Structural setting and fluid composition of gold mineralization along the central segment of the Keraf suture, Neoproterozoic Nubian Shield, Sudan: implications for the source of gold.

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ABSTRACT

We provide the first large field investigation of more than 20 gold deposits and sites along the Keraf suture zone, covering an area of ~15000 km^2. The area shows diverse structural settings for gold mineralization in greenschist, amphibolite, and hornfels metamorphosed rocks. The reverse fault and dyke-hosted settings appear to be the most favourable for forming gold deposits. Two major N-S-trending, ~300-km-long corridors of deformation are delineated (West and East) but only the West seems important for gold. From fluid inclusions, 6 types of fluids are distinguished based on specific volatile contents and proportions. Most types can be related to fluid evolution by hydrothermal reactions and phase separations from a primitive fluid of metamorphic origin, containing H_2O, CO_2, N_2, CH_4, C_2H_6, and H_2. Regional hydrothermal fields are identified based on the combinations of structural settings and fluid types. The northern field is defined as a single large hydrothermal system accounting for the mineralization of the 3 gold deposits (WG-03, UTM and Central). For sites along the West Corridor, such as Toubi, Anas, NW and Shereik, multiple and overlapping hydrothermal systems are necessary to explain the various fluid types and structural settings, even at the deposit scale (Shereik). Conversely, other sites (SW, Yasmine, Korup, Saijd, Dardora, Negeim, and SE) formed by localized

individual hydrothermal systems. The documentation of fluids containing ethane at numerous sites and deposits is the most significant outcome. Such ethane-bearing fluids are generated by the metamorphism of carbonaceous-pyritic sedimentary rocks. These rocks are considered one of the best sources for providing ligands and gold for the formation of orogenic gold deposits. Consequently, the Keraf suture zone, composed mainly of carbonaceous turbidites, is interpreted to have provided such source rocks in the suture zone and below the adjacent cratons during the collision, forming orogenic gold deposits (graphical abstract).

Keywords: Orogenic Gold Deposits, Sudan, Keraf Shear Zone, Gold Source, Ethane, Solid Probe Mass Spectrometry, Neoproterozoic, Structural Setting

1. INTRODUCTION

The Neoproterozoic Nubian Shield in northern Sudan is an important artisanal gold production area. In 2019, Sudan produced between 120 and 200 tons (3.6 to 6.0 Moz) of gold according to the Sudanese government with approximately 5 million workers in the mining sector (Asharq Al-Awsat journal: 15th December 2019). Gold in the northern part of Sudan has been mined since the Pharaonic period approximately 6000 years ago (Klemm et al., 2001; Klemm and Klemm, 2013). Sudan is ranked third in gold production for Africa behind South Africa and Ghana.

Although Sudan has a substantial gold endowment and history of Au production, modern studies of gold deposits, with rare exceptions (e.g., Almond et al., 1984; Cheng et al., 2017; Adam et al., 2020; Perret et al., 2020), are lacking due mostly to political instability, sanctions and embargos that have restricted physical access in recent decades (Trench and Groves, 2015). In contrast, hundreds of studies on gold deposits have been published for the northern extension of the Nubian Shield in Egypt (e.g., Botros, 2004; 2004; Zoheir, 2008; Abu-Alam et al., 2018; El Aref et al., 2020;). The Sukari mine (Helmy et al., 2004) in the Nubian Shield of Egypt, a 500,000 oz per year gold mine, is one of the world's top-10 gold deposits (Jamasmie, 2020). In Sudan, commercial gold mining is presently restricted to the Gabgaba operation by Manum, a subsidiary of the

Moroccan mining group MANAGEM. The Hassai gold mine, the first commercial gold mine in Sudan, which produced gold from oxidized massive sulphide lenses (Barrie et al., 2016), closed in 2014 after 21 years of production. Other significant gold deposits, such as the Galat Sufar and nearby Wadi Doum deposits (Orca Gold), are at the development stage. Another major limitation is the lack of reliable modern tectonostratigraphic geological maps, although the rocks are generally well exposed in the desert.

The Neoproterozoic marks the reappearance of orogenic gold deposits, which were mostly absent from 1800 to 800 Ma (Goldfarb et al., 2010; Tomkins, 2013a; Large et al., 2015). This lack is interpreted as a consequence of the oxidation state of the oceans (Tomkins, 2013a), where the gold in solution was at lower levels during this 1000 My period (Large et al., 2015). Gold from sedimentary rocks, especially from carbonaceous pyritic shales, has recently been considered the most important source for the formation of orogenic gold deposits (Pitcairn et al., 2010; Large et al., 2011; Gaboury, 2013; Tomkins, 2013a; Gaboury, 2019), but still remain debated for some deposits and districts (Goldfarb and Groves, 2015; Wyman et al., 2016; Groves et al., 2020). The Nubian Shield is thus an extraordinary natural laboratory to test whether gold deposits share the same characteristics and the same sources of fluids and gold as older (Neoarchaean and Palaeoproterozoic) and younger (Palaeozoic) deposits (Gaboury, 2013).

In this paper, we describe the structural settings and styles of gold mineralization occurring along the central segment of the Keraf suture, a major regional Neoproterozoic suture zone. More than 20 sites have been investigated for deciphering the gold mineralization contexts in an area of approximately 15 000 km^2. Google Earth and Landsat 8 images have been used to interpret structural features and to decipher regional corridors with higher potential for gold exploration. Fluid inclusions and their volatile contents have been studied to document the composition of the mineralizing fluids and to provide further constraints for the genetic model. Numerous orogenic mineralizing systems are recorded within and proximal to the Keraf structure. Most of them are related to metamorphic fluids generated by dehydration of deeper carbonaceous sedimentary

rocks, recognized as the most favourable sources for forming gold deposits (Gaboury, 2019).

2. GEOLOGICAL SETTING

The Arabian–Nubian Shield (ANS - Fig. 1) is an accretionary shield related to the Pan-African orogeny that formed during convergence between East and West Gondwana from ~900 to 500 Ma (e.g., El-Gaby et al., 1988; Pohl, 1988; Stern et al., 1990; Stern 1994; Stern and Johnson, 2010; Johnson et al., 2011; Merdith et al., 2017). The ANS is composed mainly of juvenile crustal material (Greenwood et al., 1980; Kröner et al., 1987; 1992) from structurally complex assemblages of island arc, back-arc and ophiolitic rocks (e.g., Teklay et al., 1998; Yibas et al., 2002; Johnson and Woldehaimanot, 2003; Stern et al., 2004). The ages of the volcanic rocks and related intrusions range from 900 Ma to 600 Ma. Deformation, metamorphism and accretion occurred between 850 Ma and 500 Ma, with a peak of metamorphism and shearing occurring between 650 and 500 Ma (Johnson et al., 2011, Fritz et al., 2013). The ANS has been segmented by the opening of the Red Sea, which separates the Nubian Shield to the west from the Arabian Shield to the east (Fig. 1). The ANS hosts numerous orogenic gold and volcanogenic massive sulphide deposits (e.g., Almond et al., 1984; Botros 2002; Tadesse et al., 2003; Ghebreab et al., 2009; Johnson et al., 2017). The ANS is considered the Earth's largest gold resource of the Neoproterozoic (Johnson et al., 2017).

3. THE KERAF SUTURE ZONE

The Keraf suture zone is an ~500 km-long and ~50 to 100 km-wide N-trending continental arc suture (Almond and Ahmed, 1987; Stern, 1994; Abdelsalam et al., 1995, Abdelsalam and Stern, 1996a; Abdelsalam et al., 1998; Bailo et al., 2003) between the Neoproterozoic ANS in the east and the older East Sahara Craton to the west (Fig. 1), which formed during the Neoproterozoic consolidation of Gondwana. Its interpretation as a major suture zone is relatively recent: it was first recognized by Almond and Ahmed (1987). The high-grade gneissic terrane to the west, referred to here as the Saharan Metacraton (Abdelsalam et al., 2002; 2003), is considered pre-Neoproterozoic. It is also referred to as the Nile Craton (Rocci, 1965), the Eastern Saharan Craton (Bertrand and

