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Reconstructing the Mesozoic–early Cenozoic evolution of northern Philippines: clues from palaeomagnetic studies on the ophiolitic basement of the Central Cordillera

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SUMMARY

The first reliable palaeomagnetic data from the Cretaceous to Eocene ophiolitic basement rocks in the Philippines are presented. A total of 12 drill core sites from five localities in the Central Cordillera in northern Luzon, Philippines were sampled. Eight drill core sites were from pillow basalts, and four were from diabase feeder dykes. Combining the characteristic remanent magnetization direction from these sites gives a mean *in situ* direction of Dec = 162.2°, Inc = −21.4° (α_{95} = 17.0°, k = 21.1) and a tilt-corrected direction of Dec = 159.3°, Inc = −12.5°, α_{95} = 6.0°, k = 162.5. Along with other lines of palaeomagnetic evidence, this clustering suggests that the magnetization is primary and that the ophiolitic basement rocks of the Central Cordillera formed at subequatorial latitudes (6.3°N ± 3.1°). This information further suggests that the basement rocks of northern Luzon were formed close to where the island was during the early Cenozoic. These rocks could represent relicts of the proto-Philippine Sea Plate.

Key words: Paleomagnetism applied to tectonics; Asia.

1 INTRODUCTION

As in the other regions of the western Pacific, reconstructing the Mesozoic–early Cenozoic evolution of the Philippine arc is still problematic. The lack of any model showing the evolution of the region during this period is likely a result of the limited information base that is available. It is long recognized, however, that Mesozoic ophiolite and ophiolitic complexes exist in the Philippines, which, when carefully studied, could provide clues on the early evolution of the region. Already, geochemical studies (e.g. Yumul *et al*. 2003; Tamayo *et al*. 2004, Encarnacion 2004; Queaño 2006; Yumul *et al*. 2006) have been conducted in many of these ophiolite sequences and their associated sedimentary carapace, the results of which point essentially to formation in subduction-related geodynamic settings. The question, however, still remains: did these units originate from a single marginal basin or from several marginal basins? In addressing this point, it is crucial that information relating to the palaeolatitude formation of these ophiolites be obtained. No reliable palaeomagnetic data have been reported previously from these rocks to determine the position of the basin at the time of their formation. This work reports the first reliable palaeomagnetic result from the ophiolitic basement rocks in Luzon, providing crucial information on the origin of these rocks and conversely, the early evolution of the Luzon arc. The data were obtained from the Cretaceous–Eocene (?) ophiolitic basement rocks (herein referred to as the Chico River pillow basalts and dykes) in the Central Cordillera in northern Luzon.

2 TECTONIC SETTING OF NORTHERN LUZON

The Central Cordillera in northern Luzon forms part of the Philippine Mobile Belt (PMB), an active deformational zone bounded by two oppositely dipping subduction zones namely the Manila-Negros Sulu-Cotobato Trench to the west and the East Luzon Trough–Philippine Trench to the east (Fig. 1). The western trench system is where the marginal basins (South China Sea, Sulu Sea and the Celebes Sea) of the Eurasian Plate are subducting (Rangin & Pubellier 1990; Ringenbach *et al*. 1993). In the central Philippines, convergence of the Eurasian Plate with the PMB is expressed as a continent (Palawan Microcontinental Block)–arc collision zone. It is to be noted that the Palawan Microcontinental

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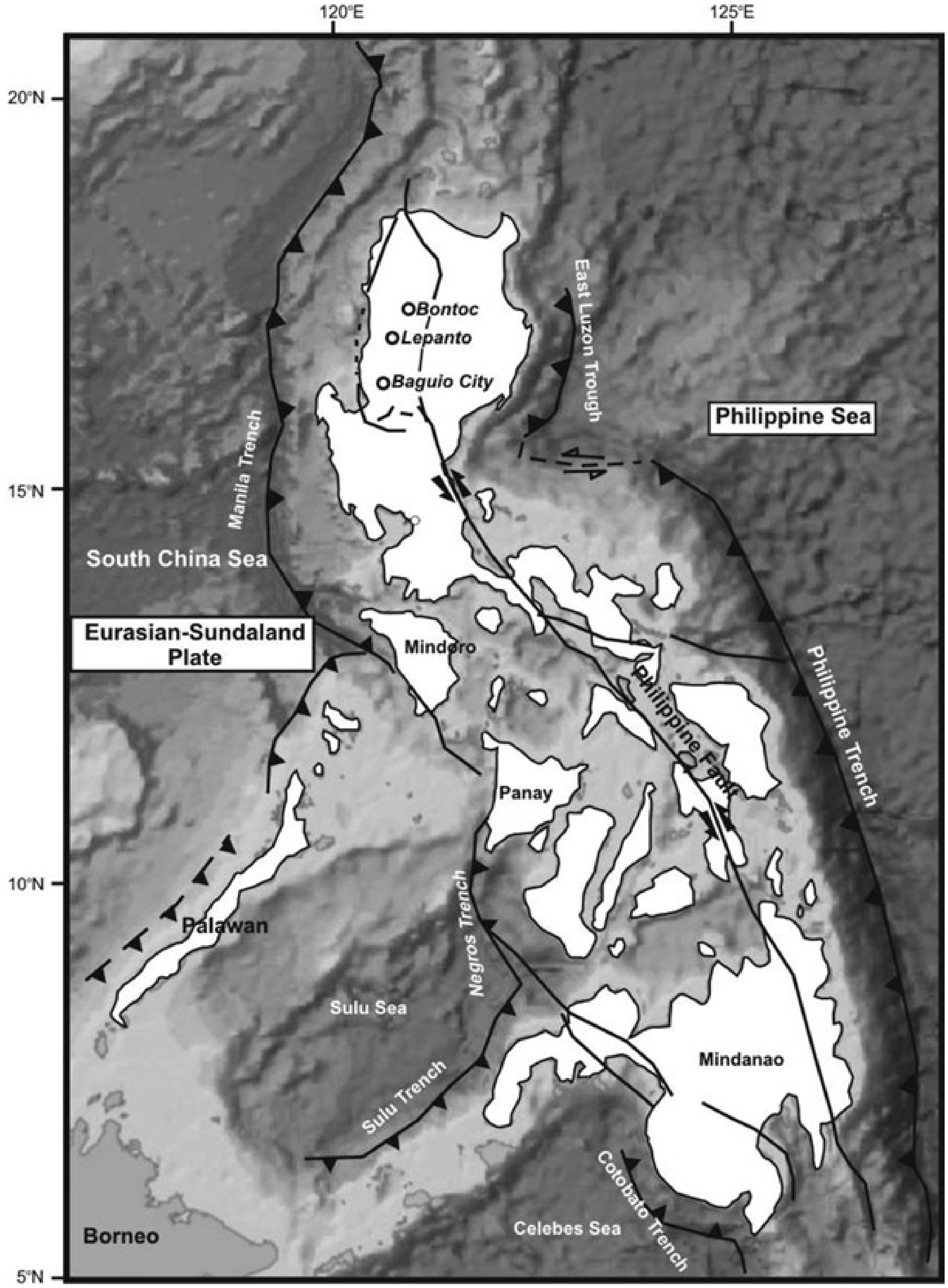

