Rotations in the actively colliding Finisterre Arc Terrane: paleomagnetic constraints on Plio-Pleistocene evolution of the South Bismarck microplate, northeastern Papua New Guinea

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Rotations in the actively colliding Finisterre Arc Terrane: paleomagnetic constraints on Plio-Pleistocene evolution of the South Bismarck microplate, northeastern Papua New Guinea

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Abstract

We report paleomagnetic results from 12 Plio-Pleistocene localities in the actively colliding Finisterre Arc Terrane of northeastern Papua New Guinea (PNG). Calcareous, hemipelagic cover rocks possess a stable, syn-collisional remagnetization indicating a clockwise rotation of the colliding terrane through about 40° in post-Miocene time. A decrease in paleomagnetic declination anomalies as a function of along-strike distance in the Finisterre Arc Terrane, analyzed by our preferred model of a linear remagnetization and a migrating Euler pole, suggests an average rotation rate of 8° Ma⁻¹, in good agreement with the instantaneous rate from global positioning system geodesy. Thus, we propose that this rotation results from a coherent, rigid-body rotation of the Finisterre Terrane rather than from sequential docking of independently colliding blocks of the terrane. Moreover, we conclude that these paleomagnetic declinations result mainly from South Bismarck Plate motion, and not decoupled rotation of the crustal terrane independent of the underlying lithosphere. We examine models of a syn-collisional remagnetization with both fixed and migrating Euler poles of South Bismarck/Australia plate relative motion, and suggest that the Euler pole describing South Bismarck/Australia Plate motion has migrated southwestward to its present location on the collision suture in response to the propagating collision. This plate kinematic model agrees with the variability in depth of the seismogenic slab beneath the collision zone. Our best-fit model of pole migration describes South Bismarck/Australia relative motion producing a highly oblique collision in its early stages, with the Finisterre Arc Terrane converging along a left-lateral Ramu-Markham suture, gradually changing to the nearly orthogonal convergence observed today.

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1. Introduction

1.1. Regional tectonic setting

The island of New Guinea comprises a portion of the deforming edge of the Australian continent, with a mountain chain extending along its northeastern coast (Fig. 1). These coastal ranges are primarily volcanic island arcs of Cretaceous to Cenozoic age (Pigram and Davies, 1987), which have been sutured to the continental margin in a series of arc-continent collisions (Cooper and Taylor, 1987; Davies et al., 1987). The latest of these, the geographically and geologically continuous Finisterre and Sarawaget mountain ranges, make up the Finisterre Arc Terrane (Fig. 1) which is now actively colliding with the mainland (e.g., Pigram and Davies, 1987).

The Finisterre Terrane is composed of Paleogene through earliest Neogene volcanic arc rocks overlain by Miocene to Plio-Pleistocene limestones (Robinson et al., 1976; Jaques and Robinson, 1977, Abbott, 1993). This stratigraphy corresponds to that of New Britain, New Ireland, the Solomon Islands and Vanuatu, supporting the theory that these islands were part of a continuous, Oligocene to early Miocene Outer Melanesian Arc (Robinson, 1974). An early palaeomagnetic survey of these islands (Falvey and Pritchard, 1984) provided additional evidence to support this argument and proposed that the currently fragmented nature of the Outer Melanesian Arc was due to the

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Fig. 1. Regional tectonic setting of PNG, showing modeled South Bismarck/Australia pole migration path of model 3 (see text).
mainland (e.g. Jaques et al., 1982; Carter and Carter, 1984; Jaques and technician; 1992; this stratigraphy Jaques and Jaques, 1976) indicate that of a continuous, New Ireland, the northward subduction of a new island arc is that of a continuous, the subduction spreading occurred along the New Britain Trench, and its extension along the present-day Ramu and Markham river valleys, by the Late Miocene (Berger et al., 1992) to earliest Pliocene (Johnson and Jaques, 1980). Subduction of the Solomon Sea Plate at the New Britain Trench led to formation of the Bismarck Volcanic Arc, a 1000 km chain of active volcanoes along the northern margin of New Britain Island, extending westward to about 144°E longitude (Fig. 2). The volcanoes of the Bismarck Arc formed to the north of the Paleogene arc rocks of the Finisterre Terrane, thereby placing the Finisterre Arc in the Bismarck forearc.

Taylor (1979) identified four segments in the Manus Basin (Fig. 1) as a spreading segment with two bounding transforms, and one 'leaky' transform across the New Guinea Basin. Taylor's study concluded that the Manus Basin was formed during the last 3.5 Ma by asymmetric seafloor spreading with a total opening rate of ~130 km Ma⁻¹, and determined a best fitting pole of relative motion between the Pacific and South Bismarck plates (SBIS) at about 141°E, 18.5°S.

**Fig. 2.** Study area showing Finisterre Terrane and Ramu-Markham suture to the south.
Johnson and Molnar (1972) hypothesized a North Bismarck Plate between the SBIS and Pacific Plate (Fig. 1). The Outer Melanesian Trench, extending from the Wewak Trench in the west to near Bougainville Island in the east bounds the North Bismarck plate to the north. The southern boundary is the Bismarck Sea seismic lineation. The Outer Melanesian Trench has morphological features of an active subduction zone, but lacks significant seismicity and arc volcanism. Global positioning system (GPS) data (Tregoning et al., 1998) indicate that the North Bismarck Plate has present motion indistinguishable from Pacific motion; thus the plate appears to be a relict plate with motion changed from early orthogonal convergence with Pacific, to Pacific Plate motion today.

The Bismarck Arc lies on the SBIS, while most of the island of New Guinea lies on the Australian Plate (AUS) (Fig. 1). Spreading in the Manus Basin and subduction along the New Britain Trench and southern margin of the Solomon Sea Plate, to the east, has brought rocks of the Bismarck forearc into collisional contact with the Australian margin along the Ramu-Markham Fault Zone (RMFZ) (Fig. 2). This north-dipping thrust fault is generally regarded as the plate boundary separating the South Bismarck and Australian plates (Davies et al., 1987; Silver et al., 1991). Thus, a collision tip has migrated southeastward through time, bringing Australian continental margin into contact with the overriding SBIS. Today’s location of incipient collision is the point along the New Britain trench where Australian continental crust first contacts the eastern Finisterre Arc. Silver et al. (1991) interpreted collisional marine basin facies in seismic reflection data at the triple junction in the western Solomon Sea (Fig. 2), suggesting that this collision tip is very near the triple junction.

Motion on the RMFZ has been considered by various authors to be left-lateral strike slip (e.g. Cullen and Pigott, 1989), right-lateral strike slip (e.g. Falvey and Prichard, 1984), and pure thrusting (e.g. Abers and McCaffrey, 1994). Earthquake data identifies thrust motion on the RMFZ (Abers and McCaffrey, 1994). Results of a 6 year GPS study confirm that instantaneous SBIS/AUS motion is nearly orthogonal and, moreover, that today’s Euler pole of SBIS/AUS plate motion lies nearly on the surface trace of the RMFZ (Tregoning et al., 1998; Fig. 1). Some past component of strike slip motion on the RMFZ, however, is plausible depending on the mechanism of emplacement for the Finisterre Terrane. The oblique geometry of the colliding elements and the strikingly steep and straight geometry of the RMFZ at the suture favor some strike slip component to the terrane emplacement.

The geometry of the RMFZ and underlying oceanic slab are constrained by gravity modeling (Abbott et al., 1994a; Abers and McCaffrey, 1994), seismic reflection (Abbott, 1993), structural style of folding and thrusting in the collision zone (Abbott, 1993), GPS data (Stevens, 1998) and earthquake data (Abers and McCaffrey, 1994; Abers and Roecker, 1991). The terrane-bounding fault is nearly vertical (75°) where it reaches the surface at the trace of the RMFZ (Fig. 3). Below 30–35 km it flattens to a dip of 15–25° beneath the Finisterre Terrane and northern Huon Peninsula (the easternmost, peninsular portion of the Finisterre Terrane north of the Huon Gulf; Fig. 2) (Abbott, 1993; Abers and McCaffrey, 1994).

