Features of gold-bearing quartz veins in an artisanal mining-dominated terrain, Batouri gold district, Eastern region of Cameroon

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Introduction

In a bid to identify features useful in discriminating barren from gold-bearing veins and thus assist in the training of locals on site suitability selection for shallow-depth gold exploitation from weathered veins, we investigated a major vein set in the Batouri gold district of eastern Cameroon hereafter referred to as the Mama vein system. The mineralized veins trend NE-SW and are foliated with sericitic, carbonate, sulphides and hematitic alterations. Quartz in the mineralized veins is brecciated, fibrous and smoky. Gold grains occur as inclusions in hematite mainly derived from the weathering of sulphides. Thus brecciated to stock work hematite-bearing veins in prospective mining sites is the main target for the local miners since they are the main host of primary mineralization in Batouri. The gold grains are rich in Ag and show low gold fineness (maximum 615). Bulk geochemistry reveals Au-As-Hg-Zn-Pb-Sb-Mo element association indicative of a low sulphidation environment. Fluid inclusion data affirm to moderate salinity brine as the ore-bearing fluids and mesothermal conditions of ore deposition consistent with the magmatic source of gold. The δ³⁴S values for this system reflect a single homogenous and general light source for sulfur.

Primary mineralization within the Central Cameroon Shear Zone (CCSZ) system is hosted by quartz ± carbonate veins (Suh et al., 2006; Asaah et al., 2014; Vishiti et al., 2015). These auriferous quartz veins show evidence of brittle/ductile deformation (Vishiti et al., 2017). Although lode gold mineralization in the Bétaré Oya area has been characterized (Vishiti et al., 2017), as well as gold grains recovered from exploration pits in the Batouri gold mining area (Vishiti et al., 2015), the trace element signature of sulphides and gold microchemical signature of the auriferous veins are still poorly constrained. Also, fluid inclusion studies widely used in mineral exploration and metallogenic studies (Ulrich et al., 1999; Wilkinson, 2001; Yudovskyaya et al., 2006; Suh, 2008; Zoheir et al., 2008; Soloviev et al., 2013) have not been completed on the Mama vein system. Furthermore, although δ²⁸S isotope data has been reported in the Bétaré Oya gold mining district of eastern Cameroon (Vishiti et al., 2017), the δ³⁴S isotopic signature of sulphides in Batouri is not known. All these data sets are relevant in developing exploration predictive models in the Batouri area.

Here we present the textural, geochemical and fluid inclusion characteristics of the mineralized veins and discuss their usefulness in prospection. We also present sulfur isotope data for the system more
Figure 1. (a) Map of Cameroon locating the study area Batouri in the eastern region of Cameroon (red rectangle not to scale). (b) Map of the eastern region of Cameroon showing the distribution of Au occurrences. Note the concentration of gold in the eastern region of Cameroon (black rectangle not to scale). (c) Geologic map (modified after Suh and Lehmann 2003; Suh et al., 2006) of Batouri with the main structural and lithologic units. The square box defines the Mama vein system. The World Geodetic System 1984, Universal Transverse Mercator Zone 33N coordinate was used.
for the purposes of a better scientific understanding of this auriferous system.

**Location, Regional and Deposit Geology**

The Batouri gold mining area in southeastern Cameroon belongs to the Adamawa Yade domain (Fig. 1a) of the Central African fold belt (Pan African; Toteu et al., 2004; Van Schmus et al., 2008; Kouske et al., 2012; Asaah et al., 2014). The evolution of the Central African Fold belt can be attributed to the convergence and collision between the São Francisco-Congo Craton and the West African Craton (WAC) and a Pan African Mobile belt (Castaign et al., 1994). It underlies Cameroon, Chad and the Central African Republic, between the Congo Craton to the south and the Western Nigeria shield to the north (Van Schmus et al., 2008; Li et al., 2017). The Adamawa Yade Domain extends eastwards from Cameroon into the Central African Republic where it is known as the Yade massifs (Van Schmus et al., 2008) and is bounded to the north by the Tcholliré-Banyo fault and to the south by the Yaoundé Domain. The Adamawa Yade domain is underlain by a variety of granitic rocks including alkali-feldspar, granite, quartz alkali granitoids, syeno-monzogranite, granodiorites, diorites and tonalite (Asaah et al., 2014; Tata et al., 2018). The granites are Pan African, metaluminous, I-type granites. Biotite-gneiss xenoliths are ubiquitous in most rocks occurring in the area. These enclaves are believed to represent fragments of the underlying Palaeoproterozoic–Archaean basement rocks or Neoproterozoic high-grade metasedimentary rocks (e.g. Toteu et al., 1994, 2004, 2006; Van Schmus et al., 2008).