123 Caby, 1978), the Sahara-Congo Craton (Kröner, 1977) and the East Sahara Ghost Craton
124 (Black and Liegeois, 1993, Evuk et al., 2014; Karmakar and Schenk, 2015).
125
126 As a suture zone, Keraf is a complex belt in terms of lithologies, deformation,
127 metamorphic history and intrusive events, with variations from north to south.
128 Consequently, the physical limits of the Keraf zone are not definitive, as no authors
129 provide the same boundary and shape on their maps (e.g., Abdelsalam and Stern 1996b;
130 Bailo et al., 2003; Evuk et al., 2014; Karmakar and Schenk, 2015). As this suture zone is
131 overprinted by a late sinistral movement, it is referred to in the literature as the Keraf
132 shear zone (KSZ: Abdelsalam et al., 1995, 1998; Abdelsalam and Stern, 1996a; 1996b;
133 Abdelsalam et al., 2003). In the study area, rocks are dominated by greenschist to
134 amphibolite siliciclastic and carbonate-rich metasedimentary rocks (turbidites)
135 intercalated with sills of metabasalt and microdiorite and some pillow basaltic lavas, with
136 lesser basement windows of high- to intermediate-grade gneisses, ophiolitic nappes and
137 molasse-type sedimentary rocks cut by various types of syn- to post-tectonic intrusions
138 (Bailo et al., 2003). Bailo (2000) concluded that high-grade metamorphism occurred at
139 ~730 Ma, whereas post-tectonic plutons were emplaced as early as 710 Ma with the last
140 thermal event at 560 Ma. More recent ages for the plutonic rocks indicate that alkaline
141 magmatism occurred between 605 and 591 Ma and that later cooling continued up to 555
142 Ma (Evuk et al., 2014).
143
144 In the KSZ area, 6 deformational phases (D_1 to D_6) associated with 2 major tectonic
145 events were identified by Abdelsalam et al. (1998). D_1 and D_2 are related to the
146 emplacement of SSE-verging ophiolitic nappes due to collision between ENE-trending
147 terranes at 800-700 Ma. The E-trending Atmur-Delgo suture is the D_1-D_2 manifestation
148 and is related to the closure of an oceanic basin at approximately 750-650 Ma (Harms et
149 al., 1994; Schandelmeier et al., 1994; Abdelsalam et al., 1998, 2003). The younger
150 deformations D_3 to D_6 reflect shortening across the KSZ (Abdelsalaman et al., 1998).
151 Specifically, D_3 produced N-trending, upright, isoclinal to open folds. D_4 corresponds to
152 coaxial W-verging tight folds superimposed on D_3. D_5 refolded older structures about
153 steeply, E- to ENE-plunging fold axes. Finally, D_6 is manifested by the development of

local NE-trending dextral and NW-trending sinistral shear zones. The KSZ is thus superimposed on E- and NE-trending D_1-D_2-related suture zones occurring on both sides (Fig. 1), such as the Atmur-Delgo suture to the west and the Nakasib suture to the east (Abdelsalam et al., 1995). Abdelsalam et al. (1995, 1996) proposed that the deformation in the KSZ was due to sinistral transpression associated with oblique collision between East and West Gondwana. The $^{40}Ar/^{39}Ar$ ages on biotite and hornblende separated from a deformed granitic body indicate that the last sinistral movement along the N- and NNW-trending faults took place at 580 Ma (Abdelsalam et al., 1998). According to Evuk et al. (2014), post-collisional horizontal movement along the southern KSZ was probably restricted to a narrow zone and occurred between 630 and 590 Ma. Therefore, the sinistral transpression started at approximately 650 Ma with a terminal collision at approximately 580 Ma.

4. METHODOLOGY

More than 20 gold-bearing sites and deposits, distributed in an area of 250 km (NW-SE) by 100 km (SW-NE) in northern Sudan, were mapped for this study (Fig. 2). Gold mineralization zones were systematically exposed by artisanal mining or by commercial operation. The objective was to interpret the genetic types of these sites by characterizing them in terms of the: 1) host rocks; 2) metamorphic facies; 3) hydrothermal alteration; 4) structural setting; and 5) factors controlling gold mineralization. For each site, these parameters were determined as far as possible, and the major structural features were measured (Supp. Table SM1). The metamorphic facies were established based on the occurrence of key minerals in host rocks, such as chlorite, biotite and amphibole, from outcrops and thin sections. The schistosity nomenclature is as follows: S_1 is the first fabric at the outcrop scale, commonly occurring as a weakly penetrative schistosity. Crosscutting fabrics, named S_2 generally occur as shear zones hosting gold mineralization. However, S_1 and S_2 fabrics are not necessarily correlative at the regional scale, as each site is mapped according to its structural features. Planar features are reported using the right-hand rule (strike/dip).

Google Earth and Landsat 8 satellite images were used to visualize the regional structural features because a regional tectonic map is lacking and because the KSZ limits are not well constrained (Fig. 2). The public Google Earth images have very high resolution, and because there is no vegetation, outcrop features can be interpreted easily where sand cover is thin. Lineaments are defined from: 1) alignment of strata; and 2) crosscutting of strata. In the first case, lineaments define stratification and in the second case, structural features. On the other hand, circular structures are common, clearly defining plutons. Plutons are identified by: 1) the bulging of the strata around the circular edges; 2) metamorphism in the hornfels facies, which has indurated the rocks and accounts for the positive and dark-coloured relief; and 3) strata and foliation interrupted by circular structures. Subsequently, these structures are validated and plotted precisely with the Landsat 8 satellite image using MapInfo (Fig. 2).

In addition, 59 samples of gold-bearing quartz veins from all the sites and deposits were collected for fluid inclusion gas analyses according to the method of Gaboury et al. (2008) and Gaboury (2013). The analyses were performed at the Laboratoire de métallogénie expérimentale et quantitative (LAMEQ) of the University of Quebec at Chicoutimi, Canada (UQAC). Fluid inclusions in pure quartz samples of ~10 mg were analysed by solid probe mass spectrometry using Stanford Research System RGA100 residual gas analyser (California, USA) with an electron multiplier. Ten volatiles (H_2O, CO_2, N_2, C_2H_6, He, Ar, CH_4, SO_2, H_2S and H_2) were monitored in real-time during progressive heating (6°C/min) up to 500°C of samples under vacuum. The raw data were converted to quantitative values by background signal subtraction and correction for mass interference (N_2 and CH_4). The abundance of each volatile was calculated based on internal calibration parameters from the RGA100 software. Since fluid inclusion decrepitations induce small pressure bursts manifested by a sawtooth signal above the background, any contamination from air and other substances can be easily detected. All samples were analysed at least in duplicate to ensure representativeness of the released gas signal, as the fluid inclusions are not homogeneously distributed in natural samples. Petrographic examination of fluid inclusions was performed on 22 selected samples to characterize the fluid inclusion assemblages and to look for daughter minerals, such as

215 halite. The selection of samples for petrographic examination was based on the release of
216 a significant quantity of gas from fluid inclusion decrepitation following the solid probe
217 mass spectrometry analysis. The selection covers all the studied gold-bearing sites.
218
219 **5. REGIONAL STRUCTURAL FEATURES**
220 The interpretative tectonic map (Fig. 2) highlights two large N-S corridors defined based
221 on the alignment of lineament segments (Fig. 2) and the limits of the KSZ (Fig. 1). They
222 are referred to as the West Corridor and East Corridor. The West Corridor includes the
223 Central C02-C04 and UTM deposits and the Toubi, Shereik, Anas and NW sites (Fig. 2).
224 It thus appears to be an important corridor of deformation more than 250 km in length
225 and hosts numerous mineralized gold sites and deposits. The curved form of the corridor
226 (Fig. 2) comes from the moulding around a voluminous intrusive body according to the
227 geological map (Geological Research Authority of the Sudan, 1988 – 1/1 000 000). The
228 West Corridor corresponds to the KSZ western limit, as defined by Abdelsalam et al.
229 (1998). The East Corridor includes the SW and Yasmine mineralized sites (Fig. 2).
230 According to this interpretation, the East Corridor is continuous for approximately 300
231 km. In addition to major corridors, numerous intrusive bodies, mostly sub-circular, are
232 also delineated, ranging in size from 2 to 25 km (Fig. 2). Some of these have previously
233 been mapped and documented (e.g., Bailo et al., 2003), but most of them are newly
234 identified intrusive features.
235
236 **6. GOLD DEPOSIT STYLES AND SETTINGS**
237 Three gold deposits in the Gabgaba area, WG-03, UTM and Central, have mineral
238 resources and are studied in more detail (Supp. Table SM1; Fig. 2). WG-03 is a
239 complicated structurally-controlled gold deposit hosted in an amphibolite-facies gabbroic
240 complex (Gaboury, 2015). Gold occurs in: 1) early reverse E-W-trending shallow north-
241 dipping S_1 shear zones manifested by amphibole foliation (Fig. 3A-B); 2) N-S-trending
242 reverse sub-vertical S_2 shear zones manifested by biotite schistosity (Fig. 3B-C); and 3)
243 late centimetric extensional quartz veins oriented E-W and dipping moderately north
244 (Fig. 3D). These later veins also occur in S_1 and S_2 shear zones. The WG-03 deposit is

hosted close to the E-trending Atmur-Delgo suture, ~30 km from the N-trending KSZ (Fig. 2).

The Central deposit includes zones C02 and C04, which are felsic dykes hosting gold-bearing quartz veins (Gaboury, 2014). The felsic dykes, with thicknesses up to 15 m, are oriented ~N-S with a steep dip to the E (Supp. Table SM1; Fig. 3E) and may be followed for kilometres. They cut across vertical sedimentary sequences of greywacke and shales having an axial planar S_1 greenschist-facies fabric (Fig. 3E). Reverse S_2 shear zones are recorded at dyke contacts, and sub-horizontal extensional quartz veins are developed in the competent dykes (Fig. 3E). Dykes and their host rocks record very strong iron-carbonate hydrothermal alteration.

