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Full Length Research Article

Application of Morphostructural and Spatial Analyses in Placer-Gold Source Interpretation within Wonaka Schist Belt, Northwestern-Nigeria

***[1]H.M. Grema and [2]W.T. Andongma**
[1]Department of Geology, Usmanu Danfodiyo University, P.M.B 2346 Sokoto Nigeria
[2]Department of Geology, Kano University of Science and Technology, Wudil Nigeria
[*Corresponding Author: Email: haruna.grema@udusok.edu.ng]

ABSTRACT

Morphologic and placer features were used to characterize, determine the provenance, and transport distances of gold grains within the River Gagare drainage basin of the Wonaka Schist Belt. Field studies, scanning electron examination coupled with energy dispersive spectrometry and binocular microscopy were utilized to study the spatial distributions, shape, size, inclusions, primary and fluvial transport-induced deformations, as well as Cailleux flatness indices. The grains are dominantly sub-rounded (71%), with the length between 35 – 800 µm and width of 10 – 778 µm while the rounded grains have a mean length of 292.5 µm and width of 179 µm. Similar values for circularity and sphericity are observed in the sub-rounded grains, with slight variations of 2.7 circularity and 2.6 sphericity distinguished in the rounded grain subset. The Cailleux flatness index range from 2.5 to 9 for sub-rounded grains and 2 – 15.5 for the rounded, indicating the multisource nature of the grains. The grains are consistent with short to moderate transport distances from the lode sources. The similarities in physical features, lack of delicate secondary growth structures and irregular grain outlines point to a detrital source for the placer deposits. Evidence of emulsion crystallisation type is indicated by the presence of sub- to anhedral inclusions within the Au grains.

Keywords: Placer gold, Cailleux flatness indices, Wonaka Schist Belt, Provenance, Northwest Nigeria

INTRODUCTION

Gold (Au) grains have been recovered from stream sediments as early as the Pre-Romans times, providing significant sources of this valuable metal (Kerr *et al.,* 2017; Rivas *et al.,* 2017; Makshakov *et al.,* 2019). These placers result from the liberation of detrital Au grains by weathering and erosion of lode sources that afterwards get deposited in different parts of the fluvial system. The Au grains subsequently undergo physico-chemical evolutions during fluvial transport that grades to flattening, folding, pitting (Leake *et al.,* 1995; Garnett and Bassett, 2005) and other transformations in shape and structures (Youngson and Craw, 1999; Knight *et al.,* 1999; Stewart *et al.,* 2017). The use of these grains' characteristics in tracing primary sources has, however, only been employed in the past 50 years (Cailleux and Tricart, 1959; Dilabio, 1991; Youngson and Craw, 1993, 1995, 1999; Rasmussen *et al.,* 2007; Dill *et al.,* 2009; McClenaghan and Cabri, 2011; Barrios *et al.,* 2015; Vishiti *et al.,* 2015; Alves *et al.,* 2020). However, other minerals may be used with varying successes in detecting Au deposits (as pathfinders). Au grains have been known to be the best indicator mineral for the presence of its economic deposits (Gleeson and Boyle 1980).

Studies of surface characteristics of Au grains provide greater insights to mineralization styles (Potter and Styles 2003; Townley *et al.,* 2003; Chapman *et al.,* 2010; Vishiti *et al.,* 2015; Fuanya *et al,* 2019), growth, dissolution, deformation and in distinguishing grain populations (Leake *et al.,* 1991). These include properties such as shape, roundness, surface texture, mineral inclusions and associations as well as flatness used to describe the morphology of Au grains and for the interpretation of distance to source in fluvial environments (Youngson and Craw, 1999; Knight *et al.,* 1999; Townley *et al.,* 2003; Nakagawa *et al.,* 2005; Chapman and Mortensen 2006; Alves *et al.,* 2020). Newly liberated Au grains have primary textures and are usually irregularly shaped with complex outlines indicative of closeness to the source (Higgins, 2012). As a result of the progressive transformation and separation in stream flow, they become semi-spherical, wafer-shaped, and finally flake-shaped, with rounding being the dominant within the first 10 km of transport (Youngson and Craw, 1999). Their surfaces evolve from smooth and clean to pitted, hackly, and, finally, to lobate-textured, although variations in the stream's composition, energy and sediment type somewhat modify this general trend (Knight *et al.,* (1999); Youngson and Craw, (1999); Youngson *et al.* (2002) and McClenaghan and Cabri (2011). Youngson and Craw (1999) have shown that the Cailleux flatness index, a measure of the mass redistribution a malleable particle undergoes in fluvial systems (Cailleux and Tricart, 1959), ranges from approximately 1 (spherical or cubic) to just over 130 - highly flattened and folded discoid, or elongate/irregularly folded discoid, or sub-spherical/ellipsoidal, for the most far-traveled grains. Based on the data compiled by Youngson and Craw (1999), Au grains with maximum Cailleux flatness values of less than 7 are found in proximal primitive-placer zones and are largely undeformed; having traveled 1 to 10 km from the lode Au source.

