Evidence for Late Eocene emplacement of the Malaita Terrane, Solomon Islands: Implications for an even larger Ontong Java Nui oceanic plateau

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[1] Most tectonic models for the Solomon Islands Arc invoke a Miocene collision with the Ontong Java Plateau (OJP) to halt cessation of Pacific Plate subduction, initiate Australian Plate subduction, and emplace the Malaita Terrane, which shares the characteristic basement age and geochemistry of OJP. Existing paleomagnetic evidence, however, required the Malaita Terrane to have been fixed to the arc from at least the Late Eocene. New sampling has yielded a paleomagnetic pole from Aptian–Albian limestones and mudstones that falls between the apparent polar wander paths for the Australian Plate and OJP, confirming the extended period of residence of the Malaita Terrane on the arc. Arc-derived turbidities within Late Eocene through Miocene limestones on Malaita and Santa Isabel, and related clasts in broadly contemporary sandstones and conglomerates on Santa Isabel, also attest to early emplacement. Modeling the emplacement at 35 Ma satisfies both the paleomagnetic data and the sediment provenance. Continuing the reconstruction to 125 Ma leaves the Malaita Terrane far from OJP at the time of plateau formation. OJP is now understood to have formed as part of a larger Ontong Java Nui, also comprising the Hikurangi and Manihiki plateaus, separated by spreading during the Cretaceous. Restoring the separation of the known elements, and invoking an additional triple junction, unites the (now largely subducted) Malaita Terrane with the rest of Ontong Java Nui. Subduction of substantial areas of the Ontong Java Nui plateau, with little geological signal other than a reduction in arc volcanism, is a corollary.


1. Introduction

[2] Malaita and Santa Isabel, two islands of the Solomon Islands Arc in the southwest Pacific (Figure 1), expose accreted oceanic sediments and volcanic basement which closely resemble materials recovered in drill core from the neighboring Ontong Java Plateau (OJP). An earlier paleomagnetic study of the southern part of Malaita [Musgrave, 1990] challenged the accepted model of OJP-Solomons collision, by requiring that Malaita had spent a protracted time fixed to the Australian Plate prior to the Late Miocene reversal of polarity of the Solomon Islands Arc. Here, I present further paleomagnetic results from the Cretaceous to Eocene sequence of northern Malaita and Santa Isabel, which confirm and extend the earlier study and are consistent with an arc provenance for Late Eocene to Miocene terrigenous sediments found on the two islands. Apparent conflict between the constraint that Malaita and Santa Isabel were fixed on or near the Solomon Islands Arc throughout the Oligocene and Miocene, and the geochemical evidence for a common origin of the large igneous province (LIP) crust of the two islands and the OJP, may be resolved by invoking Late Eocene emplacement of Malaita and Santa Isabel as part of a terrane accreted from a now-subducted additional fragment of the greater OJP-Manihiki-Hikurangi LIP (“Ontong Java Nui”) recently identified as originating as a single entity in the Early Cretaceous [Taylor, 2006; Worthington et al., 2006; Chandler et al., 2012]. Preservation of this Malaita Terrane following subduction of the rest of the LIP fragment lends weight to the interpretation of Mann and Taira [2004] that oceanic plateaus are preserved through emplacement of imbricate slices limited to the uppermost part of the plateau crust.

2. Ontong Java Plateau and the Solomon Islands Arc

[3] Oceanic plateaus distinguish themselves from the bulk of the oceanic crust by their shallow bathymetry (typically 2000 m above surrounding oceanic crust), crustal thickness (greater than 20 km), and plume-related basalt composition [Coffin, 1992; Mahoney, 1987; Richards et al., 1989]. With...
an area of approximately $1.9 \times 10^6$ km$^2$, and a volume estimated to be between $24 \times 10^6$ and $65 \times 10^6$ km$^3$ [Schubert and Sandwell, 1989; Tarduno et al., 1991], the Ontong Java Plateau is the largest of the LIP oceanic plateaus. Adding the geochemically similar Manihiki Plateau, and the surviving, unsubducted extent of the Hikurangi Plateau, enlarges this LIP to about 1% of the Earth’s surface [Taylor, 2006].

The Ontong Java Plateau borders the Solomon Islands Arc, and the northeastern edge of the arc—the “Pacific Province” of Coleman [1966, 1970], comprising the islands of Malaita and most of Santa Isabel, and herein referred to as the Malaita Terrane—is floored by oceanic plateau basaltic basement and pelagic sediments. Early models for the tectonic evolution of the Solomon Islands Arc were variations on a theme, in which Eocene to Miocene subduction of the Pacific Plate below a northeastward facing arc is thought to have been halted by the arrival at the North Solomons Trench of the thick crust of the OJP, which obstructed and halted subduction, reversed the polarity of the arc to initiate Miocene/Pliocene to present subduction along the South Solomon Trench on the southern flank of the arc, and emplaced the Malaita Terrane as an obducted “flake” of the plateau [Karig and Mamerickx, 1972; Halunen and von Herzen, 1973; Hughes and Turner, 1977; Coleman and Kroeneke, 1981; Kroeneke, 1984; Cooper and Taylor, 1985]. An early consensus held that collision of the plateau with the trench brought an immediate and permanent end to subduction of the Pacific Plate, effectively transferring the whole of the Solomons Islands Arc from the Australian Plate to the Pacific Plate.

Subduction-related volcanism was reduced or absent in the Solomon Islands Arc during the Early and Middle Miocene. Yan and Kroeneke [1993] inferred from this time gap in arc volcanism that collision of the Ontong Java Plateau with the arc, and cessation of Pacific Plate subduction, occurred between 25 and 20 Ma [Kroeneke et al., 1986; Kroeneke, 1989; Petterson et al., 1999]. Significant deformation and uplift of the arc were delayed until the Pliocene [Resig et al., 1986; Musgrave, 1990; Petterson et al., 1997], leading to the adoption of the concept of “soft
docking for the initial Early Miocene plateau-arc collision [Yan and Kroenke, 1993; Petterson et al., 1999], with a following “hard docking” event in the Pliocene. Initiation of north-eastward dipping subduction on the opposite side of the arc was placed between the “soft” and hard” docking events at about 12–6 Ma, begging the question of the location of Pacific-Australia convergence in the mid-Miocene. Kroenke [1984] suggested that the motion could have been accommodated on a now-subducted transform from the northern end of the proto-Tonga Trench to the Trobriand Trough, isolating both the Solomon Islands Arc and the New Hebrides/Vitiaz Arc from the Australian Plate.

