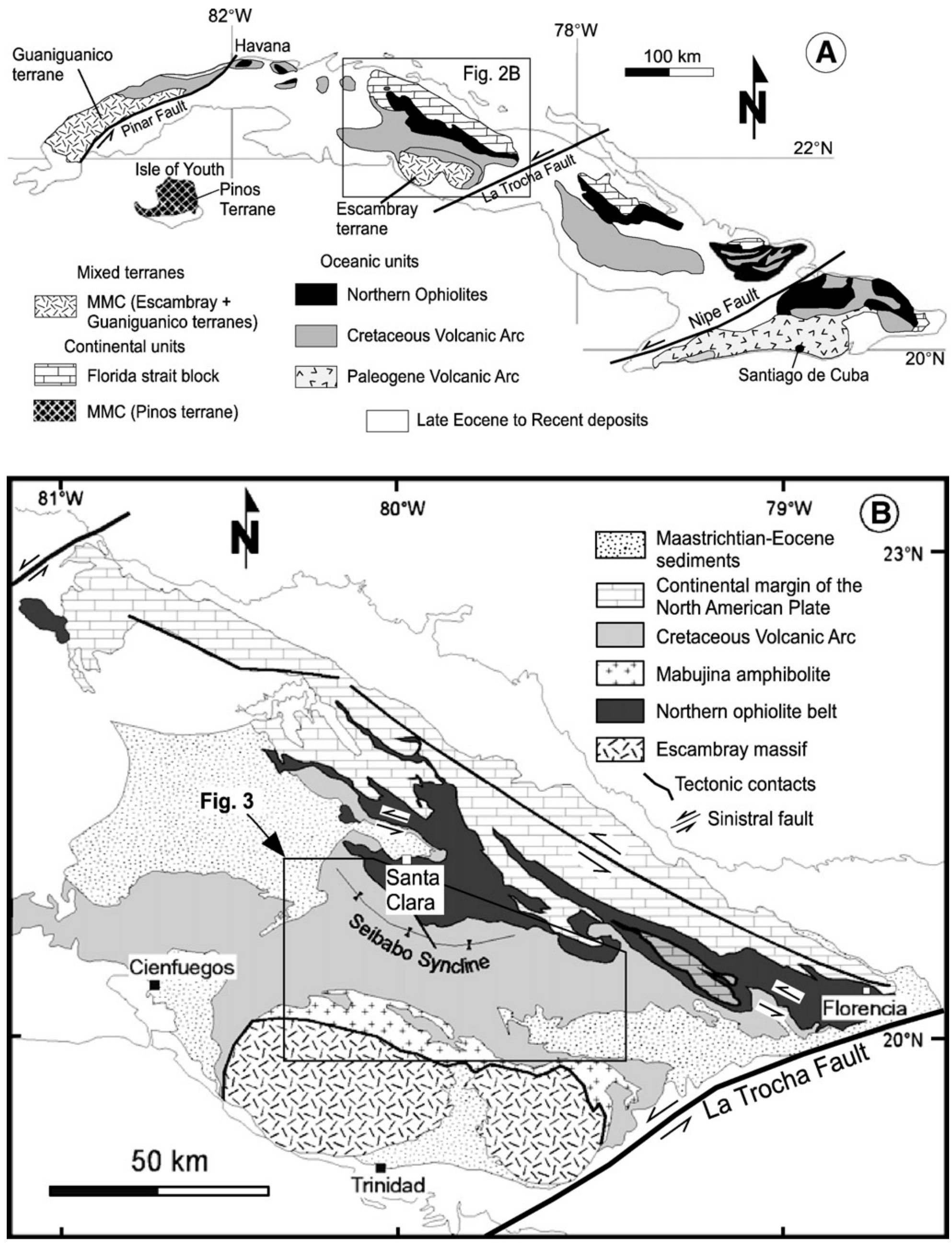

Fig. 2. (A). Simplified geological map of Cuba, after Iturralde-Vinent (1994, 1998). Abbreviations: MMC: Mesozoic metamorphic complex. (B) Geological map of central Cuba, after García-Delgado et al. (1998) and Iturralde-Vinent (1998). Inset shows location of Fig. 3.

across the island (Iturralde-Vinent, 1996, 1998; Millán-Trujillo et al., 1998). The first tectonic phase occurred during the latest Cretaceous-early Tertiary when the leading edge of the Caribbean plate collided with Caribeana (García-Casco et al., in press). This event affected mostly the CVA/Northern Ophiolites and led to consolidation of these oceanic structures after the extinction of Cretaceous magmatic activity. This resulted in uplift and tectonic juxtaposition of the CVA with the Northern Ophiolite mélange (Iturralde-Vinent, 1998; Millán-Trujillo et al., 1998). During this phase, a terrigenous flysch and molasse-type orogenic succession of latest Campanian–Maastrichtian age was deposited, composed of clastic material derived from the ophiolites and Cretaceous volcanic arc rocks. The late Campanian–Maastrichtian basins were partially deformed together with the pre-orogenic oceanic complexes, and new basins developed with the onset of the second Paleocene–Eocene orogenic phase (Iturralde-Vinent, 1998).

2.1. Brief description of the arc

The Cretaceous Volcanic Arc (CVA) of central Cuba (Figs. 2 and 3) is in tectonic contact to the north with the northern Ophiolite Belt (north-directed thrusting) and to the south with the Mabujina Amphibolite Complex and the Escambray metamorphic terrane (south-directed thrusting). As summarised in Fig. 4, the oldest unit (the Berriasian-Barremian Los Pasos Fm.) within the CVA is made up of tholeiitic basalt and rhyolite, representative of the so-called “primitive island-arc” (PIA) (Dublan and Alvarez-Sánchez, 1986; Diaz de Villalvilla, 1997, 1998); dacites and intercalations of pyroclastic, epiclastic and sedimentary rocks have also been described (Iturralde-Vinent, 1998). The Los Pasos Formation is unconformably overlain by volcano-sedimentary units of the calc-alkaline to high-alkaline volcanic arc. These include basalts, andesites and reef limestones of the Aptian–Albian Mataguá Formation; tuffs, lavas and