A well-defined deep seismic zone is nearly flat at a depth of 100 km beneath the Finisterre Terrane, and abruptly steepens to nearly vertical north of the Finisterre Range, beneath the Bismarck Arc. Beneath 125 km, this seismic zone is continuous along-strike with the New Britain Benioff zone, where earthquakes are recorded to a depth of 600 km (Abers and Roecker, 1991), suggesting that the deep seismic zone is evidence of the subducting slab. Above 100 km, active convergence seems to be partially transferred upward to the overlying crustal RMFZ, and seismicity along the flat seismic zone terminates abruptly at the surface trace of the RMFZ. Thrust faulting earthquakes at 30–40 km depths are interpreted by Abers and McCaffrey (1994) as indicating terrane emplacement and, therefore, that the arc is being obducted on the continent throughout crustal depths. Thus, a major question is whether or not the crust is decoupling from the underlying lithosphere along the RMFZ, which might then accommodate some degree of differential motion.
of the colliding, crustal terrane relative to SBIS motion.

To the NW of the Finisterre Range, the Adelbert Block (Fig. 2), a distinct geologic unit, has a similar strike, but is offset northeastward from the trend of the Finisterre Range. Recent GPS data (Tregoning et al., 1998) indicates that the city of Madang, on the Adelbert Block, has constant baseline lengths with two sites near the center of the SBIS, indicating that Madang is rotating clockwise with the SBIS. Based on the overthrusting of Finisterre Arc volcanics above deep-water Pliocene sediments in the Adelbert Range, Abbott (1995) argued that the collision of the eastern Adelbert block occurred in the Middle to Late Pliocene, and is therefore part of a continuous time-transgressive collision of the Adelbert and Finisterre blocks occurring above a single northward-dipping subduction zone. Left-lateral earthquakes near Madang and range-normal seafloor lineations in the Astrolabe Bay, between the Finisterre and Adelbert blocks (Fig. 2), suggest that some differential motion is being accommodated by strike-slip faulting of the seafloor.

Collision of New Guinea with the Finisterre Block began at 3.0–3.8 Ma (Abbott et al., 1994b), and has uplifted the mountains of the Finisterre Range to ca. 4 km. Quaternary coral terraces on the northern coast of the Huon Peninsula (Chappell, 1974), Holocene river terraces in the fluvial sediments along the southern flank of the range (Abbott, 1993), and marine strata near the city of Lae (Crook, 1989) indicate that rapid uplift continues to the present.
1.2. Geological setting

The active collision of the Finisterre Block is uplifting a limestone nappe on the northeastern flank of the range, which lies unconformably on a core of Finisterre Volcanics. This limestone cover dips 10–20° NE from the range crest to a series of normal faults along the north coast of PNG (Abbott, 1993; Jaques and Robinson, 1977). Thrust fault seismicity (e.g. Abers and Roecker, 1991) indicates that this anticlinal nappe is actively forming.

The limestone cover, composed mainly of members of the Gowop Group (Findlay, in preparation), is up to 4 km in thickness. Our reconnaissance paleomagnetic study of various rock types outcropping in the Finisterre Mountains revealed that the very pure limestones of the Gowop Group do not possess a stable remanent magnetization, being too weakly magnetized to undergo a stepwise demagnetization experiment (JNRM < 10^-5 A m^-1).

With the exception of one site (Pindiu; Table 1.) the paleomagnetic data reported here are from the Nokopo Formation, a thin, rapidly eroding, mudstone to marl unit, conformably overlying the limestone plateau. The Nokopo Formation is uplifted on top of the limestone sheet on the northern side of the colliding terrane. Because it is away from the intensive deformation of the collisional suture, the Nokopo mudstone is well suited to record terrane-scale tectonic displacements rather than local, more chaotic movements.

1.3. Nokopo Formation interpretation

The highest stratigraphic unit in the Gowop Group depositional sequence is a hemipelagic, calcareous mudstone unit named for Nokopo village near the type section. The type section is very thick (625 m), whereas most outcrops are in the range of a few meters to about 200 m in thickness. The Nokopo Formation lies conformably on the Yupna and Urawa Limestone units, typically separated from the limestones by a gradational contact about 2 m in width. It is dominated by blue-gray to olive calcareous mudstones, interbedded with foraminiferal calcarenites and fine to coarse volcanoclastic sandstones. Grain size and thickness of the coarse clastic beds increases strikingly updip. A 10 m thick medium-grained sandstone in the type section is deposited as a channel fill, displaying erosive contacts with the surrounding mudstone and containing angular blocks of the mudstone within the sandstone lens. Many of the mudstone outcrops are massive, but sometimes display planar or convolute laminations. Bedding planes are generally devoid of trace fossils, though planktic foraminifers and lignites are common, with logs up to 60 cm long observed in the uppermost type section.

The Nokopo Formation is very poorly lithified, and slumps and landslides are common in the unit. Carbonate content of the mudstones varies between 2 and 60% and samples from near the top of the formation have porosities of 50–70% (L.D. Abbott, pers. commun.), indicating minimal burial. This is confirmed by a single vitrinite reflectance value of 0.15%, demonstrating peak temperatures well below 65°C, for a lignite sample nearly 600 m below the top of the formation at the type section (M. Bustin, pers. commun. to L.D. Abbott, 1993). Benthic foraminifera indicate deposition of the unit at mid to lower bathyal depths, chiefly between 1500 and 3000 m water depth.

Benthic and planktic foraminifers and calcareous nanofossils from 207 Nokopo Formation samples throughout the Finisterre Mountains are dated as late Early Pliocene to earliest Pleistocene (foraminifera zones N19/20, N21 and N22, and nanofossil zones CN10C-CN11, CN12 and CN13-CN14a). Calibrated to the most recent timescale of Berggren et al. (1995a,b), the biostratigraphy indicates that the Nokopo Formation is diachronous, becoming younger to the SE (Fig. 4; Abbott et al., 1997, and Abbott, pers. commun., 1998). These biostratigraphic age determinations give uncertainties in the range of 1 Ma or greater for most Nokopo Formation sites.

An approximate deposition rate for the Nokopo Formation determined from microfossil ages is 0.5–1 m ka^-1. This range is consistent at a number of sites along the range; however, the evidence comes predominantly from the 625 m thick type section. At the type section, both the basal contact
The thickness of the section varies accordingly.

(a) The sandstone in the channel fill, display-
ing a matrix of surrounding mudstones of blocks of the channel walls. Many of the blocks are apparent, but sometimes are not. Bedding planes are riddled with the hanging beds, though the mudstones are common, especially concentrated in the upper-

(b) The sandstone is poorly lithified, with soft, friable sandstone common in the unit. The thickness of the sandstones varies from a few centimeters near the top of the channel to a few meters of 50–70% L.D., indicating minimal sedimentation. Single vitrinite reflectances of the core demonstrate the tightness of the formation at the top and the total. The lowest sample (815-10) was a lower upper bathyal facies, with 300 Ma water depth.

(c) Vitrinite reflectance and calcareous
calcite horizons. The Nokopo Formation (Fig. 4) The Nokopo Mountains are the youngest of the area. The earliest Pleistocene excavations, to N22, and later to N21, CN12 and CN11, are the most recent of which (b), the biot-

determinations from the 1 Ma or greater deposits.