Hall [2002] modeled collision of OJP with the Solomon Arc at 18 Ma, although he noted that the first stages of collision may have occurred earlier, as an unknown amount of the leading edge of OJP may have been subducted during the “soft-docking” phase. In Hall’s model, the Solomon Islands were fully coupled to the Pacific Plate after 18 Ma, with Pacific-Australia convergence accommodated at a subduction zone on the southern side of the Solomon Sea at the Trobriand Trough, linked to the New Hebrides Trench by a transform fault. Initiation of north-dipping subduction of the Solomon Sea on the southern flank of the Solomons Arc at 6 Ma halted subduction at the Trobriand Trough and motion on the transform but had no significant impact on the motion of the Solomon Islands Arc, which continued to be coupled more or less completely to the Pacific Plate.

[7] Deflections in seamount tracks in the Tasman Sea indicate a reduction in the rate of northward movement of the Australian plate between 26 and 23 Ma, which Knesel et al. [2008] ascribed to collision of OJP with the arc. Indications of a collision at this time appear to be absent from the Solomon Islands Arc, where the principal geological event in the Late Oligocene and earliest Miocene is the intrusion of calcalkaline intrusives [Hackman, 1980].
Petterson et al. [1997] cited mid-Miocene to Pliocene volcanism on Choiseul [Ridgeway and Coulson, 1987], together with seismicity and swath mapping evidence [Cooper and Taylor, 1984; Cooper et al., 1986; Kroenke, 1995], to infer some degree of subduction of the Pacific Plate along the northeastern margin of the Solomon Islands Arc from the mid-Miocene to the present. Subduction of part of OJP after collision with the arc is a corollary; however, this has commonly been seen as a minor, attenuated remnant of the earlier Pacific Plate subduction and was described as underthrusting accompanying obduction [Cooper et al., 1986], or as “localized, intermittent, passive subduction” of OJP [Petterson et al., 1997].

Marine geophysical surveys and seismicity studies of the Solomons-Ontong Java convergent zone led a joint US-Japan research group [Mann and Taira, 2004; Taira et al., 2004] to conclude that subduction of the Pacific Plate along the northeastern flank of the Solomon Islands Arc has continued without interruption to the present day. In their view, only the upper 20% of the plateau crust has been emplaced on the arc, as an accretionary prism comprising a series of fault blocks forming anticlinoria of fault-propagation folds. Subduction of the lower 80% of the plateau has continued, although the rate of subduction has slowed. In this model, collision of OJP with the northeast margin of the Solomon Islands Arc did not occur until 4 Ma. Mann and Taira [2004] suggested that, prior to accretion of the Malaita prism, subduction occurred on a suture now marked by the Kaipito-Korighole Fault (KKF), which divides the accreted Malaita Terrane from the older arc in Santa Isabel.

Paleomagnetic results from the Late Eocene to Pliocene sequence from the southern part of Malaita [Musgrave, 1990] appear incompatible with the conventional tectonic histories for the Solomon Islands Arc. Instead, both an Early Miocene pole and an Eocene pole lie far from the Pacific apparent polar wander path (APWP) and close to the Australian APWP, indicating a prolonged motion of Malaita in concert with the Australian Plate throughout the Oligocene and Miocene. However, the tectonic model originally proposed to explain this result appeared to be incompatible with evidence for an Ontong Java Plateau origin for Malaita [Tejada et al., 1996, 2002; Petterson et al., 1997, 1999; Phinney et al., 1999, 2004; Taira et al., 2004], and several authors [Kroenke, 1989; Hawkins and Barron, 1991; Mann and Taira, 2004] casted doubts on the validity of the paleomagnetic data from Malaita. Other paleomagnetic evidence bearing on the tectonic history of the Solomon Islands Arc, from Buka at the northwestern end of the bathymetric ridge defining the pre-Miocene extent of the arc, also indicates motion in concert with the Australian Plate since the Oligocene [Falvey and Popichard, 1985].

3. Geological Setting

Late Cretaceous to Miocene limestone and chalk sequences of the Malaita Terrane contrast strongly with contemporary volcanics and arc-derived sediments on the rest of the Solomon Islands Arc. Immediately to the north of the Solomons, the anomalously thick oceanic crust of OJP is covered by a Late Cretaceous to recent carbonate
sequence, revealed from seismic reflection profiling and DSDP and ODP drilling [Packham and Andrews, 1975; Berger et al., 1991; Fitton et al., 2004a]. Cretaceous basement in the Malaita Terrane shows a similar LIP geochemical signature to that recovered from drilling on OJP [Fitton et al., 2004b].

[12] Malaita shares the Malaita Terrane stratigraphic sequence (Figure 2) with the Zabana Province of Santa Isabel, northeast of the major crustal suture of the KKF [Hughes and Turner, 1976, 1977; Hawkins and Barron, 1991; Pettersson et al., 1997]. Basement tholeiitic lavas (Sigana Volcanic Formation of Santa Isabel, Malaita Volcanic Group of Malaita) dominantly yield 40Ar/39Ar ages of about 122 Ma, similar to ages of the ODP basement recovered in several ODP drill holes [Tejada et al., 2002; Fitton et al., 2004a]. The Malaita volcanic group has been divided into an upper Singgalo Formation and a lower Kwaimbaita Formation [Tejada et al., 2002]. Rocks of Kwaimbaita affinity have been found at all but one of the drill sites that penetrated OJP basement, but Singgalo-type volcanics have been recovered only from ODP Site 807, on the northern flank of OJP [Fitton et al., 2004a].