Figure 1. Tectonic setting of the study area.

Block is that fragment in southern China, which translated southeastwards, following the opening of the South China Sea sometime during the Oligocene (Lewis & Hayes 1984; Rangin 1989; Pubellier *et al.* 1991; Quebral *et al.* 1996; Yumul *et al.* 2003 2008).

The Philippine Trench and the East Luzon Trough comprise the eastern trench system, where the West Philippine Basin, the oldest marginal basin of the Philippine Sea Plate, is subducting. Activity along the eastern trench system is generally considered to be young. Ozawa *et al*. (2004) suggest southern propagation of subduction along the Philippine Trench from about 8 Ma, based on the temporal and spatial distribution of volcanic rocks along the eastern Philippines. Similarly, activity along the East Luzon Trough is thought to be young, given the shallow west-dipping Benioff zone associated with this plate boundary (Bautista *et al*. 2001). The presence of an eastward verging thrust zone observed in Taiwan (north of Luzon) also suggests incipient convergence between the Benham Plateau (a large igneous province within the West Philippine Basin) and Luzon along the East Luzon Trough (e.g. Cardwell *et al*. 1980; Stephan *et al*. 1986; Rangin & Pubellier 1990). The left-lateral Philippine Fault Zone accommodates the oblique convergence between the Philippine Sea and Eurasian plates bounding the Philippine Archipelago (Fitch 1972; Barrier *et al*. 1991; Aurelio 2000).

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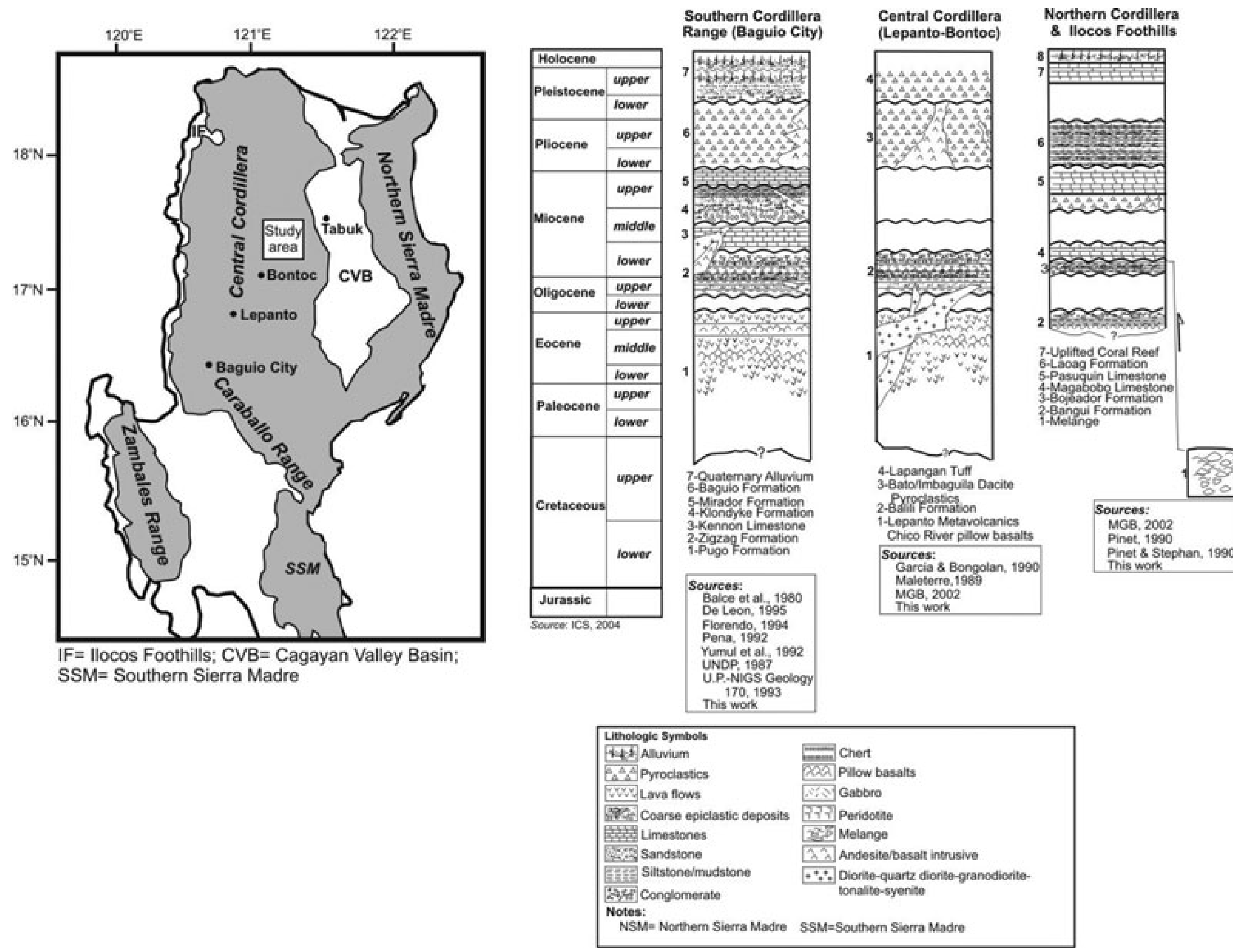

Figure 2. Stratigraphy of the study area.

