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A Geochemical Approach on the Provenance Signatures of the Klondyke and Zigzag Formations and its Implication on the Oceanic to Island-arc Setting Evolution of the Baguio Mineral District, Philippines

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ABSTRACT

To resolve the question on the tectonic evolution of Baguio and its vicinity, the source geology of the sedimentary formations and their correlatives are investigated. Petrographic examination and geochemical analyses of sedimentary samples are carried out to address this problem. Whole rock major and trace element compositions of the sampled sedimentary units were analyzed using an X-Ray Fluorescence spectrometer and an inductively-coupled plasma mass spectrometer. Petrographic examination of selected samples shows a distinction between the Zigzag samples vis-à-vis the Klondyke, Amlang, Cataguintingan and Damortis samples. The Zigzag sandstones contain more quartz whereas the sandstones from the other formations are dominated by feldspars and lithic fragments. The geochemical signatures of the Zigzag samples are also distinct from the other sedimentary units. When plotted on various major oxides and trace element ratio diagrams, the Klondyke, Amlang and Cataguintingan samples are shown to have been derived from mafic igneous rocks. Geochemical data from the Zigzag samples suggest intermediate to felsic igneous rock sources. In terms of the tectonic setting, the Zigzag samples are inferred to be derived from a more evolved arc or an active margin based on their high K_2O/Na_2O values. Sediments that make up the other sedimentary units (Klondyke, Amlang, Cataguintingan) originated in an oceanic island arc setting. These information further constrains the recognized evolution of the Baguio Mineral District from an oceanic to an island arc environment.

Keywords: sediment petrography, sedimentary geochemistry, provenance, tectonic setting, Baguio District

Introduction

Investigations involving the petrography and geochemistry of sedimentary rocks have continued to increase within the past years. Results from such studies provide information on the provenance or source of the sediments, source weathering, tectonic setting and paleoclimatic environment (e.g. Bhatia and Crook, 1986; Roser and Korsch, 1988; Von Eynatten, 2003; Batumike et al., 2006; Ullah *et al.,* 2006; Campos Alvarez and Roser, 2007; Augustsson and Bahlburg, 2008; Clift *et al.*, 2008; Von Eynatten *et al.,* 2008; Gabo *et al.*, 2009; Yu *et al.*, 2009). For some time now, determining the maturity and provenance of clastic sedimentary sequences has been carried out through sandstone petrography. The petrographic examination of a clastic rock reveals the abundance of its detrital-sized components such as quartz, feldspar and lithic constituents. This is very useful in distinguishing sediments sourced from different tectonic provinces or terranes. Stable cratons, for example, will be characterized by quartzose sands whereas magmatic arcs will exhibit high amounts of volcanic rock fragments (Tucker, 2001). Recently, geochemical analysis of clastic rocks has become a popular tool to determine the abundances of the components of the clastic rock such as the major detrital phases, matrix, heavy minerals and diagenetic or metamorphic minerals (Roser, 2000). The petrographic and geochemical methods have become complementary techniques which are valuable in deciphering the tectonic evolution of areas underlain by these stratigraphic units.

In the Philippines, it was only in 2000 when these techniques were first applied. Suzuki *et al.* (2000) carried out a petrographic and geochemical study of the Cretaceous to Eocene sandstone succession in Palawan. The objective was to determine the provenance and tectonic setting of the Palawan clastic rocks. The high amount of quartz grains and acidic volcanic fragments coupled with the high SiO_2 and low FeO plus MgO contents of the Palawan sedimentary units suggest their derivation from a continental source region. Such results helped constrain the tectonic evolution of this part of the Philippine island arc system especially since Palawan is modeled to be a fragment derived from the southern margin of China.

An initial attempt to use these techniques on the Baguio district was carried out by Tam *et al.,* (2005) to characterize the Zigzag and Klondyke Formations. The petrographic and geochemical data indicate different sources for the two sedimentary sequences. The Zigzag Formation is proposed to have been sourced from an active continental margin whereas the Klondyke Formation shows derivation from an oceanic island arc.

Investigations of the arc-continent collision zone in Central Philippines are also benefitting from the complementary methods of sandstone petrography and geochemistry. Results were recently obtained for the sedimentary units found in Northwest Panay which is believed to be the site of an arc-continent collision zone. Two terranes were identified based on the differences in petrographic and geochemical signatures of the sampled rocks (Gabo *et al.*, 2009).

For the purpose of this study, clastic rocks such as sandstone, siltstone and mudstone were sampled from the sedimentary formations exposed in the Baguio District and nearby areas (Figure 1). The sampling done complements the previous work reported by Tam *et al.* (2005). This study reports the petrographic and geochemical compositions of these sedimentary samples. Aside from constraining the composition of the source rocks, the tectonic setting of the depositional basin can be further understood. This, in turn, will give insights into the geologic evolution not only of Northern Luzon but also of the whole Philippine island arc system. The results contained herein will also help build up the database on the petrographic and geochemical compositions of sedimentary units in the Philippine island arc system, which, at the moment, is almost lacking.

Geologic Setting of the Baguio Mineral District and Vicinity

The Baguio Mineral District is part of the Central Cordillera magmatic arc of Northern Luzon, which was produced by complex processes that produced the Philippine island arc system (e.g. Balce *et al.* 1980; Bellon & Yumul 2000). The igneous lithologies in the area consist of the Cretaceous-Paleogene basaltic to basaltic andesite pillow lavas and sheet flows. These are believed to be part of the uppermost portion of an oceanic lithospheric fragment which has been termed the Pugo Metavolcanics (Yumul *et al.* 2003). These volcanic rocks exhibit transitional island arc mid-ocean ridge geochemical characteristics. This signature is similar to some of the present-day back-arc basins that make up the Western Pacific region (e.g. Falloon *et al.* 1992; Stern *et al.* 1996). The basaltic to basaltic andesite basement complex is intruded by Miocene intrusive complexes, ranging in composition from granodiorite through diorite to andesite (Figure 1). These intrusive rocks are petrographically and geochemically similar to island arc volcanics. From available information and the change in composition of the clasts in the sedimentary rocks in the Baguio Mineral District, it is proposed that the area evolved from a marginal basin to an island arc setting (Yumul *et al.*, 1995; Yumul *et al.*, 2008).

Igneous, metamorphic and sedimentary units are found in the Baguio District (Figure 1). These lithologic units formed from the interaction of tectonic features such as subduction zones, marginal basins and magmatic arcs (Dimalanta, 1996). Magmatism in Northern Luzon was initially attributed to subduction of the Philippine Sea Plate along the proto-East Luzon Trough. A collision event between the Palawan microcontinental block and the Philippine Mobile Belt during the Early Miocene is believed to have caused arc polarity to flip to the western side. This led to the initiation of subduction along the Manila Trench which produced the calc-alkaline rocks in the Baguio District (Yumul *et al.*, 2003, 2009).