[13] In the northern part of Malaita, the volcanics are overlain by the Kwaraae Mudstone Formation, a radiolarian/foraminiferal siliceous mudstone with an Aptian–Albian age. Overlying the Kwaraae Mudstone Formation in parts of northern Malaita, and directly above the basement lavas at other localities, is a series of porcellanous limestones extending to the Middle Eocene (Alite Limestone Formation of Malaita, Bara Limestone Formation of Santa Isabel). Chert lenses and nodules are abundant in most of this limestone sequence, including the sequence sampled in southern Malaita in the earlier study but are absent in the lowermost part of the Alite Limestone Formation in northern Malaita sampled in this study. Van Deventer
and Postuma [1973] recognized a very Early Cenomanian foraminiferal assemblage in rocks toward the base of the Alite Limestone Formation and inferred a late Albian age for the lowest parts of the formation. In the analogous sequence at ODP Site 1183, conspicuous chert bands characterize the Eocene lithological subunit IIA at this site, and chert was rare in the limestones of subunit IIB (Palaeocene) and unit III (Aptian to earliest Palaeocene). Micropaleontological ages for the Bara Limestone Formation span the Late Campanian to early Miocene, and chert beds are common, suggesting that the bulk of the Bara Limestone Formation postdates the Albian age of the lower part of the Alite Formation.

[14] Middle Eocene alkali basalts (Maramasike Volcanic Formation) occur near the top of the porcellanous limestones in Malaita; $^{40}$Ar-$^{39}$Ar gives an age of 44.2 ± 0.2 Ma [Tejada et al., 1996]. Similar alkaline basalts are present as intrusives within the Sigana Volcanic Formation on Santa Isabel [Hawkins and Barron, 1991].

[15] Conspicuously banded limestones (Maruto Limestone Formation of Santa Isabel and Haruta Limestone Formation of Malaita) conformably overlie the porcellanous limestones and alkali basalts. The bands represent the supply of vitric-crystal-rich muds with a likely arc provenance [Hughes & Turner, 1976] and alkali basalts. The bands represent the supply of vitric-crystal-rich muds with a likely arc provenance [Hughes & Turner, 1976].

Table 1. Anisotropy of Magnetic Susceptibility

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<th>$P$</th>
<th>$P’$</th>
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<th>$K_2$</th>
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$L$ = lineation; $F$ = foliation; $P$ = anisotropy degree; $P’$ = corrected anisotropy degree; $K_1$, $K_2$, and $K_3$ = maximum, intermediate, and minimum eigenvalues; $h_3$% = mean anisotropy, as percentage, using method of Howell et al. [1958].

*Result using unoriented sample.

[4.1] Techniques

[4.1.1] Sampling

[18] Sampling in Malaita (Figure 3) comprised five sites in the Kwaraae Mudstone Formation (sites SI186–188 and SI200–201) and eight sites in the Alite Limestone Formation (SI189–196). All sites in the Alite Limestone Formation were
less than 100 m stratigraphically above the base of the formation, and samples display the pattern of strongly flattened burrows, anastomosing seams, and microflasers, characteristic of the lithologically similar Aptian–Albian Subunit IIIB, which forms the lowermost 42 m of the sedimentary sequence at ODP Site 1183 [Shipboard Scientific Party, 2001]. Five sites in Santa Isabel sampled the Bara Limestone Formation (SI204–208).

[19] Each site was sampled by six independently oriented, 2.5 cm diameter cores. Orientation was by magnetic compass; weather conditions and rainforest cover precluded the use of a sun compass. However, magnetizations of all sampled rocks were not sufficiently high to produce a significant deviation in the magnetic compass. Cores were packed in sealed plastic bags to minimize any acquisition of drying or oxidation-related overprints prior to storage in field-free space in the laboratory.
4.2. Paleomagnetic and Rock Magnetic Analysis

Paleomagnetic specimens from sites SI1189-193 were thermally demagnetized in a pilot study at 50°C C demagnetization steps in specimens of 25 mT served to remove viscous components acquired during time in storage after the pilot study. Specimens from other sites were demagnetized completely by the thermal method, in 5 mT steps to a maximum field of 50 mT. AF stages up to 20–25 mT served to remove viscous components acquired during time in storage after the pilot study. Specimens from other sites were demagnetized completely by the thermal method, in 50°C steps from 100 to 500°C, then 25°C steps to 600°C, and where a systematic remanence persisted, two further 15°C steps. Remanences were measured on either a ScT or 2G cryogenic magnetometer, or in the case of the AF-demagnetized specimens, a Molspin spinner magnetometer. Linear components of magnetization were fitted by principal component analysis [Kirschvink, 1980].

Rock magnetic analyses comprised measurements of hysteresis and isothermal remanance properties on a Molspin Nuvo vibrating sample magnetometer (VSM), bulk magnetic susceptibility on a Bartington MS 2 system, and anisotropy of magnetic susceptibility (AMS) on an AGICO Kappabridge KLY-3. VSM specimens were prepared by gentle hand grinding of off-cuts of the paleomagnetic specimens to sand-grain size. Susceptibility was measured on each of the paleomagnetic specimens following NRM measurement and repeated after each thermal demagnetization step, to monitor changes in magnetic mineralogy that might allow acquisition of spurious AMS. AMS in the present study was determined on one representative specimen from each site, and the mean anisotropy percentage was calculated as $h_k = 100(K_{max} - K_{min})/K_{int}$ [Howell et al., 1958], to facilitate comparison.

5. Results

5.1. Rock Magnetism

Representative specimens from all sites display simple hysteresis loops with a small ferrimagnetic contribution superimposed on a paramagnetic background (Figure 4). There is no evidence of a significant antiferromagnetic component. Specimens of the Alite Limestone, Kwarae Mudstone, and Bara Limestone formations form three distinct fields on a Day plot [Day et al., 1977], broadly scattered along a single-domain (SD)-multidomain (MD) mixing curve [Dunlop, 2002]. On this basis, the Alite Limestones are the most likely to preserve a primary remanence, the Bara limestones the least.

Specimens of both the limestone formations exhibit changes in susceptibility after successive thermal demagnetization stages typical of greigite-bearing sedimentary rocks [Snowball and Thompson, 1990; Roberts et al., 2011]. Decreases in susceptibility of the Alite Limestone Formation specimens after heating above 300°C are never more than 25% of the initial susceptibility, suggesting that the thermally stable ferrimagnet magnetite is also present and is the dominant contributor to the magnetization. Susceptibility decreases in Bara Limestone Formation specimens are proportionally larger, suggesting that greigite constitutes a greater proportion of the magnetic mineralogy.

Room-temperature susceptibility increases suddenly after the 350–450°C demagnetization steps in specimens of the Kwarae Mudstone Formation. The increase in susceptibility may result from liberation of iron from the dehydation of the clay minerals that are abundant in this formation, to produce magnetite or (in specimens where the susceptibility declines with further heating) metastable maghemite.