Furthermore, grains with maximum Cailleux flatness values of 1 to 3 are found in primary or colluvial sources and have crystalline and delicate morphologies; they in turn have traveled less than 1 km from the lode Au source. Moreover, Knight *et al.,* (1999) reported Au grain roundness and flatness increase rapidly within the first 3 km from the source. After 5 km, the flatness continues to increase slowly while roundness remains essentially unchanged. This makes roundness a sensitive and more reliable estimator for distances less than 5 km while flatness is better at a distance greater than 5 km (McClenaghan and Cabri, 2011). Townley *et al.* (2003) further added that extreme flattening denoted by the folding of the Au grains often serve as an indicator of significant transportation in the fluvial environment. Thus, Dilabio (1991), Knight *et al.* (1999), Youngson and Craw (1999), Townley *et al. (*2003) and McClenaghan and Cabri (2011) concluded that the degree of rounding, flattening, folding, and polishing of the grains provide valuable information about the stream transport system. McClenaghan and Cabri (2011) and Alves *et al.,* 2020) further stated that mechanical abrasion and collision in general control the shape while with time, roundness, smoothing and in-folding protrusion and increase flatness in such transportation medium. Alluvial and eluvial placers as well as primary veins host Au in several parts of the supracrustal (schist) belts in the western half of Nigeria, however, few occurrences are reported outside of these major zones (Garba, 2000; 2003).

Recent addition to these mineralized zones is the occurrence in the Wonaka Schist Belt (Amuda *et al.,* 2013), with Au mineralization essentially hosted along the stretch of the River Gagare drainage basin with extensive but non-uniform, erratic distributions (Geoprobe limited, 2014). These placer occurrences are understudied with no lode sources identified. The type of Au grains; either authigenic or detrital in nature and its crystallinity has also not been determined, nor are the fluvial system transportation deformational features investigated. Thus, this study aims to characterize the placer Au deposit, provide insight on the lode sources, and estimate the distance to sources based on the morphostructures and spatial distribution of the placers.

Regional and Local Geologic Settings

The Wonaka Schist Belt is part of the supracrustal rocks of the Nigerian Basement Complex that also comprise of four major lithological units namely; The Migmatite – Gneiss Complex, the Schist Belt (Metasedimentary and Metavolcanic rocks), the Older Granites (Pan African Granitoids) and Undeformed Acid and Basic Dykes. The Wonaka Schist Belt consists of locally hornfelsic schist, quartz mica schist that seldom contains sillimanite, garnet or cordierite with thin beds of calc-silicate rocks that are widely distributed within (Obaje, 2009; Amuda *et al*., 2013; Oke *et al*., 2014).

The study area comprises of metasediments (quartz-mica schist, phyllite, metasandstone), granitoids (porphyritic granite, and diorite) and granitic gneisses (Figure 1), with aplite, quartz and quartzo-feldspathic veins forming the minor rock occurrences. The placer Au mineralization in the Wonaka Schist Belt occurs predominantly along the stretch of the River Gagare drainage basin with extensive but non-uniform, erratic distribution. Geographically, the Gagare River has its sources in the Precambrian crystalline terrain in Bakori town, Katsina state, and subsequently flow downstream in a northwest direction for over 200 km and joined the Rima River in Sokoto State. On its course, it drains the geologically heterogeneous highlands of the study area and the Wonaka Schist Belt by extension. Although the Gagare is an ephemeral system with flow peaks during the rainy season (May/June to October/November), the drainage density and surface runoff are high on the basement complex rocks of the high plains, and the River and its tributaries carry a large volume of sediments when they flood. On entering the level plains, these rivers lose energy and deposit large amounts of sediment along the plain (Figure 1). Compositionally, it consists of sand, silts and clay and rock fragments of the metasediments.