(d) The evidence for the Nokopo Group microfossil ages is inconsistent at a number of sample levels. Nevertheless, the evidence suggests that the 2.5 Ma thick type section is located at the basal contact.
and uppermost facies are present, and there is a distinct stratigraphy in water depths and microfossil ages. Ages at this site range from about 4 Ma at the base to about 3 Ma at the top of the section (Abbott, personal communication, 1998). This provides an average rate of about 0.6 m ka⁻¹, in good agreement with deposition rates reported for hemipelagic sediments deposited on the continental margins and adjacent abyssal plain (e.g. Karlin and Levi, 1985).

Based on lines of evidence discussed above, Abbott et al. (1994b) interpreted the Nokopo Formation as the rapidly deposited, dominantly terrigenous sediment shed from the rising collisional mountain belt as the underlying limestone was progressively uplifted along the margin. The gradational basal contacts, the presence of interbedded volcanic sandstones coarsening and thickening upward, channel deposits, lignites in upper mudstone units, and biostratigraphy which confirms that the base of the Nokopo Formation is diachronous, all support this interpretation. Thus, the transition from micritic limestone to mudstone at the basal contact marks the encroachment of the depositional basin to the northern New Guinea margin, with clastic debris shed from the rising Finisterre Mountains reaching the basin for the first time. The increasing coarse clastic component upsection in the Nokopo Formation records increasing proximity of the depositional basin to the site of collision. This interpretation implies that the Nokopo Formation is a late pre-collisional to syn-collisional, time-transgressive deposit, which records the propagation of the oblique collision from NW to SE.

Fig. 4 shows the midpoints of biostratigraphic age ranges for Nokopo sites plotted as a function of distance along the 122° average strike of the range. As shown in Fig. 4, excepting one site in particular (Lengbati), which falls far off the
expected slope, the age versus distance relationship generally confirms the interpretation of a time-transgressive deposit. Ages for four sites sampled by Abbott (in preparation) are also given in Fig. 4. These sites were not used for paleomagnetic analysis, in most cases because they are isolated outcrops which do not span enough time to give reliable time-averaged paleomagnetic mean directions. Sites included as part of this study are shown in Fig. 8. Horizontal bars shown in Fig. 8 are not strict formal errors; rather, they indicate the range of ages determined at a particular site, typically from several samples. Uncertainty in the age determined for a particular sample is dependent on the preservation and diversity of its microfossil biota.

A least-squares regression line fit to the midpoints of the age ranges in Fig. 4 gives an along-strike rate of propagation of the Nokopo Formation deposition of about 23 km Ma\(^{-1}\) (this rate does not change substantially if the upper or lower age ranges are plotted instead of the midpoints). Given our interpretation of Nokopo Formation as a time-transgressive deposit, we would expect deposition along the margin to roughly reflect the rate of propagation of the collision tip along the RMFZ suture. The resulting rate, however, is only 10–20% of estimates ranging from 120 (Abbott et al., 1994a) to 240 km Ma\(^{-1}\) (Silver et al., 1991). Such estimates of propagation rate are based on Taylor’s (1979) estimate of 93 km Ma\(^{-1}\) convergence rate at the triple junction, the assumed collision geometry given an E-W-trending arc (similar to that of New Britain), and ages from the youngest occurring collisional marine basin facies in the suture zone. Instantaneous convergence rates given by the GPS results of Tregoning et al. (1998) nearly agree with Taylor’s estimate, suggesting that the present rate may be relatively constant through time. In this case, the low rate of Nokopo Formation propagation given by the microfossil ages may indicate that the onset of time-transgressive deposition is altered by factors such as along-shore transport of the terrigenous sediment.

Estimating the propagation rate of Nokopo Formation deposition from these data is very inexact, however, since we ignore the stratigraphic position of the outcrops at these sites. In a few cases (principally Wasu 1 and 2) folding of the underlying limestone has exposed two sites of quite different stratigraphic position at about the same along-strike distance. The Wasu 2 site is only 9 km north of Wasu 1, but is exposed near the axis of a broad, filled syncline in the underlying limestone sheet, whereas Wasu 1 is exposed near the contact with the underlying limestone. Thus, the stratigraphic difference between Wasu 1 and 2 may be up to about 600 m, and the >1 Ma median age difference is reasonable. In other cases the stratigraphic position of Nokopo Formation outcrops relative to the limestone contact is difficult to estimate. In such cases, an assessment of the grain-size facies relative to the type section is the only information about relative stratigraphic height. If Wasu 2 and Lengbati are removed from the least squares regression (Fig. 4) for the reasons discussed above, the rate of propagation increases to 37.6 km Ma\(^{-1}\), and the coefficient of determination \(r^2\) improves to 0.37.

The Pindiu site in the easternmost Finisterre Mountains (Table 1; Fig. 6) is a turbidite deposit of very poorly constrained age. Microfossil assemblages in the sampled section at this site give ages of 0.1–3.7 Ma (Abbott, 1993), but we do not treat the section as a Nokopo Formation facies equivalent, and we do not analyze the paleomagnetic data from Pindiu as a function of microfossil age.

2. Sampling, laboratory and analytic procedures

2.1. Field sampling

We collected a total of 727 independently oriented cores, from 17 site localities or traverses in Nokopo Formation or facies equivalents, during 1993 through 1996. We rejected data from five sites due to pervasive chemical or structural alteration (e.g. landslide deposits), or insufficient outcrop to average secular variation of the geomagnetic field. Twelve remaining sites produced useful paleomagnetic results.

Typically, we collected cores at 30 cm–1 m stratigraphic intervals in the Nokopo Formation, except at the 625 m thick type section near Nokopo Village which we sampled at 3–5 m stratigraphic
intervals. We made an effort to record bedding attitudes within a few centimeters of the sampled core as often as possible. Bedding is usually recognizable by thin laminations, though Nokopo mudstone is characteristically lacking easily identified sedimentary structures. In some cases, we have used bedding attitudes measured several meters away from the sampled area, or we have averaged several measurements, in order to make the bedding-tilt corrections. We checked for potential local magnetic field anomalies during orientation with a Brunton compass by back-sighting to one or more mapped landmarks or by recording sun compass measurements and applying corrections. Sun compass and back-sighting corrections typically produced no more than 1–3° change in the recorded magnetic bearings.

2.2. Laboratory and analytic procedures

We cut standard 2.3 cm laboratory specimens from the oriented cores collected in the field, and measured magnetization vectors using a 2G three-axis cryogenic magnetometer at UC Santa Cruz. We completed stepwise thermal demagnetizations in a custom-made, magnetically shielded rock demagnetization oven at UC Santa Cruz, and made additional measurements of rock magnetic parameters using a Princeton Measurements Corporation alternating gradient force magnetometer and Geofyzika Kappabridge KLY-2 and CS-2 oven.

Typical intensities of Natural Remanent Magnetization (NRM) in Nokopo mudstone samples are about \(5 \times 10^{-5}\) emu cm\(^{-3}\) \((5 \times 10^{-2} \text{ A m}^{-1}\)) but vary from \(10^{-4}\) to \(10^{-7}\) emu cm\(^{-3}\) \((10^{-1} \text{ to } 10^{-4} \text{ A m}^{-1}\)). Results reported in this study are stepwise thermal demagnetizations. Alternating field (AF) and thermal demagnetization experiments on companion specimens from single cores indicate that AF demagnetization proves either unable to remove a low temperature component present in many samples, or that the thermal demagnetization method gives much better separation of the magnetization components in the Nokopo Formation.

Generally, the ChRM (component 1; Table 1) was isolated by 300–400°C, and we formally analyzed demagnetization vectors by principal component analysis (Kirschvink, 1980) to provide best-fit line determinations. ChRM vectors in the Nokopo mudstone are exactly determined by six or more temperature steps to constrain the ChRM line fit, and these ChRM best-fit vectors typically give maximum angular deviations (MAD) between 3 and 6°. All ChRM components are anchored along line fits that is, the line is forced to pass through the origin, but the origin is not treated as a data point.

