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South China continental margin signature for sandstones and granites from Palawan, Philippines

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ABSTRACT

We report results of heavy mineral analysis and U–Pb dating of detrital zircons from metasediments and Cenozoic sandstones, and U–Pb dating of zircons from Cenozoic granites of the North Palawan Continental Terrane (NPCT) and the South Palawan Terrane (SPT). The NPCT metasediments are derived mainly from granitic and metamorphic rocks of continental character. They contain zircons that indicate a maximum depositional age of Late Cretaceous and other age populations indicating a South China origin. The sediments were deposited on the South China margin before rifting of the continental margin during opening of the South China Sea. Miocene SPT sandstones contain similar heavy mineral assemblages suggesting sources that included NPCT metasediments, metamorphic basement rocks at the contact between the SPT and the NPCT, South China Sea rift volcanic and/or minor intrusive rocks, and the Palawan ophiolite complex. The SPT sandstones are very similar to Lower Miocene Kudat Formation sandstones of northern Borneo suggesting a short-lived episode of sediment transport from Palawan to Borneo in the Early Miocene following arc-continent collision. U–Pb dating of zircons shows that the Central Palawan granite is Eocene (42 $\pm$ 0.5 Ma). The Capoas granite was intruded during a single pulse, or as two separate pulses, between 13.8 $\pm$ 0.2 Ma and 13.5 $\pm$ 0.2 Ma. Inherited zircon ages from the Capoas granite imply melting of continental crust derived from the South China margin with a contribution from Cenozoic rift-related and arc material.

1. Introduction

Palawan, the westernmost island of the Philippine archipelago, lies at the southern margin of the South China Sea, approximately 400 km to the northeast of Borneo (Fig. 1). Geologically, Palawan can be divided into two blocks, the North Palawan Continental Terrane (NPCT) and the South Palawan Terrane (SPT) (e.g. Hamilton, 1979; Taylor and Hayes, 1983; Faure et al., 1989; Yumul et al., 2009). The NPCT is interpreted as a continental fragment that was derived from the South China margin (e.g. Holloway, 1982; Taylor and Hayes, 1983; Hall, 1996). This is supported by previous provenance studies (Suzuki et al., 2000; Walia et al., 2012) which suggested that Upper Cretaceous to Eocene sandstones of Central Palawan (NPCT) were derived from the Kwangtung and Fukien regions of South China. The SPT includes a Lower Cretaceous–Eocene ophiolitic complex (e.g. Yumul et al., 2009) and Oligocene to Miocene sediments. Almost nothing is known about the provenance of these sediments from this terrane.

As an area with proven hydrocarbon potential, Palawan has been the attention of a number of recent studies (e.g. Yumul et al., 2009; Knittel et al., 2010; Walia et al., 2012). Despite this, many aspects of the tectonic evolution and geology of this region remain unclear. In particular, there are still outstanding questions about the ages of igneous, metamorphic and sedimentary rocks on Palawan. For example, metasedimentary rocks that were previously considered Palaeozoic have yielded Cretaceous detrital zircons (e.g. Walia et al., 2012). The geology of Palawan is also similar to that of North Borneo and both include Mesozoic ophiolitic rocks that are overlain by Mesozoic–Cenozoic sedimentary rocks and are intruded by granites. Both areas share a strong NE–SW orientation (Fig. 1). In both cases (e.g. Hutchison, 2010) the onshore regions are flanked to the west by significant bathymetric troughs (the NW Borneo and Palawan Troughs) that are in turn flanked by bathymetric highs (the Dangerous Grounds and Reed Bank). Perhaps most notably, both areas are intruded by young granite plutons: the Mt Kinabalu pluton in northern Borneo (Cottam et al., 2010), and the Mt Capoas intrusion in Palawan (Encarnación and Mukasa, 1997).