The UTM deposit, the only deposit in commercial production, corresponds to a N-S-trending shallow E-dipping quartz vein system hosted in a S_2 reverse shear zone (Supp. Table SM1; Fig. 3F), as indicated by CS fabrics and downdip stretching lineations (Gaboury, 2014). Mineralization, as fault-fill quartz veins with metric thickness, may be traced for kilometres and is developed at the contact between a large dioritic intrusion and volcanic rocks in the greenschist facies. Iron carbonates and haematite dusting (Fig. 3F) are the main hydrothermal alterations.

7. STYLES AND SETTING OF THE GOLD-BEARING SITES

The different sites are grouped below according to the kinematics of the mineralized structures (Fig. 4). This approach allows grouping of mineralization styles to better define their economic potential based on geometry and lateral and vertical continuities. All gold mineralization occurs as quartz veins and veinlets with very low sulphide contents (<1%) and traces of muscovite (large crystals), white micas of clay size referred as sericite, biotite, chlorite and carbonate minerals (Supp. Table SM2; Fig. SM1). In some cases, gold is associated to the dissemination of sulphide minerals in the wall rocks.

7.1. Reverse shearing

Gold mineralization associated with reverse shearing is the most common structural setting in the study area (Fig. 4). Mineralization occurs as fault-fill quartz veins occupying the C plane of reverse shear zones (Fig. 5A) developed along geological contacts (Fig. 5B) or dykes (Fig. 5C). These veins commonly show pinch and swell geometry in cross-section and plan views, but they correspond to the veins reaching the largest thicknesses locally (Fig. 5D). These structures show lateral extensions up to 700 m (Negeim). Iron carbonates are the main hydrothermal alteration. Mineralization is hosted in S_2 high-strain zones cutting across already deformed rocks. Examples include the Negeim, Yasmine West, Shereik-99 and NW sites (Supp. Table SM1).

The special case of Shereik-118, which will be a future commercial operation, is noteworthy. In this specific case, the mineralization is associated with a reverse shear zone, manifested by the folding of S_1 foliation (Fig. 5E). It is a ~20 m thick zone of intense deformation dipping shallowly towards the west mainly (Supp. Table SM1). The alteration envelope is auriferous, and the quartz and iron carbonate veins occupy the hinges of centimetric to metric folds in the shear envelope (Fig. 5E).

Mineralization at WG-14 is also included in this group (Supp. Table SM1). The veins are essentially hosted along an E-W-trending, shallow N-dipping S_1 high-strain zone with a 2-5-metre thickness (Fig. 5F). Although no kinematic indicator is observed, the geometry of the veins is compatible with a compressional tectonic regime having a vertically oriented σ_3 stress field.

7.2. Strike-slip movement

The gold mineralization associated with strike-slip shearing (Fig. 4), irrespective of sense of movement (dextral or sinistral), is expressed by sub-vertical quartz veins. Veins are thin (<30 cm) but have constant thickness with exceptional (> 1 km) lateral continuity. Overall, hydrothermal alteration is very weak. The controlling factors correspond to 1) mostly dyke contacts (Fig. 6A), 2) lithostratigraphic contacts (Fig. 6B), and 3) bands of volcanic-sedimentary rocks (Fig. 6C). The veins are hosted in S_2 high-strain zones where the intensity of deformation is typically low. It is common, especially in the volcanic-

sedimentary bands, to observe the S_2 trajectory deflection zone in plan view. In these cases, the quartz veins are best developed as dilatant jogs within the deflections, which are compatible with a strike-slip movement for providing dilation. The mineralization is commonly developed as a family of parallel quartz veins. However, the spacing between the veins is generally large (> 30 m). Some sites remain unclassified in terms of movement sense, but they have all the attributes to classify them as strike-slip movements (Supp. Table SM1). The Yasmine Principal is such a case, where a narrow quartz vein is tracked over > 1 km along a dyke contact within a granitoid (Supp. Table SM1).

7.2.1. Dextral shearing

The SW sector (SW-1 and SW-2: Supp. Table SM1; Fig. 4) is a typical example of dextral shearing. Numerous dykes of various compositions are intruded N-S and vertically into an already deformed volcanic-sedimentary sequence (Fig. 6A). The dykes cut across the S_1 fabric. The contacts of the dykes serve as S_2 shearing C planes along which the veins are developed. Locally, the S fabric is developed in the dykes (Fig. 6D), forming a CS relationship that confirms their dextral kinematics.

In the NW sector (Supp. Table SM1; Fig. 4), some stations expose a thin sub-vertical quartz vein that appears to be better developed in the S_2 deflection compatible with a dextral movement. The hydrothermal alteration of the wall rocks is characterized by gold-bearing biotite, as indicated by its recovery by artisanal miners.

The Korup sector is characterized by two steeply dipping NW-SE gold-bearing S_2 high-strain zones (Supp. Table SM1) spaced 30 m apart. One is developed along a volcano-sedimentary horizon between massive mafic volcanic rocks (Fig. 6C). Sub-horizontal stretching lineations imply a strike-slip movement. The second deformation zone corresponds to an envelope of iron carbonates up to 5 m thick. Sub-vertical extensional quartz veins oblique to the deformation zone and a main quartz vein parallel to the carbonate envelope are developed. The geometry of the quartz vein system is coherent with a dextral movement.

7.2.2. Sinistral shearing

The Dardora principal sector (Supp. Table SM1; Fig. 4) exposes all the typical characteristics of gold mineralization associated with strike-slip movement. The mineralization is associated with whitish quartz veins oriented N-S with sub-vertical dips. Several parallel veins, spaced at least 20 m apart, are mined by artisans along a maximum length of 300 m. N-S felsic dykes control the locations of veins within andesites. Along the contacts between dykes and andesite, S_2 deformation zones ~1 m thick show a schistosity parallel to the contacts with parallel veinlets of whitish cherty quartz <3 cm thick. The only structural element for kinematic evaluation is a mined quartz vein oriented at 130/90 oblique to the main N-S trend. Assuming that it was formed during extension along the axis of the main NW-SE stress ($\sigma 1$), the movement along N-S dykes would then have been sinistral. Similarly, deflection from N-S to NW are developed along the lengths of the veins and are also compatible with a sinistral movement.

The Sajid sector is also interpreted as related to sinistral shearing (Supp. Table SM1). The N-S trending sub-vertical quartz veins are developed in S_2 shear zones along lithological contacts in the host sequence and some dykes. An extensional sub-vertical gold-bearing vein oriented oblique to the N-S trending vein system is used as the $\sigma 1$ stress field indicator for establishing the direction of movement (Fig. 6B).

7.3. Normal Shearing

Two cases of normal shearing are specifically documented, in addition to the late gold-bearing quartz veins at the WG-03 deposit. These are the northern stations of the NW and Shereik-118 sectors (Supp. Table SM1; Fig. 4). In the first case, CS fabrics and retrograde chloritization indicate normal movement (Fig. 6E) developed along the contact between massive mafic volcanic and volcano-sedimentary rocks. The mineralization occurs as quartz veins in a <2 m-thick shear zone. The lateral continuity of the quartz veins appears weak. For the Shereik-118 sector, the dragging of S_1 fabric at the edge of the S_2 shear zone is used to establish the movement (Supp. Table SM1; Fig. 6F). The mineralization takes the form of spaced (50-100 m) parallel extensional quartz veins with constant thicknesses and lateral continuities over 100 m.

7.4. Mineralized dykes

This style of mineralization occurs as quartz veinlets and disseminated pyrite hosted within voluminous intrusive bodies mostly occurring as dykes. These deposits are similar to the mineralization of zones C02 and C04 in the Central gold deposit (Supp. Table SM1). Hydrothermal alteration is manifested by iron carbonates and reddish haematite dusting. The ore potential lies in the combination of the following parameters: 1) the dimension of the exposed intrusive body and its continuity; 2) the intensity and diversity of the quartz veinlets within the intrusive rocks; 3) the intensity of the iron carbonate alteration; and 4) the presence of disseminated pyrite. From these criteria, Anas and SE are the most significant sectors for this type of mineralization (Supp. Table SM1; Fig. 4). This style of mineralization also occurs together with other styles in these specific sectors: Shereik-118, Shereik-116, Toubi and NW (Supp. Table SM1; Fig. 4).

