Origin of the Northland Ophiolite, northern New Zealand: discussion of new data and reassessment of the model

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Abstract This paper discusses new results from the Northland Ophiolite in northern New Zealand that indicate that it formed in a supra-subduction zone setting, c. 26–29 m.y. ago, and very near to its late Oligocene obduction site. This is in contrast to previous studies which have suggested that the ophiolite is a far-travelled igneous Cretaceous–Paleocene terrane. Cretaceous rocks formerly mapped as part of the ophiolite are minor and represent an autochthonous Late Cretaceous–Paleocene volcanic arc. The tectonic setting, age, and location of formation suggest that the ophiolite formed as part of the southernmost South Fiji Basin crust. Obduction of the Northland Ophiolite initiated subduction and volcanism resulting in the development of the Northland volcanic arc during the early Miocene.

Keywords Northland Ophiolite; Southwest Pacific; Oligocene; tectonics

INTRODUCTION

The tectonic evolution of the Southwest Pacific region during the last 100 m.y. has involved a complex interaction between the extension, dismemberment, and dispersal of eastern Australian continental lithosphere and formation of

extensional marginal seas coupled with convergence between the Australian and Pacific plates (e.g., Yan & Kroenke 1993; Crawford et al. 2003). The eastern edge of Australasia formed a convergent boundary in the early Cretaceous against which oceanic terrains were accreted. Eastern Gondwana experienced large-scale extension and fragmentation from c. 80–55 Ma and a number of slivers of Australian basement simultaneously separated from the margin, extending the Australian plate >2000 km eastwards (Falvey & Mutter 1981; Gaina et al. 1998). In the Paleocene, the eastern edge of the plate became a convergent boundary and oceanic terranes were accreted to the Australian plate at various stages in New Guinea, New Caledonia, and northern New Zealand (Malpas et al. 1992, 1994). The system has become more complicated since the beginning of the Neogene.

A major problem in deciphering the evolution of the Southwest Pacific is the limited subaerial outcrop and paucity of submarine data. One key area of subaerial exposure is the Northland Peninsula of northern New Zealand. Here, a complex succession of igneous rock associations together with sedimentary rock sequences can be grouped into lithostratigraphic packages that reflect the tectonic evolution of the region. Of particular significance are packages consisting mainly of Cretaceous and Paleocene submarine volcanic rocks that form the Mt Camel Terrane and the Northland Ophiolite, because these represent the time period during which New Zealand separated from Australia and leading up to the development of the convergent plate boundary that accounts for the Miocene Northland volcanic arc. One of the more intractable problems of Northland geology lies in the characterisation and interpretation of these igneous/sedimentary packages.

The Mt Camel Terrane is a sequence of terrigenous mudstones and sandstones with intercalated mafic and felsic volcanic rocks that are exposed in the Houhora–Doubtless Bay area of northern Northland and on Three Kings Islands (Fig. 1). Fossil ages and U/Pb dates on zircons from felsic samples indicate that these rocks are early–mid Cretaceous in age (Isaac et al. 1988, 1994). They are interpreted to represent an autochthonous ocean floor sequence that developed on the margin of the continental crust of the Northland–Norfolk Ridge system (Isaac et al. 1994; Herzer et al. 1997; Mortimer et al. 1998).

A second, more extensive and arguably more controversial package of rocks is the Northland Allochthon, which was interpreted as a series of thrust sheets emplaced from the northeast in the late Oligocene in the seminal work of Ballance & Spörli (1979). Although primarily composed of sedimentary rocks, the uppermost of these thrust sheets emplaced rootless massifs of mainly volcanic rocks that rise above the general land surface and rest on the allochthonous Cretaceous–Oligocene sedimentary sequences (Ferrar 1934). These allochthonous igneous massifs were originally referred to as Tangihua and Wangakea Volcanics. In later work, they have been referred to as Tangihua Volcanics (Brothers 1983),

Fig. 1 Geological sketch map of northern New Zealand showing the location of Northland Ophiolite and Cretaceous–Paleocene arc-related outcrops. *Inset:* Location of Northland in the Southwest Pacific with respect to New Caledonia and Papua, New Guinea (PNG), and Hikurangi Plateau (HP).