In the Batouri area, gold is hosted by hydrothermally altered granitoids with concentrations reaching a high of 103.7 ppm (Tata et al., 2018). Gold mineralization is accompanied by sericitization, silicification and sulphidation in the altered granitoids. The granitoids represent part of regional scale batholiths with small-scale, high-grade auriferous quartz veins in structurally favorable sites (Asaah et al., 2014). The quartz veins are defined by NE-SW-trending shear zone which forms part of the Central Cameroon Shear Zone system (Suh et al., 2006). This shear zone is a Pre-Mesozoic crustal strike-slip fault system that extends from central Africa, across the Atlantic into NE Brazil (Toteu et al., 2004; Neto et al., 2008). The tectonic evolution of the Pan-African belt in central and southern Cameroon resulted in structures including a N70°E sinistral shear zone of central Cameroon (Central Cameroon Shear Zone (CCSZ)) to the north and Sanaga fault (SF) to the south (Ngako et al., 2003; Fig. 1). The gold bearing quartz veins are enclosed by hydrothermally altered zones traceable into the wall rock (Suh and Lehmann, 2003; Suh et al., 2006; Suh, 2008; Asaah et al., 2014) as well as in the soils (Vishiti et al., 2015). The mineralized quartz veins are ferruginized and sulfidized. Consequently albite, sericite, silica, chlorite, epidote, calcite, hematite and pyrite appear in the foliated altered rock. Gold in this area is mined by artisanal methods from primary pyrite-bearing quartz veins, eluvial and alluvial workings (Fig. 1b). Alluvial Au exploitation strictly follows current river channels. The Batouri gold mining area is underlain by variably deformed deeply weathered granitic rocks (Fig. 1c).

**Quartz Vein Characterization: Structure, Texture, Mineral Microchemistry, Trace Element Geochemistry, Fluid Inclusion and Sulfur Isotope Analysis**

Initial field visit to Batouri was made to create contacts with the administrative authorities where they were briefed on the mission. Contacts were created with local mining communities and also local authorities. Interactions with artisans were made in the field where they were educated on how to use the features of quartz veins to select suitable sites for artisanal mining.

The quartz vein system was mapped and collected samples polished and studied under reflected and transmitted light, while the composition of various mineral phases was determined using electron microprobe. The major and trace element composition of pyrite and gold grains were obtained quantitatively by wavelength dispersive spectrometry (WDS) using a JEOL SUPERPROBE 8200 analyzer at GEOMAR, Kiel. In order to achieve surface conductivity, representative polished sections were coated with carbon film prior to the EMPA analysis. During EMP-analysis, care was taken to select analytical points free from cracks.

Pyrite in quartz vein samples from the Mama quartz vein systems was analyzed for Sn, As, S, Cu, Cd, Se, Hg, Fe, Ag, Au, Sb, and Zn using a 1 µm beam at 15 kV accelerating voltage and 50 nA beam current. In order to improve the statistics of the count rates, counting times were 60 s for Sn, Hg, 40 s for As, 30 s for S, and 20 s for Cu, Cd, Se, Fe, Ag, Au, Zn. Standard specimens used for calibration were: cassiterite (Sn), GaAs (As), chalcopyrite (for Fe, S, Cu), CdS (for Cd), Bi₂Se₃ (for Se), HgS (for Hg), AgTe (for Ag) Au₁₀₀ (for Au), InSb (for Sb), and sphalerite (for Zn). A chalcopyrite standard was used after every 10 analyses to ensure quality control on the data.

Identified gold grains within the samples were analyzed for Au, Ag, As and Hg using a 1 µm beam at 15 kV accelerating voltage and 50 nA beam current. Counting times were 20 s for Ag, Au, 40 s for As and 60 s for Hg. Standard specimens used for calibration were Au₄₉Ag₅₁ (for Au, Ag), GaAs (for As) and HgS (for Hg). The Au₄₉Ag₅₁ standard was run after every 5 analyses and Au fineness was calculated using the formula Au¹⁰⁰⁰/Au⁺Ag (Hallbauer and Utter, 1977).

The quartz vein samples were also analyzed for whole rock composition. Selected trace elements were analyzed for using a combination of instrumental neutron activation analysis (INAA) and inductively coupled plasma mass spectrometry (ICP-MS) following a lithium metaborate/tetraborate fusion and dilute nitric digestion at Acme and Activation Labs., Ltd (Canada). Duplicates were fused and analyzed after every 15 samples, and the instrument was recalibrated after every 40 samples. Fusion ensures that also the highly refractive REE and HFSE are dissolved. Loss on ignition was determined by weight difference after ignition at 1000°C. The detection limits and quality assurance indicators are available at www.acmelabs.com and www.actlabs.com.

For the fluid inclusion studies, doubly polished sections were prepared for each sample. These sections were reduced to wafers ~33 µm thick, mounted on glass slides, and the nature of the fluid inclusions in them studied under a high magnification transmitted light petrographic microscope. To liberate the wafer from the glass slide, each slide was immersed in acetone for about 10 minutes to dissolve the
Canada balsam glue and subsequently rinsed with distilled water several times. Inclusion of interest were then analyzed for their microthermometric data using a United States Geological Survey-type heating freezing stage (Roedder, 1984) in the microthermometric laboratory in GEOMAR, Kiel. This stage consists of a high resolution microscope that is equipped with a heating device and connected to a liquid nitrogen tank by a tiny tube. During the freezing runs, liquid nitrogen is passed over the quartz wafer slowly until the inclusion freezes completely (at ~100°C). The frozen inclusion is subsequently heated up at a rate of about 0.1°C/second until the ice starts melting. This initial ice melting temperature (Tm) is noted. Heating continued until the vapour and liquid phases of the inclusions homogenized into a single phase (usually into the liquid phase), and the meniscus between then disappeared. This is known as the total homogenization temperature, Th.

Samples for S-isotope analysis were prepared by drilling with a Proxxon Minimot 40/E hand drill to obtain a fine powder at the Hydrothermal Laboratory in GEOMAR, Kiel. About 0.8 g of sulphur concentrate from each sample was bottled for sulphur isotope analysis. δ34S data of sulphide minerals were determined at the Institut für Geologie und Paläontologie, Westfälische Wilhelms-Universität Münster, Germany, using a Thermo Finnigan Delta Plus mass spectrometer coupled with an elemental analyser (Carlo Erba).