Thermal demagnetizations of Nokopo mudstone ordinarily reveal a high-temperature, ChRM component (component 1) and a low-temperature component (component 3). Often, an intermediate-temperature direction (component 2) is apparent as well, especially in reversed polarity demagnetizations. Since these intermediate components lie along great circles between the vector components 1 and 3, we interpret the intermediate directions as overlapping spectra, or mixed directions, rather than as discrete directional components, and do not list them in Table 1.

3. Paleomagnetic results

3.1. Paleomagnetic directions

Fig. 5 illustrates representative vector plots of thermal demagnetization for Nokopo Formation rocks. Ordinarily, a viscous overprint giving a recent normal polarity field direction is easily removed by thermal demagnetization and a ChRM with a vectorial decay over about half of the magnetization is easily identified. Thermal demagnetization is nearly complete by 600°C. All but 3% of the samples from the 12 localities used in the tectonic analysis yielded stable endpoint ChRM (Table 1).

Site-specific equal area projections of the ChRM vector directions from the 12 Nokopo Formation sites are shown superimposed on a map in Fig. 6.Paleomagnetic directional data and site statistical parameters for all three components of magnetization are summarized in Table 1, as well as distance along a 122° average strike of the range (deter-
Fig. 5. Representative vector plots of thermal demagnetizations of Nokopo Formation at Wasu 1 site; reversely magnetized (left) and normally magnetized (right).

3.2. Fold tests

Since Nokopo Formation sites are generally homoclinal, time-transgressive, and differentially rotated throughout the range, two-limb fold tests, traditionally used in paleomagnetic studies, cannot be performed. To evaluate the significance of the bedding corrections we have performed 'tilt-tests' using the methods of McFadden (1990; Table 2). In this test, the paleomagnetic directions, the direction of the bedding corrections, and the in situ and tilt-corrected mean directions are tested for correlation. A correlation is measured as the angle between the dip direction and the vector between the mean and sample directions. The sum of the cosines of these angles (referred to as the SCOS statistic) is then computed. When the SCOS value exceeds a critical value for 95% confidence, the directions are said to be correlated with the tectonics. This fold test is positive if the sample directions give a statistically significant correlation with the dip direction before structural correction, but not after. In cases where both the in situ and tilt-corrected test statistics either exceed or are less than the critical value the test is inconclusive, and in the former case may point to a syn-tilt clustering intermediate between in situ and tilt-corrected directions.

As shown in Table 2, 5 sites pass the McFadden Fold two-test at 95% confidence; two sites fail, giving 95% critical correlation with the tectonics after the tilt correction is applied. The test statistics exceed the critical value in both in situ and tilt-corrected coordinates at one site (Tuyap),
Fig. 6. Equal area projections of ChRM directions for analyzed Nokopo Formation sites superimposed on map of the Finisterre Range and Huon Peninsula, showing locations of Bunum Fault and Kwama River Fault. Note horizontal overlap in three panels. Open symbols are upper hemisphere. Site statistics are given in Table 1. Arrows indicate mean declination anomaly (reversed sites are inverted for calculation of means).
suggesting a correlation with tectonics at an intermediate unfolding, and three sites (Pindiu, Worrin, and Matoko) are uncorrelated in both in situ and tilt-corrected coordinates. One remaining site (Kip) has a single bedding attitude throughout the outcrop; thus statistical significance of the structural correction cannot be evaluated for that site.

3.3. Origin of remanent magnetization in the Nokopo Formation

Fig. 7a shows representative temperature dependence of low-field magnetic susceptibility, and representative hysteresis parameters are shown in Fig. 7b. Curie temperatures, typically low-coercivities, and ratios of saturation remanence to saturation magnetization (\(M_r/M_s\)) between about 0.2 and 0.4 are consistent with the main remanence carrier being magnetite with small grain size (<1 μm), and concentrations of about 0.05% by volume. This is consistent with an expected ferromagnetic mineralogy of terrigenous and volcanogenic detritus. Some of the sampled sites in the Nokopo Formation also contain the signature of authigenic goethite (FeOOH), a magnetic mineral which is widespread in calcareous sediments. It is commonly precipitated from solution, either as a result of diagenetic alteration or during subaerial weathering of porous sediments. Goethite has a Curie temperature of 120°C and, on heating to higher temperatures (300–400°C), dehydrates to form hematite. Fortunately, at most sites the goethite seems to represent only a small fraction of the magnetic mineralogy of Nokopo mudstone, which carries a low-temperature component that is removed by about 150°C during thermal demagnetization.

The presence of goethite in the Nokopo mudstones is consistent with evidence of subaerial oxidation in the upper few centimeters of mudstone outcrop, which is often yellow-brown in color. Below the upper few centimeters, the mudstone is typically green to blue-gray, and less affected by a chemical remanent magnetization (CRM). One Nokopo Formation site (Wiliwilan) proved to be pervasively overprinted, probably by such a CRM. Outcrop at the Wiliwilan site was deeply oxidized and uniformly yellow-brown in color, and even thermal demagnetization was not able to isolate an interpretable ChRM.

Two Nokopo sites (Isan and Konge; Table 1), give eastward low-temperature components. These low-temperature components are highly scattered, and most typically represent only a few percent of the NRM removed during thermal demagnetizations. Since some of the low-temperature component directions lie near great circles between a clockwise-rotated normal ChRM and a reversed field direction, however, they may indicate goethite formed early (prior to 780 ka).

3.4. Remagnetization during early uplift

Various lines of evidence indicate that the ChRM (component 1; Table 1) recorded by the
Fig. 7. (a) Representative thermomagnetic curve from Nokopo Formation (specimen 215a; Nokopo section) and (b) representative hysteresis behavior of Nokopo Formation (specimen 135c; Gabutamon section), susceptibility is given in SI units times $10^{-6} \text{g}^{-1}$, hysteresis parameters are in CGS units.
Nokopo mudstone is not depositional in origin but, rather, an early remagnetization acquired during collisional uplift. Evidence arguing against a depositional remanence is outlined below.

The most complete section sampled as part of this study is the Nokopo Formation type section. This site has the most extensive microfossil data, giving dates of 4 Ma at the base to about 3 Ma in the uppermost portions of the section. Uniform normal polarity magnetization throughout 102 cores collected at 3–5 m intervals strongly suggests a remagnetization; there should be three significantly long reversed polarity intervals in this section according to the microfossil ages and the time scale of Cande and Kent (1992) (Fig. 8). The longest continuous, normal polarity expected in this biostratigraphic interval is about 250 ka. Moreover, if the section represents on order of 1 million years of deposition, we would expect to see some hint of systematic change in the declination anomaly from the base to the top of the section, which we do not.

Five of the 12 sites reported here (Lengbatu, Konge, Wasu 1 and 2, and Worrin) give an estimate of the precision parameter \( k \) for the ChRM which greatly exceeds that calculated from the expected VGP scatter of paleosecular variation models [ca. \( k = 20 \) for model G; Merrill et al. (1996)]. A very high \( k \) statistic suggests a remagnetization because the whole section usually is remagnetized over nearly the same interval, though it can also result if each sample were remagnetized over different intervals, each long enough to average secular variation.

Additionally, although all but one Nokopo site are dominantly single polarity, four sites show evidence of one, or several, isolated specimens with ChRM directions of opposite polarity. These isolated specimens are often surrounded by samples giving the dominant polarity, even as close as a few centimeters away. Though there are too few examples to observe differential declinations, and very careful high-temperature demagnetization gives no evidence of additional high-temperature components, these isolated samples are most plausibly interpreted as the last remaining depositional remanence within an otherwise fully remagnetized section.

Finally, at several localities, Nokopo Formation outcrops were noted in the field as displaying wavy to convolute bedding, and have clearly been subjected to soft-sediment deformation or down-slope transport. Samples collected within these zones give magnetization directions that are indistinguishable from planar laminated outcrop within the same site, and were probably acquired after such deformation occurred.