8. HYDROTHERMAL ALTERATION AND METAMORPHIC FACIES

The most common type of hydrothermal alteration is iron carbonates developed within rocks in the greenschist facies (Supp. Table SM1; Figs. 3F, 5E-F). Sericite is locally developed in quartz vein margins at the UTM and Central deposits. In the amphibolite facies, biotite is the dominant mineral. Chlorite is locally developed at the margins of quartz veins hosted in normal shear zones. Haematite dusting is common in intrusive rocks hosting gold-bearing veinlets, such as Toubi, Dardora and SE (Supp. Table SM1, Fig. SM2A-B), but this feature may be also related to surface oxidation. Aluminous hydrothermal alteration, manifested by sillimanite and locally garnet, is developed in mafic volcanic rocks in the Shereik area (Supp. Table SM1, Fig. SM2C-D). The penetrative regional S_1 foliation at amphibolite facies is expressed by the alignment of this mineral. This alteration is not related to gold mineralization and could be the result of metamorphic overprint of volcanogenic-related hydrothermal alteration (Dusel-Bacon, 2012).

9. MINERALIZING FLUIDS

Fluid inclusions are the only direct witnesses of fluids involved in the formation of hydrothermal deposits. For structurally controlled quartz-vein type gold deposits, and especially orogenic gold deposits, multiple events are recorded by veins from repeated fracturing and quartz precipitation (e.g., Boullier and Robert, 1992; Robert et al., 1995) and even post-mineralization fluid overprint (e.g., Kerrich, 1976). Fluid inclusions can also be physically modified (necked inclusions) over time (e.g., Tarantola et al., 2012). It is thus fundamental, when studying fluid inclusions, to determine their genetic link with gold (e.g., Wilkinson, 2001; Goldfarb and Groves 2015). Since our study is aimed at providing regional characteristics, bulk volatile analysis of fluid inclusions by solid-probe is considered the best approach for comparing deposits and providing constraints for genetic interpretation (Guha et al., 1990). Rather than trying to link specific fluid inclusions to the gold event, which may be impossible in most cases, the bulk gas analysis provides an average proportion of specific gas from all the fluid inclusions. This approach is also possible because numerous studies established a relatively consistent ore-forming fluid through geological time (e.g., Garofalo et al., 2014; Abu-Alam et al., 2018; Prokofiev and Naumov, 2020) that can be used for comparison and validation of the bulk gas analyses. The petrographic documentation is also needed to support the interpretation that gas is released from fluid inclusion assemblages expected from vein-type gold deposits.

At a larger-scale, the direct link between gold and the analysed fluid inclusions remains the weakness of any study because gold occurs at trace concentrations with an inherent erratic distribution (nugget effect). To overcome this, quartz samples were only taken from active stopes in artisanal operations, and in zones with gold grades for deposits at exploration stage or in commercial operation. It is thus considered than the analysed samples are representative of gold mineralization.

The representativeness of samples is also a major issue for any regional study and especially for characterizing fluids in gold deposits. Between 2 and 6 samples were used to document fluids from the various sites, depending on their known significance. As stated by Ramsey and Hewitt (2005): “a representative sample is one that answers a

question about a population with a certain confidence." In that sense, establishing fluid types based on the bulk volatile compositions, even from a limited number of samples, is considered the most representative method for addressing the fluid source and fluid evolution at the regional-scale.

9.1. Fluid inclusion gas compositions

Six fluid types can be distinguished based on the contents of specific volatiles in fluid inclusions and their relative proportions (Table 1, Supp. Table SM3, Fig. 7A).

Type 1 (n=19: number of samples) is aqueous-carbonic fluid, dominated by water, with a complex signature including H_2O, CO_2, N_2, CH_4, C_2H_6 and $\pm H_2$. The compositional ranges are as follows (Fig. 7B): H_2O (60.3 – 95.8%), CO_2 (2.1 – 29.4%), N_2 (0.8 – 11.8%), CH_4 (0 – 6.5%), C_2H_6 (0.3 – 2.7%) and $\pm H_2$ (0 – 1.5%). This fluid type is the most common and is present in gold deposits at WG-03, Central, UTM and the sites at Shereik, Saijd, Korup, Yasmine, Toubi and WG-14 (Fig. 7A).

Type 2 (n=4) fluids are similar to type 1 (Fig. 7) with ethane content but significantly less water, having a complex signature with CO_2, N_2, CH_4, C_2H_6 and $\pm H_2$, Ar and H_2S (Fig. 7A). The water proportion is below 50% (0 – 49.7%), with CO_2 (0 – 35.3%), N_2 (7.2 – 52.9%), CH_4 (2.6 – 30.6%), C_2H_6 (1.0 – 4.4%), H_2 (0 – 0.7%), Ar (0.17%) and H_2S (0.4%) (Fig. 7B). This particular fluid type is present at NW, Dardora, Sajid and Korup.

Type 3 (n=6) is an aqueous-carbonic fluid similar to type 1 (Fig. 7), dominated by water but without ethane, with proportions of H_2O (70.5 – 96.6%), CO_2 (0.4 – 15.0%), N_2 (1.2 – 10.4%), CH_4 (0.4 – 7.6%) and $\pm H_2$ (0 – 1.9%). This type of fluid is documented at WG-03 deposit and the sites at Shereik, Yasmine and WG-14 (Fig. 7A).

Type 4 (n=13) is an aqueous-carbonic fluid without hydrocarbons but containing nitrogen and some hydrogen (Fig. 7). Their composition ranges are H_2O (64.2 – 95.8%), CO_2 (2.1 – 28.5%), N_2 (1.4 – 7.3%) and H_2 (0 – 1.4%). Type 4 is the only fluid documented at the Negeim site. It also occurs at SW, Anas, Yasmine, WG-03, Shereik and Korup (Fig. 7A).

460

461 Type 5 (n=11) are fluids without water (Fig. 7), having variable proportions of CO_2 (0 –
462 100%), N_2 (0 – 62.8%) and CH_4 (0 – 42.4%). It is the dominant fluid at the NW site and
463 occurs at Shereik, WG-03, SE and Korup (Fig. 7A).

464

465 Finally, type 6 (n=2) is composed only of water (H_2O at 100%). It occurs only at 2 sites:
466 SE and Shereik (Fig. 7).

467

468 **9.2. Fluid inclusion petrographic characteristics**

469 Petrographic observations were performed on selected quartz samples to validate if fluid
470 inclusions can account for the released gas. Phase assemblages were established at room
471 (22°C) temperature. Quartz samples are characterized by assemblages of fluid inclusions,
472 mostly distributed as clusters and trails of secondary origin (Fig. 8) as expected for vein-
473 type gold deposits (e.g., Boullier and Robert, 1992). Fluid inclusions in all samples occur
474 in 3 distinct groups (Fig. 8): 1) translucent, two-phase liquid-vapour inclusions that have
475 water-dominated compositions and are commonly ovoid shaped with 10-30% of the
476 volume in the bubble; 2) dark, one-phase gaseous inclusions, generally ovoidal in form;
477 and 3) one-phase gaseous inclusions that are flame-shaped with darker colour. The later
478 could be partly necked inclusions from group 2. All groups have dimensions less than
479 <30 μm. For all fluid inclusion types, no daughter mineral such as halite is observed,
480 hence suggesting that the salinity of the fluids is low. Such assemblages are typical of
481 orogenic gold deposits, being composed of (1) low salinity, liquid-water inclusions with
482 bubbles of CO_2 and H_2O coexisting with (2) vapour-rich inclusions, commonly CO_2-rich
483 with variable proportions of other gas (N_2, CH_4, C_2H_6 and $\pm H_2$, Ar and H_2S) (e.g., Ridley
484 and Diamond, 2000; Garofalo et al., 2014), resulting from pressure-induced unmixing
485 (phase separation).

486

487 In terms of fluid types, type 1 and 3 are characterized by the occurrence of the 3 groups
488 of fluid inclusions (Fig. 8). For type 2, all three groups of fluid inclusions are also
489 present, but with smaller proportions of water-dominated fluid inclusions of group 1.
490 Type 4 is also indistinguishable from types 1 and 3, being composed of the 3 groups of

fluid inclusions. Type 5, which is devoid of water, is dominated by gaseous fluid inclusions of groups 2 and 3. Simply, the observed proportion of the 3 groups of fluid inclusions (Fig. 8) is consistent with the percentage of gas and water released by decrepitations (Fig. 7) and used for establishing fluid types. Consequently, the vapour-rich fluid inclusions of groups 2 and 3 are carrying most of all the gaseous species (N_2, CO_2, H_2, CH_4, and C_2H_6) of the fluid types 1 to 5. This is a validation that the defined fluid types are well-represented by fluid inclusion groups, which are also consistent with what is expected for gold deposits. The genetic implications between fluid types and fluid inclusions are discussed below.

9.3. Link between fluid type and structural setting

Fluid types are compared to structural settings (Fig. 9A) and metamorphic facies (Fig. 9B). For the structural setting, some relationships between structural setting and fluid types can be established. For reverse kinematics, including reverse-oblique movements, which are the most common settings for gold-bearing quartz veins, type 1 fluid is dominant (20% of the database), with smaller proportions of types 4 (14%) and 3 (8%). For quartz veins hosted in normal shear zones, water-devoid type 5 is dominant (8%). For dextral, sinistral and strike-slip settings, no clear dominance of fluid type can be established. Dyke-hosted quartz veins are characterized by the occurrence of only type 4 fluids, but the dataset is weakly representative (n=3). Overall, the kinematics of the structures hosting gold-bearing quartz appear to have a link with the established fluid types. The implications of such a link are discussed below.