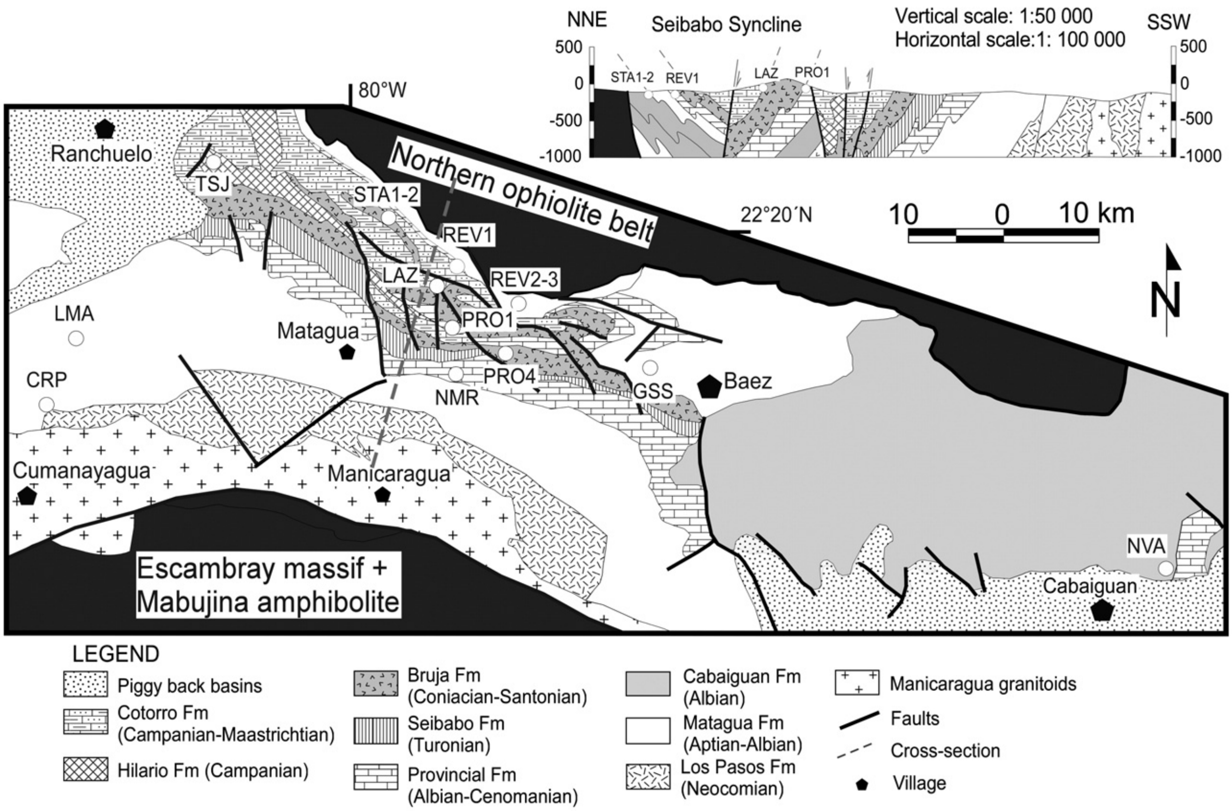

Fig. 3. Geological map of the working area with sample locations (after García-Delgado et al., 1998). A section across the Seibabo syncline appears in the top right.

carbonate rocks of the Albian Cabaiguán Fm.; carbonates of the late Albian–Cenomanian Provincial Formation; and the Coniacian–Santonian lavas of the Bruja Fm. The calcareous and sedimentary rocks from the Hilario Fm (Campanian) represent the upper part of the Cretaceous volcanic arc. Four units of the calc-alkaline arc and one from the Campanian sedimentary rocks were sampled for palaeomagnetic analysis. The stratigraphy is based mainly on biostratigraphic controls, for further information see García-Delgado et al. (1998).

The most significant structure within the Cretaceous arc of central Cuba is the Seibabo Syncline (Fig. 3) which extends for 37 km and varies in width from 1.5 to 4 km. The central part of the syncline is internally complicated, with faults and minor folds. The steeply dipping to overturned northern flank is reduced and tectonically cut by the ophiolite massif. The southern flank dips more gently to the north and extends to the south, thus forming a monoclinal structure at the contact with the Manicaragua granitoids. Frequent tight to isoclinal south-plunging folds are also found in this area. The extinct Cretaceous arc was covered by Campanian deposits (Hilario and Cotorro Formations) that were folded together with the rest of the arc sequences. These Campanian deposits are now the main component of the axial part of the syncline.

3. Previous palaeomagnetic studies in Cuba

Palaeomagnetic data from cores obtained during Leg 165 of the Ocean Drilling Programme indicate that in late Cretaceous times the Caribbean plate was situated 5° to 15° south of its present position (Acton et al., 2000). On mainland Cuba, four palaeomagnetic studies have been carried out; two on Jurassic–Palaeocene sequences of the Guaniguanico terrane and Cretaceous rocks of the Bahia Honda zone in western Cuba (Bazhenov et al., 1996; Alva-Valdivia et al., 2001) and two on Cretaceous Volcanic Arc rocks of central Cuba (Chauvin et al., 1994; Renne et al., 1991). With the exception of the data of Alva-Valdivia et al. (2001), these studies were of a reconnaissance nature. Two further studies of Cretaceous rocks from the Dominican Republic and Jamaica (Fundora Granda et al., 2003, extended conference abstract) and late Jurassic to middle Eocene rocks of Cuba (Pérez Lazo et al., 1995) have also been carried out. Whereas some of the results obtained in these two latter studies show certain similarities to other work, it is difficult to evaluate the quality of the data as they have not been presented in full and no examination of primary versus secondary remanence acquisition has been attempted, and so they will not be discussed further.

Bazhenov et al. (1996) and Renne et al. (1991) identified apparently primary directions from mid-late Cretaceous age rocks of the Bahia Honda zone and the CVA of western and central Cuba. The inclination values obtained from the two regions are in good agreement ($23 \pm 9°$ from W Cuba and $26 \pm 14°$ from central Cuba), and correspond to palaeolatitudes of approx. 14°N, some 8° south of the present-day location and in good agreement with the ODP data for the Caribbean plate as a whole (Acton et al., 2000). Chauvin et al. (1994) sampled the same unit as Renne et al. (1991) in central Cuba, and reported a rather scattered late Cretaceous remagnetisation direction, with an inclination value of $11 \pm 15.6°$. All these studies yielded inclination values that are much shallower than those expected for Cretaceous or younger times from the apparent polar wander (APW) path for North America (Besse and Courtillot, 2002). The interpretation drawn by the original authors was that of significant northward displacement (up to 1500 km) of both central and western Cuba in latest Cretaceous–Palaeocene times with respect to North America. The declination values indicate anti-clockwise rotation with respect to North America of up to 120° in the western Bahia Honda zone, and 60° in central Cuba. These magnitudes of rotation are compatible with the general structural trend of Cuba and may be indicative of oroclinal bending (Bazhenov et al., 1996).

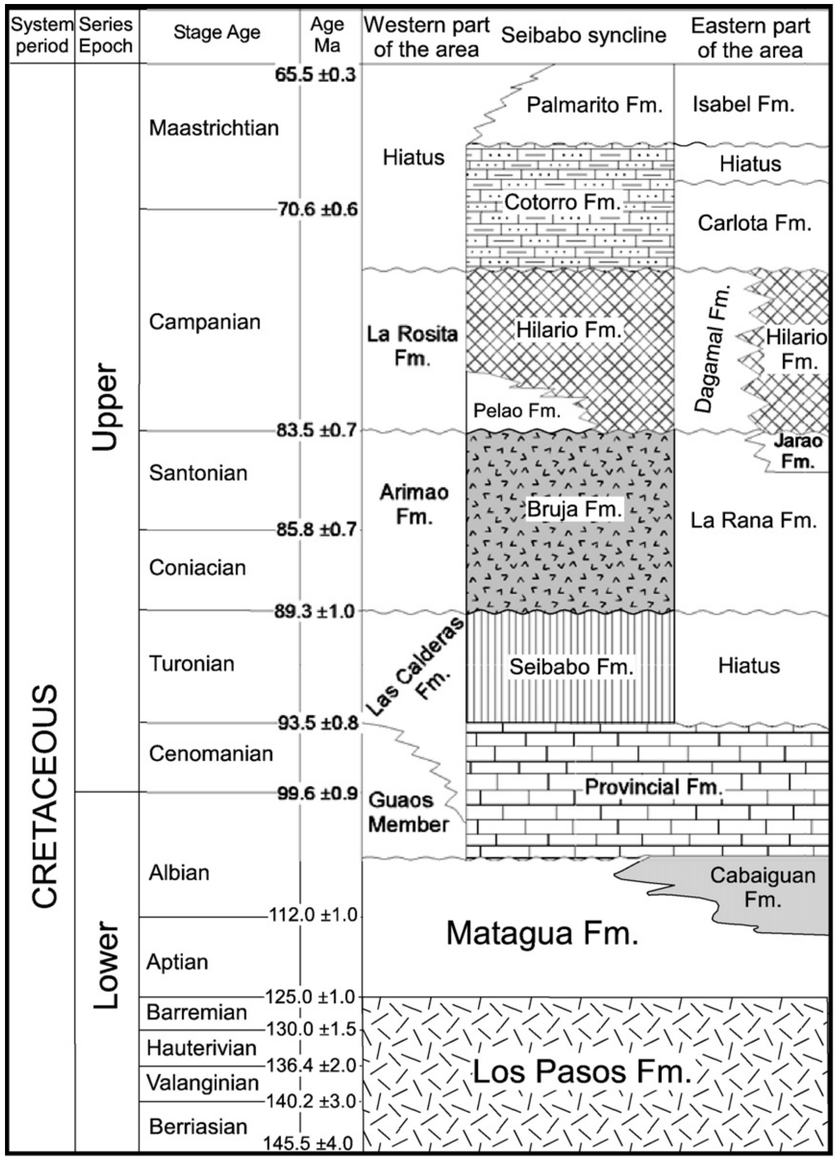

Fig. 4. Cretaceous stratigraphy of central Cuba, ages after Gradstein et al. (2004).