Vein Structure

Two main types of quartz veins were observed within the Mama auriferous vein system: mineralized and barren quartz veins. The veins cut through a granitic host rock and are oriented NE-SW. Within the vein system granitic wall rock selvages are common (Fig. 2). The

![Figure 2. Quartz vein characterization in Mama.](image)

(a) regolith

(b) quartz vein

(c) regolith

(d) quartz vein

(e) S1 foliation

(f) granitic salvage

(g) sericite alteration

(h) S2 foliation

(i) Close view of the granitic salvage at the contact between the quartz vein and the granitic host rock. (h) Close view of the S2 foliation (i) Contact between the quartz vein and granite characterized by sericite alteration (yellowish).
mineralized quartz veins exhibit S1 and S2 foliations (Figs. 2 and 3). The S1 foliation follows a general E-W trend and it is marked by distinct hematite bands truncated by S2 surfaces. The S2 foliation is defined by mm-scale slickenside coating and the surfaces are cross-cut by N-S-trending hematite-bearing veinlets (Fig. 2). These veinlet are zoned; hematite in the core and silica along the margins. The barren quartz veins are late and follow S3 surfaces.

**Vein Texture and Alteration Mineralogy**

The veins show a wide variation in texture (Figs. 4 and 5). Hematite-rich quartz veins are either banded or brecciated. Some show a characteristic stock work texture comprising a network of narrow discontinuous and closely spaced fractures. Brecciation is enhanced by transgranular fractures thus hematite distribution within the brecciated quartz vein is fracture-controlled. The mineralized quartz veins are defined by rose to milky white vuggy quartz. Although some of these vugs are empty, most are filled with euhedral quartz crystals and sulphides. The barren veins in contrast are composed predominantly of whitish-vuggy quartz. Unlike the barren veins the mineralized veins have carbonate, hematite, goethite, sulphides and gold. Three generations of quartz based on morphology have been identified (Fig. 4). They include coarse-grained quartz with deformed grain boundaries (qz1, Fig. 4), incipient recrystallized quartz (qz2) defined by small polygonal quartz grains and subgrains occupying intergrain planes mainly parallel to the grain boundaries and vein margins (Fig. 4) and deformed-elongated (stretched) quartz ribbons (qz3). The quartz crystals display undulate extinction (Fig. 4).

Pyrite is euhedral, vesicular and in some cases it is fractured (Fig. 5) and/or crosscut by quartz + hematite veins (Fig. 5). Chalcopyrite inclusions are common in pyrite. Carbonate occurs in association with the granitic selvage and sericite is abundant at the contact with the granitic wall rock. Gold occurs as inclusions in hematite (Fig. 5e, g, h, i) and it is intergrown with covellite and sphalerite forming tiny slender crystals (Fig. 5). Goethite occurs around the rims of hematite. Alteration processes thus identified in the Mama quartz vein system include: silicification, carbonatization, sericitization, hematitization, sulphidation and carbonitization.

**Sulphide and Gold Microchemistry**

Data from EMP-analyses of sulphides and gold from the quartz vein system are summarized in Table 1. Pyrite has 0.13 to 0.34 wt.% Au and minor amounts of As. Analyses on gold grains yielded gold content that varies between 59.74 and 60.33 wt.% and a Ag content that varies from 36.9 to 37.7 wt.%. This confirms the EDS patterns of gold grains that indicate that the grains are rich in Ag. Au shows a fineness that ranges from 609 to 615 (Table 1).
Trace Element Geochemistry

The concentrations of trace elements in bulk quartz vein samples from the Mama vein system are listed in Table 2. The veins are characterized by an Au+As+Hg+Zn+Pb+Sb+Mo association with 0.04 ppm Au, 44.9 ppm As, 57 ppm Hg, 650 ppm Zn, 489 ppm Pb, 5 ppm Sb and 25 ppm Mo. It also contains elevated concentrations of Co (155 ppm), Cu (77 ppm), U (3.7 ppm) and Ba (10 ppm, Table 2).

Fluid Inclusion Petrography and Microthermometry

Typical morphologies of fluid inclusion from quartz vein samples are illustrated in Fig. 6 and their microthermometric measurements are presented in Table 3 and Fig. 7. The inclusions occur as scattered groups or clusters trapped in coarse-fine-grained and ribbon quartz. Based on the host vein, petrographic characteristics and relative timing, the fluid inclusions can be divided into: early (intragranular) and late (occurs as trails in healed fractures and define grain boundaries). The monophase inclusions mainly define gain boundaries or healed fractures although a few intragranular inclusions have been identified. The microthermometric data including Tm and Th for inclusions in all the quartz varieties are given in Fig. 7. Although the inclusions show a wide range of Tm in all the quartz generations, a distinct Tm ranging from -5.5 to -3 and homogenization temperature varying between 230 and 330°C can be identified. Although the calculated salinities for fluid inclusions range from 0.50 to 9.05 wt.% NaCl equivalent, a cluster between 4.23 and 9.05 wt.% NaCl equivalent is also discernible. This is slightly higher than seawater salinity.