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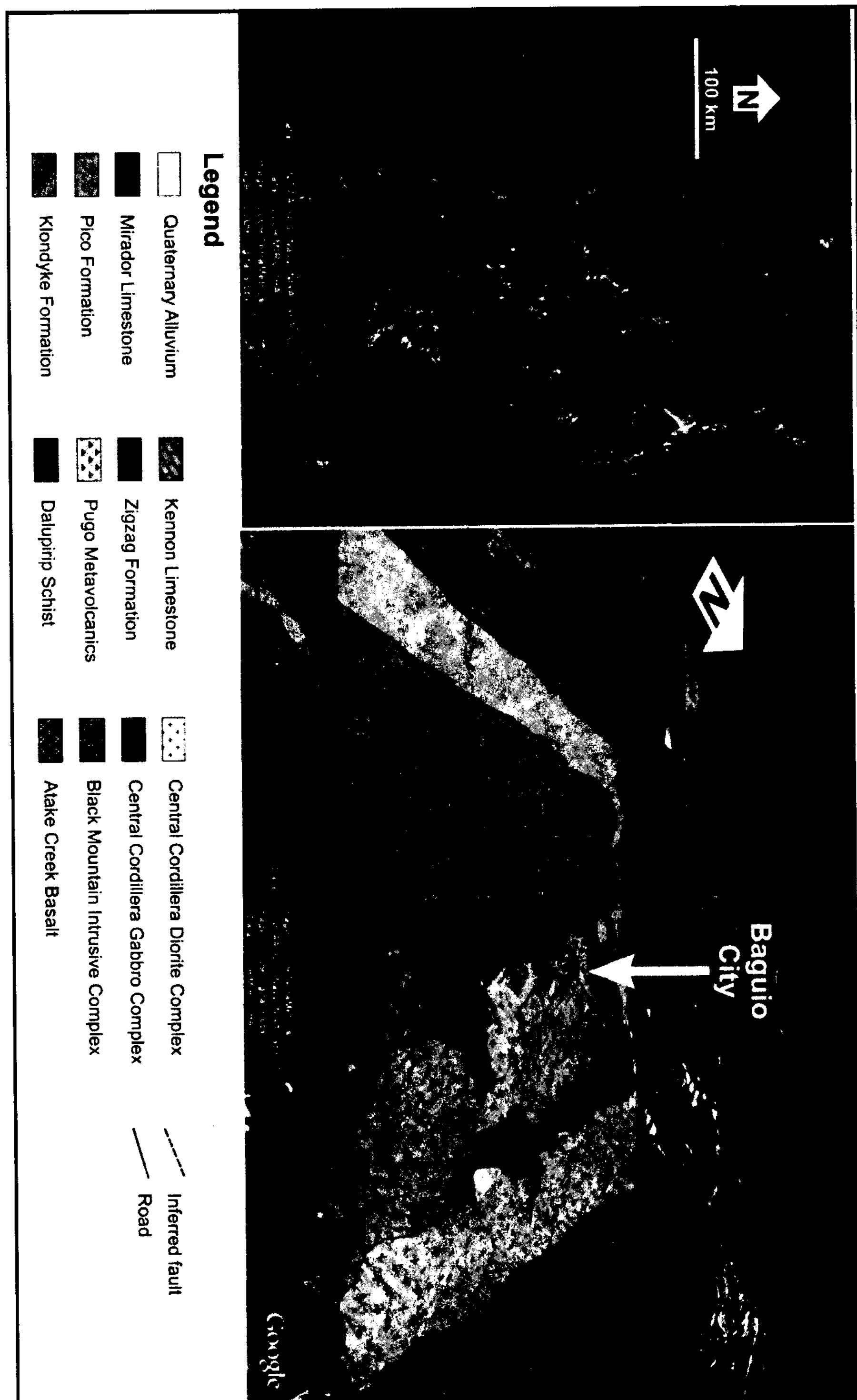


Figure 1. The Baguio Mineral District (area marked by red fox on the left figure) is made up of igneous and metamorphic units capped by sedimentary sequences (right).

Sedimentary sequences

Some of the investigations that discuss and report the details of the stratigraphy of the Baguio Mineral District and nearby areas include those done by Balce *et al.* (1979), Tamesis *et al.* (1982), De Leon *et al.* (1981), Yumul *et al.* (1992), Tam *et al.* (2005), among others. In this paper, a brief description of the sedimentary sequences in the Baguio Mineral District and nearby areas is shown in the succeeding sections (Figure 2).

Zigzag Formation

Leith (1938) was the first to describe the Zigzag Series to refer to a sedimentary sequence consisting of interbedded green sandstones and red siltstones, oligomictic conglomerates and minor limestone units (e.g. Peña and Reyes, 1970). Peña and Reyes (1970) subdivided this formation into the Early to Middle Miocene Upper Zigzag and Oligocene Lower Zigzag members which are separated by an unconformity. The alternating layers of red and green sandstones and siltstones best exposed along Kennon Road comprise the Lower Zigzag. Upper Zigzag, on the other hand, is made up of massive, well indurated and oligomictic conglomerates consisting dominantly of basalt to basaltic andesite clasts.

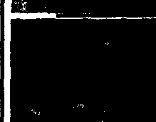
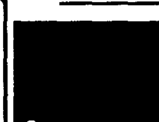
AGE		FORMATION	LITHOLOGY	DESCRIPTION	ENVIRONMENT
PLEISTOCENE		Damortis		Sandstones, calcarenites, siltstones and marls, mostly exposed along the coast. In angular unconformity with Cataguintingan Formation.	littoral
PLIOCENE		Cataguintingan		Tuffaceous sandstones with interbeds of siltstones, shales and conglomerate; contains minor limestone lenses.	littoral
MIOCENE	Late	Amlang		Rhythmically interbedded turbiditic sandstones and shales with minor conglomerate beds. Bouma sequence is complete.	bathyal
MIOCENE	Middle	Klondyke		Conglomerates, conglomeratic sandstones, massive sandstones, interbedded sandstones-siltstones and shales representing distal, mid-fan and proximal slope deposits. Clasts of the conglomerate range from red and green sandstones and siltstones, gabbros, basalts and diorites.	bathyal
MIOCENE	Early	Zigzag		Interbedded green sandstones and red siltstones with oligomictic conglomerates and occasional limestone beds. Clasts of the conglomerates are dominantly basalt to basaltic andesite.	bathyal
OLIGOCENE					

Figure 2. Samples were collected from the sedimentary formations in the Baguio Mineral District and nearby areas for petrographic and geochemical analyses.

For this study, sandstone and siltstone samples were collected from the type localy ofthe Zigzag Formation found along Kennon Road (~16°22′7.9′N, 120°36′18′48"E) (Figure3).

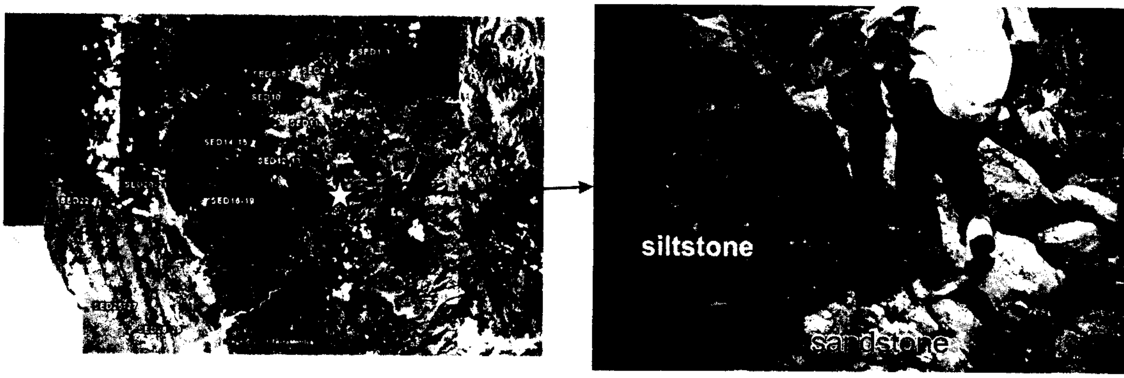


Figure 3. This outcrop of the Zigzag Formation is exposed along Kennon Road (Photo by C.B. Dimalanta).