A more detailed study was carried out on Jurassic to Palaeocene age rocks from the Guaniguanico terrane, western Cuba (Alva-Valdivia et al., 2001). These data are of higher quality and were interpreted by the authors as representing primary magnetisations due to a positive fold test and the presence of reversals. The data obtained, however, are significantly different from to the results presented by Bazhenov et al. (1996) from the Bahia Honda region of western Cuba and the CVA data of central Cuba. In particular, the inclination values are much higher and the pole position is in agreement with Jurassic–Cretaceous poles from North America (Besse and Courtillot, 2002). This was taken by the authors as evidence that the Guaniguanico terrane has been a stable part of the North American plate since Jurassic times.

However, these data have a negative fold test. Unfortunately, the authors did not fully present the low temperature (overprint) direction which is removed, nor did they quote the unblocking temperature spectra for their interpreted primary directions of normal polarity. However, from the thermal demagnetisation data which are presented (Fig. 6A and B of Alva-Valdivia et al., 2001) it can be seen that their primary normal direction (which is removed by 300 °C), is almost identical to the secondary overprint direction removed in samples which also have a higher unblocking temperature component. It may be concluded, therefore, that the normal direction of magnetisation identified by these authors is actually an overprint direction.

This scenario is supported by the observation that Bazhenov et al. (1996) also identified very similar directions in the same formations of the Guaniguanico terrane, which they were able to demonstrate as being post-folding and secondary in character. Removing the normal directions from the original dataset of Alva-Valdivia et al. (2001) results in a mean high unblocking temperature reversed direction of 145.8°/−52.6°, $\alpha_{95}=9.4$, $k=24.3$ (11 sites), identified from rocks of late Jurassic to early Palaeocene age. This is rather similar to a direction identified by Bazhenov et al. (1996) from similar age rocks from the same region which they were able to describe as being variously pre-, post-, and syn-deformational. As the structural data for the results of Alva-Valdivia et al. (2001) are not given, it is not possible to test whether the data are syn-deformational in character. The mean inclination value is too steep for any Cenozoic overprint (approx. 30–36° from the North American APW path of Besse and Courtillot, 2002),

and was discussed by Bazhenov et al. (1996) who argued in favour of structural controls on the remanence direction.

4. Palaeomagnetic sampling

Samples for palaeomagnetic analysis were collected from a total of 12 localities (32 sites, 195 samples) in six different formations, spanning the mid-early Cretaceous (Barremian) to mid-Upper Cretaceous (Campanian), and mostly located in the Seibabo syncline of central Cuba (Fig. 3). Standard 2.54 cm diameter cores were collected using a hand-held petrol driven rock drill, and oriented prior to extraction from the rock using magnetic and, where possible, sun compasses. With the exception of samples from site PRO4 of the Bruja Formation, multiple sites at different stratigraphic levels were sampled to average out secular variation at all localities except for the Bruja Formation at PRO4 where outcrop was very limited in extent. Laboratory analyses were carried out at the Palaeomagnetic Laboratory, Munich University. All samples were subjected to detailed thermal and/or AF demagnetisation with measurement of the natural remanent magnetisations using a 2G superconducting rock magnetometer. The thermal demagnetisers and cryogenic equipment are all housed in a magnetically shielded space to avoid contamination of the samples by the present day Earth magnetic field during analysis. Results were analysed using principal component analysis with orthogonal (Zijderveld, 1967) and stereographic projection of the data. Fisher (1953) statistics were used in all cases.

5. Palaeomagnetic results

5.1. Upper Los Pasos Formation (Barremian)

At locality CRP well-bedded, uniformly dipping, red coloured lavas from the upper part of the Los Pasos Formation were sampled along a large roadcut section (2 sites, 12 samples) on the southern limb of the Seibabo structure (Fig. 3). All samples show very stable behaviour during demagnetisation with high natural remanent magnetisation intensities (up to 344 mA/m) and almost exclusively single well-defined components of magnetisation (Fig. 5C). Haematite is the carrier of remanence with extremely narrow unblocking temperature spectra (650–700 °C). In one or two cases present-day overprints are removed at lower temperatures. The high temperature direction is identified in eight samples (2 sites, Table 1) yielding an overall sample mean direction of $D=087°$, $I=-44°$ *in situ* and $D=060°$, $I=-17°$, $\alpha_{95}=10.9°$, $k=26.9$ after structural correction. Although it was not possible to carry out any field tests, the in situ inclination value (44°) does not correspond to any expected post Barremian direction, and the inverse polarity identified is compatible with the Barremian age of the rocks and extrusion prior to onset of the Cretaceous long normal chron.

5.2. Lower Matagué Formation (Early Aptian)

Volcanic and volcanoclastic rocks of the Lower Matagué Formation were sampled at three localities (LMA, GSS and REV, 9 sites, 60

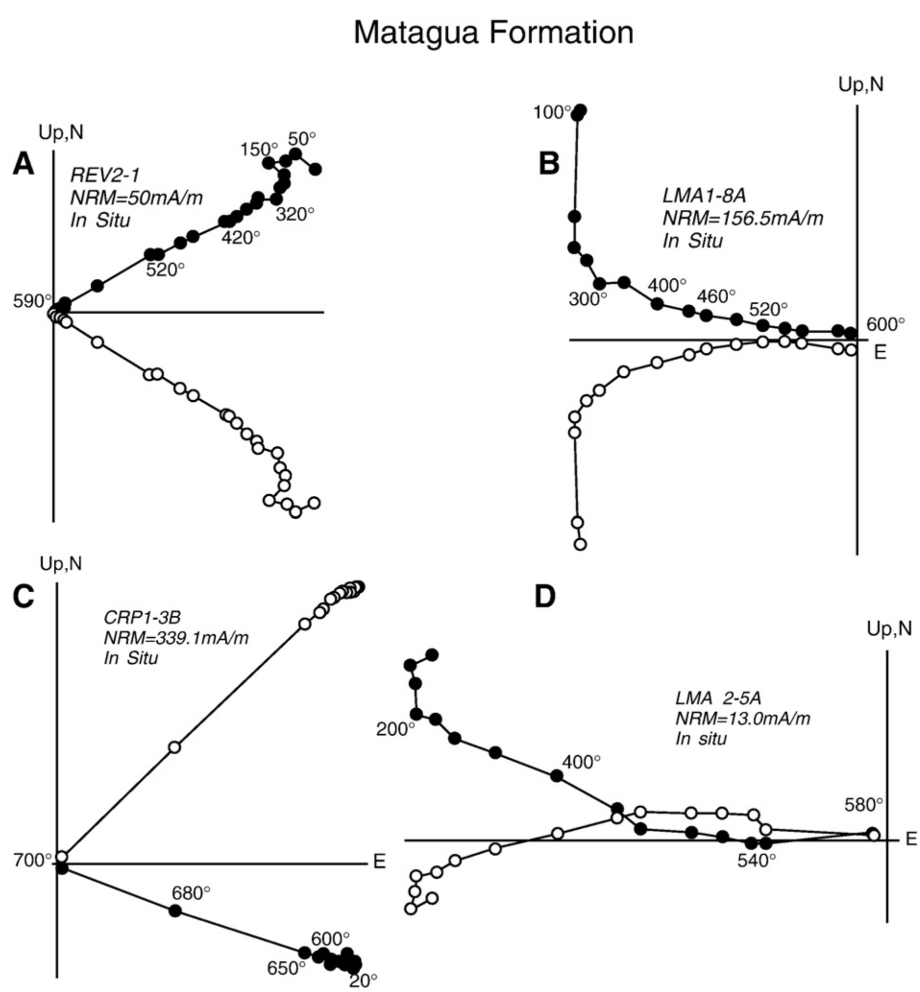

Fig. 5. Orthogonal projections of thermal demagnetization characteristics from the Los Pasos and Matagué Formations. Solid (open) circles represent the horizontal (vertical) component, NRM values given are before thermal treatment.