All specimens exhibited mildly oblate AMS ellipsoids (Table 1); mean and maximum foliations recorded for each
formation were 1.023 and 1.032 for the Kwaraee Mudstone Formation, 1.018 and 1.044 for the Alite Limestone Formation, and 1.050 and 1.055 for the Bara Limestone Formation. The mean corrected anisotropy degree, $P$ [Jelinek, 1981] is 1.029 for the Kwaraee Mudstone Formation, 1.024 for the Alite Limestone Formation, and 1.072 for the Bara Limestone Formation. Mean anisotropy expressed as $h_K$ is 2.55% for the Kwaraee Mudstone Formation, 2.19% for the Alite Limestone Formation, and 6.62% for the Bara Limestone Formation.

5.2. Demagnetization of Remanence

5.2.1. Kwaraee Mudstone Formation

[26] Specimens of the Kwaraee Mudstone Formation display a variety of demagnetization paths (Figure 5), ranging from linear convergence on the origin, indicating a dominant characteristic remanence (ChRM), to noisy and more strongly overprinted, with a small proportion of samples demagnetizing chaotically. All stable ChRM directions are normally polarized. Only three specimens from site SI186 yielded a stable ChRM, insufficient to calculate a mean for this site with well-defined confidence limits. All other specimens from the other four Kwaraee Mudstone Formation sites exhibited well-defined ChRM.

5.2.2. Alite Limestone Formation

[27] After removal of overprinted components at demagnetization temperatures up to 300°C, Alite Limestone Formation specimens consistently display a convergent, linear ChRM during further thermal or AF demagnetization, consistent with the rock magnetic evidence for the magnetic stability of these sites. Again, the ChRM from all samples at all sites is normally polarized.

[28] Overprint components could be isolated by thermal demagnetization at temperatures up to 300°C in samples from sites SI190, SI194, and SI196. Given that the demagnetization temperature needed to eliminate this component corresponds to the greigite decomposition temperature, it is likely that greigite is the overprint carrier.

5.2.3. Bara Limestone Formation

[29] Most Bara Limestone Formation specimens follow roughly linear demagnetization paths close to the direction of the present field, which become increasingly noisy above 300°C. As for the Alite Limestone Formation, this linear demagnetization trend is likely to represent an overprint carried at least partly by greigite. A minority of Bara Limestone Formation specimens show evidence of a more stable, reversed polarity component, but in the majority of specimens, this component is revealed along a curved demagnetization path, indicating overlapping stability spectra between this and another, apparently normal component. Only two specimens, one from each of sites SI207 and SI208, showed linear demagnetization of the reversed component, an insufficient number to calculate a mean direction at site or formation level. Poor preservation of paleoremanence in the Bara Limestone Formation is consistent with the low stability indicated by their hysteresis behavior, and the likelihood that overprints are carried in authigenic greigite.

5.3. Characteristic Remanence

[30] Mean characteristic remanence directions were determined for eight sites from the Alite Limestone Formation and four sites from the Kwaraee Mudstone Formation (Table 2); no sites from the Bara Limestone Formation yielded a reliable ChRM. Formation mean directions for the Alite Limestone and Kwaraee Mudstone formations are statistically indistinguishable both before and after bedding correction, so their results have been combined. Even so, the data set is too small ($N=12$) for reliable application of the simple form of the bootstrap fold test [Tauxe et al., 1991; Tauxe and Watson, 1994]. Bedding is scattered over a range of orientations, rather than falling into two planar fold limbs, so the fold test of McElhinny [1964] was more appropriate than that of

![Figure 6](image-url)

**Figure 6.** Site mean virtual geomagnetic poles on southern hemisphere projection: (a) before bedding correction, geographic coordinates; (b) after bedding correction, stratigraphic coordinates. Italic numbers distinguish Kwaraee Mudstone Formation. Grayed sites in Figure 6b are distributed around a suspected plunging fold. Preferred mean paleomagnetic pole is indicated by black star with A$_{0.5}$ circle; gray star indicates mean including suspect sites.
Unfolding bedding increases $k$ from 11.25 (0% unfolding, geographic coordinates) to 48.46 (after 100% unfolding, stratigraphic coordinates): $k_{100\%/k_{0\%}} = 4.31$, which exceeds the $F$-distribution for 99.9% confidence for the sample size, so passing the conventional fold test. However, maximum $k$ occurs at 82% unfolding, suggesting the possibility of either syn-deformational acquisition of the ChRM, plunging fold axes, or an unrecognized vertical-axis rotation of some of the sites. Most fold axes in Malaita plunge at low angles, and there is no evidence of second-generation folding [Hughes and Turner, 1976]. Sites SI194, SI195, and SI196 have a distinctive structural setting: they are distributed around a small anticline-syncline pair with limbs which dip more steeply ($75^\circ/C14$) than at any of the other sites. Omitting sites SI194, SI195, and SI196 from the calculation of the mean ChRM improves the precision parameter over the whole unfolding range and shifts the peak in $k$ to 97% unfolding. The fold test remains satisfied, $k_{100\%/k_{0\%}} = 5.22$, still exceeding the $F$-distribution for 99.9% confidence for the reduced sample size.

5.4. Paleomagnetic Poles

Virtual geomagnetic poles (VGPs) for site mean directions of the Alite Limestone and Kwaraee Mudstone formations (Figure 6) combine to give a mean south paleomagnetic pole for the Malaita Terrane for the Aptian–Albian (122–100 Ma) at 152.9°E, 66.6°S, with $A_{95} = 5.7°$. Means drawn from the Alite Limestone Formation only, both including and excluding the three suspect sites, and from the Kwaraee Mudstone Formation sites alone, are not significantly different from the combined pole (Table 3).