Klondyke Formation

A thick sequence of coarse clastic rocks, polymictic conglomerate, conglomeratic sandstones, sandstones, flow breccias, vitric tuffs, with minor shales and siltstones was formerly named by Leith (1938) as the Klondyke Conglomerate. Various investigations in the Baguio district revealed that the Klondyke Formation has well-defined proximal, midfan and distal slope portions (Figure 2). The Klondyke Formation is widely distributed in the Baguio Mineral District and is best observed along Marcos Highway, Naguilian Road, Asin Road and the lower portion of Kennon Road. From the calcareous nannofossil assemblage, De Leon *et al.* (1991) was able to assign a Middle to Late Miocene age for this formational unit.

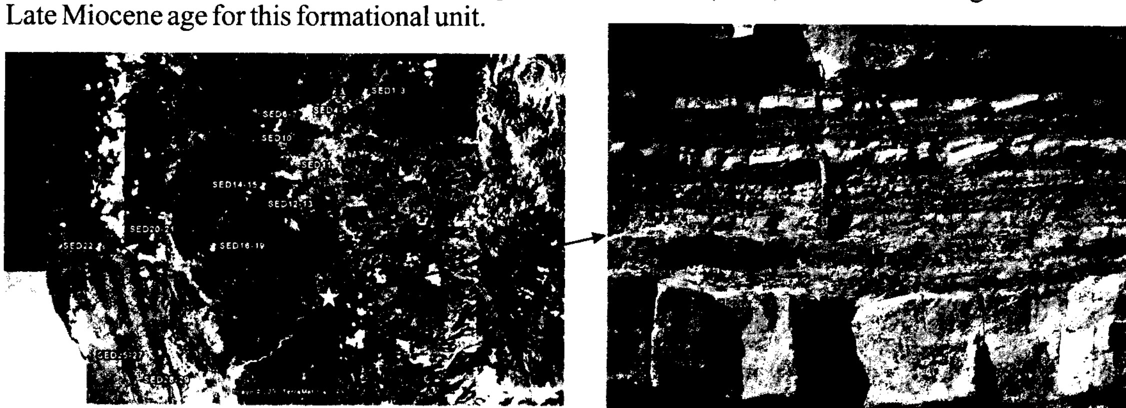


Figure 4. Interbeds of fine-grained sandstones, siltstones and mudstones of the Klondyke Formation as seen in Kennon Road (Photo by T.A. Tam III).

Another section of the Klondyke Formation was sampled along Marcos Highway between 16°23'52.4"N, 120°34'46.9"E and 16°19'58.6"N, 120°29'15.3"E. The outcrops in this section consist dominantly of sandstone with some siltstone and shale beds. The sandstone-shale beds near Km. 273 are oriented N10°W, 45°SW (Figure 4). Another outcrop consists of medium- to coarse-grained sandstone and siltstone interbeds which strike N25°E and dip 60°NW.

Amlang Formation

The Amlang Formation was first used by Lorentz (1984) to describe a "flysch-type" sequence of thin, rhythmically interbedded sandstones, shales and minor conglomerates (Figure 5). Sedimentary structures that include ripple marks, load casts, scour marks, graded bedding, parallel lamination, cross-lamination, flute casts and groove casts have been observed in this sequence. There is a gradational contact between the basal portion of the Amlang Formation and the Klondyke Formation. Shale samples were submitted for paleodating and yielded a calcareous nannofossil assemblage consisting of *Catinaster sp., Discoaster pentaradiatus* and *Sphenolithus abies*. This assemblage suggests a Middle to Late Miocene age (De Leon, pers. comm.).

Cataguintingan Formation

Lorentz (1984) assigned the name Cataguintingan Formation for the sequence of rocks which consist primarily of tuffaceous sandstones interbedded with siltstones, shales and conglomerates with some limestone lenses. Parallel laminations were observed in the sampled siltstone beds. The Cataguintingan Formation unconformably overlies the Amlang Formation. Maleterre (1989) gave this formation a Late Pliocene age based on the molluscan shell fragments, echinoid spines, ostracods and red algae.

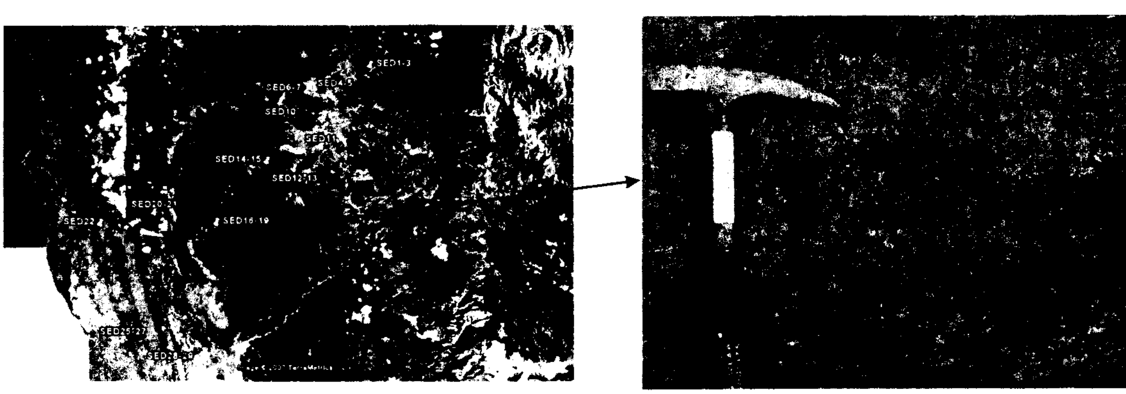


Figure 5. Outcrop of the Amlang Formation as seen in San Juan, La Union. The sequence consists of interbedded shale and fine-grained sandstone (Photo by T.A. Tam III).

In one outcrop in La Union (16°20'30.8"N, 120°25'57.2"E), the Cataguintingan Formation overlies the sandstone unit of the Amlang Formation. Beds of the Cataguintingan Formation strike due north and dip 10°W (Figure 6).

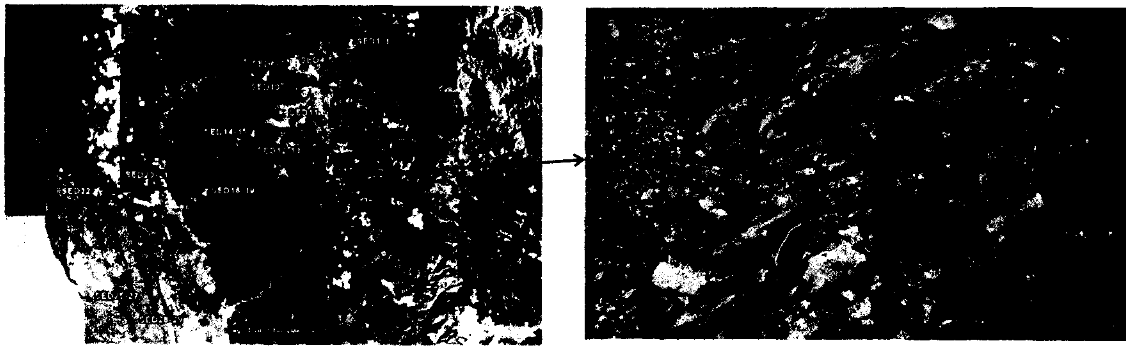


Figure 6. Beds of the Cataguintingan Formation dip to the west (Photo by G.P. Yumul Jr.).