Table 1
n, number of samples used in calculation of site mean: Dec/Inc, declination/inclination (in degrees) in situ (IS) and after tilt correction (TC): *k*, precision parameter (after Fisher, 1953): α_{95}, semi-angle of the cone of 95% confidence, and including the data of Renne et al., (1991).

Site	Loc (W:N)	n	D_{IS}	I_{IS}	α_{95}	k	D_{TC}	I_{TC}	α_{95}	k
Los Pasos (Barremian)										
CRP-1	80.186: 22.202	4	97	−43	10.9	50.3	67	−22	10.9	50.3
CRP2	80.186: 22.202	4	72	−44	10.3	55.6	52	−10	10.3	55.6
	Mean	**8**	**87**	**−44**	**10.9**	**26.9**	**60**	**−17**	**10.9**	**26.9**
Mataguá Formation (Aptian)										
LMA-1	80.170: 22.246	5	284	4	6.2	153.3	292	11	6.2	153.3
LMA-2	80.170: 22.246	3	284	0	28.0	20.5	289	9	28.0	20.5
LMA3	80.170: 22.246	4	280	−1	6.4	206.4	284	11	6.4	206.4
REV2*	79.882: 22.265	4	65	33	10.5	77.6	137	10	22.7	17.4
REV3*	79.882: 22.265	7	54	40	5.6	114.5	138	16	8.0	56.0
Mean		3	283	1	5.3	532.5	289	11	5.3	532.5
RenneA		*5*	*265*	*22*	*5.5*	*193.0*	*304*	*29*	*5.5*	*193.0*
RenneB		*6*	*299*	*41*	*4.0*	*518.0*	*283*	*27*	*4.0*	*518.0*
RenneC		*7*	*278*	*21*	*7.5*	*66.0*	*292*	*14*	*7.5*	*66.0*
Mean with Renne data		**6**	**281**	**14**	**16.2**	**18.0**	**291**	**17**	**9.3**	**52.4**
Cabaiguán/Provincial Formations (mid Albian–Cenomanian)										
NVA-1	79.456: 22.107	4	293	−19	14.3	42.1	294	35	14.3	42.1
NVA-2	79.456: 22.107	3	299	−24.3	8.4	120.1	300	30	8.4	120.1
NVA-3	79.456: 22.107	4	289	−23	4.9	347.1	289	32	4.9	347.1
NVA-4	79.456: 22.107	3	301	−19	3.4	1308.9	303	34	3.4	1308.9
NVA-5	79.456: 22.107	3	278	−23.4	6.2	151.7	277	31	6.2	151.7
NVA-6	79.456: 22.107	8	297	−32.4	6.3	92.0	296	22	6.3	92.0
NMR-1	79.921: 22.224	3	257	27	5.9	438.8	278	40	5.9	438.8
NMR-2	79.921: 22.224	8	275	47	5.8	92.6	311	46	5.8	92.6
NMR-3	79.921: 22.224	3	296	39	17.8	49.1	318	28	17.8	49.1
PRO1*	79.917, 22.245	5	35	4	14.5	28.7	56	−36	14.5	28.7
REV1*	79.914, 22.286	6	20	55	12.7	28.9	213	38	12.3	30.8
Mean		9	288	−4	23.2	5.9	296	34	8.4	35.8
RenneD		*12*	*316*	*28*	*6.0*	*42.0*	*337*	*21*	*6.0*	*42.0*
RenneG		*5*	*283*	*17*	*8.9*	*75.0*	*305*	*33*	*8.9*	*75.0*
Mean with Renne data		**11**	**290**	**1**	**20.1**	**6.1**	**301**	**33**	**9.4**	**24.8**
Brujas Formation (Coniacian–Santonian)										
PRO4	79.903, 22.25	5	243	−11	6.4	144.2	265	−39	6.4	144.2
Hilario Formation (Campanian)										
TSJ-1	80.079: 22.359	4	259	16	26.6	12.9	284	46	26.6	12.9
TSJ-2	80.079: 22.359	6	263	1	9.4	51.8	275	32	9.4	51.8
STA-1	79.967: 22.32	7	285	49	13.2	22.0	250	2	13.2	22.0
STA-2	79.967: 22.32	4	300	40	8.3	122.7	260	15	8.8	122.7
LAZ-1	79.93, 22.275	7	285	34	6.5	87.6	301	29	7.0	75.5
Mean		**5**	**276**	**29**	**23.9**	**11.2**	**272**	**26**	**24.1**	**11.1**
					50% unfolding		**271**	**30**	**12.6**	**37.6**

*Site mean directions are post-folding in origin.

samples, Fig. 3). Locality LMA is situated on the south-western limb of the Seibabo syncline, close to locality CRP and at some distance from the main axis of the structure. Localities REV and GSS are located on the northern limb of the structure, close to the main axis of the syncline (Fig. 3). At the La Guasasa locality (sites GSS1–4, 21 samples), tuffs and lavas of the Mataguá Formation are generally fairly altered and weathered. Samples were collected from the least altered outcrops exposed along farm tracks. While most samples have fairly high NRM values and fairly well defined magnetisation directions, there is little within and between site consistency, due most likely to weathering and alteration. No meaningful results, therefore, were obtained from this locality.

At the Revacadero locality (REV2–3) volcanoclastic rocks were sampled at roadside outcrops SE of Santa Clara (11 samples, 2 sites), and at the La Lomita locality (LMA), in a small abandoned quarry of grey coloured lavas and tuffs, quite weathered in places, 26 samples (3 sites) were collected. Samples from both localities generally have high initial natural remanent magnetisation (NRM) intensities (up to 280 mA/m) and show stable behaviour during thermal demagnetisation (Fig. 5A, B, D). After removal of a low unblocking temperature component below 300–350 °C, most samples then show a moderately to well defined single component direction of magnetisation with maximum unblocking temperatures of approx. 580 °C (Fig. 5). Occasionally in samples from sites REV2–3 this direction persists up to 620 °C, indicating the presence of both magnetite and haematite as the magnetic carrier, both of which carry the same remanence direction. Identified in all eleven samples, this higher temperature magnetisation yields an overall sample mean direction of $D=059°$, $I=38°$, $\alpha_{95}=5.6°$, $k=67.3$, $n=11$ *in situ*, and $D=138°$, $I=14°$, $\alpha_{95}=8.0°$, $k=33.8$ after structural correction. The decrease in statistical parameters indicates a secondary post-folding magnetisation.

For the La Lomita locality, magnetite is the remanence carrier of the higher temperature component (max. T_{UB} 580 °C) which is shallow and westerly directed (Fig. 5B and D) and identified in 12 samples (LMA1–3, Table 1). The overall site mean direction for these uniformly dipping beds is $D=283°$, $I=01°$, $n=3$, *in situ*, and $D=289°$, $I=11°$ $\alpha_{95}=5.3°$, $k=532.5$ after bedding correction.

5.3. Cabaiguán Formation (mid-Albian)

The Cabaiguán Formation was sampled at locality NVA to the east of the main Seibabo structure in a small abandoned quarry near the village of Neiva (Fig. 3). The sequence consists of uniformly dipping, well-bedded lavas, tuffs and carbonates. Six sites (30 samples) were

collected, spanning more than 50 m of stratigraphic thickness. Initial NRM intensities are generally in the range 80–200 mA/m. Most samples have maximum unblocking temperatures of between 500 and 580 °C and are demagnetised by alternating fields of up to 600 mT, indicating magnetite as the dominant remanence carrier (Fig. 6A and D). A low temperature present-day type direction is often removed below 250 °C, after which most samples yield reasonably well defined, single component directions of magnetisation which decay linearly to the origin in orthogonal projection (Fig. 6A and D). This direction can be identified in a total of 27 samples from all 6 sites at this locality (Table 1), yielding an overall site mean direction of $D=293°$, $I=-24.1°$, $n=6$ *in situ*, and $D=293°$, $I=31°$ $\alpha_{95}=7.6°$, $k=79.4$ after bedding correction.