3 GEOLOGY OF THE CENTRAL CORDILLERA

The Central Cordillera is the longest mountain range in the Philippines (Fig. 2). Geological data from the southern (Baguio City) and central (Lepanto-Tabuk) portions of the range suggest that it is a magmatic arc, formed mainly in response to subduction along the Manila Trench since the early Miocene (Bellon & Yumul 2000). This magmatic arc is floored by a Cretaceous-Eocene (?) ophiolitic complex, referred to as the Pugo Formation in the southern Central Cordillera. Correlatives of this formation are the Chico River pillow basalts and dykes exposed in the central portion of the range. Cenozoic volcaniclastic and epiclastic (mostly occurring as turbidites) rocks as well as reefal limestones overlie the ophiolitic basement rocks. Fig. 2 summarizes the stratigraphy of the Central Cordillera.

It is worth noting that Florendo (1994) combined the units of Pugo Formation with gabbroic plutons, mafic sheeted dykes and volcano sedimentary cover exposed in Baguio City in the southern Central Cordillera and adopted the term 'Itogon Ophiolite'. This was first introduced by the United Nations Development Programme (UNDP) (1987). He then assigned a late Oligocene to early Miocene age based on the radiometric dating of high-level gabbro and the age of the overlying volcanic carapace (Halfway Creek Formation). However, studies conducted by other workers (e.g. Pena 1992; Yumul 1994; this work) in Baguio City indicate the presence of lithologies different from those reported by Florendo (1994). These studies report diorite, quartz diorite, granodiorite and andesites as the dominant igneous bodies rather than the gabbros reported by Florendo (1994). They were emplaced in different pulses during the late Oligocene to Pliocene (Maleterre 1989; Bellon & Yumul 2000). Florendo (1994) also reported the sedimentary carapace (the Halfway Creek Formation) as being composed of a sequence of basaltic pillows, pillow breccia and conglomerates, turbiditic wackes and rare massive rhyolite flows, red shales, calcarenties, calcirudites and micritic limestone. However, field mapping of areas where the Halfway Creek Formation is supposedly exposed, reveals widespread exposures of tuffaceous conglomeratic sandstone (part of the Zigzag Formation) and limestone (Kennon Limestone; Pena 1992; this work). Only minor volcanic flows were encountered. Encarnacion (2004) also recognized that some of the areas mapped by Florendo (1994) as sheeted dykes were, in fact, fractured lava flows.

Although the findings of Florendo (1994) appear to be in conflict with those obtained by other workers, there seems to be a consensus suggesting that the Central Cordillera has an ophiolitic basement. For instance, Maleterre (1989) introduced the Pingkian Ophiolite for the gabbro–pillow–basalt–dyke complex association presumably of pre-Oligocene age in the southern Cordillera. Ringenbach (1992) also recognized the ophiolitic units (largely massive and pillow basalts and sheeted dykes) of the Cretaceous?

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Lepanto Metavolcanics as forming the basement of Lepanto-Cervantes region situated in the central part of the range. Yumul *et al*. (1992) argued for a possible correlation between the Lepanto Metavolcanics and Pugo Formation and further suggested formation of these units in a subduction-related marginal basin based on the chemistry of the volcanic-hypabyssal rocks.

Obtaining a reliable radiometric age for the ophiolite basement of the Central Cordillera is unsuccessful to date (including this work). However, previous authors commonly agree on a Cretaceous, possibly as young as Eocene age, for the basement rock of the Central Cordillera, based on stratigraphic relationships with the overlying sediments.

4 PALAEOMAGNETIC SAMPLES AND TECHNIQUES

Palaeomagnetic samples were obtained mainly along the Chico River, between Bontoc and Tabuk, in the central portion of the Central Cordillera (Fig. 2). In that locality, good exposures of ophiolitic basement rocks exist, mostly of pillow lavas intruded locally by diabase dykes. The orientation of the pillow lavas varies between outcrops, but generally is towards the west. Attempts were also made to collect samples from the Pugo Formation in the southern Central Cordillera. Unfortunately, exposures are limited and are too weathered and/or fractured for palaeomagnetic sampling.

A total of 12 drill core sites from five localities ($\sim$9 km stretch of ground) were sampled. Eight drill core sites were from pillow basalts whereas four were from diabase feeder dykes. A portable gas powered rock-drill was used to obtain six to eight, 2.54-cm-diameter core samples at each site.

Stepwise alternating field and/or thermal demagnetization were applied in the core specimens. Demagnetization behaviour was examined by visual inspection of vector endpoint diagrams (Zijderveld 1967) and equal area stereographic projections. The characteristic and secondary magnetization components were identified via principal component analysis (Kirschvink 1980) and/or the use of the statistics of Fisher (1953). Remanence carriers were determined by conducting isothermal remanent magnetization (IRM) and the Lowrie test (1990). The former experiment also involved looking at the IRM ratio developed by Ali (1989, in Ali & Hall 1995; Ali *et al*. 2001), with a ratio above 0.9 being indicative of magnetite as the dominant carrier. Demagnetization spectra of the IRMs adopting Lowrie's method provided more concrete results, suggesting remanence contribution from different carriers.

Specimens displaying chaotic behaviour (i.e. those with components having a maximum angular deviation or MAD $\geq 10°$) were discarded in the determination of the site mean directions. The ratio of natural remanent magnetization (NRM) to the IRM demagnetization technique developed by Fuller *et al*. (1988) and Cisowski *et al*. (1990) was also applied on representative specimens to discriminate primary remanence from secondary chemical signal. This method is particularly useful for specimens bearing fine magnetite in that primary thermoremanent magnetization and secondary chemical signal are suggested when NRM/IRM ratios are greater than 10^{-2} and less than 10^{-3}, respectively.