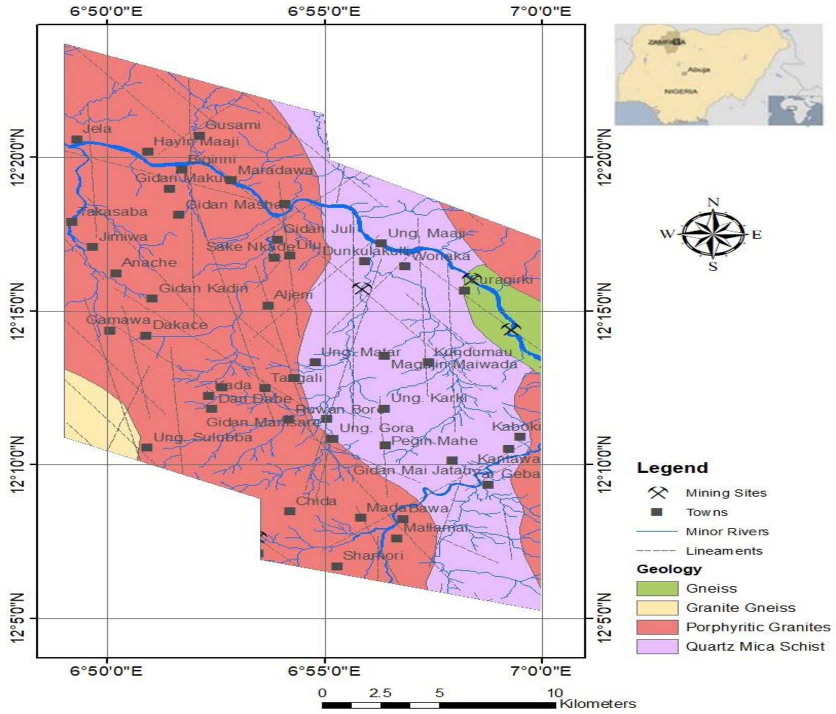

Figure1: Geological map of the study area with inset map of Nigeria showing the location (Grema *et al.,* 2020)

MATERIALS AND METHODS

Sample Collection and Preparation

Field geological mapping and stream sediment survey was undertaken within the River Gagare drainage basin, bounded between Latitude 12º 03' 46"N - 12º 24' 10"N and Longitude 06º 49' 00"E - 07º 00' 32"E (Figure 2), Sheets 54 Gusau (NE and SE). To obtain the Au grains, sixty-seven (67) stream sediment samples were collected from 2nd and 3rd order streams channels and from confluences with a higher order (larger) streams to avoid sampling mixed sediments resulting from flood flow. About 15 kg of representative composited stream sediment samples were collected at the middle of the streams' channel at a depth of 20 – 55 cm at each location - to avoid the thick accumulation of seasonally deposited sands. Spade was used to scope the sample into stainless steel, flat-bottomed conical pan or sample sac. Heavy mineral concentrates were extracted from the collected material by panning – a circular and pendulum motions of the pan within the channel under the water level. This process was repeated until a residue of heavy minerals was obtained. All the sampling sites were located using a Garmin Global Positioning System. At the base camp, the samples were air-dried for a week and repackaged for analysis. The Au grains were handpicked from the heavy mineral concentrates under a binocular microscope, in line with Chapman and Mortensen (2006), with representative grains chosen for detailed studies.