5.4. Provincial Formation (Upper Albian–Cenomanian)

A total of eight sites (55 samples, 3 localities) were sampled from calcareous sandstones (PRO1–2), calcareous mudstones and limestones (PRO3 and REV1), tuffs and grey coloured limestones (NMR1–4). All of these sites are located close to the main axis of the Seibabo syncline (Fig. 3). Samples from sites PRO2 and PRO3 yielded fairly well defined directions, but there is poor within-site consistency of results (.95>28°) due to weak magnetisations and effects of weathering, and the data will not be discussed further.

After removal of a soft component at low temperatures, samples from site PRO1 show single component behaviour with reasonably well defined magnetisations which are directed towards the origin in orthogonal projection with shallow north/northeasterly in situ directions (Fig. 6B). Samples from site REV1 have much weaker NRM intensities (0.1 to 0.5 mA/m) and yield moderately well defined north/northeasterly intermediate in situ directions with unblocking temperature spectra of 100 to 300–400 °C. At higher temperatures the intensities were too low to yield any reliable data. Nevertheless, the within-site grouping of this intermediate temperature direction is fairly good and in good agreement with samples from site PRO1 (Table 1) and yield an overall mean direction of $D=029°$, $I=32°$, $\alpha_{95}=18.6°$, $k=7.0$, $n=11$, *in situ* and $D=044°$, $I=-38°$, $\alpha_{95}=9.8°$, $k=22.7$, after structural correction. The improvement in statistical parameters after structural correction is positive at the 99% level of confidence using the fold tests of McFadden (1990) and McElhinny (1964), at 94% unfolding. The reversal test (McFadden and McElhinny, 1990), however, is negative (observed angular difference is 17.5°, critical angular difference is 17.2°), and the reversed polarity directions themselves are rather unusual, given the Albian–Cenomanian age of the sediments. Two periods of reversed polarity, the mid-Albian M-2r and upper Albian M-3r, have been suggested in the literature (see Gradstein et al., 2004). While precise biostratigraphic age control for these rocks are lacking, they may correspond to one of these proposed intervals of reversed polarity. However, given the negative reversal test, low unblocking temperatures, and that the samples were collected from very steeply dipping beds (dips of 71° and 88°), thus the deviation from antipodality may be a structural artefact of plunging fold axes which were not observable in the field, these directions are not used in calculation of the overall mean.

Samples collected from uniformly dipping tuffs at sites NMR1–2 have initial NRMs of up to 5 mA/m and yield moderately well-defined directions of magnetisation during thermal treatment, generally with linear intensity decay and maximum unblocking temperatures of 580 °C (Fig. 6C). The pale grey carbonate samples (NMR3–4) are much more weakly magnetised (NRMs of approx. 0.1–0.5 mA/m), and only three samples from NMR3 yield stable directions of magnetisation. A total of 14 samples from sites NMR1–3 yield a high unblocking

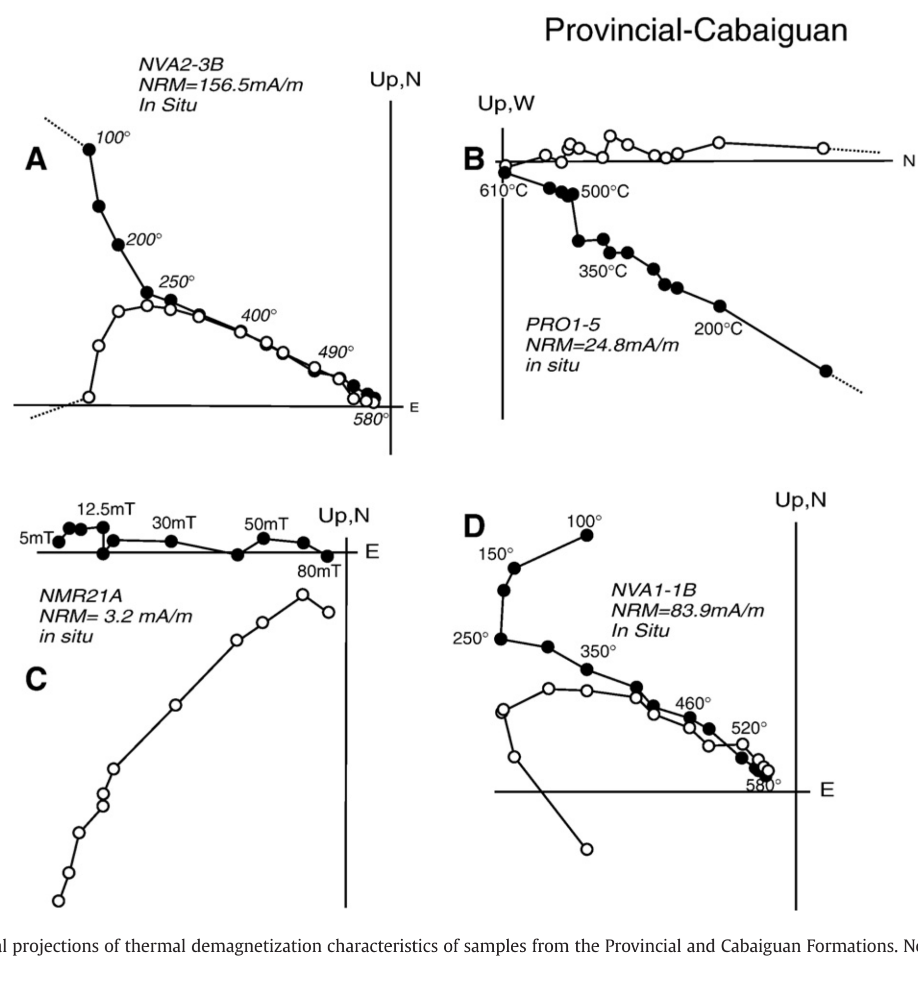

Fig. 6. Orthogonal projections of thermal demagnetization characteristics of samples from the Provincial and Cabaiguan Formations. Notation as in Fig. 5.

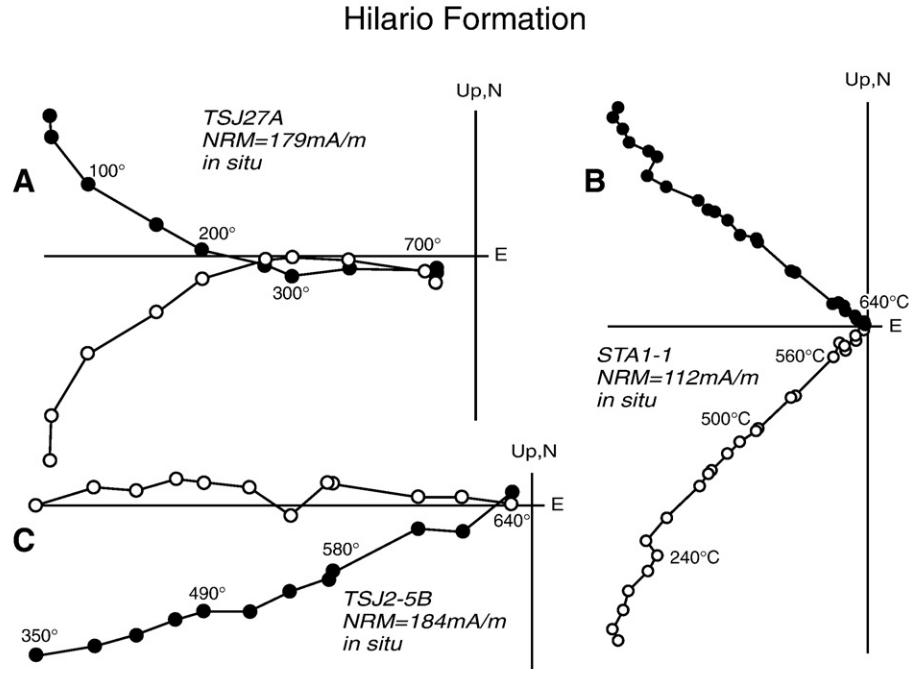

Fig. 7. Demagnetization characteristics of samples from the Hilario Formation, notation as in Fig. 5.

temperature component with consistent westerly down *in situ* directions of magnetisation (Table 1), giving an overall site mean direction of $D=275°$, $I=39°$, $n=3$, *in situ* and $D=303°$, $I=39°$, $\alpha_{95}=29.1°$, $k=18.9$, after bedding correction.