Sulfur Isotopes

The δ³⁴S values vary between 4.8 and 5.3‰ δ³⁴S. These values overlap with those of the Bétaré Oya vein system (Vishiti et al., 2017) and are discussed further hereafter.

Interpretation and Discussion

Structural Configuration of the Mama Vein System

The Mama vein system is structurally controlled mainly by a NE-SW-trending shear zone that would have contributed significantly to gold mineralization. Recent studies (e.g. Suh and Lehmann, 2003; Suh et al., 2006; Suh, 2008; Fon et al., 2012; Vishiti et al., 2017; Wambo...
| Sample No | Analyses No | Fe  | S   | Ag  | As  | Hg  | Cd  | Sn  | Cu  | Au  | Sb  | Zn  | Total | Au | Ag | As  | Hg  | Total | Au/Ag | Fine- ness |
|-----------|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|-----|-----|-----|-----|-------|-------|------------|
| DL        |             | 0.01| 0.01| 0.01| 0.35| 0.02| 0.01| 0.01| 0.12| 0.01| 0.01| 0.03  | 0.21 | 0.01| 0.71| 0.06|       |
| MA-26     | 45.03       | 54.83| 0.01| bdl | bdl | bdl | bdl | bdl | 0.14| bdl | bdl | 100.0 | Gold | 20  | 59.74| 36.92| 1.46| 0.10  | 98.2  | 1.6 | 609      |
| BRE4-27   | 44.95       | 54.58| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | 0.02| bdl | 0.03  | 99.6  | 21  | 60.33| 37.7 | 1.22| 0.11  | 99.4  | 1.6 | 615      |
| 28        | 47.01       | 53.71| 0.02| bdl | bdl | bdl | bdl | bdl | bdl | 0.01| bdl | 0.03  | 101.1 |     |     |     |     |       |       |     |          |
| 29        | 44.97       | 54.69| bdl | bdl | bdl | 0.02| bdl | bdl | bdl | 0.01| bdl | 0.03  | 100.6 |     |     |     |     |       |       |     |          |
| 30        | 47.22       | 53.84| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | 0.01| bdl | 0.03  | 100.7 |     |     |     |     |       |       |     |          |
| 31        | 46.88       | 53.41| 0.01| bdl | bdl | 0.03| bdl | bdl | bdl | 0.21| bdl | 0.01  | 100.6 |     |     |     |     |       |       |     |          |
| 32        | 47.02       | 53.78| bdl | bdl | bdl | bdl | bdl | bdl | bdl | 0.02| bdl | 0.03  | 100.9 |     |     |     |     |       |       |     |          |
| 33        | 47.08       | 53.64| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | bdl | 0.01| bdl | 0.03  | 100.7 |     |     |     |     |       |       |     |          |
| 34        | 45.63       | 54.07| 0.01| bdl | bdl | 0.02| bdl | bdl | bdl | 0.03| bdl | 0.03  | 99.8  |     |     |     |     |       |       |     |          |
| 35        | 44.96       | 53.96| bdl | bdl | 0.05| 0.01| bdl | bdl | 0.02| bdl | bdl | 0.03  | 99.0  |     |     |     |     |       |       |     |          |
| 36        | 45.87       | 53.98| 0.01| bdl | bdl | bdl | bdl | bdl | bdl | 0.15| bdl | 0.04  | 100.5 |     |     |     |     |       |       |     |          |
| 37        | 45.91       | 53.86| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | 0.04| bdl | 0.03  | 99.8  |     |     |     |     |       |       |     |          |
| 38        | 45.35       | 53.78| bdl | bdl | bdl | 0.02| bdl | bdl | bdl | 0.02| bdl | 0.01  | 99.2  |     |     |     |     |       |       |     |          |
| 39        | 45.26       | 53.91| bdl | bdl | bdl | 0.02| bdl | bdl | bdl | 0.03| bdl | 0.13  | 100.4 |     |     |     |     |       |       |     |          |
| 40        | 45.72       | 53.82| 0.01| bdl | bdl | 0.01| bdl | bdl | bdl | 0.34| bdl | 0.05  | 99.9  |     |     |     |     |       |       |     |          |
| 41        | 44.87       | 53.79| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | 0.06| bdl | 0.02  | 98.7  |     |     |     |     |       |       |     |          |
| 42        | 45.32       | 53.46| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | 0.02| bdl | 0.06  | 98.9  |     |     |     |     |       |       |     |          |
| 43        | 46.75       | 53.18| 0.01| bdl | bdl | 0.04| bdl | 0.01| bdl | bdl | 0.03  | 100.0 |     |     |     |     |       |       |     |          |
| 44        | 46.75       | 53.25| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | 0.01| bdl | 0.03  | 100.0 |     |     |     |     |       |       |     |          |
| 45        | 46.78       | 53.18| bdl | bdl | bdl | 0.02| bdl | 0.01| bdl | bdl | 0.01  | 100.0 |     |     |     |     |       |       |     |          |
| 46        | 46.65       | 52.76| bdl | bdl | bdl | 0.02| bdl | bdl | bdl | 0.01| bdl | 0.01  | 99.4  |     |     |     |     |       |       |     |          |
| 47        | 46.67       | 52.99| bdl | bdl | bdl | 0.02| bdl | bdl | bdl | 0.04| bdl | 0.01  | 99.7  |     |     |     |     |       |       |     |          |
| 48        | 46.80       | 53.12| bdl | bdl | bdl | 0.01| bdl | bdl | bdl | 0.01| bdl | 0.01  | 99.9  |     |     |     |     |       |       |     |          |
| 49        | 46.73       | 52.90| 0.01| bdl | bdl | 0.02| bdl | 0.02| bdl | 0.01| bdl | 0.01  | 100.1 |     |     |     |     |       |       |     |          |