For the metamorphic facies of the host rocks (Supp. Table SM1, Fig. 9B), the quartz samples in the greenschist facies are characterized by greater occurrences of type 1 fluids (19%), but all other fluid types also occur. In the amphibolite facies, type 5 fluid is the most abundant (14%), but all the other types are documented. For the hornfels facies, represented only by the samples from Korup, fluids 1, 2, 4 and 5 are present. Overall, although there are some variations from amphibolite to greenschist facies, no significant relationship is detected between the metamorphic facies of the host rocks and the types of fluids. The genetic implications are discussed below.

9.4. Fluid type distribution

The distribution of fluid types is of interest at the deposit and regional scales for defining hydrothermal systems. Fluids of various types are commonly recorded at the deposit scale. For example, the gold deposits of WG-03 (n=7) and Shereik-118 (n=5) record various types of fluids (Fig. 10). However, Negeim records a unique and relatively homogeneous fluid, a contrasting feature from other sites. It is noteworthy that type 1 fluid, the most complex in composition, occurs in all gold deposits with calculated resources, such as UTM, Central (SCMC) and WG-03 (Fig. 10).

At the regional scale, the distribution of fluid types cannot be systematically linked with the two established regional corridors (Fig. 4) or with the interpreted contour of the KSZ (Fig. 1). Conversely, the spatial distribution of fluid types can be grouped within 3 discordant, NW-elongated fields (Fig. 10). The southern and northern fields are defined by the occurrence of type 1 fluids. They are separated by a central field including Anas, NW, SE, Negeim, Dardora and SE (Fig. 10), where fluids of types 1 and 3 are lacking. However, fluids of type 2 are present for NW and Dardora. Fluids of type 4 are present at Negeim. Fluids of type 5 are rather common, with samples at Dardora, NW and SE. This central field thus appears to be dominated by fluids generated from a more localized source. Except for the apparent NW-SE alignment of plutonic rocks in the northern field (Fig. 10), there is no direct geological evidence supporting such an interpreted NW-trending field. As orogenic gold deposits are related to deep processes (e.g., Gaboury, 2019; Groves et al., 2020), such apparent NW alignment may be related to deeper inherited features and is discussed below.

10. DISCUSSION

The studied gold-bearing sites are distributed over a very large area and are associated with two interpreted major regional deformation corridors and multiple intrusions. Although restricted mostly to the quartz vein type, gold mineralization is hosted in various metamorphic facies with different structural settings and specific hydrothermal alterations. Furthermore, at least 6 types of fluids are documented. From a genetic

553 viewpoint, the main questions are as follows: 1) is gold mineralization related to single or
554 multiple events; 2) is there a more favourable structural setting for fluid upwelling and
555 forming economic gold deposits; 3) what are the fluid sources, and is there a better fluid
556 type for carrying gold; 4) what is the genetic significance of the various fluid types; 5)
557 what is the implication of the various metamorphic facies; and 6) what is the gold source?
558 These questions are addressed below.
559
560 **10.1. Single or multiple gold events**
561 All the studied gold-bearing sites and deposits exhibit mineralization that is structurally
562 controlled. For the vast majority of the mineralized sites, gold is hosted in S_2 high-strain
563 zones, cutting across the S_1 fabrics. These S_2 structures mostly strike NW to NE (Fig. 4),
564 corresponding to the last deformations recorded at the site scale. However, kinematic
565 regimes are different, ranging from reverse to reverse-oblique, normal, and strike-slip
566 with dextral and sinistral movements. At regional scale within KSZ (Fig. 4), the S_2 gold-
567 bearing fabric is correlative with the D_6 deformation of Abdelsalaman et al. (1998)
568 corresponding to local NE-trending dextral and NW-trending sinistral shear zones (Fig.
569 4). For the reverse and reverse-oblique S_2 gold-bearing shear zones, they can be formed
570 during the D_3 to D_5 shortening. However, they are most probably related to vertical
571 movement during the last D_6 transpressive deformation. It is also possible that gold
572 mineralization hosted in S_1 fabrics (Supp. Table SM1; Fig. 4) was introduced by
573 reactivation of pre-existing structures during D_6. The WG-03 is an example of such
574 reactivation as the mineralization within the S_1 and S_2 structures are the same (Supp.
575 Table SM1). Normal shear zones appear to be a late feature, probably post-dating the D_6
576 deformation.
577
578 Gold sites outside of the KSZ (Fig. 4: WG-03, Negeim, Sajid, Dardora, SE, and Korop)
579 share the same kinematics (strike-slip to reverse) and trending of their S_2 gold-hosting
580 fabrics with gold sites inside the KSZ. Genetically they are likely related to the regional
581 shortening corresponding to the D_6 deformation recorded in the KSZ. However, without
582 age of gold mineralization, it is impossible to establish if all sites are related to the same

583 mineralizing event. Nevertheless, most gold mineralizations are related to late structural
584 features consistent with the last deformations recorded by the KSZ.
585
586 **10.2. Implications of various structural settings**
587 Although major gold deposits can be hosted in various kinematic regimes (Gaboury,
588 2019), it is of interest to discuss the economic potential of the various structural settings.
589 The reverse shear veins show considerable thicknesses (> 3 m) and some depth continuity
590 (~ 400 m), despite the pinch and swell geometry that is typical of this type of mineralized
591 structure (e.g., Robert and Poulsen, 2001). In contrast, gold mineralization associated
592 with strike-slip movements forms very narrow but laterally quite continuous veins (> 1
593 km) occurring as a family of parallel veins, defining a mineralized area ~ 200 m wide.
594 However, the spacing between the individual veins (> 20-30 m) is large. Mineralization
595 in normal shear zones is, according to Supp. Table SM1, an unusual type regionally.
596 However, at the WG-03 deposit, numerous gold-bearing quartz veins are developed as
597 extensional features in previously mineralized shear zones from two different generations
598 (S_1 and S_2). Mineralization in these quartz veins may be the result of later gold
599 remobilization. Regionally, these extensional veins are late features and occur in zones
600 where other styles of mineralization are present (Fig. 4). They could then represent the
601 end of an important hydrothermal system active during crustal shortening up to the final
602 extensional exhumation (e.g., Wilkinson and Kesler, 2007). The mineralized dykes
603 appear to be the style with the greatest potential for ore volumes. In some cases, such as
604 Anas, mineralized dykes reach thicknesses > 20 m, with apparent continuities of several
605 tens of metres for the mineralization. Mineralization at Central C02 and C04 is also dyke-
606 hosted, and these dykes can be traced for tens of kilometres, although they do not
607 consistently contain gold.
608
609 An important element to highlight is the presence of different kinematic shear zones
610 hosting gold mineralization along the same trend. Three cases are noteworthy: the sectors
611 of Shereik, Anas-NW and Toubi (Fig. 4), which are all located along the West Corridor.
612 Moreover, the hydrothermal alterations are different according to the styles. These
613 variations can be explained by a major deformation zone having recorded gold

614 mineralizations at different times during its tectonic evolution. This aspect is developed
615 below on a regional scale.
616
617 **10.3. Sources of volatiles in hydrothermal fluids**
618 Our results reveal various assemblages of volatiles in fluid inclusions, such as 1)
619 aqueous-carbonaceous, 2) CO_2-rich, 3) H_2-bearing fluids, 4) C_2H_6-bearing fluids, 5) N_2-
620 CH_4-only fluids, and 6) water-only fluids. These were grouped into 6 types for genetic
621 considerations. It is also noteworthy that all analysed samples have fluid inclusions
622 containing nitrogen, except for the 2 samples with water-only fluids. The sources and
623 origins of these volatiles are discussed below to provide further constraints on the origin
624 of the fluids.
625
626 Sources of nitrogen have been discussed by Gaboury (2013). Three sources are possible
627 (Kreulen and Schuiling, 1982; Andersen et al., 1993). 1) Organic matter from sediments
628 may break down where nitrogen can be fixed in K-bearing silicates by substitution of K^+
629 for NH_4^+, notably in micas (e.g., Sadofsky and Bebout, 2000). 2) Hydrothermal alteration
630 of NH_4^+-bearing silicates and formation of N_2 may occur by the equations postulated by
631 Kreulen and Schuiling (1982):
632 $3CO_2 + 8NH_3 = 3CH_4 + 4N_2 + 6H_2O$ (EQ. 1)
633 and by Wang et al. (2018) under oxidizing conditions between 350 and 600°C:
634 $2NH_4^+ + 2O_2 = N_2 + 4H_2O$ (EQ. 2)
635 3) Primary N_2 may be liberated from magma or through metamorphism of the lower
636 crust. Consequently, nitrogen itself is not diagnostic for fluid sources.
637
638 N_2-CH_4-only fluids are quite atypical, documented only in some gold deposits, such as
639 the Maldon gold deposit in central Victoria, Australia (Fu et al., 2014). For this deposit,
640 CO_2-rich and N_2-CH_4-rich fluids coexist. Fu et al. (2014) proposed that genetically, N_2-
641 rich fluids were produced locally by NH_4-bearing phyllosilicate minerals in wall rock
642 slates (and/or by maturation of organic matter in shales) during contact metamorphism,
643 with limited involvement of high-temperature magmatic fluids.
644

Methane alone can be generated by reduction following the reaction (Gaboury, 2013):

$CO_2 + 4H_2 = CH_4 + 2H_2O$ (EQ. 3)

Metamorphic reactions involving carbonates with H_2 (Giardini and Salotti, 1969) and serpentinization reactions (Abrajano et al., 1990; Huang et al., 2019; Reeves and Fiebig, 2020) can also produce CH_4.