5.5. Bruja Formation (Coniacian–Santonian)

Due to limited outcrop conditions, the Bruja Formation was sampled at only one site (PRO4; Fig. 3). During thermal demagnetisation, these volcanic samples, all of which have high NRM intensities (up to 550 mA/m), show very stable behaviour. After removal of a present day type direction at low temperatures, demagnetisation trajectories show great circle behaviour until temperatures of about 450 °C when the stable end point direction can be identified in all samples as a shallow south-westerly direction *in situ*. The site mean direction is $D=243°$, $I=-11°$, $n=5$, *in situ* and $D=265°$, $I=-39°$, $\alpha_{95}=6.4°$, $k=144.2$, after bedding correction (Table 1). This is not similar to any direction isolated at other sites (see Table 1) and although an apparent sequence of flows was sampled, the stratigraphic spread was only 5–10 m. It is likely, therefore, that secular variation has not been averaged out and these directions will not be discussed further.

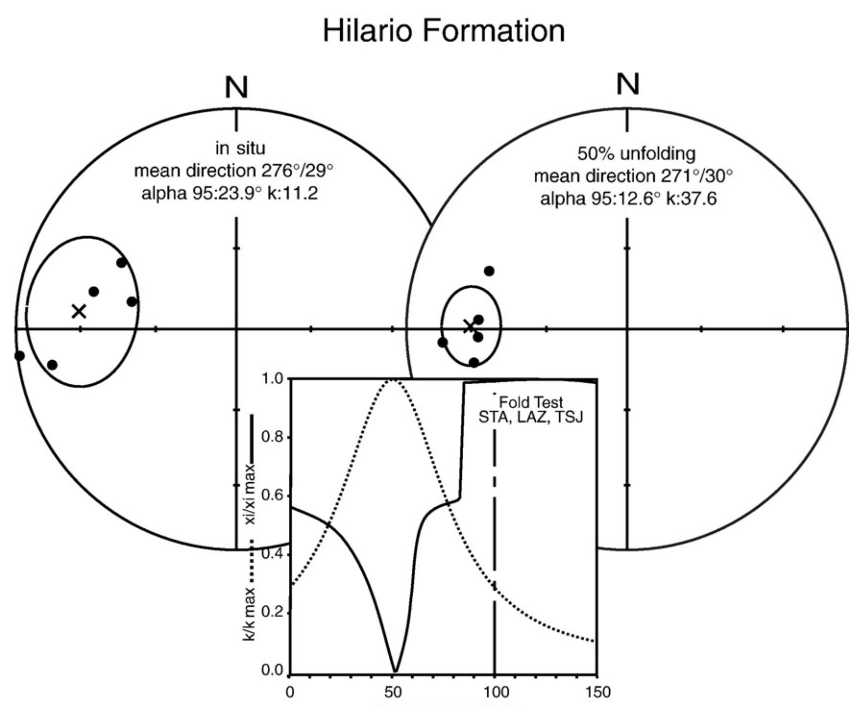

Fig. 8. Site mean directions and stepwise unfolding for the Hilario Formation. Notation as in Fig. 9.

5.6. Hilario Formation (Campanian)

The Hilario Formation was sampled at three different localities (6 sites, 40 samples) within the core of the Seibabo synclinal structure (Fig. 3). Sites STA1–2 (13 samples) were collected from volcaniclastic rocks on the northern limb of the syncline; LAZ1 (7 samples) from calcareous sandstones on the southern limb, and TSJ1–3 (20 samples) from sandstones and tuffs, also on the southern limb. The STA samples have high NRM intensities (approx. 110 mA/m), and during thermal demagnetisation a very well defined stable end point direction can be identified in a total of nine samples between 200 and 580–650 °C (Fig. 7B). The NRM intensities for the LAZ samples are much lower (approx. 2 mA/m), and yield less well defined directions of magnetisation. Nevertheless, a direction very similar to the high temperature northwesterly *in situ* direction isolated from sites STA1 and STA2 (Table 1) can be identified with maximum unblocking temperatures of approx. 480 °C.

At locality TSJ, the tuffs and sandstones of the Hilario Formation are poorly exposed along road tracks and are generally fairly weathered and altered. Initial NRM intensities range from 58.1 to 671.4 mA/m. Twenty three samples were demagnetized using thermal and AF techniques. Most specimens were only weakly magnetised with maximum unblocking temperatures of about 450 °C. Nevertheless, a westerly down direction of magnetisation can be identified in 4 samples, although the error parameters are rather high. Samples from TSJ2 are more strongly magnetised and more stable with max. T_{UB} 650 °C (Fig. 7A and C), indicating the contribution of both magnetite and haematite as carriers. A westerly shallow direction is identified, often after removal of a present day-type direction. Samples from TSJ3 are also fairly strongly magnetised but only scattered or present day-type directions could be identified. Combining the data from sites STA1–2, LAZ1 and TSJ1–2 yields an overall Formation mean direction of $D=276°$, $I=29°$, $\alpha_{95}=23.9°$, $k=11.2$, $N=5$ *in situ*, and $D=272°$, $I=26°$, $\alpha_{95}=24.1°$, $k=11.1$ after structural correction. Using the correlation test of McFadden (1990) this is a syn-folding magnetisation, with optimal statistical parameters at 50% unfolding which yields a mean of $D=271°$, $I=30°$, $\alpha_{95}=12.6°$, $k=37.6$ (Fig. 8).

6. Interpretation

6.1. Los Pasos and Mataguá Formations

The samples collected from upper Los Pasos and lower Mataguá Formations have a stratigraphic spread of approx. 10 My and so will be