K–Ar age determinations on the Kinabalu granite in northern Borneo by a number of authors (Jacobson, 1970; Rangin et al., 1990; Bellon and

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Rangin, 1991; Swauger et al., 1995; Hutchison et al., 2000) suggested that the granite may be as old as ~14 Ma. However, U–Pb dating of zircons by Cottam et al. (2010) showed that the Kinabalu granite is a Late Miocene pluton emplaced and crystallised in less than 800,000 years between 7.85 ± 0.08 and 7.22 ± 0.07 Ma. Encarnación and Mukasa (1997) had reported Middle Miocene ages (~14 Ma) for the Capoas granite based on U–Pb dating of zircon and monazite but recognised that these were discordant and could be mixtures of older cores and younger magmatic rims. The new SHRIMP age data for the Kinabalu granite raised the question of whether the Capoas granite is possibly of similar age and origin.

Heavy minerals are sensitive provenance indicators, because of the diversity of common assemblages, restricted parageneses of many common heavy mineral species and their ability to preserve geochemical characteristics of parental source rocks. Heavy mineral analysis has been successfully applied in provenance studies across the world (Morton et al., 1994; Mange et al., 2005; Garzanti and Ando, 2007), including SE Asia (e.g. van Hattum et al., 2006; Clements and Hall, 2011; Suggate, 2011; Sevastjanova et al., 2012; Witts et al., 2012; van Hattum et al., in press), in areas where there are sufficient differences between sediment source areas. Several authors have suggested that initial heavy mineral assemblages undergo modifications during sediment generation, transport and storage. The most significant of these include (a) hydraulic sorting (density fractionation), (b) dissolution during deep burial (diagenetic dissolution) and (c) dissolution during tropical weathering. It is recognised that these secondary processes change the initial abundances of the minerals (e.g. Garzanti et al., 2011; Andò et al., 2012) or possibly can selectively remove minerals from the initial assemblage (e.g. Morton and Hallsworth, 2007). However, minerals that remain in the heavy mineral assemblage still yield useful information about their source rocks.

Recent provenance studies based on heavy minerals suggest that during the Early Miocene Palawan shed granitic and metamorphic detritus to northern Borneo (van Hattum, 2005; Suggate, 2011; van Hattum et al., in press). Provenance studies of NPCT metasediments (Suzuki et al., 2000; Walia et al., 2012) concentrated on light minerals and U–Pb dating of detrital zircons. Detrital heavy minerals were briefly described from thin section, but interpretations of provenance were based on limited data, insufficient for detailed characterisation of heavy mineral assemblages (e.g. Mange and Maurer, 1992).

In order to address these uncertainties, we carried out fieldwork in Palawan to collect igneous rocks, metasediments and Cenozoic sandstones from the NPCT and SPT. We report here the results of heavy mineral analysis, U–Pb dating of detrital zircons and zircons from Cenozoic granites from Palawan.

2. Geological background

There is general agreement that parts of northern Borneo and Palawan (Fig. 1), along with areas such as the Dangerous Grounds and Reed Bank in the South China Sea, are extended and attenuated continental fragments rifted from the South China margin. The rifted material has been termed the Palawan Continental Terrane (PCT; e.g. Holloway, 1982; Taylor and Hayes, 1983), the North Palawan Block (NPB; e.g. Almasco et al., 2000), and the North Palawan Continental Terrane (NPCT; e.g. Encarnación et al., 1995; Encarnación and Mukasa, 1997). The term North Palawan Continental Terrane (NPCT) is used here. This continental crust was originally envisaged to be a single large fragment rifted from the South China margin (Holloway, 1982; Taylor and Hayes, 1983), but recent studies (Yumul et al., 2009) have suggested that there are several internal sutures and multiple fragments. Continental crust has been identified in northern Palawan, parts of the islands of Mindoro and Panay, and Reed Bank (Holloway, 1982; Taylor and Hayes, 1983; Kudrass et al., 1986; Schluter et al., 1996; Encarnación and Mukasa, 1997; Yumul et al., 2009; Franke et al., 2011; Knittel, 2011). The NPCT moved south during subduction of the proto-South China Sea beneath NW Borneo and the Cagayan Arc and the opening of the South China Sea (Holloway, 1982; Taylor and Hayes, 1983; Kudrass et al., 1986; Vogt and Flower, 1989; Rangin et al., 1990; Hall, 1996; Hutchison, 1996; Schluter et al., 1996; Encarnación and Mukasa, 1997; Hutchison et al., 2000; Hall, 2002; Replumaz and Tapponnier, 2003; Cottam et al., 2010; Hutchison, 2010; Franke et al., 2011; Hall, 2012). Subduction of the proto-South China Sea terminated in the Early Miocene after collision of the NPCT with the active continental margin of Sabah and the Cagayan Arc (Holloway, 1982; Rangin et al., 1990; Tan and Lamy, 1990; Hinz et al., 1991; Hall, 1996; Hall and Wilson, 2000; Hutchison et al, 2000). Oceanic spreading in the South China Sea ceased in the Early or Middle Miocene (Taylor and Hayes, 1983; Briais et al., 1993; Barckhausen and Roeser, 2004).