The evidence outlined above indicates that the ChRM throughout the Nokopo Formation is not depositional in origin. Nearly dipolar inclinations of the Nokopo sites tilt-corrected directions, however, as well as passage of the McFadden tilt test at five sites, indicates that the magnetization was acquired prior to most of the 20° or more of tilting accompanying uplift on the margin. Thus, we interpret the ChRM as an early, syn-collisional remagnetization, probably associated with early uplift. Such a syn-collisional remagnetization would nonetheless be time-transgressive along-strike of the colliding terrane due to the obliquity of the propagating collision.

Since the Nokopo Formation has not been buried or thermally altered, possible remagnetization mechanisms are primarily physical or chemical in origin. CRMs during geochemical alteration of magnetic mineral carriers due to fluid migration or dewatering during the transition from submarine to subaerial exposure is one possibility, but the ChRM at these sites gives near the expected axial dipolar inclination. The amount of uplift expected at subaerial exposure would be expected to produce a significantly steepled inclination after structural correction. Moreover, hysteresis parameters and thermomagnetic curves (Fig. 7) indicate magnetite is the dominant magnetic mineral, with no evidence of significant amounts of other phases except the very low temperature goethite discussed above. Thus, physical processes such as shaking of saturated sediments during earthquakes or tectonic compression or diagenetic strain effects associated with collision are the most plausible mechanisms in this case. Occurrences of diagenetic ‘events’ during uplift are becoming increasingly well known. Factors other than burial, including fluid mobility associated with compression, magnetic ‘shaking’ during earthquake events,
or reactions triggered by rock fracturing during folding and uplift have been shown to be important. Given the observed coherent decrease in paleomagnetic declination anomalies along-strike (Table 1), we conclude that remagnetization of these sediments occurred in a diachronous fashion as the result of compression or earthquake shaking associated with oblique convergence and obduction along a continental margin 'ramp'.

4. Discussion

An early paleomagnetic reconnaissance study obtained results from four units in the Finisterre Terrane (Falvey and Pritchard, 1984). That study was directed at a regional paleogeographic reconstruction of the many island arcs in the region, and only limited sampling was done in the Finisterre Terrane. Samples of Miocene to Pliocene units from the Huon Peninsula provided mean paleomagnetic declinations of ca. 15°; thus the probability of clockwise rotation of the eastern terrane was already recognized.

We initiated the present study to distinguish between several models for terrane emplacement. Two end-member models are:

1. rigid-body rotation of the whole terrane into the Australian margin; and
2. segmentation of the terrane into independently colliding and rotating blocks as suggested by Abbott (1993), Abers and McCaffrey (1994), Kulig et al. (1993), and others.

These mechanisms imply different histories of vertical-axis rotations.

Segmentation of the terrane could be accommodated by a series of faults that trend NE across the Finisterre Terrane, normal to the strike of the range. Some of these faults offset young structures in the range, though the amount and sense of motion is poorly known. The largest and best documented of these are the Bunum Fault and the Kwama River Fault (Fig 6). Both are steeply dipping and, although the dip angle and direction are unknown, field relations and earthquake evidence suggest a combination of left-lateral and SE-down motion (Abbott, 1993; Kulig et al., 1993; Abers and McCaffrey, 1994). These faults divide the Finisterre Terrane approximately into thirds, and have been proposed to be acting as tear faults, which take up differential slip perpendicular to the RMFZ, or accommodating extension of the terrane parallel to the margin (Kulig et al., 1993; Abers and McCaffrey, 1994) or both.

The time-transgressive Nokopo Formation provides an opportunity to test these competing models of terrane emplacement. If the volcanic arc and its cover rocks are being dissected into sequentially rotating blocks by the collision, then discordance in the paleomagnetic declinations in the Nokopo Formation should be approximately equal from northwest to southeast, because each block will have Nokopo sediment deposited prior to rotation into the margin. Alternatively, if the terrane rotated as a rigid block, then discordance with the expected direction will be greater in the NW than in the SE because the younger sediments in the SE would have been deposited and magnetized after much of the rotation had already occurred.

Since we have shown that the paleomagnetic declinations reported here are probably a remagnetization, rather than a depositional magnetization, the simple interpretation described above requires qualification. The Nokopo sites would retain a signature of paleomagnetic declinations as a function of age, and thus provide information about the scale of rotation of the colliding arc, only if they acquired their remagnetization in a time-transgressive fashion. Since Nokopo Formation sites are uniformly deposited at mid to lower bathyal depths, we can expect that these sediments were deposited at similar distances offshore from the colliding margin. Therefore, a syn-collisional remagnetization would give a similarly time-transgressive pattern, but record a little less rotation than would be recorded by a depositional magnetization.

Below, we evaluate the paleomagnetic data using three models of a remagnetization gained in a linear, time-transgressive fashion along the propagating collision. First we examine the declination anomalies as a function of biostratigraphic age, assuming that the remagnetization was soon after deposition. In the second model, we examine declination anomalies as a function of distance along
4.1. Declination anomaly versus age

Fig. 8 shows declination anomalies of the nine microfossil-dated sites plotted as a function of depositional age. A simple, straight-line, least squares regression gives an average rotation rate of $6.2^\circ$ Ma$^{-1}$. Since we showed in Fig. 4 that Lengbati gives an anomalous age versus distance relationship, we have removed it from the age versus declination anomaly regression as well. As shown in Fig. 8, a simple linear least-squares fit gives a coefficient of determination ($r^2 = 0.378$). The coefficient of determination is a measure of the closeness of fit of a scatter graph to a curve, which measures the ratio of the explained variation resulting from the curve to the total variation. When all variation is explained, $r^2 = 1$. This statistical parameter is useful since it can be used for nonlinear relationships as well.

The general decrease in declination anomalies as a function of age argues against the domains of independently rotated blocks of hypothesis 2, but suggests a relatively coherent rotation of a rigidly...
colliding Finisterre Terrane as in hypothesis 1. The simple linear regression rotation rate of 6.2° Ma⁻¹ agrees relatively well with a present-day rotation rate of 7.9° Ma⁻¹ determined by GPS (Tregonon et al., 1998).

4.2. Declination anomaly versus distance

We obtain a better fit by analyzing the palaeomagnetic declinations as a function of along-strike distance (Figs. 9–12) rather than as a function of microfossil ages. Additional sites for which there is no microfossil age determination can now be added to the analysis of palaeomagnetic declinations, and some locations with microfossil ages that do not fit a time-transgressive deposition model (especially Lengbati) give near expected declinations when plotted as a function of distance.

This evidence supports the hypothesis that the declinations result from a remagnetization and are, therefore, diachronous as a function of location along the terrane rather than of depositional age.

If the present-day South Bismarck/Australia pole has remained relatively fixed, however, we must make a geometric correction to a linear regression. Due to the proximity of the SBIS/AUS pole, the plate velocity relative to Australia increases along the Finisterre Terrane from 0 at the pole to about 50–60 km Ma⁻¹ at 147°E. Increasing plate velocity toward the SE will have the effect of preferentially recording younger remagnetizations with respect to deposition toward the SE. That is, in the SE, where the plate convergence rate is higher, the delay between bathyal deposition and collisional remagnetization is less. Thus, the eastern sites will collide with the margin

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**Model for remagnetization with fixed Euler Pole**

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Fig. 9. Sketch illustrating effect of rotation about a fixed pole on remagnetization of Nokopo Formation along strike, illustrating RMFZ and offset collision ramps at 123 and 193 km (see text).
more rapidly after deposition than sites nearer the SBIS/AUS pole, and sites toward the NW would be expected to lose a larger portion of the clockwise plate rotation than would be recorded by a depositional ChRM. Therefore, the slope of a line plotting declination anomaly versus age will be shallowed.