DL= Detection Limit, bdl=below detection limit
| Sample No | Analyses No | Fe   | S    | Ag   | As   | Hg   | Cd  | Sn  | Cu   | Au   | Sb   | Zn   | Total | Au | Ag | As | Hg  | Total | Au/Ag | Fine-ness |
|-----------|-------------|------|------|------|------|------|-----|-----|------|------|------|------|-------|----|----|----|-----|-------|-------|-----------|
| MA-106    | 46.91       | 53.27| bdl  | bdl  | 0.02 | 0.01 | bdl | bdl | bdl  | bdl  | bdl  | bdl  | 100.2 |     |    |    |     |       |       |           |
| BRE3107   | 46.56       | 53.18| 0.01 | bdl  | bdl  | 0.03 | bdl | bdl | bdl  | bdl  | bdl  | bdl  | 99.8  |     |    |    |     |       |       |           |
| 111       | 46.90       | 53.77| 0.01 | bdl  | bdl  | 0.01 | bdl | bdl | 0.03 | bdl  | 0.01 | bdl  | 100.7 |     |    |    |     |       |       |           |
| 112       | 46.89       | 53.90| bdl  | bdl  | bdl  | 0.01 | bdl | bdl | 0.01 | bdl  | 0.02 | bdl  | 100.8 |     |    |    |     |       |       |           |
| 114       | 46.82       | 53.77| bdl  | bdl  | bdl  | 0.02 | bdl | bdl | bdl  | bdl  | 0.02 | bdl  | 100.6 |     |    |    |     |       |       |           |
| 115       | 47.02       | 54.04| bdl  | bdl  | bdl  | bdl  | bdl | bdl | 0.02 | bdl  | bdl  | bdl  | 101.1 |     |    |    |     |       |       |           |
| 116       | 46.95       | 53.85| bdl  | bdl  | 0.02 | 0.01 | bdl | bdl | 0.03 | bdl  | bdl  | bdl  | 100.9 |     |    |    |     |       |       |           |
| 117       | 47.03       | 53.77| bdl  | bdl  | bdl  | 0.01 | bdl | bdl | bdl  | 0.03 | bdl  | bdl  | 100.8 |     |    |    |     |       |       |           |
| 118       | 47.09       | 53.99| bdl  | bdl  | bdl  | bdl  | bdl | bdl | bdl  | bdl  | bdl  | bdl  | 101.1 |     |    |    |     |       |       |           |
| 119       | 47.02       | 54.09| bdl  | bdl  | 0.02 | 0.02 | bdl | bdl | 0.03 | bdl  | bdl  | bdl  | 101.2 |     |    |    |     |       |       |           |
| 120       | 47.00       | 53.94| bdl  | bdl  | bdl  | bdl  | bdl | bdl | 0.01 | bdl  | 0.03 | bdl  | 100.9 |     |    |    |     |       |       |           |
| 121       | 46.92       | 53.84| bdl  | bdl  | bdl  | bdl  | bdl | bdl | bdl  | bdl  | 0.01 | bdl  | 100.8 |     |    |    |     |       |       |           |
| 122       | 47.00       | 53.65| bdl  | bdl  | bdl  | bdl  | bdl | bdl | 0.01 | bdl  | bdl  | bdl  | 100.7 |     |    |    |     |       |       |           |
| 123       | 47.03       | 54.12| bdl  | bdl  | bdl  | 0.01 | bdl | bdl | bdl  | bdl  | bdl  | bdl  | 101.2 |     |    |    |     |       |       |           |
| 124       | 46.99       | 53.94| bdl  | bdl  | bdl  | 0.01 | bdl | bdl | 0.06 | bdl  | 0.02 | bdl  | 101.0 |     |    |    |     |       |       |           |
| 125       | 47.01       | 53.93| bdl  | bdl  | bdl  | 0.02 | bdl | bdl | bdl  | bdl  | bdl  | bdl  | 100.9 |     |    |    |     |       |       |           |
| 126       | 46.90       | 53.69| bdl  | bdl  | bdl  | bdl  | bdl | bdl | 0.20 | bdl  | 0.03 | bdl  | 100.8 |     |    |    |     |       |       |           |
| 127       | 47.16       | 53.36| bdl  | bdl  | bdl  | 0.01 | bdl | bdl | bdl  | bdl  | 0.02 | 0.03 | 100.6 |     |    |    |     |       |       |           |
| 128       | 47.13       | 54.05| 0.01 | bdl  | bdl  | bdl  | bdl | bdl | bdl  | bdl  | bdl  | bdl  | 101.2 |     |    |    |     |       |       |           |
| 129       | 47.25       | 53.85| bdl  | 0.02 | bdl  | bdl  | bdl | bdl | bdl  | bdl  | bdl  | bdl  | 101.1 |     |    |    |     |       |       |           |
et al., 2018) have highlighted the importance of this shear zone to gold mineralization in the eastern region of Cameroon. Field evidence shows that shearing in this zone is ductile and was followed by brittle deformation that post-dates the emplacement of the Au quartz veins. Samples from the Mama vein system bear evidence of protracted progressive deformation at macroscopic and microscopic scales. Ribbon quartz attests to ductile deformation along the shear zone superimposed on various precursor stages of brittle failure documented by the abundance of breccias. These deformation structures focused and enhanced crustal fluid circulation and mineralization. Whether the shearing was contemporaneous with distal granite plutons observed is unclear, however the felsic magmatism is implicated in the hydrothermal fluid related to the gold mineralization along these structures. The veins show incorporated wall-rock selvages diagnostic of a shear zone system (Vishiti et al., 2017) but lacks sigmoidal features. The absence of such features renders it difficult to identify the direction of shear which can be used to establish its kinematics. A number of gold mineralization associated with shear zones have been reported worldwide (Harraz, 1999; Khalil et al., 2003; Chiaradia et al., 2008; Zoheir, 2008; Zoheir et al., 2017). The most suitable veins for artisanal mining in this area should have the ductile features itemized above.