6. Discussion

6.1. Reference Apparent Polar Wander Paths

Existing models for the tectonic history of the Solomons Islands Arc differ in the age of the collision with OJP, how soon the emplacement of the Malaita Terrane followed after the collision, when subduction of the Australian Plate commenced, and when (and how abruptly) subduction of the Pacific Plate terminated (if indeed, it is not continuing today). These issues boil down to a comparison of the

---

### Table 3. Aptian–Albian Mean Paleomagnetic Poles for the Malaita Terrane

<table>
<thead>
<tr>
<th>Formation</th>
<th>N</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>$A_{95}$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alite Limestone</td>
<td>8</td>
<td>−67.4</td>
<td>159.4</td>
<td>75.68</td>
</tr>
<tr>
<td>Excluding SI194-196</td>
<td>5</td>
<td>−64.3</td>
<td>158.8</td>
<td>111.11</td>
</tr>
<tr>
<td>Kwaraee Mudstone</td>
<td>4</td>
<td>−69.2</td>
<td>143.9</td>
<td>121.63</td>
</tr>
<tr>
<td>Combined Aptian–Albian sites:</td>
<td>12</td>
<td>−68.2</td>
<td>154.5</td>
<td>71.93</td>
</tr>
<tr>
<td>Excluding SI194-196*</td>
<td>9</td>
<td>−66.6</td>
<td>152.9</td>
<td>92.24</td>
</tr>
</tbody>
</table>

*N* = number of sites; $k$ = precision parameter; $A_{95}$ = 95% confidence radius for pole.

*Preferred Aptian–Albian pole.

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Figure 7. Paleomagnetic poles from Malaita (open stars), compared with data defining the Australian and Pacific/Ontong Java Plateau (OJP) apparent polar wander paths. All poles surrounded by circles or ellipses of 95% confidence. (a) Australian data, with Malaita poles; (b) Pacific/OJP data; (c) Malaita poles compared with Pacific/OJP data. *Ol* = Oligocene, *LE* = Late Eocene, *EE* = Early Eocene, *Pa* = Paleocene, *Ma* = Maastrichtian.
paleomagnetic poles with the apparent polar wander path (APWP) for each of the two plates.

[34] Australian plate motion over the interval is comparatively well understood, and the Australian APWP follows the simple trajectory shown in Figure 7a [Schmidt and Clark, 2000]. The fine detail of age progression along this trajectory has been the subject of some debate. Dated poles from sedimentary formations suggest a variable rate of drift during the Late Eocene to Pliocene [Iddings, 1985, 1994], although a nonlinear rate has been challenged as overly complex [Musgrave, 1989, 1991] and appears inconsistent with the age progression of the Tasmanian hot-spot trail [McDougal and Duncan, 1988]. In their global compilation of APWPs, Besse and Courtillot [2002] applied a series of reliability criteria to the Global Paleomagnetic Database [McElhinny and Lock, 1995] to select a set of dated paleomagnetic poles for Australia: these suggest a roughly linear progression along the APWP back to about 60 Ma. Globally averaged APWP can also be used to define the Australian APWP through the seafloor-spreading circuit: Figure 7a shows the path derived from the compilation of Torsvik et al. [2008].

[35] Construction of a Pacific—or more specifically, an Ontong Java Plateau—APWP is more challenging. Although Torsvik et al. [2008] did not explicitly derive a Pacific APWP from their global mean APWP, this can be readily done via the Pacific–West Antarctica–East Antarctica–Australia plate circuit, using their listed reconstruction poles (Figure 7b). However, this path extends only to 80 Ma, the limit of the Pacific–West Antarctica spreading record and assumes the integrity of a single Pacific Plate throughout this time.

[36] Direct measurements of Pacific APWP are restricted to seamount anomaly inversions, magnetic lineation skewness analysis, and paleomagnetic studies of basalt and sediment samples from azimuthally unoriented cores. Beaman et al. [2007] combined paleomagnetic inclinations from all three data types to produce a series of five poles for the Pacific Plate spanning the Maastrichtian to the Oligocene. These broadly agree with poles from earlier studies based on seamount inversions or mixes of data types. Although internally consistent, Paleocene to Eocene Pacific paleomagnetic poles diverge from the global mean APWP in Pacific coordinates, a fact originally noted by Acton and Gordon [1994] and attributed by them to Late Cretaceous to Eocene movement between a South Pacific Plate and a North Pacific Plate. Hammond et al. [1975] determined inclinations from azimuthally unoriented sediment cores from DSDP Site 289 on OJP and noted little or no change in paleolatitude since 30 Ma. Comparing this to the northward drift indicated by paleolatitude records from the central Pacific, they concluded that OJP had been decoupled from the Pacific Plate since this time. Although Kroenke [1989] later dismissed the discrepancy between the OJP and central Pacific paleolatitudes as the likely result of inclination shallowing during sediment compaction (and concluded that similar inclination shallowing affected the paleomagnetic results from Malaita), the Site 289 paleolatitude record is, in fact, in agreement with the global mean APWP rotated to the (South) Pacific Plate (Figure 7b), which requires only 1° ± 3 of northward motion at the location of Site 289 since 30 Ma. Differences between the drift direction of OJP and the central Pacific do not require separate plates but are simply an expression of motion on a sphere.

[37] Whatever the plate geometry may have been in the Cenozoic, there is clear evidence for Cretaceous movement between OJP and the Pacific Plate. Sager [2004, 2006] found paleomagnetic poles constructed using basalt cores from Aptian-aged OJP basement to be inconsistent with comparably aged poles from similar cores from the rest of the Pacific, leading him to infer that OJP was situated in a different plate to the Pacific Plate at some time following its formation, probably during the Cretaceous Quiet Period. A compilation of paleomagnetic inclinations from basalts and sedimentary cover from OJP [Hall and Riisager, 2007] indicates very little change in paleolatitude over the protracted interval from 122 to 76 Ma (Barremian to Campanian), contrasting with a 14° northward change in paleolatitude for the Pacific Plate over the same interval. The low rate of latitude drift for OJP also contrasts with a much larger change in latitude for the Pacific Plate predicted by hotspot models for a fixed-Pacific-hotspot frame [Wessel and Kroenke, 1997, 1998; Kroenke et al., 2004; Antトレtter et al., 2004].