For example, with a present-day SBIS/AUS pole, there is a factor of 2 difference in the convergence velocity over the length of the Finisterre Range. We can make a simplest-case estimate that the depositional basin remains a few tens of kilometers offshore, to the northeast of the rising volcanic arc during its rotation into the margin. Sites in the northwestern Finisterre Range, which converges with the margin at about 30 km Ma\(^{-1}\), would then require ca. 1 Ma to be remagnetized at the margin. Sites to the SE, on the present-day Huon Peninsula, converge at about 60 km Ma\(^{-1}\), and will require only half this time to reach the same point with respect to a straight margin and be remagnetized. Given these crude assumptions, an 8° Ma\(^{-1}\) plate rotation rate would represent a 10° true rate. Although this 2° Ma\(^{-1}\) difference in rate is at, or below, the limit of resolution of the paleomagnetic data, this would imply that the data are underestimating the total plate rotation over the last 4.5 Ma by 10°.

4.2.1. A kinematic model for remagnetization with a fixed pole

With the exception of one site (Tuyap; Table 1), the remagnetizations give nearly expected axial dipolar inclinations in tilt-corrected coordinates. This indicates that the hypothesized remagnetization was acquired offshore, before most of the tilting associated with uplift. If we infer that these remagnetizations occurred along a linear 'ramp' parallel to the collision zone, such a ramp would have been offset to the northeast of the rising collisional mountain range, and the plate boundary. Because the present SBIS/AUS pole is nearly
Fig. 11. Sketch illustrating effect of rotation about southwestward migrating stage poles on remagnetization of Nokopo Formation along strike. Eight degree rotations of Finisterre Terrane at 1 Ma intervals from 4.5 to 0.5 Ma, and offset collision ramp produced at 145 km (see text).
at the surface trace of the RMFZ, the changing angle of the Finisterre terrane with respect to the offset ramp requires that the declinations be fit not to a line, but to a curve that steepens near the pole and flattens to the SE. As when the blades of a scissors close, along-strike propagation of remagnetizations in the Finisterre Range increases as a function of distance away from the pivot.

We can determine the offset distance for a linear remagnetization ‘ramp’ by rotating the Finisterre Terrane (with the Adelbert Block) counterclockwise about the present day SBIS/AUS pole, and finding the offset which best fits the declinations along the range. Fig. 9 shows the end-member distances to a margin-parallel ramp, along which the declination anomalies of each site are restored, with the appropriate clockwise rotation, to their present geographic location. That is, if the Finisterre Terrane is rigidly rotated counterclockwise about the present-day SBIS/AUS pole by the amount of the declination anomaly at Matoko (43°), then the rotated location of Matoko is 193 km from the RMFZ. Similarly, if the terrane is rotated counterclockwise 7° (the declination anomaly at Kip), the location of Kip is 123 km from the RMFZ. The curves for declination anomaly versus location along the present day strike of the range produced by these two remagnetization ramps are shown superimposed on Fig. 10.

The curves described above, and shown on Fig. 10, indicate fits through the northwesternmost (Matoko) and southeasternmost (Kip) sites, and give end-member remagnetizations at 193 and 123 km, respectively, from the RMFZ. In this model, we are assuming that the offshore distance of the depositional basin and the horizontal shortening in the Finisterre Mountains compensate one another. Abbott (1993) has estimated the shortening along major thrust faults at a few tens of kilometers, and bathyal depths assuming analogous bathymetry in the western Solomon Sea (Abbott and Silver, 1991), where Nokopo Formation equivalent is now being deposited, are on the order of a few tens of kilometers offshore.
The two curves shown on Fig. 10 give $r^2$ values of 0.611 and 0.436. Using this model, the least squares behavior of $y$ produces a best fit curve approximately midway between the endmembers, with the remagnetization at about 150 km, where $r^2$ rises slightly to 0.64.

The range of hypothetical remagnetization distances thus found is close to the location of the abrupt change in angle of the deep seismogenic zone, about 150 km from the RMFZ, beneath the New Britain volcanic arc (Abers and Roecker, 1991). This intermediate depth seismic zone changes from nearly flat to nearly vertical at this distance from the surface trace of the RMFZ. Convergence at this distance is also well delineated by 12 large thrust earthquakes above this zone at 22–37 km depths reported by Abers and McCaffrey (1994; the North Huon events). Abers and McCaffrey interpreted these earthquakes as representing slip on the RMFZ; thus, the influence of the change in dip angle of the deep slab may correlate with the northern extent of the shallow RMFZ, with the deep seismogenic slab exerting compressional stresses upward to crustal depths.

We speculate that compression associated with obduction of the crust above this oceanic slab is, in some form, a mechanism for remagnetization of the uplifting Nokopo Formation. This might occur, for instance, if the point at which the deep slab changes angle is where early folding deformation occurs in the colliding crust. Alternatively, large earthquakes on the deep slab or on the Ramu-Markham thrust fault are themselves a potential mechanism for remagnetization resulting, for instance, from the shaking of saturated sediments. Abers and McCaffrey (1994) estimated that uplift rates over the last 100 years of seismicity are consistent with significant (Mo = 1019–1020 Nm) event sequences every 30–100 years. Thus, at about 150 km from the surface trace of the RMFZ, the colliding crust crosses into a zone of relatively continuous seismic activity.

Fig. 10 shows two regions of ‘smearing’ of the paleomagnetic declinations at about 80 and 160 km along-strike distance. These distances are coincident with the locations of the Bunum and Kwama River Faults, respectively. The smeared distribution of declination anomalies at these regions may be the result of the local tectonic effect of left-lateral shear near these fault zones, which would produce local counterclockwise rotations reducing the clockwise paleomagnetic declinations. If this interpretation is correct, then we would expect that the upper curve produced by this model, which traces higher declination anomalies, is more representative of the rotations along the range. It also produces a better statistical fit to the paleomagnetic declinations. Choosing the upper curve implies a greater distance between remagnetization and the RMFZ; note, however, that it is a poor fit to three sites east of the Kwama River Fault (Lengbati, Pindiu and Kip) which give 5–7° mean declinations (Fig. 10). This observation raises the possibility that the eastern portion of the terrane is nearly unrotated, with differential motion taken up by the Kwama River Fault, an interpretation that we discuss next.

Differential rotation of a large block about a vertical axis would require that a portion of the terrane no longer be attached to the SBIS. This might occur if an earlier obducted part of the Finisterre Terrane became fixed to the Australian margin and moved with the Australia Plate. However, we would then expect right-lateral motion on the terrane-crossing faults as evidence of northeast motion of the collided block to the west. Field evidence from both cross-faults, and earthquake evidence from the Lae seismic zone (LSZ; Kulig et al., 1993), which is likely continuous with the Kwama River Fault, and from Madang (Abers and McCaffrey, 1994; Milson, 1981) indicates left-lateral motion. Moreover, the GPS results of Tregoning et al. (1998) indicate that present SBIS motion extends at least as far northwest as Madang. Alternatively, differential motion of portions of the terrane might occur if the crust were partially decoupled from the underlying lithosphere along the 15–25° dipping RMFZ, or if a portion of the SBIS broke vertically, producing small blocks of lithosphere that freely rotate in the plate boundary zone. Preliminary GPS data, however, indicate present motion of the Huon Peninsula is consistent with SBIS motion, as is Kaiapit, well west of the Kwama River Fault (C. Stevens, pers. commun., 1998). In addition, statistical analysis of lineation populations from digital
The kinematic effect of left-lateral shears, which would produce rotations reducing paleomagnetic declinations. If this were the case, we would expect a change in the declination of the terrane, as it is probable that the anomaly is more reflective of the paleomagnetic declination along the range. It is not clear whether such a change is reflected in the upper curve of the paleomagnetic declination, or whether it is more reflective of the paleomagnetic declination along the range. If the latter is the case, it is possible that the anomaly is more reflective of the paleomagnetic declination along the range.