**Brecciation as a Ground Preparation Event for Mineralization**

Faults and shear zones are major fluid conduits in crustal basement (Kerrich, 1986; Knipe, 1993). Breccias are a common product in the highest, most fluid-saturated part of crustal fault zones where the potential for dilatation strain increases the range of breccias formation processes (Woodcock and Mort, 2008). Brecciation is an excellent precursor to mineralization, as circulating hydrothermal fluids will readily interact with the fractured rocks. Enhanced permeability created in breccia zones provides pathways for crustal fluids that are sometimes metal- or hydrocarbon-rich (Woodcock and Mort, 2008). Thus breccias are associated with numerous types of ore deposits both

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**Table 2. Trace element composition of the Mama mineralized vein samples**

| Location  | Sample ID | Batouri |     |
|-----------|-----------|---------|-----|
| Au (ppm)  | 0.002     | 0.04    | 0.024 |
| Ag        | 5         | bdl     | bdl  |
| As        | 0.5       | 44.9    | 1.3  |
| B         | 10        | 20      | 10   |
| Ba        | 3         | 10      | 13   |
| Be        | 3         | bdl     | bdl  |
| Bi        | 2         | bdl     | bdl  |
| Br        | 0.5       | bdl     | 1.1  |
| Cd        | 0.2       | bdl     | bdl  |
| Ce        | 0.8       | bdl     | bdl  |
| Co        | 1         | 155     | bdl  |
| Cr        | 5         | bdl     | bdl  |
| Cs        | 0.1       | bdl     | bdl  |
| Cu        | 2         | 77      | bdl  |
| Dy        | 0.3       | bdl     | bdl  |
| Er        | 0.1       | 0.1     | bdl  |
| Eu        | 0.2       | bdl     | bdl  |
| Ga        | 0.2       | 3.2     | bdl  |
| Gd        | 0.1       | 0.2     | bdl  |
| Ge        | 0.1       | 4.6     | 1.5  |
| Hg        | 1         | 57      | 6    |
| Hf        | 1         | bdl     | bdl  |
| Ho        | 0.2       | bdl     | bdl  |
| In        | 0.2       | bdl     | bdl  |
| Ir        | 5         | bdl     | bdl  |
| La        | 0.5       | 0.8     | bdl  |
| Li        | 3         | bdl     | bdl  |
| Lu        | 0.05      | bdl     | bdl  |
| Mn        | 3         | 59      | bdl  |
| Mo        | 1         | 25      | bdl  |
| Nb        | 2.4       | bdl     | bdl  |
| Nd        | 0.4       | 0.5     | bdl  |
| Ni        | 10        | 10      | bdl  |
| Pb        | 0.8       | 489     | 14.4 |
| Pr        | 0.1       | 0.2     | bdl  |
| Rb        | 15        | bdl     | bdl  |
| Sr        | 0.1       | 25      | 0.3  |
| Sc        | 0.1       | 0.3     | 0.1  |
| Se        | 3         | bdl     | bdl  |
| Sm        | 0.1       | 0.1     | bdl  |
| Sn        | 0.5       | bdl     | bdl  |
| Sr        | 3         | 10      | 7    |
| Ta        | 0.5       | bdl     | bdl  |
| Tb        | 0.2       | bdl     | bdl  |
| Te        | 6         | bdl     | bdl  |
| Th        | 0.1       | bdl     | bdl  |
| Ti        | 0.1       | bdl     | bdl  |
| Tm        | 0.1       | bdl     | bdl  |
| U         | 0.2       | 3.7     | 0.1  |
| V         | 2         | 47      | 10   |
| W         | 1         | 5       | bdl  |
| Y         | 0.1       | 1       | bdl  |
| Yb        | 0.1       | 0.1     | bdl  |
| Zn        | 50        | 650     | bdl  |
| Fe wt%    | 12.5      | 0.14    | 0.03 |
| S (T)     | 0.5       | 0.3     | 0.03 |
| Vein type  | Quartz texture | Relative timing | Occurrence | Fluid inclusion assemblage | Filling grade vol % | Size range (µ) | Th (°C) | Tm (°C) | Salinity wt% NaCl
equivalent |
|-----------|----------------|----------------|------------|----------------------------|---------------------|---------------|---------|---------|-------------------------------|
| Mineralized | Coarse quartz | Early | Intragranular | Two phase (L+V) | <10-30 | <2-25 | 63 | 166 | 364 | 275.3 | 40.3 | 66 | -6.9 | -2.8 | -4.3 | 0.8 | 37 | 5.32 | 8.79 | 6.70 | 0.97 |
| MA-BRE3 | Late | Trails, grain boundary, healed fractures | Two phase (L+V) | 11-20 | 2 | 2 | 251 | 268.9 | 259.9 | 12.6 | 2 | -4.7 | -3.5 | -4.1 | 0.84 | 2 | 5.62 | 7.39 | 6.51 | 1.25 |
| Fine quartz | Early | Intragranular | Two phase (L+V) | ≤10-30 | 1-14 | 19 | 178.9 | 329 | 260.4 | 52.8 | 12 | -5 | -1.1 | -3.6 | 1.3 | 12 | 1.82 | 7.82 | 5.77 | 2.07 |
| Ribbon quartz | Early | Intragranular | Two phase (L+V) | ≤10-30 | <4-16 | 26 | 200.2 | 309 | 256.5 | 28.7 | 20 | -5.9 | -3.5 | -4.2 | 0.6 | 18 | 5.62 | 9.05 | 6.77 | 0.92 |
| Barren | Coarse quartz | Early | Intragranular | Two phase (L+V) | ≤10-30 | 4 | 40 | 161.9 | 299.0 | 234.3 | 41.18 | 43 | -5.7 | -0.3 | -3.3 | 1.3 | 39 | 0.50 | 8.79 | 5.2 | 1.9 |
| MA-BU | Late | Trails, grain boundary, healed fractures | Two phase (L+V) | ≤10 | 4 | 6 | 196.1 | 282.7 | 251.7 | 30.7 | 6 | -4.2 | -2.4 | -3.22 | 0.5 | 7 | 3.92 | 6.67 | 5.26 | 0.9 |
| Fine quartz | Early | Intragranular | Two phase (L+V) | ≤10-30 | 2-12 | 19 | 235.6 | 346.6 | 282.9 | 30.22 | 15 | -5.6 | -2.1 | -3.86 | 1.01 | 14 | 1.17 | 8.65 | 5.60 | 2.09 |
| Ribbon quartz | Early | Intragranular | Two phase (L+V) | ≤10-30 | 2-14 | 14 | 245.9 | 330.4 | 283.9 | 22.18 | 26 | -4.9 | -3.1 | -3.86 | 0.55 | 14 | 5.01 | 7.68 | 6.25 | 0.89 |