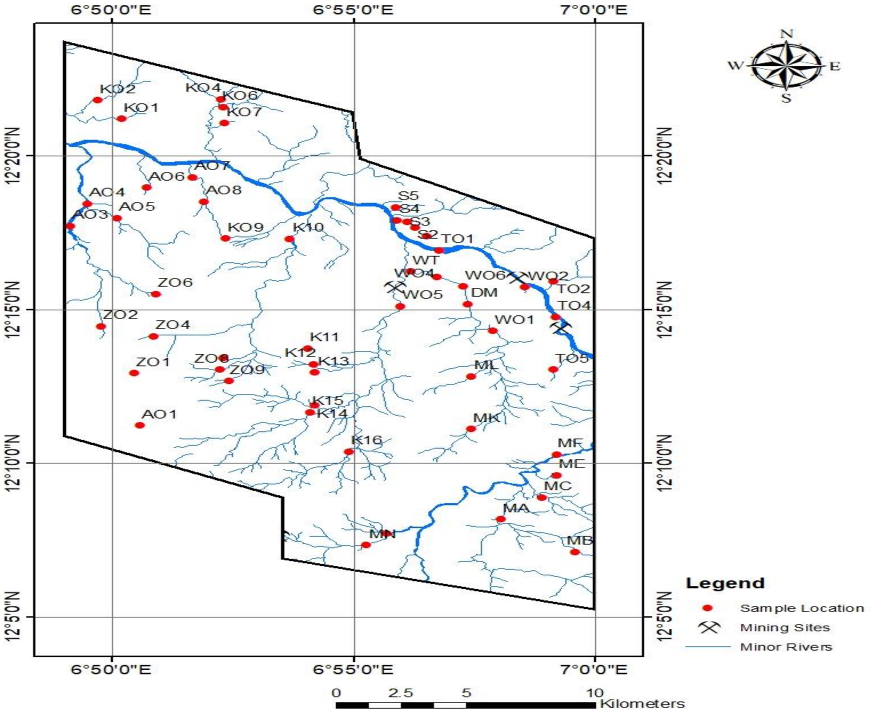

Figure 2: Drainage map of the study location with the sample point distribution.

Morphological and Structural Analyses

The Au grains were subjected to microanalyses using binocular microscopy and Phenom ProX scanning electron microscopy (Back Scattered Electron imaging and spot analyses) coupled with energy dispersive spectroscopy, operated at 10-15 Kv as previously recommended (Youngson and Craw, 1999; Knight *et al.*, 1999; Chapman and Mortensen, 2006; McClenaghan and Cabri, 2011; Vishiti *et al.,* 2015). The techniques allowed for the identification, examination and measurements of morphological characteristics, lengths, width, thickness, outline, shape, inclusions, alteration, as well as fluvial transport features from grain collision, abrasion features, and secondary growth. Qualitative and semi-quantitative determination of the composition of the Au grains were also carried out. ImageJ Java 1.8.0 software was used for the grain dimensional measurements in addition to visual binocular cross-hair utilization with varying zoom levels (Crawford and Mortensen, 2009; Schindelin *et al.,* 2012). Morphological characteristics were clustered according to the degree of modifications (Figure 3), adopted from the grouping of Au grains of Townley *et al*. (2003), Higgins (2012), Vishiti *et al*. (2015) and Barrios *et al., (*2015). Flatness indices calculations follow that of Cailleux and Tricart (1959). Cailleux Flatness Index (CFI) = (a + b) / 2c; (where *a* is length, *b* width and *c* the grains' thickness).

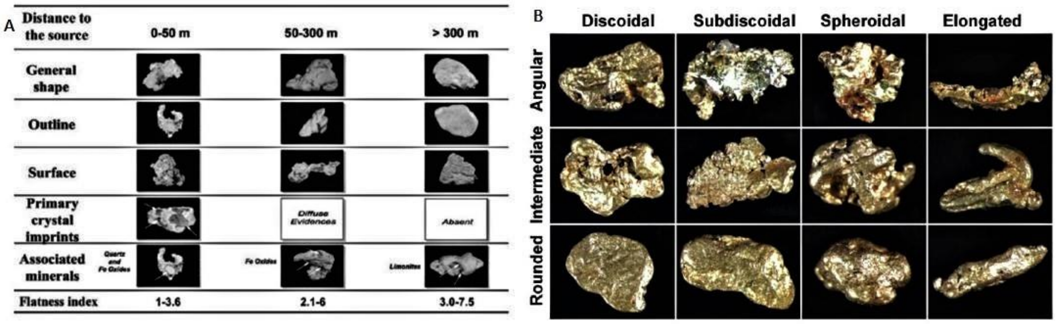

Figure 3: (a) Distance to source morphological characteristics of Au grains (after Townley et al., 2003). (b) Circularity and sphericity Au grain morphotextural chart (after Barrios et al., 2015)

Map Digitization

Study area and distribution maps of parts of Sheet 54 Gusau NE and SE were produced using MapInfo digitizing software (version 11.4) and Global Mapper (version 20.0.0) in this study.

RESULTS AND DISCUSSION

Gold Grain Classification

Six watershed zones (WZ) were delineated (Figure 4), with watershed zones 1, 4, 5 in addition to Rivers Gagare and Kutiri observed to be auriferous and described as.follows:

Watershed Zone 1

This watershed zones cover a total surface area of approximately 25.7Km^2 (Figure 4), occurring mostly in the northern to eastern parts. Gold grains recovered from this zone consist of mostly sub-rounded [Figure 5a] (45.4%) and minor (9.5%) angular types (Figure 6), with the rest being rounded. The sub-rounded grains range from 132 – 750 µm in length (Figure 5a and b) with a width of 93 – 386 µm, while the rounded grains are between 55 – 400 µm and 28 – 199 µm in length and width respectively. Discoidal and elongated (Figure 6a) grains account for most of the grains (both 36.3%), with 18.1 % subdiscoidal (Figure 6b) and 9.3% spheroidal.