4.2.2. A kinematic model for remagnetization with a migrating pole

The kinematic model for remagnetization with a migrating pole is based on the assumption that a fixed SBIS/AUS Euler pole throughout the opening of the Manus Basin. It is much more likely, however, that the pole has migrated, or jumped, in response to progressive collision of the Sinister Terrane with Australia. Since the arc—continent collision would be expected to be more resistant to compression than the oceanic subduction at the New Britain Trench, a potential response to the progressive collision with Australia would be a change in SBIS motion such that the SBIS/AUS pole moves toward the collision suture.

Since the present-day SBIS/AUS pole is very near the colliding terrane, very small changes in pole proximity lead to large changes in local velocity and geometry. Therefore, we tested various Euler pole migrations to identify how much motion is necessary to fit the observed declination anomalies as a function of range—parallel distance. The desired effect is to steepen the remagnetization versus distance curve such that 40° declinations in the NW and 5° declinations in the SE acquire their respective magnetizations along one line parallel to the plate margin. We find that the shortest pole path to produce maximum steepening of the remagnetization versus distance curve is a straight line to the NE, perpendicular to the RMFZ, such that the increasing distance to the pole produces a better convergence of the along-strike declination anomalies. Rotating about 1 Ma stage poles along a neperd (N45°E) path from the present location of the SBIS/AUS pole, we find that a pole migration of about 675 km since 4.5 Ma is required to fit the observed declinations at such a line parallel to the RMFZ (Fig. 11). This model produces a line at a 145 km offset to the RMFZ where both ends of the terrane cross at their respective paleomagnetic declinations, again quite close to the northeastern extent of the intermediate depth seismic zone.

The changing propagation rate of remagnetization with respect to along-strike distance is represented by the curve shown in Fig. 12. The paleomagnetic data are fit by a single curve, with 8° rotations in the SE portion of the terrane and nearly 40° rotations in the NW (Fig. 12). Thus, with this pole migration we now fit both the smaller declination anomalies east of the Kwama River Fault, as well as the declination anomalies in the west. The r² statistic is our best fit at 0.672, the 'smeared' declinations from Gabutamou to Nokopo are distributed equally above and below the curve, and Wasu 1 and Worrin are the main outliers. In the case of Wasu 1, it is reasonable to call on the Kwama River Fault zone as a potential source of local tectonic disruption; the left-lateral shear would be expected to produce counterclockwise rotations, thereby reducing the paleomagnetic declination. In the case of Worrin, the outcrop lies on the edge of the deep Urawa River Canyon, at the edge of a large, low-elevation 'gap' in the Sinister Range. Nokopo Formation in this area is commonly found in large landslide deposits. Thus, the Urawa River may mark the trace of a major normal fault, and the Worrin site may have been locally down-dropped and rotated; however, the site has consistent, regional NE dipping bed attitudes.

We chose the direction and rate of SBIS/AUS pole migration by trial and error, to fit the paleomagnetic declinations with the simplest and shortest migration. Evidence from the unusual distribution of seismicity beneath the western Bismarck Arc provides an independent check on the direction and distance of the hypothesized pole migration. Since Australia/South Bismarck relative motion is described by opposite sense rotation about the same Euler Pole, we look for evidence that our migrating pole path produces agreement with the geometry of the seismogenic slab, presumed to be subducted Australian lithosphere along the New Britain Trench.
As discussed above, the seismic zone beneath the western Bismarck Arc dips nearly vertically to the north beneath the Bismarck Arc, where it abruptly flattens at 100 km depth to sub-horizontal (Fig. 3). The seismogenic zone beneath the eastern Bismarck Arc is also steeply dipping to the north and, below about 125 km, is continuous along-strike with the seismic zone to the west (Abers and Roecker, 1991). Beneath New Britain, this zone extends to about 600 km depth, continuing to the surface east of the collision with New Guinea (Abers and Roecker, 1991). The depth of seismicity along the arc increases from about 100 km in the western Finisterre Terrane near 145°E, to 250 km beneath the Huon Peninsula at 147.5°E, and to 600 km depth at 149°E beneath New Britain where the Solomon Sea Plate is being subducted. Moreover, the intensity of seismicity increases from west to east along the New Britain Trench (Abers and Roecker, 1991; Denham, 1969). If this seismic zone is representative of slab geometry, then our modeled SBIS/AUS pole migration should not disagree with the variation in earthquake depths along the arc. That is, our solution should allow the pattern of a decrease in SBIS/AUS convergence from the triple junction toward the northwest, and an increase in SBIS/SOL convergence from the triple junction eastward. At the present convergence rate, these maximum depths of seismicity along the Bismarck Arc correspond to about 4 million years of subduction at these locations. However, the present-day pole produces very little convergence at 145°E; thus the evidence of a slab to 100 km depth there suggests that the SBIS/AUS pole cannot have remained in its present location throughout the collision. Arc volcanoes extending northwest to 144°E indicate a minimum slab depth of about 100 km along the northward-dipping Australian margin. A fixed SBIS/AUS pole near the present location would not produce sufficient relative convergence, nor could these young arc volcanics extend west of a fixed present-day pole.

If the SBIS/AUS pole migrates from northeast to southwest along our modeled path then, due to the changing pole proximity, the result is a decrease in SBIS/AUS convergence from 147.5°E toward the northwest, and conversely, an increase in SBIS/SOL convergence toward the east. Moreover, the total relative convergence using calculations at the five previously found stage poles is about 50 km in the northwestern Finisterre Range and about 200 km at the Huon Peninsula. These convergence rates correlate fairly well with the geometry of variable depths of seismicity at the locations listed above, but seem to produce about 50 km less convergence than indicated by the slab depths. Similarly, cumulative SBIS/SOL convergence is also about 550 km using the modeled pole migration, but estimates of SBIS/SOL convergence are highly speculative since past motion of the Solomon Sea microplate is poorly known. The additional 50 km of convergence required to reproduce the slab depths might result from continued subduction of a basin on the Australian Plate, between the New Britain Trench and the RMFZ. If such a basin was consumed by northward-dipping subduction, the relative convergence reproduces the variable slab depths very closely. This interpretation implies that northward-dipping subduction was occurring along the New Britain Trench just south of the Finisterre Arc by 4.5 Ma, and that continued subduction along this trench caused the eventual collision of the Finisterre Arc with the continent.

The westward component of this pole migration produces a collision that is initially very oblique, with the Finisterre Terrane moving like a pendulum grazing the Australia–PNG margin (Fig. 13). As the collision progresses, motion of the Finisterre Terrane acquires the present orthogonal motion with respect to Australia. This kinematic evolution explains a number of observations in the Finisterre Arc Terrane and regional tectonics. As discussed above, the plate kinematic predicted by the SW-migrating pole produces the least collision near the NW end of the RMFZ, with a total SBIS/AUS convergence of about 50 km over the last 4.5 Ma. SBIS/AUS convergence is about 200 km at the Huon Peninsula, where predicted collision velocity remains nearly constant at 50 km Ma\(^{-1}\), but the convergence direction changes through time from west to southwest over the past 4.5 Ma. Thus, the pole migration described above produces a collision that would have had more left-lateral strike-slip motion than
the east. Moreover, using calculations at high-angle poles is about 41°, Finisterre Range and the RMFZ. These con- ventional to the geometry at the locations predicted, in agreement with the slab depths.