Th = Total homogenization temperature, Tm = Total ice melting temperature, n = number of fluid inclusions analyzed, min = minimum, max = maximum, ave = average, std = standard deviation.
Gold mineralization in the Mama Shear zone system is associated with brecciated quartz veins (Fig. 2d, e) in steeply dipping brittle-ductile shear zones. Here brecciation is enhanced by transgranular fracturing. The quartz veins breccias show a characteristic stockwork texture with a network of discontinuous and closely spaced fractures that host mineralization. Thus brecciation is a precursor to mineralization as enhanced permeability created during the process of brecciation aid both hydrothermal fluid flow and fluid-rock interaction. As such the breccias act as a matrix for hydrothermal deposits. These

Figure 7. Histograms and XY-scattered plots indicating microthermometric measurements of fluid inclusions in quartz from the Mama vein system eastern Cameroon. The fluid inclusions homogenize into the liquid phase. (a) Frequency histogram for homogenization temperatures (Th) from the Mama mineralized vein system. (b) Frequency histogram for homogenization temperatures (Th) from the Mama barren vein system. (c) Frequency histogram for ice melting (Tm) from the Mama mineralized vein system. (d) Frequency histogram for ice melting (Tm) from the Mama barren vein system. (e, f) Homogenization temperatures and corresponding salinities, from both mineralized and barren vein system.
mineralized breccias are readily amendable to small scale gold mining considering that they are easy to crush.

**Alteration Mineralogy and Gold Precipitation**

The Mama quartz veins contain pyrite, chalcopyrite, covellite and sphalerite as the main sulphide minerals together with abundant haematite, goethite, sericite, carbonate and quartz dominated gangue minerals. The main alteration processes identified within the Mama quartz vein system include: silicification, hematitization, sericitization, carbonitization and sulphidation. It can therefore be classified as a low sulphidation hydrothermal deposit and their formation process is expected to involve a significant proportion of magmatic hydrothermal fluids (Hedenquist and Lowenstern, 1994). Quartz can be divided into three generations, coarse-grained quartz regarded as the first quartz generation and fine-grained to ribbon quartz due to recrystallization resulting from multiple episodes of deformation and fluid circulation. Sericite occurs at the boundary between the vein and the host rock, carbonate as well as sulphides fills vesicles while haematite defines fractures and is altered around the rims to goethite. The formation of sericite in the altered wallrock increases the permeability along the shear zone since sericite enhances permeability and facilitates ductile deformation (Kurz et al., 2000; Oliver, 2001; White, 2001). Quartz from the Mama Shear zone show a stock work texture with haematite filling fractures. This is similar to mineralization reported by Kreuzer (2006) and Chiaradia et al. (2008). Gold occurs as inclusions in haematite. According to Suh et al. (2006) hydrothermal haematite quartz bands offer the best potential for significant gold concentrations. Thus brecciated to stock work haematite-bearing veins in prospective mining sites should be the main target for the local miners since they are the main host of primary mineralization in the eastern region of Cameroon. Quartz from the barren veins is sugary, massive and has a comb texture. According to Kreuzer (2006), massive quartz is deposited during multiple episodes of fracturing and sealing.