[38] Sager’s pole from OJP was, in fact, an invalid hybrid, designed only to demonstrate the independent motion histories of OJP and the Pacific Plate: colatitude was determined from OJP basement, but the position of the pole on the colatitude arc was set by declinations derived from seamounts far from OJP, which presumably moved with the Pacific Plate rather than an OJP plate. Intersection of paleolatitude small circles, derived from basement basalts and Early Cretaceous volcanioclastic rocks from sites distributed across the OJP and neighboring Nauru Basin, allowed Riisager et al. [2004] to produce a valid ~120 Ma paleomagnetic pole for OJP, located much closer to the 80 Ma global mean paleomagnetic pole for the Pacific Plate, though with a large major confidence axis. Given the evidence that OJP did not move with the rest of the Pacific Plate during the intervening time, there is no need to invoke for OJP the rapid plate motion suggested for the Pacific Plate [Cottrell and Tarduno, 2003]. The most parsimonious APWP for OJP would track the global mean APWP to its limit at 80 Ma and then follow the same general trajectory, with a reduced rate of motion, to the Riisager et al. [2004] pole.

[39] Motion of OJP relative to the rest of the Pacific Plate, at least during the Late Cretaceous, is also consistent with the proposition that OJP separated from the other components of Ontong Java Nui through mid-Cretaceous spreading at the Osborn Trough [Downey et al., 2007] and in the Ellice Basin [Taylor, 2006].

6.2. Paleomagnetic Poles From Malaita

[40] Neither the Early Miocene nor the Eocene paleomagnetic poles from Malaita reported in Musgrave [1990], nor the new Aptian–Albian pole reported here, are consistent with either the Hall [2002] kinematic reconstruction for the Solomon Islands Arc, or any other of the commonly accepted variants on the post-collision history of the arc, if the parsimonious APWP for OJP is valid (Figure 7c). All models which envisage emplacement of the Malaita Terrane onto the arc in the latest Oligocene or Miocene presume cessation or at least marked slow down of subduction of the Pacific Plate immediately after this event, by transfer of the locus of Pacific-Australia convergence away from the arc, initiation of the modern phase of subduction on the southwestern side of the arc, or a combination of both. In
all these models, collision, even in the form of "soft docking", was followed by little further relative movement between OJP and the Solomon Islands Arc, requiring that the arc, and the Malaita Terrane with it, has moved in sympathy with the Pacific Plate since the time of collision. Even the Mann and Taira [2004] model, although it delays collision until the Pliocene, still requires that the Malaita Terrane moved with the Pacific Plate until that time. In all these models, any paleomagnetic pole from the Malaita Terrane, of whatever age, should fall on or near the Pacific APWP, or the APWP for OJP to the extent that this may have constituted a distinct plate. This is clearly not the case for the Early Miocene and Eocene poles from Malaita, which are distinctly different from both the global mean APWP transferred to the Pacific Plate via the plate circuit and from any of the corresponding poles directly determined for the (northern) Pacific Plate.

Figure 8. Reconstructions of the Malaita Terrane, the Solomon Islands, and New Hebrides arcs, the Ontong Java, Manihiki, and Hikurangi plateaus, and the Osbourn Trough (OT) and Ellice Basin (EB) spreading axes, relative to a fixed Australian Plate. VT = Viti Trench, SOL = Solomon Islands Arc, MT = Malaita Terrane, NH = New Hebrides Arc, KKF = Kaipito-Korighole Fault. Other abbreviations as for Figure 1. Rotation parameters follow Torsvik et al. [2008]. Contours for 2000, 3000, and 4000 m water depth are shown for OJP: likely extent of now-subducted OJP is shaded gray.

6.3. Inclination Flattening or Structural Rotation of the Paleomagnetic Data?

Values of AMS from the Kwaraae Mudstone and Alite Limestone formations are less than the low extreme of the range for Cretaceous Pacific deep-sea limestones reported by Hodych and Bijaksana [1993], suggesting an AMR lower than their minimum correlated value of $h_A = 6.2\%$. This degree of anisotropy is less than any of the OJP samples listed by Hodych and Bijaksana, which (with one exception) were associated with estimated inclination errors $\leq 9^\circ$, the lowest inclination errors of any of their deep-sea sampling sites. These inclination errors themselves were based on a model of Pacific Plate apparent polar wander and as discussed, may be an overestimate for OJP. On this basis, inclination flattening for the Aptian–Albian paleomagnetic pole for the Malaita Terrane should be substantially less than $9^\circ$ and even less for the poles from the less compacted Eocene and Miocene formations. Hall and Riisager [2007] found inclination shallowing to be negligible in their study of OJP deep-water sediments, and the reinterpretation of the DSDP Site 289 data, from sedimentary samples spanning the Late Cretaceous to Oligocene, also suggests little or no inclination shallowing.
[45] Tectonically induced rotation around a vertical axis cannot be so definitively ruled out but would require special pleading. Malaita exhibits a strongly developed and mostly uniform structural grain striking 128°, parallel to the overall trend of the arc. Some locally discordant structural domains are rotated anticlockwise by up to 20° [Petterson et al., 1997], in accord with the left-lateral transpressive environment caused by the oblique convergence of the Pacific Plate. However, the Malaitan poles are displaced from the Pacific APWP in a clockwise sense, so their disposition would require local antithetic rotation which was both relatively uniform within the sampling localities and consistent between the southern Malaita sites of the Miocene and Eocene poles and the northern Malaita sites of the Aptian–Albian pole. What is more, the Pliocene pole shows no such rotation, although it is dominantly derived from sites older than the tightly constrained Middle Pliocene age of transpressive deformation of Malaita and rapid uplift of the Malaita Terrane [Musgrave, 1990; Resig et al., 1986].

6.4. New Tectonic Model

[44] Before consideration of the paleomagnetic data, any tectonic model for the evolution of the Malaita Terrane should be compatible with the sedimentary record. As noted by Petterson [2004], supply of arc-derived material from the Solomons Islands or Vitiaz arcs, the only likely sources in the southwest Pacific throughout the Late Eocene to Late Miocene period of deposition of the Haruta limestone formation, requires that the North Solomons Trench, if it was present, did not act as a barrier to turbidites reaching the Malaita Terrane during this time. Moreover, all existing models require the Malaita Terrane and the rest of the Solomon Islands Arc to have been separated by Pacific-Australia relative plate motion until at least the latest Oligocene [Yan & Kroenke, 1993] to Early Miocene [Hall, 2002], requiring the lowermost turbidites in the Haruta limestone formation to have crossed a minimum of 550 (in the Yan and Kroenke model) to 1400 km (in the Hall model) of seafloor to reach the Malaita Terrane from the nearest point on the Solomons Islands or Vitiaz arcs. Difficulties presented by the existing models are only exacerbated by the corresponding sequence on Santa Isabel, which features boulder-sized arc-derived clasts and which appears to require uplift and erosion prior to the Oligocene. Instead, the uniformity of the turbidite sequence throughout the Haruta limestone formation, and the extremely proximal arc provenance of at least part of the contemporaneous sequence on Santa Isabel, argues for little relative movement between the Malaita Terrane and the volcanic arc over the whole Late Eocene to Late Miocene interval.