Damortis Formation

Unconformably overlying the Cataguintingan Formation is the Damortis Formation which is best seen along Damortis beach, near the old Philippine National Railway station in La Union. The sequence is made up of sandstones, calcarenites, siltstones and marl. The formation was assigned a Pleistocene age based on the C^{14} dating of a sandstone horizon in the raised terraces along the Damortis beach (Javelosa, 1994). The siltstone and sandstone beds of the Damortis Formation strike N10°W and dip 35°SW. Some pelecypod and gastropod shells extracted from the sandstone sample provide the Pleistocene age for this unit (Maac-Aguilar, pers. comm.) (Figure 7).

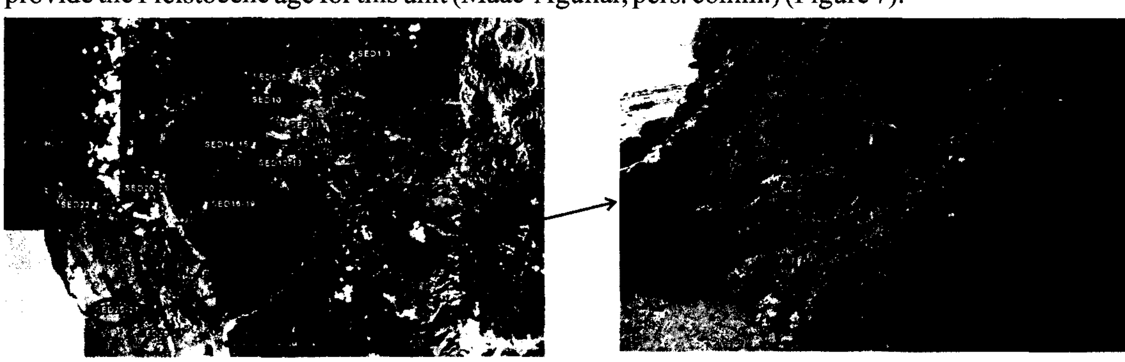


Figure 7. The Damortis Formation consists of siltstone and sandstone beds (Photo by G.P. Yumul Jr.).

Materials and Methods

Sample collection

In geochemical investigations of sedimentary rocks, shales are considered to be most useful for provenance studies owing to their homogeneity, post-depositional impermeability and the larger concentrations of trace elements (e.g. Totten *et al.*, 2000; Rashid, 2002; Calvo, 2003). Nevertheless, there has been a significant increase in the number of investigations that examine the whole rock major and trace element compositions of sandstones, specifically the fine- to medium-grained varieties (e.g. Tucker, 1991). Sandstones are also useful particularly since some of the provenance indicative trace elements, e.g. Zr and Hf, tend to be more concentrated in sandstones since these elements are not sensitive to chemical and mechanical weathering (e.g. Augustsson and Bahlburg, 2003).

Fieldworks were conducted in the Baguio Mineral District and nearby areas during which time samples were collected from exposures of sedimentary sequences. The sites where samples were collected included Kennon Road, Asin Road, Tublay, Naguilian Road and Marcos Highway. Samples were also collected from East Agoo, Damortis and Rosario in La Union (Figure 8). The shale, siltstone and sandstone samples were obtained from the Zigzag, Klondyke, Amlang, Cataguintingan and Damortis Formations.

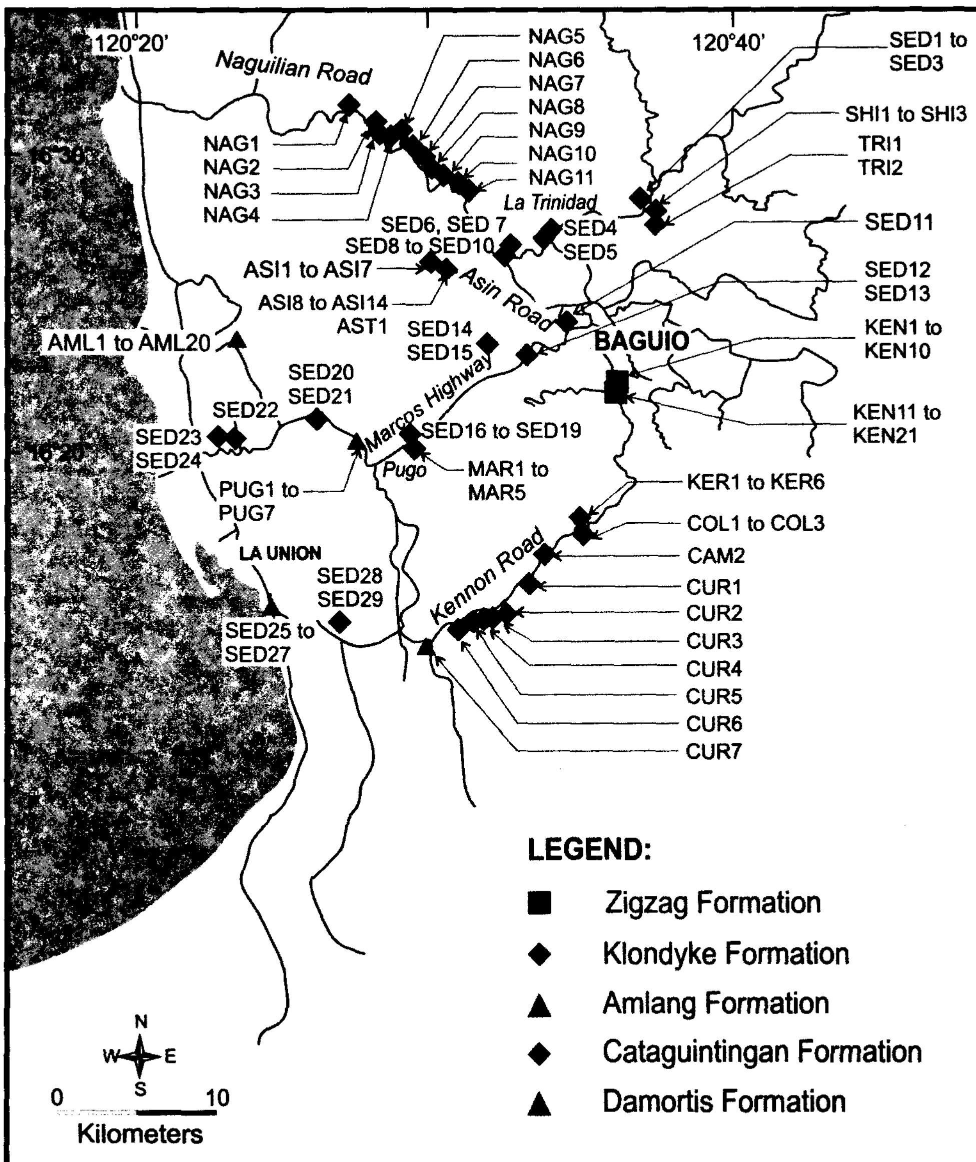


Figure 8. Map showing the location of samples collected from the different sedimentary sequences in the Baguio district and the nearby areas. Samples labeled SED were collected during this study whereas the other samples were previously collected and reported in Tam *et al.*, 2005.