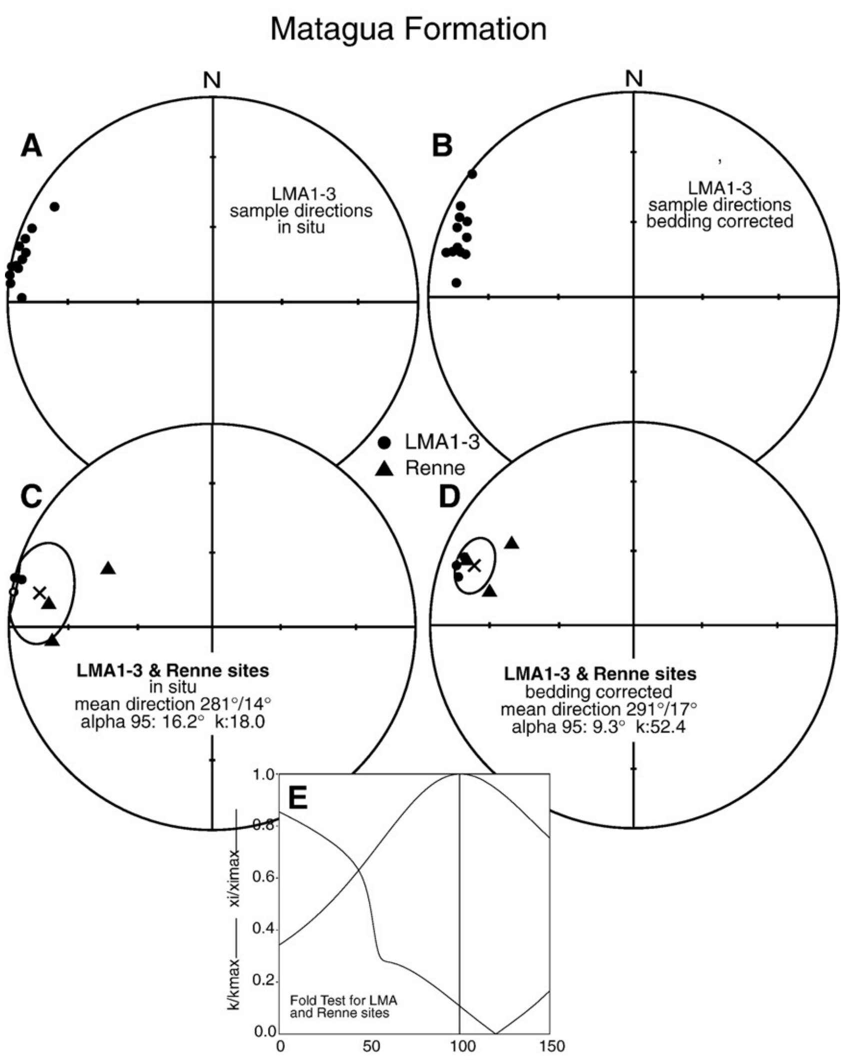

Fig. 9. Equal area projection of sample (A, B) and site mean (C, D) directions for localitites LMA and CRP. Included in panels c and d are the two results from Renne et al. (1991) for the Mataguá (triangles). Overall site mean directions for the Mataguá (sites LMA plus Renne et al., 1991) are shown in panels C and D with cone of 95% confidence. Also shown is the stepwise unfolding test of McFadden (1990) for the LMA and Renne et al. (1991) sites. Solid (open) dots indicate lower (upper) hemisphere projection. CRP site mean directions shown in 8C and 8D for reference.

discussed together. When the site mean directions identified from the three localities are compared (CRP, LMA and REV2–3, Table 1), it is clear that those from sites REV2 and REV3 are significantly different. As already mentioned, the statistical parameters for these two sites decrease significantly upon structural correction, indicating the directions identified represent post-folding remagnetisation. The in situ inclination values indicate palaeolatitudes of approx. 22° and may represent an Eocene or younger overprint. The declination values suggest significant rotation, although the beds sampled at these localities were strongly folded (overturned), thus this somewhat anomalous direction may be a structural artefact.

Samples from the Los Pasos Formation yield a well-defined direction. Although identified in only a limited number of samples, the inverse polarity and directional consistency with results from the overlying Mataguá Formation indicate a primary magnetisation For locality LMA the high temperature direction is isolated in 3 sites, 12 samples and is shallow and westerly directed (Fig. 9). In a previous study of the Mataguá Formation in Central Cuba, Renne et al. (1991) obtained reliable data from three sites which yield directions similar to those obtained here (Table 1). Combining all results for the Mataguá (6 sites, 24 samples) yields an overall mean direction of $D=281°$, $I=14°$, $\alpha_{95}=16.2°$, $k=18.0$ *in situ* and $D=291°$, $I=17°$, $\alpha_{95}=9.3°$, $k=52.4$ after bedding correction. Using the correlation test of McFadden (1990) this is positive with 99% confidence at 100% unfolding (Fig. 9). This magnetisation, therefore, is interpreted as being primary in origin.

These data indicate that for Barremian–Aptian times there was no palaeomagnetically observable latitudinal movement of the arc which was at palaeolatitudes of 9° ± 5N. Anticlockwise rotations of approx. 100° since the Barremian and 70° since the early Aptian with respect to North are suggested by the declination values. The difference in rotation between the Los Pasos and Mataguá Formations may reflect either primary movement of the arc prior to deposition of the Matagua Formation, or later vertical axis block rotation during structural deformation of the arc.

6.2. Cabaiguán and Provincial Formations

Due to the closeness in, results from the Cabaiguán (~110–104 Ma) and Provincial (104–95 Ma) Formations will be discussed together. High unblocking temperature directions (Fig. 6) are identified in 6 sites (25 samples) from the Cabaiguán Formation (NVA, Table 1), and 5 sites (25 samples) of the Provincial Formation (NMR, PRO1 and REV1). Comparing the sample and site mean directions (Table 1, Fig. 10), the in situ directions are rather scattered but after bedding correction fall into two well defined groups, the northeast/southwest PRO1 and REV1 samples, and the northwesterly directed NVA and NMR samples, which differ only in terms of declination (Fig. 10). Combining the north westerly directions (9 sites, NMR1–3 and NVA1–6) yields an overall mean of $D=288°$, $I=-04°$, $\alpha_{95}=23.2°$, $k=5.9$, *in situ*, and $D=296°$, $I=34°$, $\alpha_{95}=8.4°$, $k=38.5$ after structural correction. The improvement in statistical parameters is significant with 99% confidence (McElhinny, 1964), and at 95% confidence and 108% unfolding using the test of McFadden (1990). In an earlier study, Renne et al. (1991) obtained similar results from the Provincial Formation. Combining all these data yields a bedding corrected mean of $D=301°$, $I=33°$, $\alpha_{95}=9.4°$, $k=24.8$, (11 sites); the correlation test of McFadden (1990) is positive with 95% confidence at 101% unfolding (Fig. 10). This magnetisation is, therefore, considered to be primary in

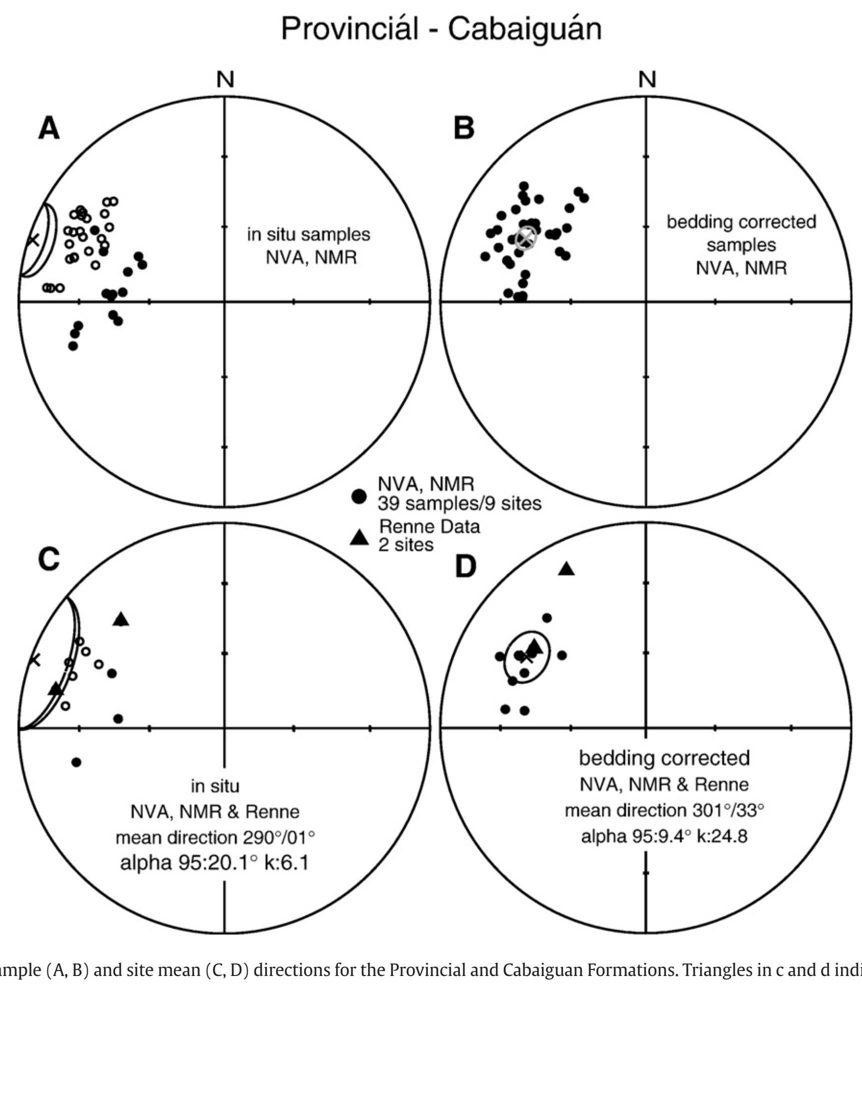

Fig. 10. Equal area projection of sample (A, B) and site mean (C, D) directions for the Provincial and Cabaiguan Formations. Triangles in c and d indicate data from Renne et al. (1991), other notation as in Fig. 9.

origin, mid Albian–Cenomanian in age and translates into a palaeolatitude of 18 ± 6.7°N. Anticlockwise rotation of approx. 70° relative to North is indicated by the declinations.