3. Geology and stratigraphy of Palawan Island

The geology of Palawan Island (Fig. 2) has commonly been interpreted to comprise two discrete tectonic elements (e.g. Hamilton, 1979; Holloway, 1982; Taylor and Hayes, 1983; Mitchell et al., 1986; Encarnación et al., 1995; Encarnación and Mukasa, 1997; Almasco et al., 2000). The northern part of the island is made up of the continental-derived metamorphic and sedimentary rocks of the NPCT. The southern part of the island comprises ophiolitic rocks and Cenozoic clastic sediments of the SPT. The NPCT and SPT are in contact along a broadly north–south trending steep fault that cuts through Ulugan Bay, in the centre of the island.

3.1. North Palawan Continental Terrane metamorphic and sedimentary rocks

The NPCT includes a succession of low to medium grade metamorphic rocks and sedimentary rocks related to the pre-, syn- and post-rift stages of the opening of the South China Sea (Sales et al., 1997; Suzuki et al., 2000; Franke et al., 2011) and isolated granite bodies in central and northern Palawan. Reviewing the stratigraphy of the NPCT, Sales et al. (1997) classified it on the basis of three distinct tectonic environments: pre-rift and rift; drifting and South China Sea (SCS) seafloor spreading; collision and post-collision. Based on the region's offshore seismostratigraphy, Franke et al. (2011) recognised four main phases: (1) Mesozoic pre-rift sedimentation associated with the margin of the Asian mainland; (2) Latest Cretaceous–Eocene sedimentation associated with rifting of the South China Sea basin; (3) Oligocene to Early Miocene sedimentation concurrent with the drifting episode of the Palawan–Mindoro microcontinental block during South China Sea seafloor spreading; (4) Late Miocene to Recent sedimentation during and after the collision between the microcontinental block and the Philippine Mobile Belt.

The oldest rocks reported from the NPCT (Fig. 3) are a series of Upper Palaeozoic to Lower Mesozoic metasedimentary rocks (Sales et al., 1997). They include sandstones, tuffs, slates, phyllites and schists (Sales et al., 1997; Yumul et al., 2009) that have undergone medium-grade regional metamorphism (e.g. Suzuki et al., 2000). Metamorphic rocks from Mindoro in the north of the NPCT have variously been dated as Late Palaeozoic (Knittel and Daniels, 1987), older than Late Cretaceous (Sarewitz and Karig, 1986), and Paleocene (Faure et al., 1989). Dating of igneous and detrital zircons from metamorphic rocks exposed in southern Mindoro suggests a Late Palaeozoic (Middle to Late Permian) age for the metamorphic rocks of the NPCT (Knittel et al., 2010). These rocks were suggested to have formed in association with a Permian magmatic arc that extended along the south coast of Asia (Knittel et al., 2010) prior to the opening of the SCS. In places, the metasediments are overlain by a sequence of cherts, clastic sediments and carbonates, exposed mainly in the north of Palawan and on the Calamian Islands (e.g. Sales et al., 1997; Suzuki et al., 2000; Yumul et al., 2009). All of these rocks belong to the pre-rift succession, and