Northland Ophiolite (Malpas et al. 1992), and Tangihua Ophiolite Complex (Nicholson et al. 2000a). In the following we use the name Northland Ophiolite.

As an ophiolite, the igneous massifs of Northland represent a key fragment in a commonly accepted regional model (Aubouin et al. 1977; Walcott 1978; Parrot & Dugas 1980), in which it forms the youngest emplaced segment of an almost continuous Late Cretaceous–Eocene oceanic belt that collided diachronously with eastern Gondwana. Collision was initiated in the north in New Guinea in the Paleocene (Davies 1971) and continued southward into New Caledonia in the late Eocene (Ali & Aitchison 2000). However, although the Northland Ophiolite has been the focus of a number of recent studies (e.g., Malpas et al. 1992; Nicholson et al. 2000a), a clear consensus on its origin has not yet emerged. The critical questions are the age of the rocks forming the ophiolite, their tectonic significance, and the locality in which they were formed. In general, they have been considered to represent a single package of volcanic and associated rocks of Late Cretaceous and earliest Tertiary age that were emplaced in a convergent tectonic episode as part of the Northland Allochthon at the end of the Oligocene (Ballance & Spörl 1979). In this paper we discuss evidence from a recently completed study (Whattam 2003) that there are distinct groups of superficially similar rocks making up the Cretaceous and lower Tertiary volcanic formations in Northland and that each group has distinct tectonic significance. A key point is that because outcrops are generally poor, and rock types similar, subtle differences in trace element chemistry have become the principal means of identifying the different age groups.

AGE OF THE NORTHLAND OPHIOLITE

It is widely accepted that the Northland Ophiolite formed in the Late Cretaceous–Paleocene (e.g., Malpas et al. 1992; Nicholson et al. 2000a,b). This interpretation is based on microfaunas and macrofaunas recovered from a number of ophiolite outcrops (Farnell 1973; Brook et al. 1988; Larsen & Spörl 1989; Hollis & Hanson 1991), which show a wide spread of ages from 80 to 55 Ma for the generation of the ophiolite.

In their comprehensive study of the age of the Tangihua volcanics, Brothers & Delaloye (1982) identified a range of K/Ar ages for the various outcrops from Cretaceous to Oligocene. Because the Cretaceous and Eocene ages agree with biostratigraphic ages, it has generally been assumed that these reflect the age of formation and that the younger ages record later alteration. This interpretation is consistent with relatively pervasive low-temperature hydrothermal alteration and/or greenschist metamorphism (Black 1989; Nicholson & Black 1998), which may have resulted in loss of Ar.

More recently, two older (c. 108 Ma) $^{40}\text{Ar}/^{39}\text{Ar}$ ages from two volcanoclastic samples (Whattam et al. 2004) support the biostratigraphic ages and the older K/Ar ages and together suggest that the Northland Ophiolite massifs are Cretaceous to early Eocene. However, tectonic models for the ophiolite have been seriously constrained by the fact that it is very difficult to develop a plate model that places such old oceanic crust adjacent to northern New Zealand in the late Oligocene (Malpas et al. 1992).

Recently, Whattam (2003) used step heating $^{40}\text{Ar}/^{39}\text{Ar}$ techniques to date basalt samples from several of the ophiolite

massifs. These ages range from 25.0 ± 0.8 Ma to 29.6 ± 1.0 Ma. Zircons separated from a plagiogranite sample collected from Nukutawhiti massif (Fig. 1) gave a $^{206}\text{Pb}/^{238}\text{U}$ age of c. 30 Ma. These new ages are free from the spectre of alteration and represent the first clear indication that at least a part of the Northland Ophiolite was formed immediately prior to emplacement at the Oligocene/Miocene boundary.

We suggest that the occurrence of biostratigraphic and radiometric Cretaceous–Paleocene ages and of late Oligocene to earliest Miocene ages in the formations that hitherto have been considered as the Northland Ophiolite is best explained if there are at least two distinct groups of igneous rocks in the Cretaceous to early Cenozoic of Northland.