5 PALAEOMAGNETIC RESULTS

5.1 Pillow basalt sites

Most pillow basalt samples (e.g. LZ15, 16, 17 and 22) have low NRM intensities, with values ranging from 0.2 to 4 mAm^{-1}. Typically, the pillow basalt specimens have two component remanences comprising a low coercivity signal, usually removed at $\sim$10 mT (e.g. LZ15, 16 and 17), and a higher stability characteristic remanent magnetization (ChRM; Fig. 3). Site LZ22 has a significant low coercivity component (LCC) removed at $\sim$25 mT. The mean direction of the LCC in most sites is poorly defined ($\alpha_{95} > 15°$). However, when the LCC directions of the samples (with MADs $< 10°$) are plotted, most *in situ* directions cluster near to that of the present field, suggesting that the LCC is likely a VRM (viscous remanent magnetization).

The direction of the ChRM was determined using the statistics of Fisher (1953) instead of the conventional principal component analysis. The former method provided a more precise determination of the ChRM direction of specimens, especially those having weak magnetizations and displaying somewhat 'noisy' behaviour. Three sites (LZ11, 19 and 20) were excluded from palaeomagnetic–tectonic modelling due to secondary overprinting or inconsistency in demagnetization behaviour of the ChRM components. Four sites (LZ15, 16, 17 and 22) have ChRM directions that group well at the sample mean level ($\alpha_{95} < 10°$; Fig. 4). In tilt-corrected coordinates, the latter sites have SSE declinations and negative shallow inclinations. It is noteworthy that a specimen from LZ15 has a direction antipodal to that of the other specimens. In contrast, site LZ14 yielded a marginally acceptable ChRM grouping ($\alpha_{95} = 3.9°$). However, its inclination ($+48.4°$) is anomalously steep compared with the other pillow basalt sites, and hence, the direction from this site is excluded from tectonic modelling. The mean direction of the four pillow basalt sites with $\alpha_{95} < 10°$ is: *in situ* Dec $= 164.2°$, Inc $= -18.5°$, $\alpha_{95} = 21.4°$, $k = 19.4$; tilt-corrected Dec $= 159.9°$, Inc $= -13.3°$, $\alpha_{95} = 7.8°$, $k = 139.7$. The significant improvement in the direction clustering statistics suggests that the remanence predates folding (Table 1).

The magnetic carriers in the samples were determined using IRM experiments. Most representative pillow basalt specimens from the different localities yielded IRM ratios of 0.99, which suggests that magnetite is the principal remanence carrier (Fig. 5; Table 1). In two of the sites, some remanence contribution from maghemite and titanomagnetite is deduced from the LCC and intermediate coercivity component (ICC) fractions and the discontinuity in the LCC and ICC curves (Figs 6 and 7). Nonetheless, all specimens were adequately demagnetized and the calculated ChRM directions are consistent between specimens from each site (particularly those with $\alpha_{95} < 10°$). In addition, the application of tilt correction has also significantly improved the clustering statistics of the ChRM mean direction. Although maghemization may have resulted in a decrease in magnetic intensity, the process appears to have imparted negligible effects on the rocks, which allowed for the preservation of primary magnetization directions.

Very little palaeomagnetic information is available on palaeogene to Early Neogene rocks in Luzon. Nevertheless, Fuller *et al*. (1983) have reported Eocene rocks from the Zambales ophiolite and associated formations in nearby Tarlac and Pangasinan as characterized by shallow inclination directions (mean I $= -8°$). Similarly, Queaño (2006) has also shown Upper Eocene clastic sedimentary rocks of the Bangui formation (mean I $= 2.9°$) and Late Oligocene–Early Miocene Palaui pillow basalts (mean I $= 6.3°$) to lie intermediate between the calculated inclination angle for the Cretaceous–Eocene Chico pillow basalts (mean I $= -12.5°$) and the Middle Miocene Klondyke Formation (mean I $= 19.0°$; Queaño 2006) or the present-day geomagnetic inclination in the region (I $= 19.667°$; IGRF 2005). Therefore, all things considered, there is sufficient basis to assume that the isolated ChRM and calculated

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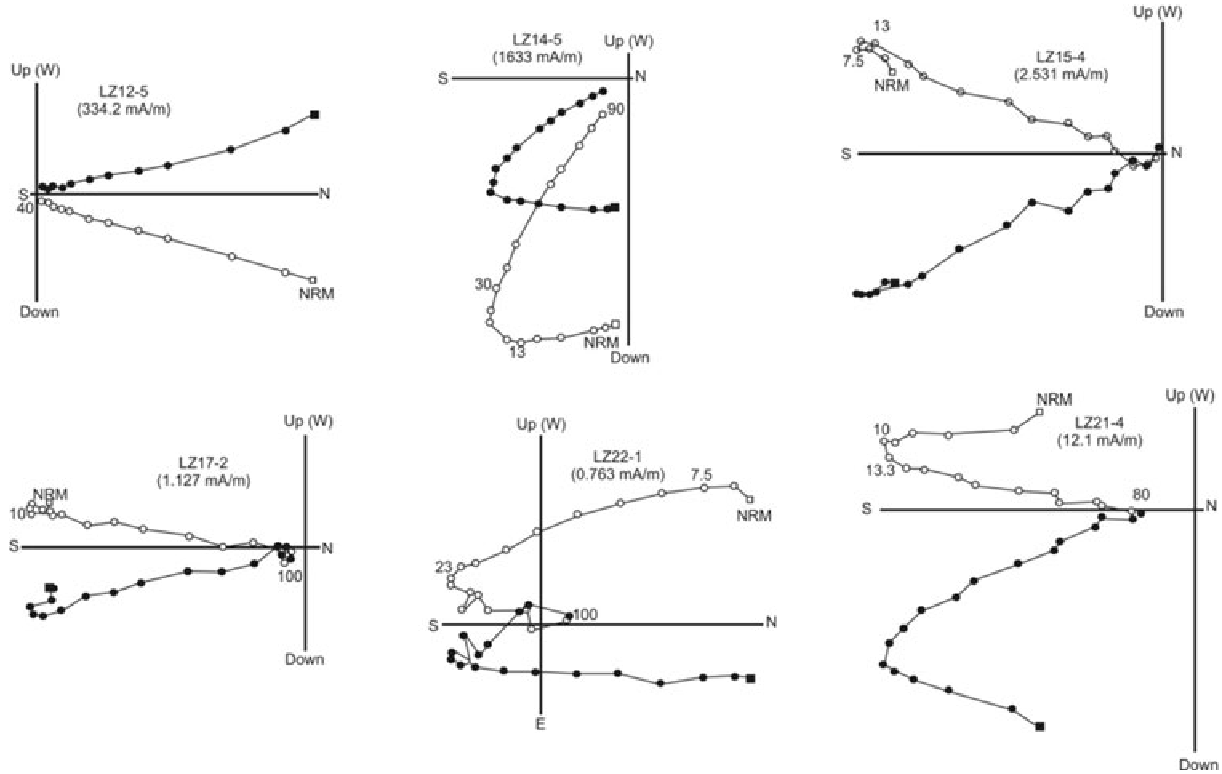