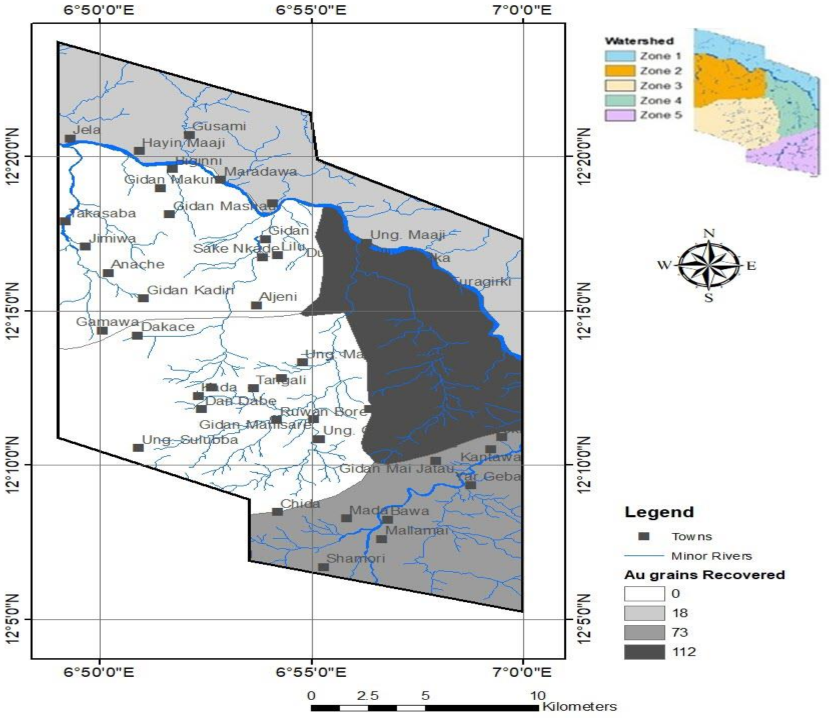

Figure 4: Distributions of the WZ and Au grains counts recovered from each watershed.

Hammered structures (Figure 6c) were observed in 20% of these grains accounting for the only fluvial transport deformational structure in this zone. They have folded edges (Figure 6d) with leached spots that have been filled by concomitant smaller grains. Mean and standard deviation of the circularity (Figure 6) are 2.1 (SD 0.4), 2.6 (SD 0.9) for the sub-rounded and rounded grains (Figures 6e) while the sphericity corresponds to 2.6 (1.5), 2.2 (1.3) for the rounded ones (Figure 5 c and e). Morphological indices (Cailleux flatness indices) for the sub-rounded grains is 4.7 (1.23; Figure 5d) and 3.2(1.1) for the rounded grains (Figures 5d, 6f, 7). Importantly, this zone consists of the highest occurrence of angular Au grains (9.5%), indicating the proximal nature of the grains to the source(s).

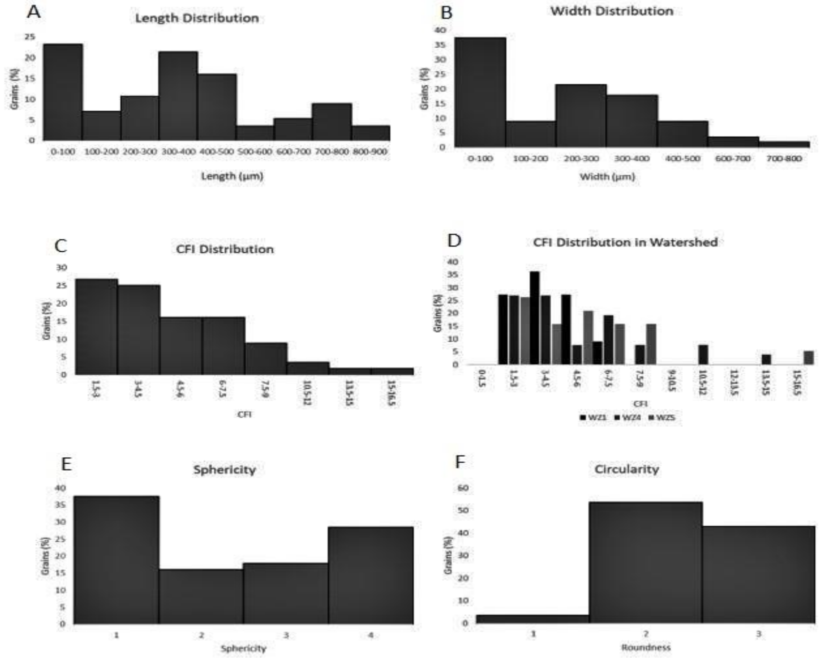

Figure 5: Histograms of Au grain dimensions (length and width); Morphological Cailleux flatness index (CFI). Distributions of Au grain sphericity and circularity in the study area. Sphericity: 1= Discoidal, 2= Subdiscoidal, 3= Spheroidal, 4= Elongated. Circularity: 1= Angular, 3= Sub-rounded, 3= Rounded