[45] Paleomagnetism imposes further constraints. Tectonic models like that of Yan and Kroenke, which could be modified to allow for an Eocene collision between OJP and the Solomon Islands Arc, thereafter fix the Malaita Terrane and the arc to the Pacific Plate, which is incompatible with both the position of the Eocene and Miocene poles from Malaita and the Oligocene result from Buka. Instead, the paleomagnetic data require the arc, including the Malaita Terrane, to have spent at least the Oligocene to Middle Miocene on the Australian Plate.

[46] Figure 8 shows a series of reconstructions, relative to a fixed Australian Plate, of the tectonic elements involved, assuming that the Malaita Terrane became accreted to the Solomon Islands Arc at 35 Ma and that the arc and the Malaita Terrane were transferred together to the Pacific Plate at 10 Ma when subduction of the Australian Plate began, with only minor continuing subduction of the Pacific Plate after this time. Reconstruction of the New Hebrides Arc follows Musgrave and Firth [1999]. The model also assumes that spreading in the Solomons Sea had ended by 35 Ma, following Crook and Belbin [1978] and Packham and Terrill [1975].

[47] At 35 Ma, corresponding to the oldest recognized age for the turbiditic limestones of the Malaita Terrane, the separation between the Malaita Terrane and OJP (even allowing for a reasonable extension of the now-subducted southwestern flank of the plateau) is more than 1300 km. However, this distance is less than the separation between the formerly contiguous Manihiki and Hikurangi plateaus separated by mid-Cretaceous spreading on the Osbourn Trough. Extrapolating the Osbourn Trough beyond its preserved limit at the Tonga Trench suggests a position roughly mid-way between the OJP and the Malaita Terrane, suggesting that the Malaita Terrane may represent a preserved fragment of a plateau having a similar conjugate relationship to OJP that the Hikurangi Plateau has to the Manihiki Plateau.

[48] Figure 9 shows the paleomagnetic poles from the Malaita Terrane after rotation according to the reconstruction steps shown in Figure 8 and conversion to a Pacific Plate frame of reference to allow direct comparison with the Pacific and OJP APWPs. All four poles now lie within confidence limits of the parsimonious OJP APWP. Note that an allowance for some amount of continued subduction of the Pacific Plate after 10 Ma produces an even closer fit. Of the four poles, the largest (albeit most poorly defined) inconsistency would appear to be between the Aptian–Albian Malaitan pole, which should represent some time around 110 Ma and the equivalent position on the OJP path: the discrepancy, however, may be attributed to some proportion of the spreading between the Malaita Terrane and OJP on the postulated extension of the Osbourn Trough.
What was the spreading geometry responsible for the fragmentation of a single plateau into the OJP, Manihiki, Hikurangi, and Malaita Terrane fragments? In their reconstruction of Ontong Java Nui, Chandler et al. [2012] invoked a triple junction where the Osbourn Trough spreading ridge intersected the Ellice Basin spreading ridge extrapolated to the southeast; the Manihiki and Hikurangi plateaus occupied the core of separate microplates, with other boundaries defined by spreading ridges with the Farallon and Phoenix plates, meeting in three additional ridge-ridge-ridge triple junctions, including the Tongarewa triple junction at the northeastern corner of the Manihiki Plateau [Larson et al., 2002]. One rift arm extended westward, running south of OJP. Subduction has removed the record of the southwestern part of the rift system, and so the pre-rift position of the Malaita Terrane relative to the rest of OJP is speculative. If the rift passed between the Malaita Terrane and the Hikurangi Plateau, the resulting geometry (Figure 10a) would require either an enormous enlargement in the original area of Ontong Java Nui or a separate origin for the Malaita Terrane. If instead the rift passed between OJP and the Malaita Terrane, the latter would have shared a plate with the Hikurangi Plateau, leading to the reconstruction of Figure 10b, still leaving OJP and the Malaita Terrane widely separated.

Chandler et al. [2012] envisaged the OJP-Manihiki-Hikurangi and Tongarewa triple junctions as fragmentation of an initially simple Pacific-Phoenix ridge; an additional triple junction, similarly nucleated along the Pacific-Phoenix ridge, could explain the offset between OJP and the Malaita Terrane (Figure 10c). One arm of this speculated triple junction parallels the linear western boundary of OJP, while the others comprise an extension of the Osbourn Trough and the Pacific-Phoenix ridge. A compact “greater Ontong Java Nui” results from restoring spreading on this triple junction and is made still more closely fitting by assuming that an offset between the subducted western edge of the Hikurangi Plateau [Davy et al., 2008] and the southwestern edge of OJP resulted from an initial phase of transform offset between Manihiki and Hikurangi. The original plateau fragment incorporating the Malaita Terrane is sketched as a more-or-less symmetrical extension of the western lobe of OJP; other lost fragments of the original greater OJN comprise the segments of Manihiki removed by the Tongarewa triple junction (following Larson et al. [2002]) and the subducted southwestern flank of OJP.

Spreading on the preserved parts of the OJN rift system is bracketed to between 120 and 86 Ma [Chandler et al., 2012], and so some proportion of the displacement of the Malaita Terrane relative to OJP should be preserved by the Aptian–Albian paleomagnetic pole. Applying 30%–70% of the rotation of the Malaita Terrane relative to OJP around a pole calculated for the restoration shown in Figure 10c brings the Aptian–Albian pole into close agreement with the paleomagnetic pole from OJP basement.