Figure 3. Vector endpoint plots (Zijderveld 1967) showing examples of demagnetization data in tilt-corrected coordinates of ophiolitic basement rocks along the Chico River and adjacent areas. Solid/open symbols are projections onto the horizontal/vertical planes.

palaeoinclination directions are indeed primary and are representative of the magnetization acquired by the lavas at crystallization during the Cretaceous.

5.2 Dyke sites

Three (LZ12, 13 and 21) out of four sites from the diabasic dykes have directions that could be evaluated for palaeomagnetic–tectonic modelling (Site LZ18 was rejected as the specimens exhibit different/erratic demagnetization behaviour). The dykes likely act as feeders to the pillows (and hence, they are magnetically coeval). NRM intensities of the lava flow specimens are variable, with values ranging from 0.2–400 mA m^{-1}. Sites LZ12 and 13 yielded single components of magnetization (Fig. 4). Specimens from LZ12 fully demagnetized at 35–50 mT, whereas those from LZ13 have ~20 per cent of the initial NRM remaining at 100 mT. Subsequent thermal demagnetization of specimens from the latter site did not give any useful results, as the specimens exhibited erratic magnetization behaviour. In contrast, site LZ21 yielded two components: an LCC, removed at 10–23 mT, and a higher stability ChRM, which converges to the origin ≥13 mT. It is noted, however, that three specimens from LZ21 do not directly converge to the origin, and that they showed noisy and very weak (<0.3 mA m^{-1}) magnetizations at the last stages of demagnetization treatment. As such, it was not possible to isolate the ChRM of the specimens by the conventional principal component analysis. Instead, ChRM directions of the specimens were estimated using Halls' (1978) converging remagnetization circles method.

ChRM directions for the dykes group well at the sample level with $\alpha_{95} = 15°$. However, the directions do not show any common trend in both *in situ* and tilt-corrected (i.e. using that applied for the pillow basalts assuming a coeval magnetization) coordinates. The ChRM of LZ13 appears to be a secondary overprint (VRM), with the *in situ* direction oriented subparallel to the present field. This observation is also reflected in the NRM/IRM demagnetization results that show ratio values below 10^{-3} (Fig. 7). In contrast, representative specimens from LZ12 and 21 have NRM/IRM values that sit midway between a clear primary (10^{-2}) and a clear secondary (10^{-3}). Site LZ12 has, in tilt-corrected coordinates, a NNW declination and a negative inclination (−25.0°), whereas LZ21 has a SSE declination and a negative, shallow (−9.0°) inclination. Interestingly, the palaeomagnetic behaviour (e.g. the presence of two components of magnetization) and the mean ChRM direction of LZ21 are similar to those of the pillow basalts. This observation further supports the notion that the pillow basalts and the dyke are magnetically coeval (hence, also implying a primary magnetization for the dyke). Combining the ChRM direction of LZ21 with the individual mean ChRM directions from four pillow basalt sites gives a direction of: *in situ* Dec = 162.2°, Inc = −21.4°, α_{95} = 17.0°, $k = 21.1$; tilt-corrected Dec = 159.3°, Inc = −12.5°, α_{95} = 6.0°, $k = 162.5$. These data suggest that the rocks were formed at a subequatorial location (6.3°N ± 3.1°). Passage of the fold test is determined by getting the ratio of k after correction (ka) to k before tectonic correction (kb) (Butler 1992). The ratio obtained for the Chico River samples is 7.20 This ka/kb value exceeds the value of F distribution for the 5 per cent significance level (F6,6) of 4.28. The result suggests the statistical passage of the fold test.

As for LZ12, there is no compelling evidence to suggest that the site carries a primary remanence. In fact, the tilt-corrected mean direction of LZ12 resembles the LCC direction of some specimens from the pillow basalts and hence, implying that the magnetizations of LZ12 specimens are secondary overprints.

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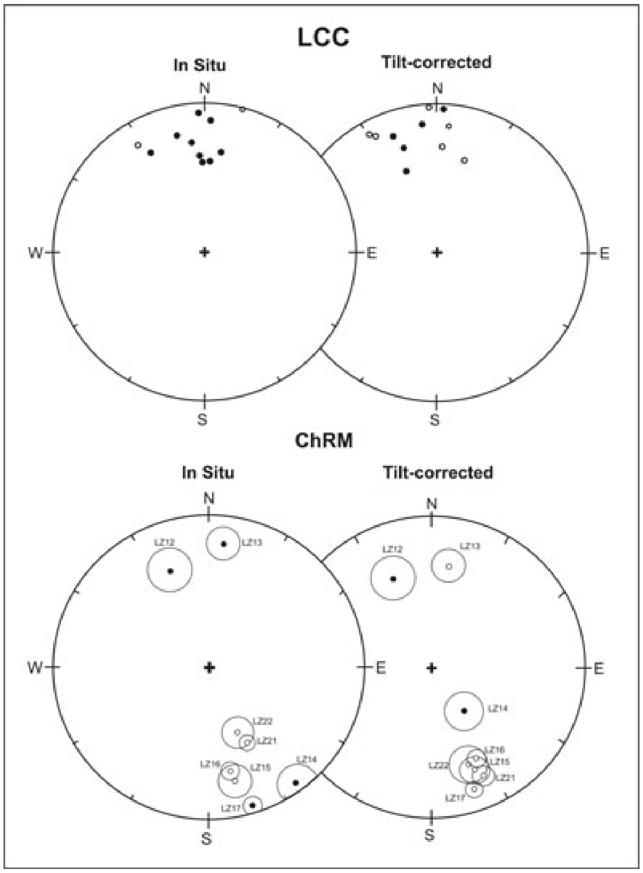

Figure 4. Summary of palaeomagnetic directional data from ophiolitic basement rocks along the Chico River and adjacent areas. Upper plots are the low coercivity component (LCC) directions of specimens (MAD < 10°). Lower plots are the characteristic remanent magnetization (ChRM) mean directions shown with their 95 per cent confidence circles. Solid/open symbols are downward/upward directed.