Sample preparation

Selected or representative samples were processed and submitted for paleontological, petrographic and geochemical analyses. Thin sections were prepared for the samples that were submitted for paleontological and petrographic analyses. For the geochemical analysis, the rock samples were fed into a jaw crusher and crushed into smaller fragments. These were then fed into an agate mill to produce the powders of the samples. The powdered samples were submitted for geochemical analyses to determine major element and trace element concentrations.

Petrographic examination

Thin sections of selected or representative sandstone samples were analyzed under a petrographic microscope. At least 400 points were counted for each thin section to determine the types of grain present (i.e. quartz, feldspar or lithic grains) and their percentages. Based on the classification of sand grain types proposed by Dickinson (1985), sandstone samples may consist of the following grains: monocrystalline quartz (Qm), polycrystalline quartz (Qp), plagioclase grains (P), potassium feldspar grains (K), acidic volcanic lithic fragments (Lav), basic volcanic lithic fragments (Lbv), plutonic lithic fragments (Lp), metamorphic lithic fragments (Lm), sedimentary lithic fragments, heavy minerals (HM), secondary minerals (SM) and matrix. During the point counting, the Gazzi-Dickinson method was adopted which minimizes uncertainties resulting from grain size variations (e.g. Ingersoll et al. 1984; Tucker, 1991). This method involves the separation of the coarse components (>0.0625 mm) from the matrix (<0.0625 mm). When a rock fragment contains mineral grains >0.0625 mm in size, it is counted as a mineral rather than as a rock fragment (e.g. Tucker 1991). Plots of ternary quartz-feldspar-lithic (QFL) diagrams are generated using the resulting point count data (Dickinson & Suczek 1979).

Geochemical analyses

Fine- to medium-grained sandstones, siltstones and shales were analyzed using the X-Ray Fluorescence (XRF) Spectrometer and the Inductively Coupled Plasma Mass Spectrometer (ICP-MS). The XRF analyses were done at the Okayama University and Kyushu University in Japan. The XRF spectrometer analyzes the major element composition of the sedimentary rock samples (e.g. SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5). Trace and rare earth element data (e.g. La, Sc, Th, Rb, Sr, Y, Zr, Nb, etc.) were analyzed using the ICP-MS at the University of Hong Kong and Chemex Laboratory. A total of 91 samples were analyzed for whole rock major element compositions and 83 samples for trace and rare earth element compositions which include samples collected previously and presented in Tam *et al.,* 2005. The accuracy of measurements is 1% for major elements and within 5% for trace elements.

Results and Discussion

Petrographic examination

Twenty-two sandstone samples (5 from Zigzag, 11 from Klondyke, 2 from Amlang, 3 from Cataguintingan and 1 from Damortis formations) were analyzed petrographically and point counted (Table 1). Generally, the samples are fine- to medium-grained and exhibit poor sorting. Furthermore, angular to sub-angular grains comprise the sandstone samples and these are embedded in <15% matrix. The matrix is typically made up of clay. The cement, on the other hand, is usually in the form of calcite and quartz overgrowth.

In terms of the rock components, the samples from the Zigzag Formation are mainly composed of quartz (60-80%). The quartz crystals are mostly monocrystalline, non-undulatory and devoid of inclusions (Figure 9). These characteristics commonly imply that the quartz might have been derived from the surrounding volcanic rocks as a result of weathering and erosion (Tucker, 2001).

A considerable amount of plagioclase minerals (17-30%) are also present in the Zigzag samples but this is much less than the number of plagioclase grains observed in the Amlang (45-58%) and Klondyke (25-50%) Formations. Abundant plagioclase crystals are indicative of a compositionally immature sandstone since plagioclase is a labile mineral. Compositional maturity reflects the weathering process in the source area and the degree and extent of reworking and transportation (Tucker, 2001). It is also evident that some of the plagioclase grains of the Klondyke samples exhibit zoning while some are almost completely altered into calcite.

Lithic fragments, which are mostly in the form of volcanic clasts, are common in the Klondyke (15-30%) samples. Lithic sedimentary rocks though are especially profuse in samples CAMP-2B (10%) and ASI II (8%) of the Klondyke Formation in which fossils of algae and benthic foraminifera can also be observed. Other detrital grains present in the samples include opaque minerals, micas (usually in the form of chlorite and muscovite) and a few mafic detritus.