In gold deposits, CO_2 can be sourced from the mantle and from metamorphic devolatilization of volcanic-sedimentary rocks (e.g., Phillips and Powell, 1993; Lowenstern, 2001; Lüders et al., 2015). In addition, CO_2-dominated fluids may be sourced from felsic magmas (e.g., Kerrich, 1988; Connors et al., 1993; Xue et al., 2013). Carbon dioxide-rich fluids have been documented in some orogenic gold deposits of various ages (e.g., Gaboury, 2013). CO_2-rich and H_2O-poor fluid inclusions have been reported from some important gold districts and deposits, such as Red Lake (Chi et al., 2006), Ashanti (Mumm et al., 1997), Tarkwa goldfield (Klemd et al., 1997), Detour Gold and Wona (Gaboury, 2013). In Sudan, such fluids have been recorded in the Hamadi gold deposit (Cheng et al., 2017). The debate about the origin of CO_2-rich fluid inclusions involves various possibilities (Klemd and Hirdes, 1997; Chi et al., 2006; Klein and Fuzikawa, 2010; Hrstka et al., 2011), including 1) specific fluid sources from high-grade metamorphism or early degassing of magmatic intrusions; 2) fluid-related processes such as selective vapour accumulation following fluid immiscibility; two fluids operating separately; or unmixing because of pressure fluctuations; and 3) post-entrapment modifications of fluid inclusions. Recently, Gaboury (2013) proposed that CO_2-rich fluids may be the result of the degradation of C_2H_6 and the consumption of H_2O, leading to the progressive enrichment of CO_2 in the fluids, following the reaction:

$C_2H_6 + 2H_2O = CO_2 + CH_4 + 3H_2$ (EQ. 4)

In short, CO_2 can be generated from various sources, and there are numerous hypotheses to account for CO_2-rich fluids in gold deposits.

The sources and implications of C_2H_6 in fluids from orogenic gold deposits have been documented by Gaboury (2013). It was demonstrated that C_2H_6 in hydrothermal fluids cannot be produced from abiotic hydrothermal reactions involving CO_2 or CH_4 but rather

implies the interaction of fluids with thermally degraded organic matter. The record of C_2H_6 in fluids from gold deposits confirms that organic matter-rich sedimentary rocks are involved in the generation of fluids by metamorphism.

Hydrogen is not a common constituent of orogenic gold deposits (Gaboury, 2013), with some exceptions (e.g., Ankusheva et al., 2019). The content of H_2 in fluid inclusions had previously been considered doubtful, with the possibility of H_2 diffusion in mineral-hosting fluid inclusions (e.g., Mavrogenes and Bodnar, 1994). Nevertheless, H_2 is not an artefact of the analytical method because there is no H_2 production generated by molecular fragmentation during ionization. Rather, hydrogen is a common product of magmatic degassing at low pressure (e.g., Landis and Rye, 2005; Klein et al, 2020). However, hydrothermal reactions in fluids, such as EQ. 4, can be proposed to account for H_2. Methane can also produce H_2 following these reactions:

$CH_4 + H_2O = CO + 3H_2$ (EQ. 5)

$CH_4 = C + 2H_2$ (EQ. 6)

The reaction of EQ. 6 was experimentally tested and produced H_2 with catalysis from 315°C up to 700°C at atmospheric pressure (Guil-Lòpez et al., 2006). It is thus estimated that with higher pressure and temperature corresponding to the amphibolite facies, this reaction can produce H_2 from CH_4. According to Gaboury (2013), ethane can be degraded in hydrothermal fluids by the following reactions to generate H_2:

$C_2H_6 + 4H_2O = 2CO_2 + 7H_2$ (EQ. 7)

$C_2H_6 + 2H_2O = CO_2 + CH_4 + 3H_2$ (EQ. 8)

Hydrothermal reactions involving the decomposition of light hydrocarbons can thus account for the H_2 contents of the fluids.

10.4. Sources of hydrothermal fluids

For most gold deposits in metamorphic terranes, hydrothermal fluids can have metamorphic or magmatic origins (e.g., Tomkins, 2013b; Goldfarb and Groves, 2015; Gaboury, 2019) and even mixing of both (e.g., Augustin and Gaboury, 2019). Type 1 aqueous-carbonaceous fluid, with its very complex composition, including N_2, H_2, CH_4, C_2H_6 and $\pm H_2$, is most probably of metamorphic origin, generated by the metamorphism

of organic-rich sedimentary rocks to account for its signature with C_2H_6 (Gaboury, 2013; Tomkins, 2013b). In addition, a carbonaceous metamorphic source, according to the above review, accounts for the contents of N_2, H_2, and CH_4. Similar complex metamorphic fluids have been documented for Detour Gold, the largest single Canadian orogenic gold deposit, and for the Mana district, the most gold-endowed district in Burkina Faso (Gaboury, 2013). Considering all the possible reactions above, type 1 fluid is thus considered a primary, unmodified or weakly modified metamorphic fluid.

Type 2 fluid, similar to type 1 but with less water, certainly has an origin similar to that of type 1 because it also contains C_2H_6. Nevertheless, its water content of less than 50% is a strong indication that type 2 was generated by a different source than type 1. Furthermore, as water-dominated fluid inclusions of group 1 are less abundant (Fig. 8E-H), post-trapping modifications of fluid inclusions sourced from type 1 fluid can be ruled out. A possible source is the metamorphism of sedimentary rocks richer in organic material to account for the higher proportion of carbon-bearing volatiles.

Type 3 fluid, similar to type 1 but without C_2H_6, probably has the same source, where C_2H_6 could have been consumed by hydrothermal reactions (EQs. 7 and 8: Gaboury, 2013), or it may be sourced from the metamorphism of sedimentary rocks less rich in organic matter or from volcanic rocks. The former hypothesis appears more valid as type 3 fluid systematically coexists with type 1 in WG-03, WG-14, Yasmine, Toubi, Shereik-118 and Korup (Supp. Table SM3; Fig. 10).

Type 4 fluids are aqueous-carbonaceous fluids with nitrogen but are devoid of hydrocarbons. Genetically, they can be sourced from 1) intrusions, 2) metamorphic devolatilization, and 3) phase separation from a more complex parental fluid. Phase separations between liquid- and vapour-rich phases are induced by pressure drops (e.g., Robert et al., 1995; Wilkinson, 2001). The coexistence of liquid- and vapour-rich fluid inclusions is considered as evidence that fluid modification occurred by the physical process of phase separations. The phase separation hypothesis likely occurred at sites where fluids of types 1 or 3 coexist with type 4 fluid, such as Korup, WG-03, Shereik-

738 118, and Yasmine. For Negeim, because the 3 samples have very similar compositions,
739 phase separation is not supported by the data. Consequently, a specific fluid from a
740 magmatic source cannot be ruled out. Other sites having only type 4 are Anas and SW-1
741 with only one sample.
742
743 Type 5 fluids are water-devoid fluids with various combinations of CO_2, N_2, and CH_4
744 volatiles, including specific fluids such as CO_2-only and N_2-CH_4 fluids. The origin of
745 these fluids could be diverse, as reviewed above. However, phase separation appears to
746 be the preponderant mechanism to account for these fluids, especially at sites where
747 fluids of type 1 or 3 coexist with type 5 fluid, such as Korup, WG-03 and Shereik. Phase
748 separation is also supported by the petrographic characteristics of fluid inclusions: the
749 samples with type 5 fluids only have gaseous fluid inclusions of groups 2 and 3.
750 Specifically, samples from SE, with fluids of types 5 and 6 (water-only), could be prime
751 examples of this extreme phase separation. Nevertheless, such fluids at SE, Dardora and
752 NW could have a different origin, such as magmatic, even if phase separation was an
753 efficient mechanism. Finally, type 6 fluids with only water, occurring at SE and Shereik,
754 can also be related to phase separation.
755
756 Fluids of types 1 and 2, which are C_2H_6-bearing, were generated by the deeper
757 metamorphism of organic-rich matter from sedimentary rocks, such as black shales.
758 These rocks have also been proposed as the principal gold source for orogenic gold
759 deposits (e.g., Large et al., 2011; Tomkins, 2010; Tomkins, 2013b; Gaboury, 2013;
760 2019). Pyritic black shales have been intersected in the drill holes (Fig. SM2E-F) of the
761 Central deposit (SCMC). Consequently, such favourable rocks occur in the study area,
762 especially within the sedimentary rocks of the KSZ. These fluids are therefore considered
763 the most important for generating significant orogenic gold deposits.
764
765 Different fluid types can be interpreted as the manifestation of different hydrothermal
766 systems. We propose that the various types of fluids were generated from a primary fluid
767 (types 1 and 2) that evolved by hydrothermal reactions and/or phase separations to
768 generate types 3 to 6. Nevertheless, the possibility of numerous specific hydrothermal

systems cannot be eliminated (see below). Our interpretation is supported by the fluid inclusion groups (Fig. 8), the occurrence of various types of fluids in the same deposits (Fig. 10), and the relative abundance and wide distribution of types 1 and 2 fluids in the study area (Supp. Table SM3. Figs. 7 and 10).