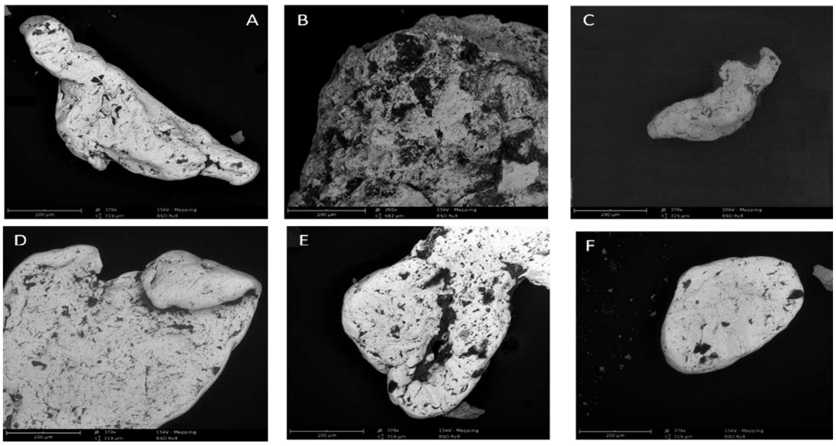

Figure 6: SEM photomicrograph of representative Au grains from watershed 5 (A) elongate, slightly sub-rounded grain. (B) Angular, complex, pitted, and indented grain. (C) Elongate with sub angular and well-rounded quartz and rutile grains. (D) Folded sub-rounded grain. (E) Elongate, rounded grain. (F) Discoidal and rounded.

Distance to Sources Analysis

Gold grains within this zone have equal proportions of discoidal and elongated types, with mean Cailleux flatness index of 4.7 (sub-rounded) and 3.2 (rounded; Figure 7). These, together with the absence of branched pristine type outlined grains coupled with low number of complex grains points to a primitive transitional placer, which is proximal to slightly moderate away from source. These are also similar to those defined by Townley *et al.* (2003) occurring from 300 -1000 m downstream from the source. They often lack mineral inclusions but have regular outlines and display vugs and undulated surfaces, which can further corroborate its short distance of transport.

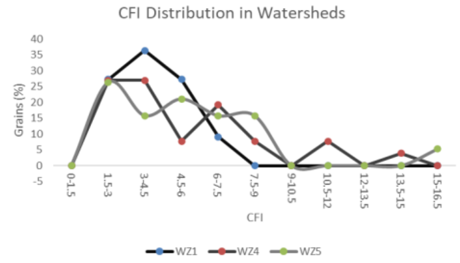

Figure 7: Morphological distribution of Au grain Cailleux flatness indices in the watershed zones. WZ 1= Watershed zone 1, WZ2= Watershed zone 2, WZ3= Watershed zone 3.

Watershed Zone 4

This watershed zone occurs in the mid to eastern part of the study area has a total surface area of 83.34 Km². One hundred and twelve (112) Au grains were recovered from stream sediments extracted within this watershed zone. Sub-rounded grains account for 50% with length ranging from 65 – 800 µm and width of 12 – 480 µm. For the rounded, the Au grains have a minimum length of 40 µm (Figure 6), with maximum reaching 880 accounting for the largest in the study area, characterised by marginally polished and well-rounded edges (Figure 8a). Discoid (34.6%) and spheroidal (30.7%) grain types are dominant with elongated 26.9%, and subdiscoidal 8.7%. Their dominance allows for the mean sphericity of 2.2 (1.2) for the sub-rounded and 3.0 (1.0) for the rounded grains. Evidence of slight folded tips on elongated grains to complete folding have been identified in 35 recovered grains (Figure 8e). Mean Circularity of 2.2 (0.4) and 2.7 (0.7) were determined for the sub-rounded and rounded grains. Groove-like marking (Figure 8b) were observed within 59 of these very grains that are juxtaposed with a fissure that could be leached out inclusion (Figure 8d). The second highest occurrence of angular grains (3.8%) follows the neighbouring watershed zone 1 (Figure 8c). They consist of branched primary shapes characterised by deformational folding with polished surfaces and edges attributed to fluvial transport (Figure 8f). Cailleux flatness index variation of 3 – 14 in the rounded grains account for the most diverse of the whole study area (mean of 7.3 (SD 4.3))