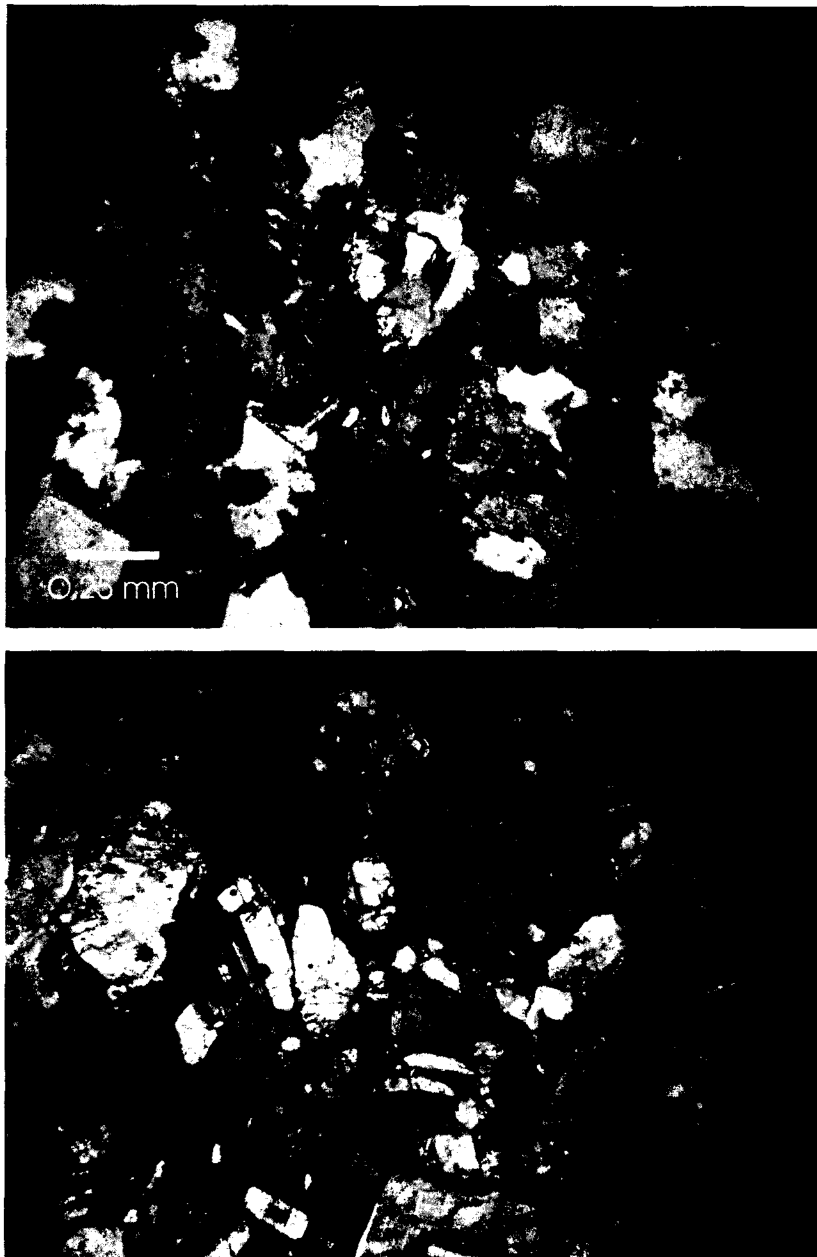


Figure 9. Top: Photomicrograph of a sample collected from the Zigzag Formation (20x magnification, taken under crossed polars). The sample is predominantly made up of quartz (qz) grains. Bottom: Photomicrograph of a Klondyke sandstone sample which consists mostly of plagioclase (pl) and lithic volcanic (lv) fragments (20x magnification, taken under crossed polars).

Geochemical results

The major and trace element composition of representative samples of the different sedimentary formations from the Baguio Mineral District and vicinity are shown in Tables 2 and 3. The clastic samples of the Zigzag Formation are characterized by SiO_2 contents varying from 49 to 73%. The Fe_2O_3 content of the samples varies from 4 to 11% and the abundances of MgO (<4%) and CaO (1-4%) are generally low. The Amlang samples have SiO_2 values ranging from 50 to 57% and Fe_2O_3 ~6 to 10%. The MgO and CaO contents are relatively higher with values between 2.5 to 6% and 5 to 14.5%, respectively. Samples collected from the Klondyke Formation show SiO_2 values ranging from 44 to 68%, Fe_2O_3 from 3 to 11%, MgO from 1 to 7% and CaO from 0 to 10%. Several samples are characterized by relatively high CaO contents (20 to 30%). The Cataguintingan Formation clastic rocks have SiO_2 values between 54 and 60%, Fe_2O_3 from 7 to 9%, MgO from 2.5 to 4.5% and CaO from 2 to 7%.

Sandstone classification

Aside from the petrographic classification of sandstones based on the amount of quartz, feldspar grains and rock fragments, whole rock major element data can also be used in sandstone classification. Using the Na_2O - Fe_2O_3 + MgO - K_2O ternary diagram of Blatt *et al.* (1980), the Klondyke, Amlang and Cataguintingan sandstones are mostly classified as greywackes. A few Klondyke and Cataguintingan samples cross over to the lithic sandstone field. The majority of the Zigzag samples plot within the lithic sandstone field (Figure 10).

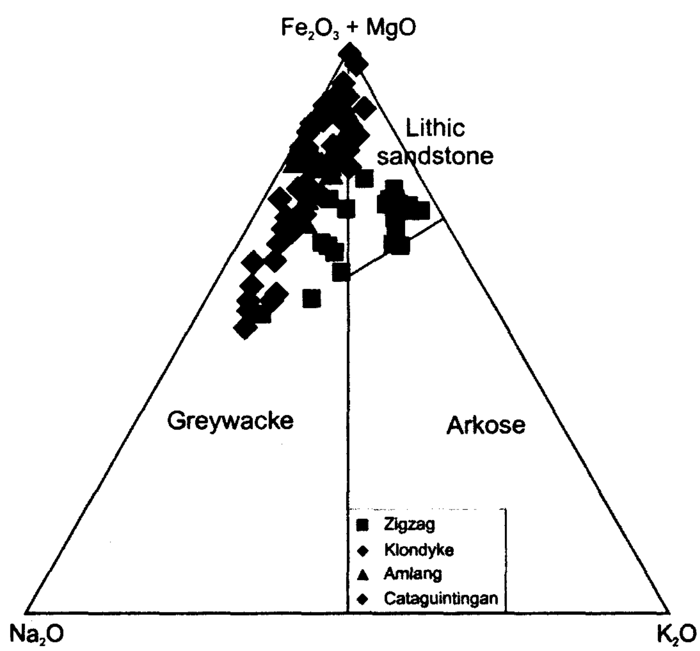


Figure 10. The majority of the Klondyke, Amlang and Cataguintingan samples new plot fall within the greywacke field whereas most of the Zigzag samples occupy the lithic sandstone field.

Sediment Provenance

An examination of the geochemical compositions of sedimentary rocks can offer useful information on the composition of its source area or source rocks. One discrimination diagram which effectively characterizes the provenance uses seven major elements (Al, Fe, Mg, Ti, K, Na and Ca). When plotted on the discrimination diagram for provenance (e.g. Yan et al., 2007), the majority of the Zigzag, Klondyke, Amlang and Cataguintingan samples plot in the mafic igneous provenance field (Figure 11). The clasts of some Zigzag samples are derived from both intermediate igneous rock sources and mafic igneous provenance (e.g. Yan *et al.*, 2007).

Some workers prefer to use immobile trace elements since these provide more constraints on provenance determination compared to major oxides due to their resistance to redistribution. These immobile elements are also thought to be quantitatively redistributed from the source to the sediment. An example of such a diagram is the Zr/Sc versus Th/Sc plot of McLennan *et al.* (1993) (Figure 12). The Klondyke and Amlang samples are observed to lie close to the volcanic arc trend from basalt to andesite. This is consistent with what is shown on the F1 versus F2 plot showing their derivation from a mafic source. Two Klondyke samples plot close to the average dacite. The Zigzag samples plot well away from the standard volcanic arc trend.

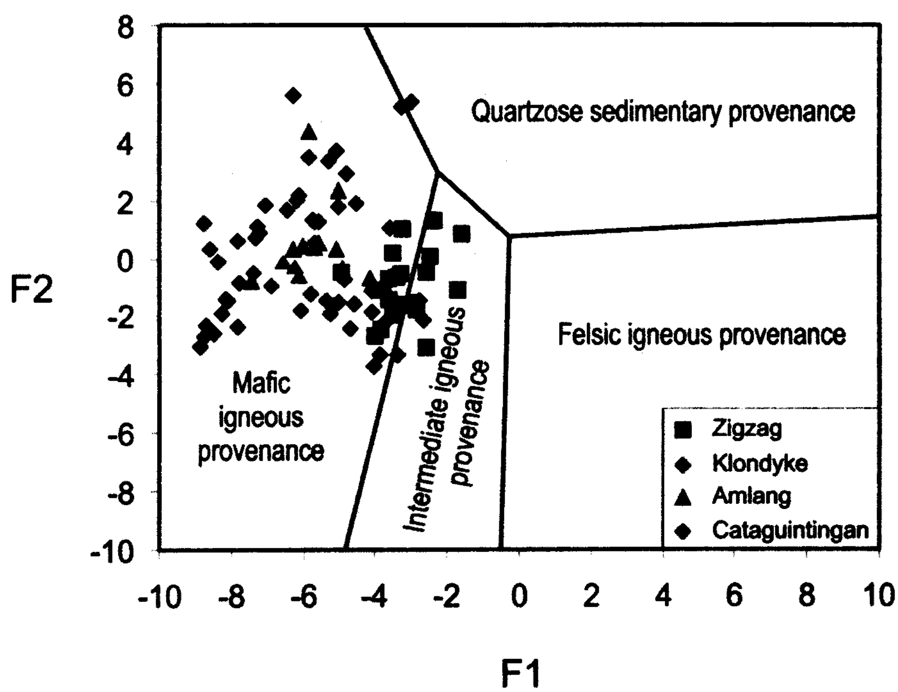


Figure 11. Major element provenance discriminant diagram (e.g. Bhatia, 1983; Yan *et al.*, 2007) shows most of the Zigzag, Klondyke, Amlang and Cataguintingan samples sourced from a mafic igneous rock.