IRM acquisition experiments followed by the thermal demagnetization of IRM of a specimen from LZ21 indicate magnetite and some maghemite as principal carriers of remanence, similar to those noted in pillow basalt specimens (Fig. 6).

6 DISCUSSION

The Chico River pillow basalts provide evidence for the existence of a Mesozoic–early Cenozoic oceanic substratum upon which Luzon and neighbouring regions within the PMB were likely built (Queaño *et al*. 2008). Other Mesozoic ophiolitic outcrops in southeastern Luzon, such as the Upper Jurassic–Lower Cretaceous Lagonoy Ophiolite (Geary *et al*. 1988; Billedo 1994; Tamayo *et al*. 1996; David *et al*. 1997) and the ? Upper Cretaceous Angat Ophiolite (Haeck 1987; Arcilla *et al*. 1989; Yumul 1993), provide additional evidence. Similar outcrops can also be found in the central Philippines (south of Luzon) that include Samar, Antique, Cebu, Bohol, Dinagat and eastern Mindanao (McCabe & Almasco 1985; Hashimoto *et al*. 1979; Geary *et al*. 1988; Rangin 1990; Louca 1992). Geochemical studies (e.g. Yumul *et al*. 1992; Billedo 1994; Tamayo *et al*. 2001; Faustino *et al*. 2006; Yumul *et al*. 2006) indicate a suprasubduction signature for the ophiolites.

In the other regions of the western Pacific, pieces of Mesozoic suprasubduction ophiolite are also scattered (Pubellier *et al*. 2003). Ballantyne (1991) and Ali *et al*. (2001) reported Mesozoic ophiolite basement on eastern Halmahera, as well as on the islands of Gag, Gebe, Waigeo, Obi and other islands along the Sorong fault zone. Radiometric dates and fossil evidence indicate an age varying from Middle to Late Jurassic (Ballantyne 1991) to Early Cretaceous or older (Pigram & Panggabean 1984; Ali *et al*. 2001) for the ophiolites.

The similarity in both age and geochemistry of the ophiolite rocks in the western Pacific region suggests that these rocks might have a common provenance or basin origin. Unfortunately, much of the pre-Cenozoic tectonic elements in the region have been destroyed, thus, making the tectonic reconstruction for the region prior to the Cenozoic problematic. In the Philippines, obtaining palaeomagnetic data from Mesozoic ophiolitic rocks for tectonic reconstruction have met with only limited success. Previously acquired palaeomagnetic data from these units (e.g. Angat Ophiolite) are not only sparse but also unreliable owing to wide scatter of the palaeomagnetic plots (McCabe *et al*. 1987). The most reliable pre-Cenozoic palaeomagnetic data come from the terranes of Palawan, Mindoro and Panay in the Central Philippines (McCabe *et al*. 1987). However, these terranes are 'exotic' and of continental origin, having been derived from southern China (Taylor & Hayes 1983; McCabe *et al*. 1987; Yumul *et al*. 2003).

Nevertheless, despite the relatively few data obtained from this study, there are strong indications based on available regional geologic and other previous data regarding the conclusions presented here. Taking the palaeomagnetic data from previous authors (e.g. Queaño *et al*. 2007), showing Luzon essentially located at lower latitudes during most of the Cenozoic (at least starting from Eocene time), it is very likely that the Chico pillow basalts also originated near these latitudes, given the time frame involved in the formation of these basalts (i.e. Cretaceous–Eocene based on inferred age).

The primary magnetization of the Chico River pillow basalts and dykes provide clues on the Mesozoic–early Cenozoic evolution of northern Philippines. The data suggest that the ophiolitic basement of the Central Cordillera was formed at subequatorial latitudes (6.3°N ± 3.1°). Determining the amount and direction of rotation the basement rocks had undergone since its formation, however, is difficult to determine given the complex Cenozoic deformation that affected Luzon. Interestingly, Ali *et al*. (2001) obtained palaeomagnetic data from two areas, where a Mesozoic ophiolite on Obi Island in eastern Indonesia is exposed. Their results also suggest formation at a subequatorial latitude (mean tilt-corrected direction for the two areas is Dec = 219.4°, Inc = 12.1°, but the angular separation of 20.1° is noted).

Tracing the plate affinity of the ophiolitic basement of the Central Cordillera and other regions in Luzon is still an enigma. Using palaeomagnetic data as principal evidence, Queaño *et al*. (2007) suggest that during the early Cenozoic, northern Luzon formed part of the Philippine Sea Plate and had also been closer to the equator. Given the results herein presented, this implies that the ophiolitic basement rock of the Central Cordillera originated not too far from where the northern Luzon and adjacent regions were during their early stage of evolution. Deducing from Queaño *et al*.'s (2007) reconstruction, it would also be likely that the ophiolite basement (including the Chico basalts) of Luzon could have been part of the Philippine Sea Plate. Note, however, that models regarding the origin of the Cretaceous ophiolites in the Philippines point to either an autochthonous (e.g. Encarnacion 2004; Tamayo *et al*. 2004; Yumul 2007) or an allochthonous nature for these complexes. The latter model suggests that Luzon's ophiolitic basement is composite, the units being amalgamated by various tectonic processes, including subduction-related collision and strike-slip faulting

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Table 1. Summary of palaeomagnetic data from the ophiolitic basement rocks along the Chico River and adjacent areas in the Central Cordillera, northern Luzon, Philippines.