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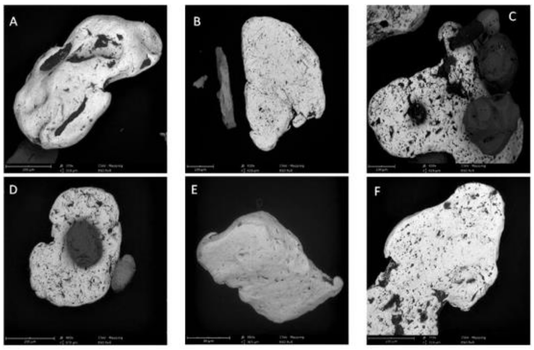

Figure 8: SEM photomicrograph of representative Au grains from watershed zone 4.(A) smoothened subdiscoidal rounded grain with mineral inclusions. Indenting and dissolution features are visible. (B)Rounded subdiscoidal grain.(C)Discoidal angular grain with low-level cavities filled by embedded minerals. (D)Sub-rounded spheroidal grain with indenting quartz grain. (E) Moderately polished and smoothened subdiscoidal grain. (F)Angular discoidal, with a pitted surface.

Distance to Sources Analysis

Gold grains recovered from this zone suggesting moderate to significant transportation from the source. The angular grains suggest short transport distance with the sub-rounded Au grains indicative of short to moderate distance(s). Further distance of >15 Km are suggest for the few smooth, equant and rounded grains with CFI between 9 – 14. This also conform to the fact that Au grains with flattening morphology require a relatively longer transport distance (Vishiti *et al.,* 2015; Alves *et al.,* 2020).

Watershed Zone 5

This zone lies within the North-Western and Western part of the study area having a total surface area of approximately 133.8 Km^2. No angular grains were recovered from this zone, however, the dominance of sub-round (63.1%) over rounded (36.9%) points to multiple sources for the Au grains (Figure 9a, b). The sub-rounded grains have lengths varying between 35 to 800 µm, width of 10 – 778 µm and Cailleux flatness indices of 2.6 - 9. Discoid (42.1%) shapes account for most of the grains with subdiscoidal and elongated grains both 26.3% (Figure 9c). The sphericity of these grains is similar (mean 2.0, SD 1.2) to those from watershed zone 4. The Au grains mostly have pitted surfaces (Figure 9b, d, e, f) appearing irregular, thereby deviating from the relatively smooth surfaces (Figure 9a, c) associated with the sub-rounded grains. Evidence of syngenetic and secondary mineral entrapment during formation and embedded during fluvial transport was observed (Figure 9b, e)

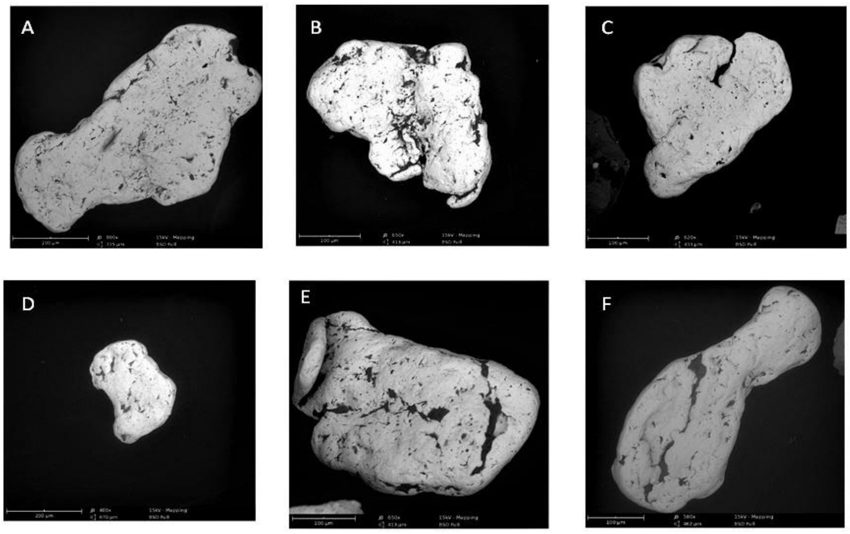

Figure 9: SEM photomicrograph of representative Au grains from watershed 5; (A) sub rounded, subdiscoidal grain. (B) pitted sub-rounded grain that is subdiscoidal and folded. (C) Fissured, rounded spheroidal grain. (D) Rounded spheroidal grain that is smooth, polished. (E) Moderately smoothened, folded, fissured grain. (F) Rounded elongate grain with folded edges and break necks.