10.5. Hydrothermal systems

Metamorphic devolatilization for generating fluids is a regional process that can form large fields of gold mineralization extending tens of kilometres (Phillips and Powell, 2010). Although more than 6 types of fluid signatures are established in the study area, all can be generated by phase separations or hydrothermal reactions from a primary fluid having the complex composition of fluid type 1 or type 2. Consequently, it is questionable to distinguish different hydrothermal systems based only on the fluid types. Furthermore, a single vein or even a group of veins forming a deposit can have recorded various fluid signatures (Gaboury, 2013).

Nevertheless, specific hydrothermal systems can be interpreted by combining fluid types, structural settings and the spatial distribution of gold mineralization. In the northern part, a single hydrothermal system can be identified at WG-03, UTM, Central and WG-14. Specifically, they share fluid of type 1 with reverse settings of gold mineralization, although later extensional gold-bearing quartz veins occur at WG-03 (Figs. 4 and 10). Toubi, with its reverse-oblique setting and type 1 fluid, can also be included in this large hydrothermal system.

Other systems are not so simple to separate and are probably superposed systems. For example, along the West Corridor, Toubi, Anas, NW and Shereik share gold mineralization hosted in various structural settings and variable metamorphic facies with all 6 types of fluids. In addition, they are distributed along a >250 km-long corridor. Numerous hydrothermal systems are thus expected, rather than one that evolved to produce all types of fluids. Such an interpretation of multiple systems is also recorded at the deposit scale. At Shereik (Figs. 4 and 10), there is a diversity of structural settings and fluids, which is more consistent with superposed hydrothermal systems.

Along the East Corridor and in the eastern part, Yasmine, SW, Negeim, Dardora and SE are located around an interpreted large central pluton (Fig. 2). They have various settings, from dextral to reverse and sinistral (Fig. 4) and various types of fluids (Fig. 10). Nevertheless, no adjacent site shares structural setting and fluids with another (Figs. 4 and 10). They are thus interpreted as formed from separate and specific hydrothermal systems. This interpretation is supported by the Negeim deposit, where fluids are only of type 4 with a possible magmatic origin.

In the southern part, the gold at Sajid and Korup is hosted in sinistral and dextral settings, respectively. Both sites record type 1 and type 2 fluids. They can be the result of a single hydrothermal system but with different strike-slip movements. Furthermore, they are located away from the KSZ but along the projection of the Nakasib suture zone (Fig. 1).

These interpretations, combining structural settings and fluid types, imply numerous hydrothermal systems. Such an interpretation is consistent with the actual knowledge of gold-endowed major faults, such as the Cadillac-Lader Lake fault in Canada (Bedeaux et al., 2017; In press), where specific segments recorded different hydrothermal systems at different times.

10.6. Implications of the metamorphic facies

Most orogenic gold deposits are hosted in greenschist-facies rocks, where metamorphic fluids are generated below the greenschist-amphibolite transition (Tomkins, 2010; Finch and Tomkins, 2017; Gaboury, 2019). Our data indicate that some important deposits, such as WG-03 and Shereik (Fig. 4), record the various types of fluids (Fig. 10) and retrograde hydrothermal alteration even hosted in rocks in the amphibolite facies (Supp. Table SM1). Such an atypical context can be explained by diachronic metamorphism: early amphibolite-facies metamorphism of the host rocks and later metamorphism of the underlying sedimentary rocks to generate retrograde mineralizing fluids. Such a model implies obduction or nappe transport of metamorphosed rocks over non-metamorphosed sedimentary rocks. The KSZ, which is a collisional belt, can provide such a tectonic

accretionary context. For example, it is possible that metamorphosed rocks at WG-03 were thrust over sedimentary rocks during the closure of the sedimentary basin now manifested by the KSZ. According to Abdelsalam (1995), the E-W, shallowly north-dipping S_1 fabric is related to the development of D_1 S-verging folds associated with ophiolitic nappe emplacement during the closure of the Atmur-Delgo oceanic suture.

For Shereik, this area is interpreted as an exotic nappe (Fig. 1; Evuk et al., 2014). The penetrative shallowly dipping S_1 foliation (Fig. 5E) more evident at Shereik than at the other study sites, and the stretching lineations indicate a thrusting movement towards the NE. Nevertheless, the mineralization is retrograde, with strong iron carbonate alteration (Fig. 5E) and quartz veining.

In short, the closure of the sedimentary basin, now represented by the KSZ, is considered to have provided fluid-bearing rocks underneath already cratonized rocks or metamorphosed nappes to generate retrograde mineralizing metamorphic fluids. Consequently, gold mineralization can occur away from the interpreted limit of the KSZ, as suggested by the location of the WG-03 deposit.

10.7. Sources of gold

The sources of gold for orogenic deposits have been reviewed by numerous authors (e.g., Pitcairn et al., 2010; Large et al., 2011; Tomkins, 2013b; Goldfarb and Groves, 2015; Pitcairn et al; 2015; Gaboury, 2019). Organic-rich and pyritic sedimentary rocks are considered one of the most important sources. Gold and other trace metals originally hosted in sedimentary pyrite can be liberated by recrystallization and hydrothermal replacement processes at metamorphic temperatures corresponding to the pyrite–pyrrhotite transition (Pitcairn et al., 2010; Large et al., 2011; Zhong et al., 2015; Finch and Tomkins, 2017; Wu et al., 2020). Gaboury (2019) concludes that the fluids, ligands, and gold are all sourced from the metamorphism of the same carbonaceous and pyrite-rich sedimentary rocks. Such deep processes are recorded in mineralizing fluids by the presence of ethane (Gaboury, 2013). For the northern part of the Nubian Shield, Abu-Alam et al. (2018) also reached the same conclusion that gold-bearing fluids were

862 generated by metamorphic devolatilization at the greenschist–amphibolite facies
863 transition of the ophiolite and sedimentary rocks.
864
865 A link between gold dissolved in oceans and the temporal distribution of orogenic gold
866 deposits was first proposed by Tomkins (2013a) and documented by Large et al. (2015)
867 using gold concentrations in primary pyrites from black shales. Oxidizing seawater
868 conditions were favourable for fixing gold in nodular sedimentary pyrite, accounting for
869 the gold endowment in black shales (Large et al., 2015). The lack of major orogenic gold
870 deposits from 1800 to 800 Ma is explained by the low levels of Au in the oceans during
871 this period (Large et al., 2015), which corresponds to the Canfield Ocean (Canfield,
872 1998). During the middle to late Proterozoic, the deep oceans were anoxic and sulfidic
873 (Canfield, 1998), hence limiting the bacterial reduction of sulfate and the incorporation of
874 gold in nodular pyrite (Gaboury, 2019). The occurrence of orogenic gold deposits in
875 Neoproterozoic time, such as those along the KSZ in Sudan, coincides with the
876 reappearance of oxygenic conditions in the oceans (Large et al., 2015; Steadman et al.,
877 2020). Ethane in fluids related to gold mineralization is thus an indication that gold was
878 sourced from the metamorphism of favourable organic-rich and gold-bearing pyritic
879 sedimentary rocks.
880
881 **10.8. Geodynamic evolution and gold deposit formation**
882 A geodynamic model for the formation of the KSF was proposed by Evuk (2013). The
883 model involves the formation of an oceanic basin from 900 to 850 Ma (Fig. 11A). Later,
884 from 850 to 630 Ma, double subduction is interpreted to accommodate the convergent
885 tectonic regime (Fig. 11B). We proposed that during this period, organic-rich shales
886 accumulated under oceanic conditions favourable for gold incorporation within primary
887 pyrite. At the end, limestone precipitated at the top of the stratigraphic succession.
888 Finally, during the collisional stage, between 630 and 500 Ma, the volcanic-sedimentary
889 rocks of the Keraf suture basin were folded, thrust faulted and metamorphosed.
890 Metamorphic gold-bearing fluids were generated by the rebound of the metamorphic
891 isograds (Fig. 11C). Gold deposits were formed in the KSZ and locally in the cratons
892 adjacent to the suture zone. The studied gold occurrences are considered orogenic

because they share the same characteristics in terms of structural settings, styles and hydrothermal alterations as classic orogenic gold deposits.