ROCKS OF THE NORTHLAND OPHIOLITE

Outcrops of the Northland Ophiolite are predominantly tholeiitic basaltic rocks that occur mainly as pillows with lesser sheet flows; dolerite and gabbro are subordinate, together with minor alkalic rocks (Larsen & Parker 1989; Malpas et al. 1992; Thompson et al. 1997). Rare ultramafic rocks occur at North Cape (Bennett 1976) and these show a diversity of lithologies including serpentinite, cumulate harzburgite and lherzolite, olivine clinopyroxenite, wehrlite dikes, and hornblendite (Malpas et al. 1992). In addition, the ophiolite includes minor intermediate and felsic intrusive rocks ranging from diorite and quartz diorite, to plagiogranite (Malpas et al. 1992; Thompson et al. 1997). These leucocratic rocks are present as irregular dikes and sills intruded into the high-level gabbros of the ophiolite.

Tholeiitic basalts of the Northland Ophiolite are composed primarily of labradorite augite and magnetite with rare orthopyroxene and olivine. They display textures characteristic of submarine basalt and exhibit secondary alteration phases typical of hydrothermally altered submarine volcanic rocks (i.e., chlorite, epidote, palagonite, and zeolites (stilbite-laumontite)).

Intrusive equivalents of the tholeiitic basalt include dolerite and gabbro, and intermediate and felsic differentiates (diorite and plagiogranite). As with the basalts, the dolerite and gabbro consist primarily of plagioclase and clinopyroxene, along with accessory magnetite. In the gabbros the plagioclase is bytownite, whereas in dolerite it is labradorite. Augite is the clinopyroxene in both the gabbro and dolerite. The diorites consist of andesine, amphibole, quartz, rare augite, and titaniferous magnetite. Plagiogranite is composed of albite, quartz, minor amphibole and augite, and accessory chlorite and titaniferous magnetite. Micrographic textures are well developed in the plagiogranite and occur as granophyric intergrowths of albite and quartz. Plagioclase compositions show a decrease in Ca and a sympathetic increase in Na with increasing fractionation from gabbro to diorite and to plagiogranite. The alkalic basalt of the ophiolite consists of labradorite, pink pleochroic titan-augite phenocrysts, and groundmass diopside. Ubiquitous olivine pseudomorphs are composed of calcite and iddingsite, amphibole, and magnetite.

There is an extensive database of 230 mainly unpublished major and trace element chemical analyses of samples of the Northland Ophiolite. This dataset is available at [www.auckland.ac.nz/geology/research/northland ophiolite](http://www.auckland.ac.nz/geology/research/northland%20ophiolite). In addition, Whattam et al. (in press) have published a subset of 62 minor trace element analyses by ICP-MS. These

datasets form the basis of the following discussion of the petrological affinities of the Northland Ophiolite.

The general compositional features of rock samples from the Northland Ophiolite are well known (Malpas et al. 1992; Nicholson et al. 2000a,b) and are summarised in Fig. 2. Most samples are basaltic, sub-alkaline, and show a MORB-like character in terms of their major element and most trace element abundances. A small proportion are alkaline in terms of major and trace element abundances. Both sub-alkaline and alkaline suites include siliceous rocks that, in the case of the sub-alkaline suite, range up to high-Si plagiogranites.

Hopper & Smith (1996) were the first to detect a supra-subduction zone signature for rocks comprising the Northland Ophiolite, based on their geochemical study of gabbros and sheeted basaltic intrusive rocks from North Cape. Research conducted by Thompson et al. (1997) on plutonic rocks, and by Nicholson et al. (2000a,b) on tholeiitic basaltic rocks of the Northland Ophiolite, corroborate these original interpretations. Geochemical data from the current study and that of Whattam et al. (in press) further substantiate these findings. The supra-subduction zone signature is expressed as a relative Nb anomaly and enriched large-ion lithophile element abundances compared to typical MORB for the sub-alkaline rocks of the ophiolite (Fig. 3). It is also indicated in the Th–Hf–Ta discriminant diagram of Wood (1980) (Fig. 4). Alkaline rocks of the ophiolite do not show the Nb anomaly and plot in the “within plate” alkaline field of the Zr–Nb–Y discriminant diagram, which is consistent with their interpretation as seamounts surmounting oceanic crust (Malpas et al. 1992).