EMP-analysis on sulphide reveal gold concentrations that vary from 0.13 to 0.34 wt.% and very low As contents when compared to As of 4.39 wt.% in Carlin type gold deposits (Simon et al., 1999(b)). Gold was precipitated from a sulphide-bearing hydrothermal system with a limited substitution of As for Fe or S in pyrite. This may account for the paucity of arsenopyrite in this gold district when compared to similar mesothermal gold deposits (Genkin et al., 1998). Analyses of gold grains show a Au/Ag ratio of 1.6 with Au contents as high as 60.3 wt.% and a gold fineness of 615. Visible nuggets exist in the Mama gold grains show a Au/Ag ratio of 1.6 with Au contents as high as 60.3 wt.% and a gold fineness of 615. Visible nuggets exist in the Mama shear zone. According to Kreuzer (2006) and Chiaradia et al. (2008). Gold occurs as inclusions in haematite. According to Suh et al. (2006) hydrothermal haematite quartz bands offer the best potential for significant gold concentrations. Thus brecciated to stock work haematite-bearing veins in prospective mining sites should be the main target for the local miners since they are the main host of primary mineralization in the eastern region of Cameroon. Quartz from the barren veins is sugary, massive and has a comb texture. According to Kreuzer (2006), massive quartz is deposited during multiple episodes of fracturing and sealing.

**Geochemical Characterization of the Quartz Veins**

Bulk geochemical analyses on the gold-quartz veins have identified an Au+As+Hg+Zn+Pb+Sb+Mo element association characteristic of low sulphidation gold mineralization. The gold quartz vein system is enriched in base metals such as Cu, Pb and Zn. Similar quartz vein-related deposits have been reported by Zhai et al. (2009) in China although the veins are depleted in base metals. Low sulphidation gold deposits associated with alkaline magmatic rocks, demonstrate a clear involvement of magmatic fluid (Sillitoe, 2002; Sillitoe and Hedenquist, 2003). Magmatic fluids are essential to scavenge Au and Cu from host magmas, promoted by changing oxygen fugacity during magma evolution, as a result of magnetite crystallization (Sun et al., 2004a) or magma degassing (Burgisser and Scaillet, 2007). At upper crustal levels, the ascending magmatic fluids may mix with seawater (Sun et al., 2004a) depending on the tectonic settings. The presence of Hg in association with Au suggests that sulphidation led to the precipitation of gold from a Hg-bearing-fluid. Although gold particles can be recovered from weathered vein systems by chemically reacting with liquid Hg to form gold-mercury amalgam, the presence of Hg within the quartz vein system can result to contamination and this presents a potential risk to human health and the environment. There is need for constant monitoring of these artisanal mining sites for potential natural Hg contamination.

**Temperature Brackets and Fluid Sources for Gold-Related Alterations**

Fluid inclusions characterized in this study are mainly two phase liquid rich inclusions (Roedder, 1984; Van den Kerkhof and Hein, 2001). Fluid inclusion studies have been used widely to constrain the temperature of hydrothermal activity in numerous gold deposits. Microthermometric data of fluid inclusion form the Mama quartz vein system reflect mesothermal temperatures (230 to 330°C) and moderate brine related salinities (4.23 and 9.05 wt.% NaCl_equivalent_cluster). The distribution of mineralization in quartz veins that crosscut granite intrusions may suggest that magmatism played an important role in the dynamics of the mineralizing fluids (Soloviev et al., 2013; Tchameni et al., 2013). The variation in vapour/liquid ratio for all the samples studied from Batouri is suggestive of large fluid pressure fluctuation that often reflects multiple episodes of deformation in quartz veins (e.g. Chi and Xue, 2011). During periods of high fluid pressure, the systems were dominated by a deeply sourced fluid related to magmatic activity.

**Source of Sulfur**

The Mama quartz vein system is hosted by granitic rocks. The δ34S values for this system reflect a single homogenous source. This directly ties with the fluid inclusion data and demonstrates that the granite plutons played an important role to Au deposition in this area. Rather than focus only on the quartz vein system, the aureoles of these plutons can also act as a significant target for the artisanal miners in the Batouri gold mining area.

**Conclusions**

The following conclusions can be drawn from this study:

1. Gold mineralization in the Mama area is constituted by quartz veins cross-cutting granitoids. Three quartz generations have been identified within the vein system. They include coarse-grained quartz (qtz 1), fined-grained quartz (qtz 2) and ribbon quartz (qtz 3). This indicates multiple episodes of brittle and ductile deformation and fluid flow. Sub-micrometer gold particles occur as inclusions in haematite.
Associated ore minerals include covellite, carbonate, sphalerite. Thus the following alteration types are recorded in the mama vein system silicification, sulphidation, sericitization, carbonatization and hematitization.

2. Trace element analysis on the veins reveals the Au+As+Hg+Zn+Pb+Sb+Mo mineral assemblage. This indicates the possibility of low sulphidation Au mineralization in the Batouri gold mining area.

3. Fluid inclusions are generally two phase liquid-rich inclusions. Their analyzes indicate a mesothermal temperature bracket for hydrothermal activity in Batouri. Calculated salinities of the fluid inclusions indicate their origin from brines and magmatic sources and this is confirmed by $\delta^{18}$S values.

4. The features listed above are essential in identifying suitable sites for small scale gold miners in the region. They also form the basis for continued field training in cooperation with governmental agencies involved in raising environmental awareness in these communities.

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