				LCC							| ChRM						
				In situ		Tilt-corrected					*In situ*		Tilt-corrected				IRM
Sample No.	Lithology	NRM (nT A J m)	N_p/N_c	Dec	Inc	Dec	Inc	α_{95}	k	N_p/N_c	Dec	Inc	Dec	Inc	α_{95}	*k*	ratio
Locality—Chico-1: Lat = 17° 12.638′N, Long = 121° 01.723′E; Strike = 018°, Dip = 50° → SE																	
LZ11	Pillow basalts	Site rejected; results overprinted by LZ12															
LZ12	Diabase dyke	334–402								4/6	338.5	21.4	355.8	–25.4	11.2	68.5	0.99
Locality—Chico-2: Lat = 17° 07.457′N, Long = 121° 02.548′E; 228°, Dip = 45° → NW																	
LZ13	Diabase dyke	73–377	–	–	–	–	–	–	–	4/6	6.5	11.7	235.6	–330	**7.1**	169.4	0.99
LZ14	Pillow basalt	274–3679	3/6	328.6	24.7	328.1	–19.6	67.8	4.4	3/6	143.7	3.7	146.6	48.4	13.9	79.8	0.99
Locality—Chico-3: Lat = 17° 09.249′N, Long = 121° 02.895′E; Strike = 168°, Dip = 34° → W																	
LZ15	Pillow basalt	0.1–3	3/4	352.3	12.7	344.2	13.7	17,2	52.5	**5/6**	167,4	–15.6	159,2	–13.3	6.9	125.0	0.99
LZ16	Pillow basalt	1–86	3/6	353.2	26.4	336.1	25.6	16.1	59.3	3/6	168.6	–20.8	156.3	–18.6	5.0	6027	0.99
Locality—Chico-4: Lat = 17° 09.639′N, Long = 121° 02.994′E; Strike = 135°, Dip = 15° → SW																	
LZ17	Pillow basalts	0.7–1.1	4/7	331.6	17.8	326.3	21.9	36.8	7.2	7/7	162.8	3.0	162.7	–4.4	3.6	275.7	0.99
LZ18	Diabase dyke	Site rejected; no common trend															
Locality—Chico-5: Lat = 17° 12.136′, Long = 121° 04.204′; Strike = 240°, Dip = 20° → NW																	
LZ19	Pillow basalt	Site rejected; only two useful specimen															
LZ20	Pillow basalt	Site rejected; no common trend															
LZ21	Diabase dyke	3–54	6/7	5.3	13.6	5.2	–11.2	9.9	46.6	6/7	153.4	–32.4	156.8	–9.2	4.8	196.9	0.99
LZ22	Pillow basalt	0.7–1	3/6	356.3	162	3564	–8 9	150	20.9	3/6	156.7	–40.5	161.2	–16.8	9.8	159.8	0.99
ChRM Mean																	
Pillow basalts (U15, 16, 17 and 22)																	
	Mean *in situ*									4/7	164.2	–18,5			21,4	19.4	
	Mean tilt-corrected											159.9	–13,3	7,8	139.7		
Pillow basalts and dyke (LZ15, 16, 17, 21 and 22)																	
	Mean *in situ*									**5/12**	162.2	–21.4			17.0	21.1	
	Mean tilt-corrected											159.3	–12.5	6.0	162.5		

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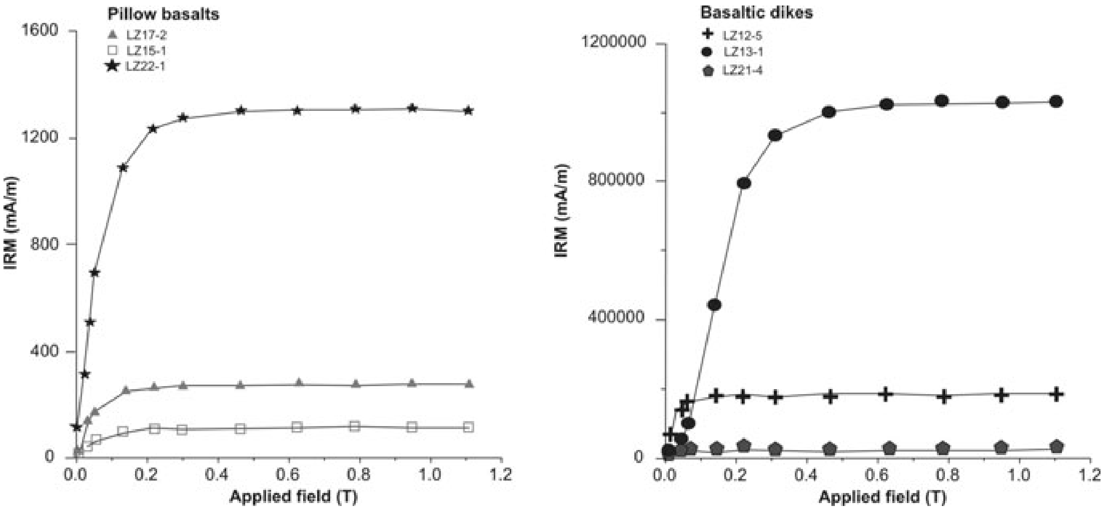

Figure 5. IRM acquisition curves for representative specimens from ophiolitic rock sites along the Chico River and adjacent areas.