11. CONCLUSION

The study areas show diverse structural settings for orogenic gold mineralization hosted in greenschist- and amphibolite-facies rocks. Most gold mineralizations occur in late S_2 shear zones correlated with the regional D_6 deformation of Abdelsalam et al. (1998). Reverse movements and dyke host rocks are considered the most favourable settings for forming gold deposits with economic potential. Two major corridors of deformation are delineated, but only the West Corridor seems to play a real role in the mineralization, based on the number of gold sites and their dominant reverse structural regime.

Six types of hydrothermal fluids are distinguished based on specific volatile contents and proportions. Most of them can be related to fluid evolution by hydrothermal reactions and/or phase separations from a primitive fluid of metamorphic origin. Hydrothermal fields are identified based on structural settings and fluid types. The northern field is interpreted as a single large hydrothermal system accounting for the mineralization at the WG-03, UTM and Central deposits as well as WG-14 and possibly Toubi sites. For sites along the West Corridor, such as Toubi, Anas, NW and Shereik, multiple and overlapping hydrothermal systems are proposed to explain the various fluid types and structural settings. Conversely, other sites, such as SW, Yasmine, Korup, Saijd, Dardora, Negeim, and SE, appear to have been formed by more localized individual hydrothermal systems, even with a possible magmatic contribution to Negeim.

The most important outcome of this study is the documentation of fluids containing ethane at numerous sites and deposits. Ethane is an indication that fluids were generated by the metamorphism of carbonaceous-pyritic sedimentary rocks (Gaboury, 2013). These rocks are also considered one of the best sources for providing ligands and gold for the formation of orogenic gold deposits (Gaboury, 2019). The KSZ, which is composed mainly of turbidites, provided such source rocks deeper in the suture zone and below the adjacent cratons during the collision. The studied orogenic gold sites and deposits in

various structural contexts and metamorphic facies are thus attributed to the deeper metamorphism of these favourable rocks.

Finally, this study adds support to a general model for the formation of orogenic gold deposits from Archaean to Palaeozoic time (Gaboury, 2013, Gaboury, 2019), involving gold extraction by metamorphism of primary pyrite in organic-rich sediments, as far as oceanic conditions were favourable for gold enrichment in pyrite (Large et al., 2015; Steadman et al., 2020).

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1315 **Table and Figure captions**
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Table 1. Fluid type established on the proportion of H_2O (mole %) and specific gas content.

Figure 1: Simplified regional geological map showing the interpreted limit of the Keraf suture zone, with the location of Figure 2, modified from Evuk et al. (2014) and Karmakar and Schenk (2015). The Hamisana shear zone location is from Stern et al. (1989). The inset shows the distribution of the Arabian-Nubian Shield.

Figure 2: Landsat 8 satellite image with the interpreted lineaments and intrusive bodies and the locations of the studied gold-bearing sites and deposits.

Figure 3. Characteristics of the gold deposits. A) Shallow-dipping S_1 fabric at the WG-03 deposit. B) Crosscutting relationship between the hornblende-plagioclase S_1 foliation (perpendicular to the core) cut by later biotite schistosity (parallel to the core), drill hole SCM-08 at 100 m, WG-03. C) Aspect of the S_2 schistosity at the surface of the WG-03 deposit. D) Late quartz vein within a normal shear zone, as indicated by the dragging of the S_1 foliation along the quartz vein, WG-03 deposit. E) Dyke-hosted gold mineralization in the Central C04 deposit. The contacts of the felsic dyke are affected by reverse shearing. F) Gold mineralization in the UTM deposit, where the fault-fill quartz veins are hosted in a S_2 shallow-dipping reverse shear zone.

Figure 4. Map showing the structural settings, metamorphic facies and trends of gold-bearing structures for the various study sites. The interpreted geological features are from Figure 2: pink areas are interpreted intrusions and light brown lines are interpreted lineaments. The blue circles are enlarged area for highlighting the variation of the structural setting at the local scale. The kilometric value is for the diameter of the circle.

Figure 5. Characteristics of the gold-bearing sites associated with reverse shear zones. A) CS fabric indicating reverse movement at the Yasmine site. Note the mined

fault-fill gold-bearing veins parallel to the C-plane. B) Reverse shear-hosted gold-bearing quartz vein at the Yasmine site. C) CS fabric indicating a reverse-shear zone controlled by a mafic dyke contact at the Negeim artisanal mine. Note that the mafic dyke contains the S fabric and that the mined fault-fill gold-bearing veins (excavation) are parallel to the C-plane. D) Thick and laminated fault-fill vein hosted in the reverse-shear zone at the Negeim artisanal mine. E) S_1 foliation in amphibolite-facies rocks, refolded by reverse movement with boudinaged quartz veinlet in the axial plane at Shereik-118. Note the strong retrograde iron carbonate alteration manifested by the orange colour. F) Mineralized zone at WG-14 marked by quartz veining hosted in a strongly deformed shallow-dipping S_1 high-strain zone with strong iron carbonate alteration.

Figure 6. Characteristics of the gold sites associated with strike-slip and normal movements. A) Narrow quartz vein (excavated) located along the dextral sheared contact of a mafic dyke at the SW-2 site. B) Sinistral shearing along the contact between basaltic and volcanic-sedimentary rocks at Sajid, with the artisanal mining of a narrow quartz vein. Note the oblique extensional quartz vein (dashed red line) used to interpret the stress field and the strike-slip sinistral movement. C) Strongly deformed and gold-bearing volcanic-sedimentary horizon between massive basaltic rocks at Korup. D) CS fabric relationship indicating dextral movement at the SE site. The S fabric is developed within the dyke, where a narrow quartz vein follows the dyke contact (C fabric). E) Normal movement along a shear zone indicated by the CS fabric relationship, NW site. Note the excavated deformed boudins of gold-bearing quartz veins. F) Normal shear zone, as indicated by the dragging of the S_1 fabric (yellow line) hosting a gold-bearing quartz vein at Shereik-118.

Figure 7. Results of the fluid inclusion analysis by solid probe mass spectrometry. A) Logarithmic graph of mole % of volatile components for the analysed samples. Samples are grouped by the type of fluids established based on specific volatile

contents and proportions and ordered according to the released total pressure (mbar). The total pressure corresponds to the quantity of volatiles released by fluid inclusion decrepitation in the sample during analysis. Red lettering indicates samples shown in Figure 8. B) Logarithmic graph of mole % of volatile components showing the ranges (maximum and minimum percentages) of volatile contents for the 6 types of fluids. Fluid types are colour-coded as detailed in A. The colour-coded dots in the 0% line indicate that at least one sample is devoid of corresponding volatiles.

Figure 8. Photomicrographs showing the petrographic characteristics used for defining the 3 groups of fluid inclusions for fluid types 1, 2, 3, 4, and 5. Note that for fluid type 5, which is devoid of water, fluid inclusions of group 1 (red arrow) are lacking or present in very low proportions. The Zerene Stacker software was used to enhance the focus.

Figure 9. Comparison of fluid type with structural setting (A) and metamorphic facies (B) on bubble charts. The size of the bubble is proportional to the number of gold-bearing sites having such characteristics, up to a maximum value of 11. For fluid type, nil refers to sample without gas released.

Figure 10. Spatial distribution of the various types of fluids. The interpreted geological features are from Figure 2. The dashed ovals are interpreted as NW-trending fields of fluids. Pink areas are interpreted intrusions and light brown lines are interpreted lineaments. The blue circles are enlarged area for highlighting the variation of fluid types at the local scale. The kilometric value is for the diameter of the circle.

Figure 11. Schematic geodynamic evolution of the central part of the KSZ, modified from Evuk (2013). The 550°C isograd, corresponding to the transition between the greenschist and amphibolite facies, is represented schematically to illustrate the fundamental role of metamorphism in generating gold-bearing fluids from

organic-rich sedimentary rocks. A) Formation of a sedimentary basin with basaltic crust separating cratons under an extensional regime. B) Interpreted double subduction during the closing of the basin with the formation of limestone representing the top part of the stratigraphic sedimentary succession. C) Closing of the sedimentary basin with folding, thrusting, late strike-slip shearing and metamorphism of the organic-rich sedimentary rocks and generation of metamorphic fluids induced by rising metamorphic isograds. Gold deposits are formed by these metamorphic fluids (red arrows) within the volcanic-sedimentary rocks of the KSZ, as illustrated by the UTM deposit, as well as in adjacent cratons, as illustrated by WG-03 and Sajid.