Journal of Asian Earth Sciences 65 (2013) 118–130

Contents lists available at SciVerse ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Geodynamic evolution of the Baguio Mineral District: Unlocking the Cenozoic record from clastic rocks

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ARTICLE INFO

Article history:
Available online 11 October 2012

Keywords:
Baguio District
Geochemistry
Philippines
Sedimentary rock
Tectonic setting

ABSTRACT

Geochemical studies done on the Baguio Mineral District had dominantly looked at the igneous rocks. A major gap is the scarcity of studies dealing with the sedimentary rock geochemistry for this district which this paper intends to address. The petrographic data and major and trace element compositions of the siltstones–sandstones from the lower member of the Late Oligocene to Early Miocene Zigzag Formation show that they are generally quartz-rich and have high K_2O, Th and La/Sc contents. The chondrite-normalized REE pattern exhibits a negative Eu anomaly, enrichment in LREEs and flat HREEs similar to typical post-Archean shales. Taken together, the data indicate derivation of the lower member of the Zigzag Formation from intermediate to acid igneous rock sources generated in an active margin setting. A likely candidate source is the Cordon Syenite Complex/Palali Formation in the Northern Sierra Madre – Caraballo Mountains. Derivation from mafic source rocks in an oceanic island arc setting is inferred for samples of the Middle to Late Miocene Klondyke, Late Miocene to Early Pliocene Amlang and Late Pliocene Cataguintingan Formations. These samples are characterized by low K_2O, Th and La/Sc but high Cr/Th values. Unroofing of the Pugo Metavolcanics and the younger plutons in the Central Cordillera provided the materials which eventually produced the Klondyke and Amlang Formations. Continuous uplift and shallowing of the basin resulted in the deposition of the Cataguintingan Formation. The petrography, geochemistry and geological features of the sedimentary rocks clearly define the change in sediment provenance from quartz-rich during the Oligocene to quartz-deficit in the Miocene. This offers additional constraints in understanding the geological evolution of the mineral district.

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1. Introduction

Provenance and tectonic setting studies using whole rock and trace element geochemistry of sedimentary rocks have evolved over the years with the results contributing to an understanding of how an area had evolved. When first introduced, the validity of these techniques, especially diagrams using major element data, was questioned since major elements are easily remobilized during weathering, alteration and diagenetic processes (e.g. Julleh Jalalur Rahman and Suzuki, 2007; Augustsson and Bahlburg, 2008; Madhavaraju and Lee, 2010). Among the diagrams that use major element data is the K_2O/Na_2O versus SiO_2 to separate sedimentary suites generated in passive margin, active continental margin and oceanic island arc. The geotectonic settings of sedimentary suites from Lemnos Island in Greece, central Anatolia in Turkey and from Hangay Basin in Central Mongolia were determined using plots of K_2O/Na_2O versus SiO_2 as well as other discriminant diagrams (Roser and Korsch, 1986; Maravelis and Zelilidis, 2010; Keskin, 2011; Purevjav and Roser, 2012). The discriminant function analysis diagrams of Bhatia (1983) and Roser and Korsch (1988) utilize the Al_2O_3, TiO_2, Fe_2O_3, MgO, CaO, Na_2O and K_2O concentrations to distinguish four provenance groups: (1) mafic igneous provenance; (2) intermediate – dominantly andesitic detritus; (3) felsic and plutonic and volcanic detritus; and (4) recycled mature quartzose detritus. The technique has since then improved to make use of trace element data as well as major and trace element ratios. The immobile character of the trace elements and their quantitative transfer from source to sediment make elements such as La, Ce, Nd, Y, Th, Zr, Hf, Nb, Ti and Sc suitable for provenance and tectonic setting determination (e.g. Taylor and McLennan, 1985; McLennan et al., 1993; Roser et al., 2002; de Araujo et al., 2010; Akarish and El-Gohary, 2011; Yan et al., 2012).

With the varied fragments coming from several geological sources that make up the Philippine island arc system, i.e.

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http://dx.doi.org/10.1016/j.jseaes.2012.09.026

continental, oceanic, ophiolitic and island arc, it would be interesting to determine what information can be obtained from the geochemical characterization of sedimentary units from these fragments. Will the major and trace element data provide information that will define the source rocks of the sediments? Can geochemical data really provide constraints on the tectonic evolution of this area? The answers to these questions are critical as they may complement what is known about this arc system, based on data and information, using other lines of evidence or they may even point to new directions and possibilities.

An initial attempt to examine the petrographic and geochemical characteristics of sedimentary rocks in the Philippines was done by Suzuki et al. (2000a,b) who investigated the Cretaceous to Eocene sandstone succession in Palawan. The petrographic examination of the Palawan sedimentary samples showed a high amount of quartz grains and acidic volcanic fragments. The whole rock major element data revealed high SiO_2 and low FeO plus MgO contents for the samples indicating their derivation from a continental source region. The results from these data are consistent with models which show that Palawan is part of the continental fragment derived from the southern margin of mainland Asia (e.g. Holloway, 1982; Zamoras and Matsuoka, 2004).