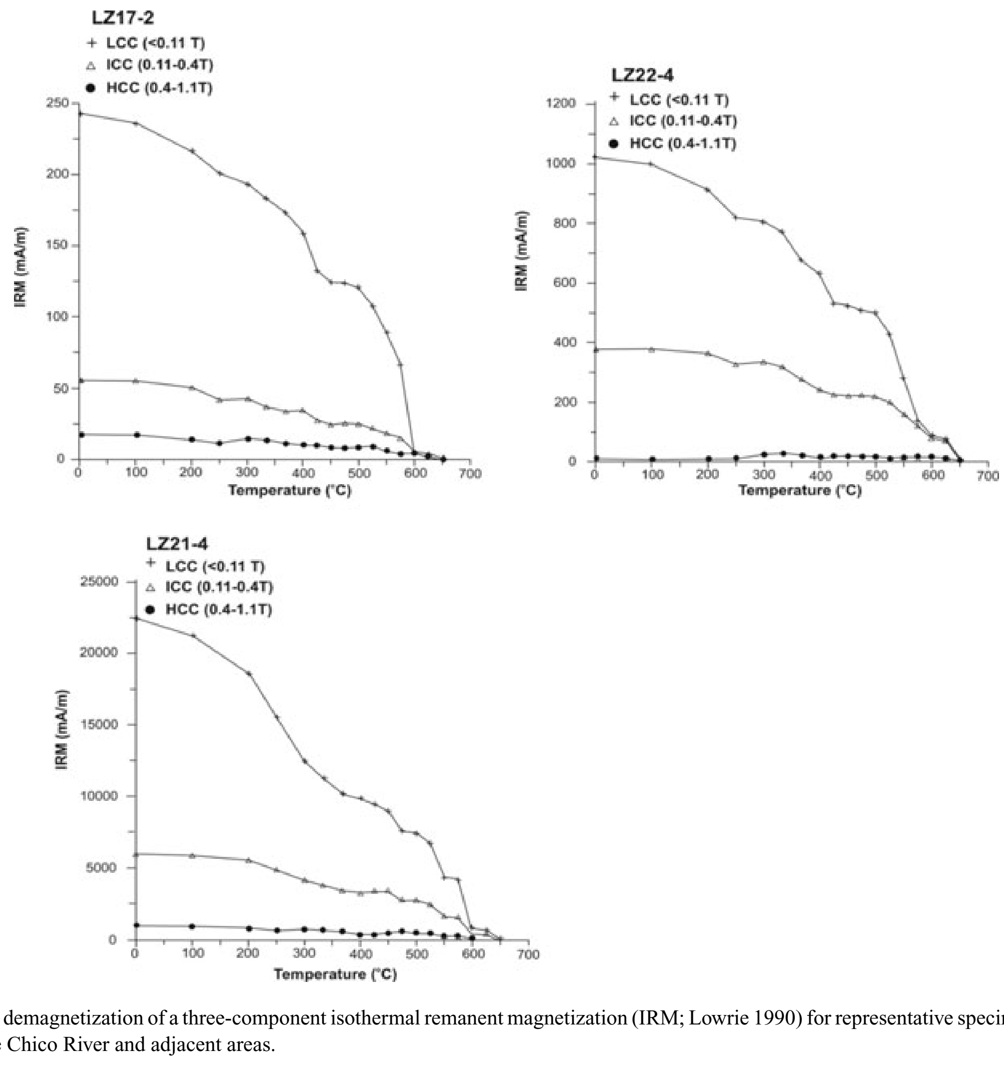

Figure 6. Thermal demagnetization of a three-component isothermal remanent magnetization (IRM; Lowrie 1990) for representative specimens from ophiolitic rock sites along the Chico River and adjacent areas.

(e.g. Dimalanta & Yumul 2004). In addition, previous workers (e.g. Yumul *et al*. 2003; Tamayo *et al*. 2004; Dimalanta & Yumul 2006) further suggested that these ophiolites could have been part of the proto-Philippine Sea Plate or proto-Molucca Sea Plate of Cretaceous age. Whether these 'proto plates' did exist is still a subject of debate. To note, Ali *et al*. (2001) implied that the Philippine Sea Plate was already existent since the Mesozoic.

Clearly, the various models relating to the origin of the Cretaceous ophiolites point to the limited information on these rocks. The palaeomagnetic data herein presented provide crucial

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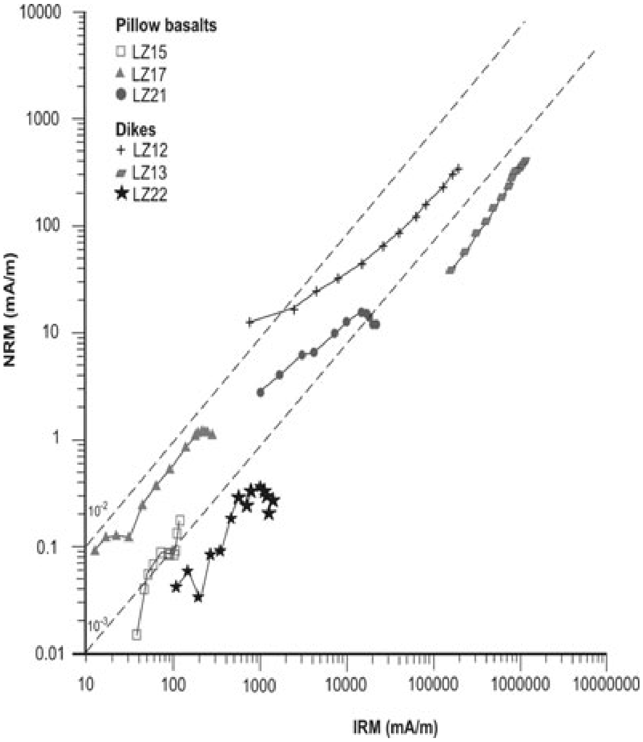

Figure 7. NRM versus IRM demagnetization curves for representative specimens from ophiolitic basement rocks along the Chico River and adjacent areas.

information for interpreting the nature and origin of these complexes. Unfortunately, this data set is very small to allow plate reconstructions and modelling (including that for northern Luzon) for this period.

7 CONCLUSIONS

The new data from the Chico River pillow basalts and dykes presented here suggest that ophiolite basement rocks of northern Luzon formed at subequatorial latitudes. Conversely, together with those previously gathered from the island, the data suggest that northern Luzon was close to the equator from as long ago as the Cretaceous (or even earlier) to early Cenozoic. Additional palaeomagnetic data are needed to decipher the basinal/plate affinity of these rocks and to allow reconstructions for the region during the Mesozoic. This situation can be remedied through palaeomagnetic studies on the Mesozoic rocks within the Philippine archipelago and surrounding regions. Potential targets include the Angat Ophiolite and the Lagonoy ophiolite in southeastern Luzon, as well as the Mesozoic ophiolite outcrops in the central and southern Philippines. Already, there is a large set of information available on the geology of these regions that can be used to support palaeomagnetic studies.

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