6.3. Hilario Formation

Reliable results were obtained from 28 samples (5 sites, 3 localities) of the Hilario Formation sediments. In terms of both inclination and declination, this direction is in keeping with the primary directions identified in the older formations. Between the late Campanian and the early Maastrichtian the Cretaceous arc ceased and was overthrust to the north over the Northern Ophiolite Belt. This magnetisation, therefore, was probably acquired during this deformation process which occurred shortly after rock formation, and indicates a late Cretaceous palaeolatitude of 16 ± 8°N. The declination values indicate 90° anticlockwise rotations relative to North.

6.4. Summary

Clearly primary pre-folding directions identified in a significant number of samples from the three different stratigraphic intervals, the lower Aptian Matagua Formation, the mid Albian–Cenomanian Cabaiguan and Provincial Formations, and a syn folding demagnetisation direction, which is thought to be early Maastrichtian in age, in the Campanian Hilario Formation. All have westerly declinations indicating anticlockwise rotations of up to 90° relative to North. Anomolous apparently pre-folding declinations in sites PRO1, REV1 and post folding REV2 REV3 are also identified. The significant deviation in declinations in these sites which are located within the main axis of the Seibabo syncline structure may be structural artefacts, or the result of vertical axis block rotations. The steepening of inclination values from 17° in the Barremian/Albian to 33° in the Aptian/Cenomanian indicates northward movement of the arc.

7. Conclusions and Palaeogeographic model

Recent palaeomagnetic studies and reviews of previously published data for the North and South American plates demonstrate that neither of these continents experienced significant apparent polar wander in Cretaceous times (Beck, 1999; Housen et al., 2003), both being characterised by significant periods of apparent "stillstand" in the early and the lower late Cretaceous. Motion of these plates at this time was restricted to westward movement and rotation about an Euler pole coincident with the geographic spin axis (Beck, 1999) whereas, in contrast, the Caribbean region was highly mobile. The new results presented here provide the first high quality palaeomagnetic data with which to constrain these movements (Fig. 11). As mentioned previously, the polarity of subduction in the Cretaceous remains a matter of discussion. The polarities shown in Fig. 11 follow those of Pindell et al. (2006).

In general, the data presented are in good agreement with previously published models and demonstrate gradual north eastward movement of the arc in the early Cretaceous (Fig. 11). At the onset of arc magmatism in the Aptian, volcanic and sedimentary

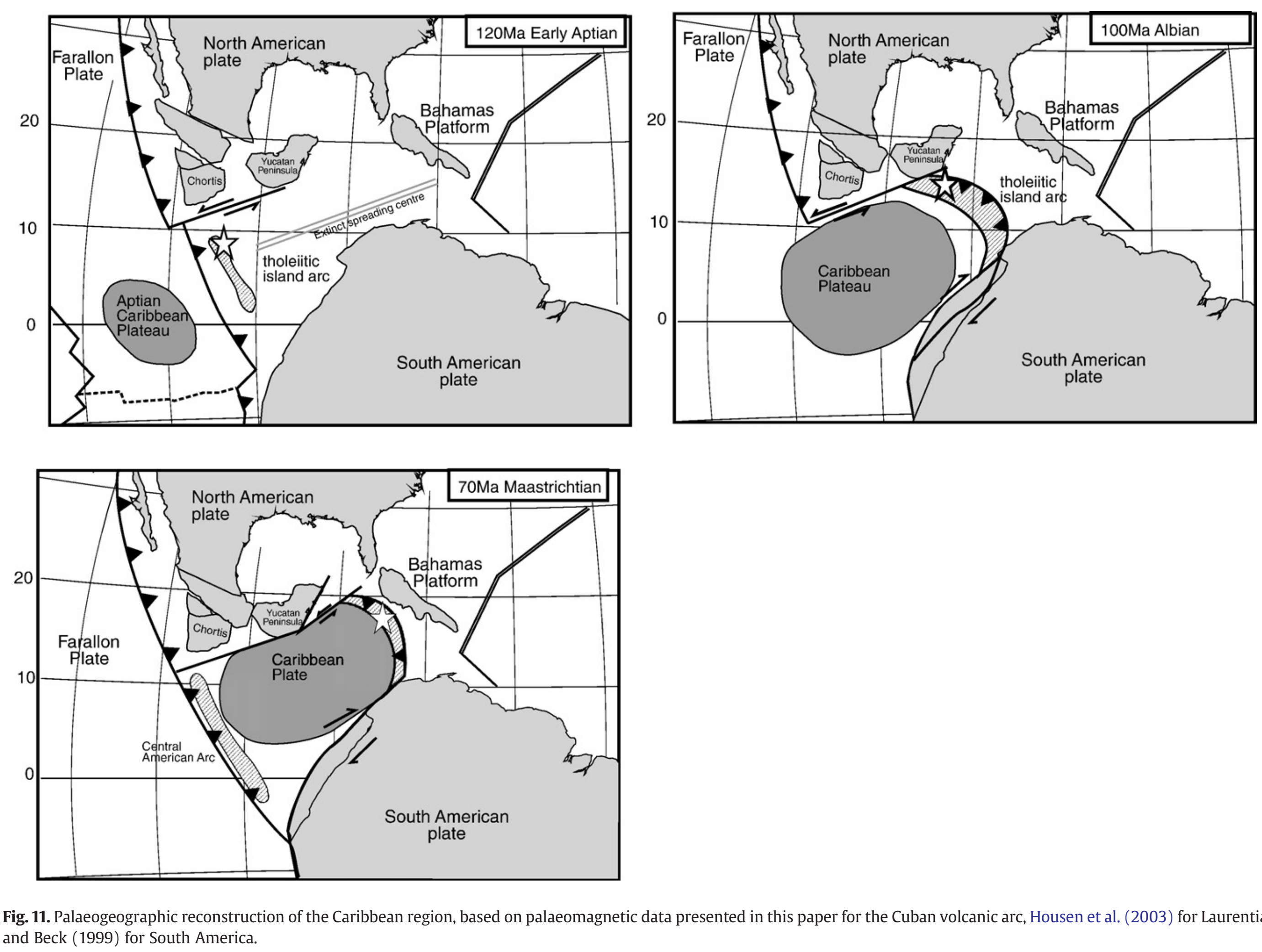

Fig. 11. Palaeogeographic reconstruction of the Caribbean region, based on palaeomagnetic data presented in this paper for the Cuban volcanic arc, Housen et al. (2003) for Laurentia and Beck (1999) for South America.

sequences now located in central Cuba clearly demonstrate that the northern segment of this new arc was located at 9 ± 5.6°N. In early Albian times there was a change to calc-alkaline magmatism, whether or not this was accompanied by a change in subduction polarity remains controversial. Nevertheless, our new data show that it was accompanied by northward movement of the arc such that by late Albian times the northern segment was some 900 km further north at a latitude of 18 ± 6.7°N (Fig. 11B). Volcanic activity in the arc ceased in the late Campanian, accompanied by collision with Bahamas Platform/Caribeana during the Maastrictian and thrusting of the arc rocks over the Northern Ophiolite Belt. This resulted in syn-deformational remagnetisation of upper sedimentary rocks (Hilario Fm.) in the arc, which were located at a palaeolatitude of 16 ± 8°N at the time of remagnetisation (Fig. 11C). These results provide important new constraints for the evolution of the Cretaceous Volcanic Arc, demonstrating that the main phase of northward movement was in the early Cretaceous. From Albian times though to collision with the N American Plate during Maastrichtian-early Palaeocene times the northern segment of the arc remained at constant palaeolatitudes. Subsequent to collision, the sequences of the central Cuban Cretaceous Volcanic Arc were rotated up to 90° anticlockwise. This was probably related to consolidation of the orogenic belt and is in keeping with the overall sinistral transpressional tectonic regime along this southern margin of the North American plate.

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