The rock samples that on the basis of associated fossil ages and two new $^{40}\text{Ar}/^{39}\text{Ar}$ ages reported by Whattam et al. (in press) are Cretaceous–Paleocene, outcrop at The Bluff, as two small outcrops near Whangaroa on the northeast Northland coast, and at the base of Houito and Apenga massifs in central Northland (Fig. 1). They occur as volcanoclastic beds, sheet flows, and less common pillow lavas. They are best characterised petrographically as spilites and keratophyres.

We have suggested above that these distinctly older rocks represent an autochthonous terrane, which, because of broadly similar lithologies, has hitherto been grouped with the ophiolite. This interpretation is supported by their subtle trace element abundance patterns, which are distinct from those shown by the ophiolite (Whattam et al. in press). For example, although they share many common compositional features with the ophiolite, the Cretaceous–Paleocene rocks display higher absolute concentrations of Nb and Zr but lower Ti and Y (Fig. 3). In a Nb–Zr–Y discriminant diagram they plot as volcanic arc basalts (Fig. 2).

Our interpretation of these data is that the rocks of the Northland Ophiolite, as previously defined by Malpas et al. (1992), can be subdivided on the basis of geochemical characteristics as well as by age. The older group of rocks show arc-type compositional characteristics, and it is logical to link these with the Mt Camel Terrane which outcrops at Houhora, on Karikari Peninsula, and at The Bluff (Fig. 1), and has been identified as representing an episode of subduction in the Cretaceous (Isaac et al. 1988). The younger rocks are the allochthonous Northland Ophiolite. The tectonic environment in which the ophiolitic rocks formed is thought to be one of seafloor spreading behind an active arc, on the basis of their supra-subduction zone chemical signature.

Fig. 3 MORB normalised signatures for volcanic rocks of the Northland Ophiolite and Cretaceous–Paleocene volcanic rocks formerly considered as part of the ophiolite. MORB concentrations from Sun & McDonough (1989). Symbols as for Fig. 2. A, Alkalic and tholeiitic rocks from the ophiolite. Shaded field corresponds to the rocks plotted in B. B, Cretaceous–Paleocene volcanics.

PLATE TECTONIC INTERPRETATION

A major obstacle to developing a model for the emplacement of the Northland Ophiolite has been the difficulty of accommodating Cretaceous–Eocene oceanic crust adjacent to the Northland Peninsula in the late Oligocene into a regional tectonic context. However, in the light of the new radiometric, geochemical, and paleomagnetic data described above, we suggest that the Northland Ophiolite represents oceanic crust formed in the southern South Fiji Basin (SFB

Fig. 2 Summary of the main compositional features of rock specimens from the Northland Ophiolite. A, Distribution of SiO₂ wt% in the suite of 230 chemically analysed samples. B, Alkali versus SiO₂ plot for the Northland Ophiolite. The line separating alkaline from sub-alkaline compositions is from Irvine & Baragar (1971). C, Zr–Nb–Y discriminant diagram from Meschede (1986). Solid dots represent alkaline samples, and open squares represent sub-alkaline samples of the Northland Ophiolite; solid diamonds represent Cretaceous–Paleocene rocks formerly regarded as part of the Northland Ophiolite.

Fig. 4 Th-Hf-Ta tectonic discrimination diagram (after Wood 1980) of rocks from the Northland Ophiolite and the Cretaceous–Paleocene volcanics. Symbols as in Fig. 2. N-MORB is normal mid-ocean basalt, E-MORB is enriched mid-ocean ridge basalt.

in Fig. 5) in the late Oligocene. At this time the southern part of this basin had a northeast–southwest-orientated spreading centre. At present, an extinct transform, the Vening Meinesz Fracture Zone (VMFZ in Fig. 5) (Van der Lingen 1967), forms a pseudo-boundary between the South Fiji Basin and New Zealand, but we suggest that the original boundary was another transform that was parallel to, and southwest of, the present fracture zone. There is evidence for this interpretation in outcrops preserved on the east coast of the Northland Peninsula (Hanson 1991).