Distance to Sources Analysis

A wide range of attributes with respect to results and occurrences were observed for recovered Au grains from these rivers. Few of the Au grains exhibit a high degree of folding, smoothening, and polishing with fewer cavities and fields indicating distal sources. These points to a longer period of transportation hence, appreciable distances from source(s). Lack of occurrence of angular grains, mean Cailleux flatness index of 5.4 (SD 2.2) and circularity of 2.2, indicate multiple sources ranging from proximal to distal.

Origin of the Gagare Basin Alluvial Au mineralization

Gold grains observed in this study lack delicate secondary growth structures such as filaments, and dendrites, with no observable pristine or sharply crystalline grains (Table 1), or indications of grain overgrowths. These attributes alongside the other examined morphological parameters imply detrital and not authigenic primary sources. The presence of mineral inclusions and leaching -related fissures further eliminate the possibility of authigenic Au occurrences within the River Gagare drainage basin (Leon, 1994; McCready *et al*., 2003; Townley *et al.,* 2003; Chapman and Mortensen 2006; Rasmussen *et al*., 2007; McClenaghan and Cabri 2011; Moles *et al*., 2013; Vishiti *et al.,* 2015; Alves *et al.,* 2020). The occurrence of these mineral inclusions as sub- to an-hedral rather than euhedral grains is characteristic of emulsion-type crystallization (crystallizes the same time as the Au), rather than representing surfaces, upon which the Au grains crystallized on. However, the mineral grain could become embedded in the surface of Au grain during transport in a stream and be physically incorporated into the grain as it is deformed on further transport. Nevertheless, such grain can only adhere to the surface of the Au grain but will not be surrounded by it (Potter and Styles, 2003; Alves *et al.,* 2020), and therefore cannot be considered as an inclusion, as observed with the incorporation of materials of variable composition within the grains. Varied polymorphs of minerals have been found incorporated in the Au grains. This degree of complexity reflects multiple sources and is further supported by the 2-point deviations on the Q-Q plot (Figure 10) for the Au within the Gagare streams, however, this does not reflect on different styles of mineralization.

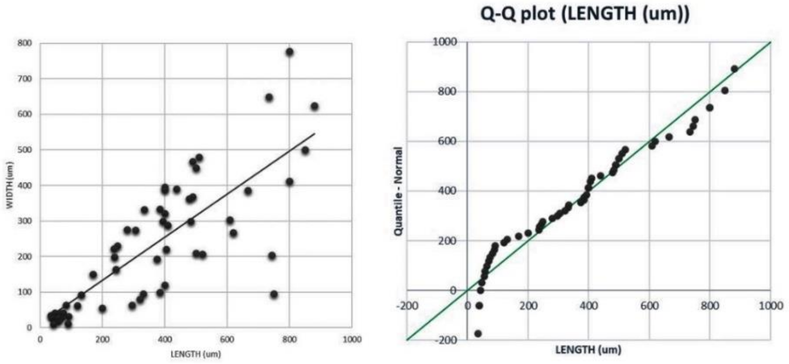

Figure 10: Gold grain major vs minor axis plot for the study area showing the size distribution. Q-Q plot for logarithm of length for the Lognormality assessment of the Au grain

CONCLUSION

This study demonstrated the applicability of morphological and structural characteristics and Cailleux flatness indices of Au grains in deducing possible nature, a distance of fluvial transport and source within stream sediments in the Wonaka Schist Belt. The Au grains of the study area are derived from primary sources (detrital), with the grain sizes typical for Au of Archean granite-greenstone terrains. However, the sources may be more distant than indicated by the ratios of angular to sub-rounded and sub-rounded to rounded grains determined by the morphological characteristics. Due to the statistically small number of Au grains recovered and the lack of primary veins, spatial distribution of the mineralization could not and cannot be fully characterized. Although the lack of occurrence of a single Au grain from all the streams emanating directly from granitoids lower the likelihood of Au occurrences within them or associated quartz and quartzo-feldspathic veins. Intense weathering, overburden and vegetation cover may have contributed in masking of the primary sources in the region. While the interpretations drawn from this study apply to the Au grains of the research area, the validity of the data can be extended to other regions of placer Au mineralization of the Wonaka Schist Belt based on similarities in lithologies, structures, climate and geographic settings.

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