Sandstone petrography and sedimentary geochemistry studies have also been employed in Central Philippines specifically in Northwest Panay to examine the collision between the North Palawan Block and the Philippine Mobile Belt. Results generated from the investigation indicate a clear distinction in the petrographic and geochemical signatures of two terranes – Buruanga Peninsula and Antique Range. Sandstone samples from the Buruanga Peninsula exhibit moderate to high SiO_2 values (65–85%), Fe_2O_3 from 1% to 6% and low MgO and CaO concentrations (<4% and <2%, respectively). Conversely, samples collected from the Antique Range are characterized by lower SiO_2 values (∼40–60%) as well as higher Fe_2O_3 (∼4–10%) and MgO (∼1–7%) contents. The geochemical characteristics of the Buruanga Peninsula sandstones are consistent with derivation from silicic rocks in a continental margin setting whereas the Antique Range clastic units were derived from mafic source rocks in an oceanic island arc setting. Buruanga Peninsula is, hence, believed to be part of the North Palawan Block which collided with the Philippine Mobile Belt which is represented here by the Antique Range (e.g. Hamilton, 1979; Zamoras et al., 2008; Gabo et al., 2009).

The studies on sedimentary rock geochemistry done in Palawan and Buruanga Peninsula, northwest Panay had offered additional evidence in constraining the geological histories of these areas. It is in this regard that a similar study has been conducted for the Baguio Mineral District. This mineral district, aside from being the most prolific area in terms of copper–gold–silver mineralization, offers an opportunity to observe first hand features specific to island arc formation (e.g. Malettere, 1989; Bellon and Yumul, 2001; Yumul et al., 2008; Cooke et al., 2011; Hollings et al., 2011b). Most of the studies done were on igneous rock geochemistry and it is only recently that studies on sedimentary rock geochemistry are being applied in the district (e.g. Tam et al., 2005).

Petrographic and geochemical investigations previously carried out by Tam et al. (2005) in the Baguio Mineral District have indicated two distinct sources for the Zigzag and Klondyke Formations. Additional whole rock major and trace element data are presented in this paper to further constrain the provenance and tectonic setting of the Zigzag and Klondyke Formations. New geochemical data from nearby sedimentary formations (e.g. Amlang and Cataguintingan Formations) are also presented in this study. The results of these petrographic and sedimentary rock geochemical studies would hopefully also offer additional constraints in understanding the geological history of this mineral district.

2. Geologic framework of Luzon island

2.1. Igneous lithologies

Luzon Island, the largest northernmost island in the Philippine archipelago, preserves a record of various episodes of magmatism resulting from subduction along the east before subduction shifted to the western side (e.g. Yumul et al., 2003, 2008; Hollings et al., 2011a). Among the prominent features in Luzon is the north–south trending Northern Sierra Madre which is situated on the eastern side of the archipelago (Fig. 1). Intrusive rocks composed of diorites, quartz diorites and tonalites form part of the Dinalungan Diorite Complex (formerly the Coastal Batholith) which has been assigned a Middle Eocene (49–43 Ma) age based on radiometric K–Ar dating (Wolfe, 1981). The southern terminus of Northern Sierra Madre connects with the northwest–southeast trending Caraballo Mountains (e.g. Yumul et al., 2008). Within the Caraballo Mountains, an Early to Late Oligocene magmatic episode is represented by the Dupax Diorite Complex (formerly the Dupax Batholith) and the Cordon Syenite Complex. These quartz diorites, including tonalites and granodiorites, have been assigned an Early Oligocene to Early Miocene (33–22 Ma) age (e.g. Peña, 2008). The Cordon Syenite Complex, on the other hand, is made up of syenites and monzonites which are best exposed at the southwestern portion of the Cagayan Valley Basin (Peña, 2008). On the western side lies a wider, north–south trending range, the Central Cordillera, which also preserves a record of multiple phases of magmatism (Fig. 1).

Among the most studied areas within the Central Cordillera is the Baguio Mineral District (Bellon and Yumul, 2001; Polve et al., 2007; Yumul et al., 2008; Cooke et al., 2011). Magmatic episodes during the Oligocene, Early to Middle Miocene and post-Miocene are recorded in the different lithologic units mapped in the area. The Oligocene and Early to Middle Miocene episodes are represented by gabbroic and dioritic bodies of the Central Cordillera Complex (e.g. Yumul et al., 1992; Dimalanta, 1996; Polve et al., 2007; Queaño et al., 2008) (Fig. 2a). Geochemical studies of these igneous rocks have shown the dominant arc-related record of the district.

2.2. Sedimentary sequences

Thick deposits of Neogene sedimentary sequences overlie the Cretaceous Pugo Metavolcanics basement in the Baguio Mineral District. The oldest of these sedimentary units is the Zigzag Formation which was originally reported by Leith (1938). Approximately 1700–1800 m thick, the lower member of this formation made up of interbedded red and green sandstones and siltstones, oligomictic conglomerates with minor limestone units is best exposed along Kennon Road (∼16°22′7.9″N, 120°36′18.48″E) (e.g. Peña and Reyes, 1970) (Figs. 2a and 3). The Zigzag Formation sandstones consist of 20–30% quartz and 10–20% plagioclase grains with few lithic fragments set in a clay matrix. The Lower Member composed of the red and green sandstone and siltstone interbeds was assigned a Late Oligocene to Early Miocene age based on the presence of molluscan fossils (Leith, 1938). Massive, well-indurated conglomerates with dominantly andesite to basaltic andesite clasts comprise the Upper Member of the Zigzag Formation. Fossils from the siltstone samples delimit the age of this sequence to Early Miocene (Peña and Reyes, 1970). Imbrication and slumps suggest that the eroded materials originated from the northeast (present-day geographic setting) (e.g. Peña and Reyes, 1970; Yumul et al., 1992). Conformably overlying the Upper Member of the Zigzag Formation is a shallow water reefal carbonate body, the Kennon Limestone. The presence of diagnostic benthic foraminifers such

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