Legend:

$F1 = 30.638TiO_2/Al_2O_3 - 12.541Fe_2O_3(total)/Al_2O_3 + 7.329MgO/Al_2O_3 + 12.031Na_2O/Al_2O_3 + 35.402K_2O/Al_2O_3 - 6.382$

$F2 = 56.5TiO_2/Al_2O_3\ 10.879Fe_2O_3(total)/Al_2O_3 + 30.875MgO/Al_2O_3 - 5.404Na_2O/Al_2O_3 + 11.112K_2O/Al_2O_3 - 3{:}89$

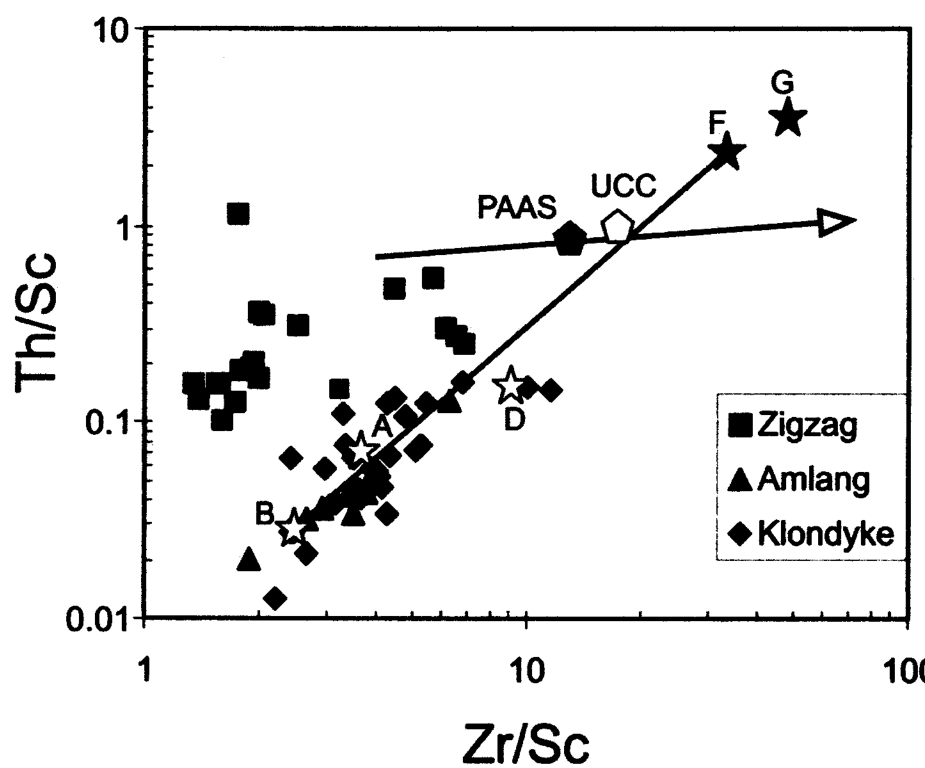


Figure 12. Average volcanic rock compositions are shown as G = granite, B = basalt, A = andesite, D = dacite and F = felsic volcanic rock (Condie, 1993). PAAS = Post-Archean Average Shale and UCC = Upper Continental Crust from Taylor and McLennan (1985).

Although the use of Rb versus K_2O diagram is questioned by some workers due to the mobile character of these elements during diagenesis or metamorphism, this diagram can still be used in tandem with other plots. The samples from the Baguio Mineral District can be divided into two groups based on the K and Rb contents. Low K, Rb and K/Rb ratios exhibited by the Klondyke, Amlang and Cataguintingan samples suggest derivation from basic igneous rocks (Figure 13). The Zigzag samples, in contrast, are characterized by high K, Rb and K/Rb ratios typical of rocks derived from intermediate to felsic igneous rocks (e.g. Patocka and Storch, 2004) (Figure 13).

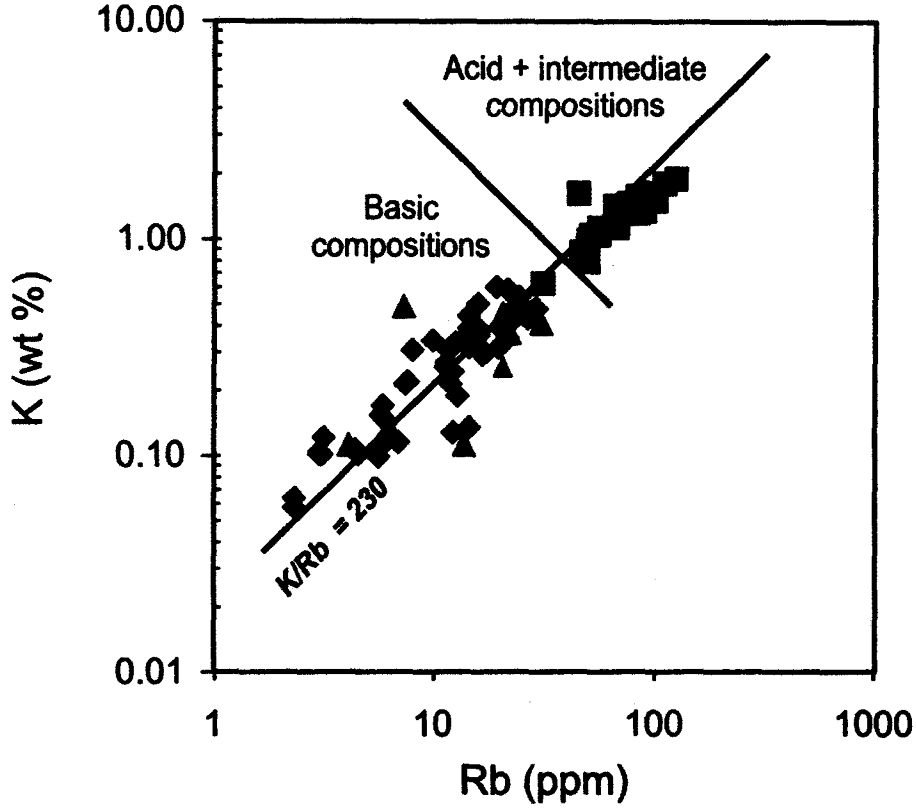


Figure 13. Binary diagram using K and Rb to characterize the source rocks of the Baguio Mineral District sedimentary units.