Cassidy (1993) published paleomagnetic results from some of the Northland volcanic massifs that indicated that

they formed at latitude 15–20°S. It is not clear which compositional group of rocks these results referred to. However, Whattam et al. (in press) report paleomagnetic results from outcrops chemically constrained as belonging to the Oligocene Northland Ophiolite group, which indicate a latitude of formation of between $38.8 \pm 10.6^\circ\text{S}$ and $34.4 \pm 9.0^\circ\text{S}$. This suggestion, that the Northland Ophiolite formed close to its obduction site at c. 34–38°S, fits well with our suggested scenario for the origin and emplacement of the Northland Ophiolite (Fig. 5).

The obduction of the Northland Ophiolite corresponds temporally with a change in relative motion of the Australian and Pacific plates (Yan & Kroenke 1993). Mortimer & Parkinson (1996) argued that the timing of collision of the Hikurangi Plateau, a submerged large igneous province, with the New Zealand southeastern margin corresponds with the emplacement of the Northland Allochthon in the late Oligocene to early Miocene. The proposed late Oligocene fracture zone would also have been a line of weakness along which the upper levels of the South Fiji Basin oceanic crust could have been “flaked” onto the continental basement of northern New Zealand, in a process similar to Oxburgh’s (1972) model and more specifically Model 2 of Malpas et al. (1992). Highly oblique subduction of the lower crustal portion and mantle initially, and a full lithospheric section soon after, led to early Miocene arc volcanism, a record of which is preserved as the NNW–SSE-orientated volcanic-plutonic belt in Northland (Ruddock & Spörli 1989; Smith et al. 1989; Hayward et al. 2001). A progressive southeast migration of the subduction zone front implies that the oldest rocks of the Miocene arc should occur in northwest Northland, and that ages should decrease to the southeast. Interestingly, this pattern, from 20 dated arc localities in Northland (Hayward et al. 2001), is largely substantiated, with only three volcanoes/volcanic complexes providing conflicting (older) dates.

Fig. 5 Sketch map showing the disposition of tectonic elements adjacent to Northland. **A**, Immediately prior to the emplacement of the Northland Ophiolite. **B**, Immediately after emplacement and as subduction began. SFB, South Fiji Basin; VMFZ, Vening Meinesz Fracture Zone; HP, Hikurangi Plateau.

CONCLUSIONS

New data from the Northland Ophiolite suggest that its constituent rocks formed in a supra-subduction zone environment between 26 and 29 Ma at c. 35°S. A likely location is in the southern South Fiji Basin, where magnetic anomaly lineations 12-7A have been mapped (Watts et al. 1977; Davey 1982). These anomalies correspond to backarc basin formation at 36–25.5 Ma and, using the time-scale of Cande & Kent (1995), suggest that the South Fiji Basin formed between 33.5 and 25.5 Ma. The widespread occurrence of early Miocene arc volcanic rocks in Northland is probably due to the highly oblique WNW-directed subduction of the South Fiji Basin, which developed after the emplacement of the ophiolite.

The dating conundrum within the Northland Ophiolite identified by Brothers & Delaloye (1982) is resolved by the recognition of two distinct episodes of volcanism within the Cretaceous to early Cenozoic volcanic massifs in Northland. Further work is required to establish whether both groups of rocks were emplaced as part of the Northland Allochthon, but we suggest that the Cretaceous arc-type rocks are more logically viewed as part of an autochthonous terrane developed at a Cretaceous convergent plate boundary. The Mt Camel Terrane may either be a part of this or part of a distinct arc-related terrane.

Finally, we suggest that the term Northland Ophiolite should be used to refer to the allochthonous late Oligocene rocks, which we suggest originated in the South Fiji Basin, not far from where they were emplaced on what is now the Northland Peninsula, at the beginning of the Miocene. Use of this term provides a link to earlier work and clearly identifies the allochthonous rocks with the regional tectonic event that emplaced ophiolites in the Southwest Pacific during the early Cenozoic.

ACKNOWLEDGMENTS

This work was funded through a Hong Kong Research Grants Committee award to JM (HKU7017/03P) and a Hong Kong University Research Committee Grant award to JRA. We are grateful to Gary Thompson and John Cassidy for their various insights. Sergei Zybrev is thanked for his help in the identification of the radiolarian assemblages. The Masters and Bellingham families kindly allowed access to their quarries. Gavin Chan helped in the field. Richard Price and Roger Briggs provided thoughtful reviews.

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