The POL convergence is modeled, but the motion of the Australian Plate, trench and the RMFZ. The northern fracture by northward-increased relative convergence followed closely. A north-dipping fracture along the New Britain slab Finisterre Arc by 4.5 Ma, along this trench fracture of the Finisterre Arc

This pole migration is substantially oblique, moving like a pendu- lately orthogonal margin (Fig. 13). The motion of the fracture is nearly orthogonal to the relative motion of Australia. This kinematic predicted by the model is the least collision margin, with a total of about 50 km over the POL convergence is about 41°, where predicted and nearly constant at 41°, convergence direction is consistent to southwest over the pole motion that would result from slip motion than...
normal convergence in the past, suggesting an explanation for the unusual geometry of the RMFZ, which is nearly vertical beneath the Markham Valley and remarkably linear along-strike in the collision suture.

Abbott et al. (1994b) pointed out the lack of provenance shifts in the sedimentary record indicating a clear date for the Adelbert collision. He suggested that the Adelbert portion of the Finisterre Arc Terrane collided with an allochthonous terrane composed of oceanic crust, resulting in a relatively 'soft' collision compared with that of the Finisterre Block, with little disruption of pre-collision patterns of sedimentation. By contrast, he suggested that the Finisterre Block collided with allochthons composed of continental crust, leading to rapid uplift and modification of sediment sources. The general trend of lower elevations and less rapid erosional patterns to the northwest through both the Finisterre and Adelbert Blocks is well explained by an initially oblique collision (Fig. 13).

This solution solves an additional problem in tectonic reconstruction of northern PNG. If the terrane rotated through 40° into the margin as a rigid block about the present Euler pole, some 300 km of oceanic crust and sediment in the intervening gap between the Finisterre Terrane and the northward dipping subduction of Australian lithosphere is absent from the collision suture zone. The intervening basin could be accommodated by a northward subducting slab that stays near the Finisterre Terrane, and steps back to the southeast along the leading edge of the Arc as the collision tip migrates. Indeed, many tectonic reconstructions have hypothesized that the igneous rocks of the Maramuni Arc, south of the present day collision on the New Guinea mainland, are the signature of a southward-dipping slab of the doubly-subducting Solomon Sea Plate that extended westward across PNG. Abbott (1995), however, argued that the trench of such a south-dipping subduction zone would block sediment derived from the Australian continent from reaching the Finisterre accretionary wedge where it is found today. Moreover, geologic mapping indicates that the Maramuni Arc was erupted on allochthonous terranes rather than on autochthonous crust. For these reasons, Abbott (1995) argued that the double subduction present in the Solomon Sea probably never extended >200 km west of its present location.

The E–W component of the migrating pole model presented above has the effect of translating the Finisterre Terrane westward during its rotation (Fig. 13). Thus, the Finisterre Terrane stays along the South Bismarck/Solomon Sea plate boundary at the New Britain Trench, and the problem of accounting for 300 km of intervening basin material is mitigated by northward subduction along the New Britain Trench without eastward migration of the triple junction across New Guinea. The E–W translation of the Finisterre Terrane, which results from this model, is consistent with evidence that the doubly-subducting Solomon Sea Plate, and indeed the triple junction, was not far to the west of its present location.

4.2.3. Caveats

Our modeled curve results from migration of the pole between 4.5 and 0 Ma, ending with the present pole just arriving at the northern tip of the RMFZ. Since the Euler pole might be considered to be stable when it reaches the plate boundary, and the coincidence of its arrival at the plate boundary today ad hoc, we tested the effect of an Euler pole that has been stationary there since 1 Ma. This produces a shallowed remagnetization curve and, although better than the straight-line fit, is less well fit to the paleomagnetic declinations than our preferred model. The rotated locations of the eastern sites changes very little, so the location of the ramp with respect to the RMFZ cannot be greatly changed and still fit the data. Thus, it appears that the model that gives the best fit to the paleomagnetic data indicates a gradual change in SBIS/AUS relative motion. It should be noted, however, that the fit of the curve is very dependent on the 43° mean declination anomaly at Matoko. If the paleomagnetic declination at Matoko is reduced to 37.5° (the lowest declination within its $\Delta D$ of 6.3°), then the shallower curve resulting from a fixed pole over the last 1 Ma and 150 km Ma$^{-1}$ migration prior to that can be well fit.

The best-fit pole migration model is very sensitive to small changes in the present location of the SBIS/AUS pole. The present pole found by the 6 year GPS study of Tregoning et al. (1998) is just


southwest of the western Adelbert Range, in the Ramu River Valley. This location is geologically sound, since the abrupt change in the azimuth of the Ramu River (Fig. 2), and the abrupt termination of the mountain range are significant geomorphic features, which may indicate divergence west of that point. Moreover, the complex transition in deformation in this area is likely to be diffuse. If the present-day pole is moved 150 km northwest, to the point where the Bismarck Sea seismic lineation intersects the coast, then the model presented here cannot be fit to the paleomagnetic data regardless of the offset between the RMFZ and the linear remagnetization. Our model is dependent on the present-day pole proximity of about 250 km to the westernmost paleomagnetic sites. This model is also very sensitive to changes in the angle of the straight-line migration path.

5. Conclusions

New paleomagnetic data from 12 sites in the Plio-Pleistocene Nokopo Formation record terrane-scale, vertical axis rotation of the Finisterre Arc Terrane as it collides with the Australian continental margin. The results indicate a general decrease in paleomagnetic declinations, from over 40° in the NW to 5° in the SE, along the propagating collision.

Based on dominantly uniform polarities, microfossil age determinations, nearly geocentric axial dipolar inclinations, positive tilt tests, and other paleomagnetic and geologic data, we interpret the characteristic magnetic remanence as an early syn-collisional remagnetization. The progressive decrease in the paleomagnetic declinations shows that it is a time-transgressive remagnetization, acquired along a linear ‘ramp’ that was offset from the surface trace of the Ramu-Markham Fault suture by about 150 km. We speculate that remagnetization is caused by compressional stress causing deformation or by seismic shaking along the outermost edge of the collision, and may be correlated with the change in angle of the deep oceanic slab at that distance.

Several authors have suggested differential rotation of blocks of the colliding Finisterre Terrane accommodated by left-lateral tear faults which cross the terrane. Since we interpret the remagnetization as time-transgressive, the pattern of paleomagnetic declinations along the strike of the range would be approximately equal from NW to SE if the terrane collided with sequential rotations of independent blocks. Since the declination anomalies vary along-strike from 40 to 5° in a relatively coherent fashion, however, we conclude that the terrane rotated as a more or less rigid body.

Interpreted as a time-transgressive remagnetization, these data are in good agreement with estimates of instantaneous SBIS motion from GPS geodesy. Thus, we suggest that the indicated rotation is not only consistent throughout the Finisterre Mountains, but, moreover, results from South Bismarck/Australia Plate motion rather than from decoupled rotation of the entire crustal terrane independent of the underlying lithosphere.

These models of syn-collisional remagnetization with both fixed and migrating Euler poles of SBIS motion suggest that the Euler pole describing SBIS motion has migrated southwestward toward the Ramu-Markham Fault suture to its present location. Our best-fitting model of SBIS motion locates a remagnetization versus distance curve resulting from the changing angle of the terrane as the Nokopo Formation acquired its magnetization. The agreement between the modeled convergence and the varying seismogenic slab depth present under the collision zone provides an independent check on the direction and rate of Euler pole migration.

Our estimate of SBIS/AUS Euler pole migration describes SBIS motion producing a highly oblique collision in its early stage, with the Finisterre Terrane converging along a left-lateral Ramu-Markham suture, gradually changing to the nearly orthogonal convergence observed today. Thus, the geometry of the modeled plate motion suggests that the Ramu-Markham Fault retains its steep and straight morphology resulting from previous left-lateral strike slip motion along the suture, and that the general trend of more subdued uplift to the northwest is a consequence of early oblique collision. Moreover, the modeled SBIS kinematic accommodates the oceanic basin between the colliding Finisterre Terrane and the Australian margin.
with little or no eastward migration of the doubly-subducting Solomon Sea Plate.

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