Tectonic Setting

Various geochemical discrimination and ratio diagrams have been proposed (e.g. Bhatia and Crook, 1986; Roser and Korsch, 1986) to distinguish among sedimentary rocks derived from different tectonic settings. The sedimentary basins can be assigned to the following tectonic settings:

- OIA (Oceanic Island Arc) adjacent to volcanic arc formed on oceanic or THIN continental crust
- CIA (Continental Island Arc) adjacent to volcanic arc formed on THICK continental crust
- ACM (Active Continental Margin) Andean-type basins close to thick continental basins
- PM (Passive Continental Margin) rifted continental margins

On the La-Th-Sc and Th-Sc-Zr/10 discriminant plots of Condie (1993) and Bhatia and Crook (1986), the majority of the Klondyke and Amlang samples cluster within and near the oceanic island arc field. The Zigzag samples plot in the oceanic to continental island arc fields (Figure 14).

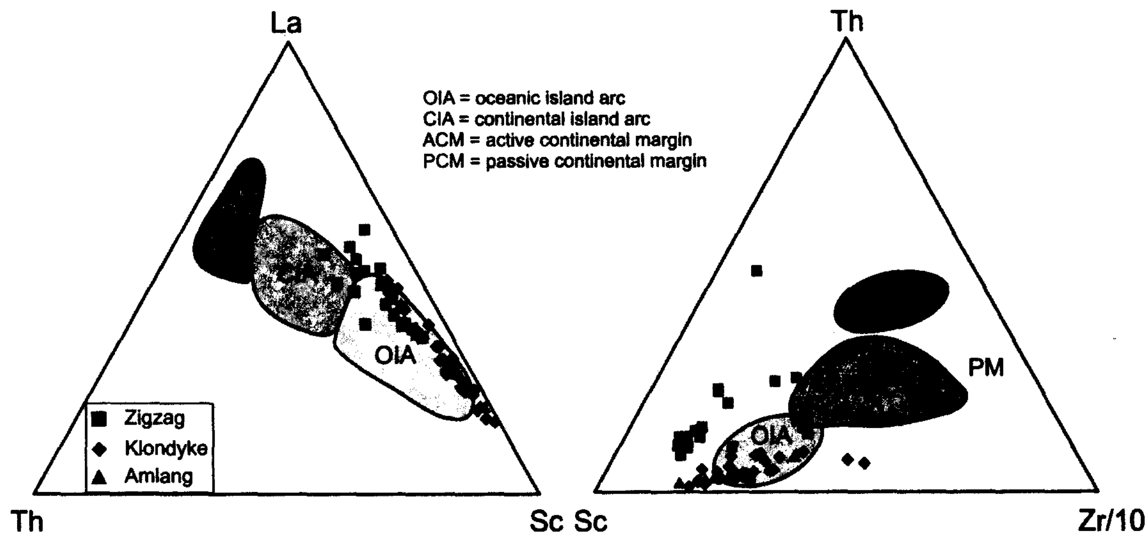


Figure 14. Samples from the sedimentary sequences in the Baguio District are plotted on the tectonic discrimination diagrams of Condie (1993) and Bhatia and Crook (1986). The Klondyke and Amlang samples plot within and near the OIA field whereas the Zigzag samples straddle the CIA and OIA fields.

Roser and Korsch (1986) proposed another diagram to determine the tectonic setting of its provenance region using SiO_2 versus K_2O/Na_2O values (Figure 15). This diagram differentiates oceanic island arc environments from more evolved arcs (i.e. active continental margins or continental island arcs). Roser and Korsch (1986) define passive margin (PM) sediments as those derived from stable continental areas and deposited in plate interiors, Atlantic-type continental margins, failed rifts or grabens or depocenters along continental edges. The active continental margin (ACM) is represented by sediments coming from sources adjacent to active plate boundaries or in subduction-related basins, strike-slip margins and near backarc basins (e.g. Batumike *et al.*, 2006; Campos Alvarez and Roser, 2007). Sediments derived from evolved arcs (ACM, PM) will have felsic components defined by high K_2O/Na_2O whereas those from oceanic island arcs are likely to be enriched in mafic components. The K_2O/Na_2O ratios of the Zigzag samples are generally higher compared to the ratios of the Klondyke, Amlang and Cataguintingan samples. The Zigzag samples occupy the active continental margin (ACM) field whereas the Klondyke, Amlang and Cataguintingan samples plot within the oceanic island arc field (ARC).

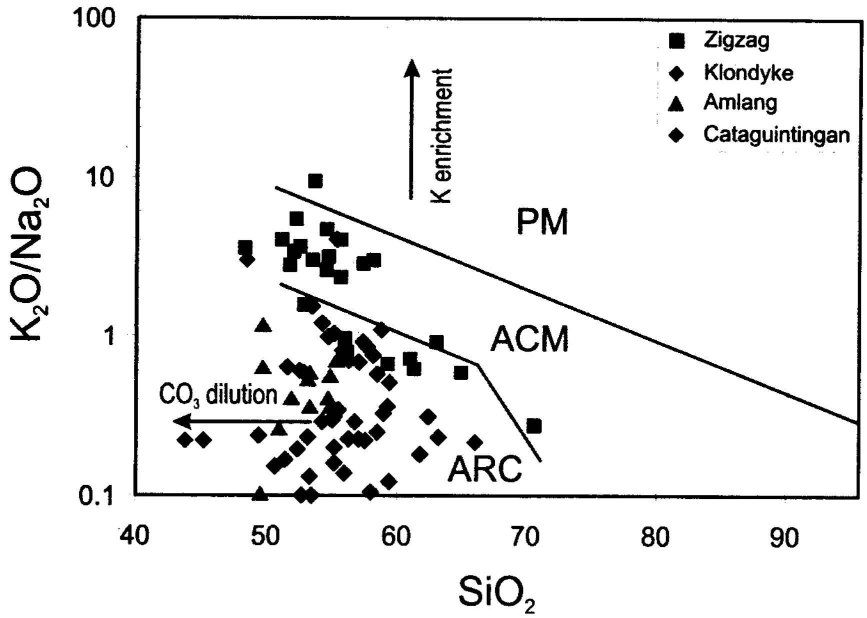


Figure 15. Discrimination diagram from Roser and Korsch (1986) shows the Zigzag Formation samples mostly occupying the active continental margin (ACM) field whereas the other samples plot within the oceanic island arc (ARC) field. PM is passive margin.

Clues to the evolution of the Baguio District

The petrographic and whole rock major and trace element data shown here are useful in defining the tectonic setting where the clastic sedimentary rocks found in the Baguio Mineral District area were deposited. The provenance of these sedimentary rocks are in consonance with the recognized respective tectonic setting: Zigzag Formation coming from an area associated with an active continental margin whereas the Klondyke, Amlang and Cataguintingan Formations are associated with an island arc setting. This recognition further constrains the evolution of this part of Northern Luzon.

Summary

The results obtained from this study are as follows:

1. Petrographic examination of samples collected from the sedimentary units in the Baguio Mineral District show that the Zigzag samples have more quartz but less plagioclase compared to the Klondyke, Amlang and Cataguintingan samples. Lithic fragments are more abundant in the Klondyke sandstone samples.
2. The major and immobile trace element data suggest that the Klondyke, Amlang and Cataguintingan samples were derived from a mafic source whereas samples from the Zigzag Formation indicate derivation from intermediate to felsic igneous rocks.
3. From the geochemical data, the Zigzag Formation is believed to have been derived from an active continental margin setting whereas the Klondyke, Amlang and Cataguintingan Formations are from an oceanic island arc environment.

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