The 20 Ma reconstruction shows the now-subducted edge of OJP encountering the North Solomons-Vitiaz trench. Continued subduction of the anomalously thick crust of the plateau through the Early and Middle Miocene may have resulted in flat-slab subduction, in turn responsible for the waning in arc volcanism [Kay and Abbruzzi, 1996] in the Solomon Islands Arc over this time. Isolation of the Solomon Islands Arc from the location of Pacific-Australia convergence during the Miocene is not necessary as an explanation. In the Hall [2002] reconstruction, Middle Miocene subduction along the Trobriand Trough linked by a transform fault to the New Hebrides Trench, bypassing the Solomon Islands Arc. After restoration to remove Late Miocene to present spreading in the Woodlark Basin and reunite the parallel Woodlark and Pocklington ridges, the eastern segment of the Trobriand Trough trends about 240°, close to the local azimuth of Pacific-Australia relative plate motion for the Middle Miocene, suggesting that the eastern segment of the Trobriand Trough acted as a transform at this time. However, this transform did not trend toward the New Hebrides Trench but rather toward the western end of the North Solomon Ridge. This suggests that this transform linked subduction on the Trobriand Trough and the North Solomon Trench during the Middle Miocene, and so the Solomon Islands Arc remained on the Australian Plate through this time.

Why the Australian Plate should have slowed from 26 to 23 Ma is less clear, at least in terms of events.
concerning elements of OJN. Although the exact extent of the southwestern, now-subducted flank of OJP is uncertain, it probably did not encounter the North Solomon-Vitiatz Trench as early as 26 Ma. The lack of a geological signature of a collision in the Solomons at this time corroborates this observation. Events responsible for the Late Oligocene reduction in drift rate of Australia may have occurred somewhere else along the convergent margin of the Australian Plate, perhaps where young crust of the Caroline Basin resisted subduction at the Manus Trench [Kroeneke et al., 2004]. Setting aside a Late Oligocene collision at the North Solomon-Vitiatz Trench, the rapid decrease in age from ~95 to ~60 Ma of crust arriving at the trench as the extinct spreading ridges of the Osbourn Trough and Ellice Basin approached the trench at a low angle, and the symmetrical increase after they were consumed may have prompted a dip and recovery in the convergence rate between the Australian and Pacific plates along this boundary, similar to the response of the Aleutian subduction system to the subduction of the then-extinct Kula-Pacific ridge [Sdrolias and Müller, 2006]. This may have contributed to the reduced rate of northward drift of Australia over this time.

[54] A reasonable objection to the new tectonic model is the seeming coincidence of OJP colliding with the otherwise similar Malaita Terrane, given their distinct post-formation histories. The coincidence in position is apparent, however, rather than real: Malaita and Santa Isabel are the emergent expressions of the Malaita Terrane precisely because the thickest crust of the OJP has since collided with and been subducted below them. Other remnants of the now-lost plateau that originally emplaced the Malaita Terrane are likely to be found below sea level along the length of the Solomons Islands and New Hebrides/Vitiatz arcs (Figure 1). Elements of isolated shallow crust lying on the Pacific side of the main arc occur northeast of Nendo in the New Hebrides Arc and continue in a line south to Maewo and Pentecost, where a peridotite, metagabbro, and metabasalt complex with metamorphic minimum ages of 35 ± 2 and 28 ± 6 Ma [Mallick and Neef, 1974] marks an ophiolite emplaced into the fore-arc of the former north-east facing arc.

6.5. Relationship Between the Malaita Terrane and Ontong Java Plateau

[55] Although the timing and mechanism of emplacement of the Malaita Terrane are changed, the new model remains faithful to the geological evidence linking the terrane to OJP, if the latter is considered in the context of the larger OJN. Both the basement and the sedimentary cover older than Late Eocene represent an accreted fragment of OJN, which is remarkably laterally uniform, so a close match between the terrane and OJP would be expected. In fact, the new model better matches the distribution of basement lithologies, by restoring the Malaita Terrane closer to the northwestern lobe of OJP, with which it shares the restricted occurrence of the Singgalo Formation (Figure 10). Late Eocene emplacement of the terrane involved out-stepping of the frontal thrust of the subduction zone from the KKF to the North Solomons Trench; the accreted terrane then acquired the Late Eocene to Miocene sedimentary sequence with its component of arc provenance, absent from the then distant OJP. Further addition to the accretionary prism was presumably delayed until the now-subducted edge of OJP encountered the North Solomons Trench at about 20 Ma (the “soft-docking” event).

7. Conclusions

[56] Aptian–Albian-aged rocks of the Kwaraae Mudstone and Alite Limestone formations from northern Malaita yielded a mean primary south paleomagnetic pole at 152.9°E, 66.6°S, with $A_0 = 5.7^\circ$. Rocks from the Bara Limestone Formation of Santa Isabel are overprinted by a remanence probably carried by greigite and did not allow determination of a pole. Neither inclination flattening nor local structural rotation is likely to have significantly affected the result. This pole, which lies between the most probable APWPs for the Australian Plate and OJP, is inconsistent with the conventional view that the Malaita Terrane was accreted to the Solomon Islands Arc in or after the Late Oligocene but is consistent with previously reported paleomagnetic poles from Malaita that fall close to the Australian APWP and suggest accretion of Malaita in the Eocene. All of the paleomagnetic poles are also consistent with sedimentological evidence for detrital input (including coarse clastics) to the Malaita Terrane from the Late Eocene onward. A kinematic model that emplaces the Malaita Terrane from the Pacific Plate onto the Solomon Islands Arc in the Late Eocene satisfies the paleomagnetic and sediment provenance constraints but leaves the Malaita Terrane far from other parts of the Ontong Java Nui megplateau, with which it shares pre-Eocene geology. The problem can be resolved by including both the known spreading between the Ontong Java, Manihiki, and Hikurangi plateaus, and a hypothesized additional triple junction. This restoration not only produces a close fit between the Malaita Terrane and its “parent” Ontong Java Plateau but also brings the known occurrences of the Singgalo Formation on Malaita and OJP, now widely separated, into close proximity.

[57] Beyond the revision of southwest Pacific tectonic history, the identification of a Malaita Plateau, originally large enough to have left markers of its collision along 1700 km of the former Solomon Islands-New Hebrides/Vitiatz fore-arc, adds yet another element to the already vast Ontong Java Nui plateau system. There are also important implications for our understanding of arc-plateau collision: now there is not only evidence that some amount of LIP plateau can be subducted, as is the case for both OJP at the North Solomons Trench and the Hikurangi Plateau at the Hikurangi subduction zone (Barker et al., 2009) but that almost an entire plateau element can be subducted, without cessation or reversal of subduction, leaving only an accreted terrane in the fore-arc.

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