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Gold mineralization occurrences of Saqez–Baneh zone (north Sanandaj-Sirjan, Iran): structural settings in a microscopic scale

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ABSTRACT

The Sanandaj-Sirjan Zone (SSZ) is the metamorphic-magmatic core of Zagros Orogen in Iran. The SSZ has produced several styles of gold deposits during the Phanerozoic eon. The Saqez–Sardasht zone includes a NE-trending goldfield belt, located at the northern SSZ. This area, embodying the main orogenic gold deposits (e. g. Qolqoleh, Kervian, Qabaqhlujeh, Hamzeh Gharanain, Mirgeh Naghshineh) was chosen for this research in order to study the relationship between deformation phases and gold-accompanying minerals in a microscopic scale. It is demonstrated that the study area has experienced 2 ductile phases, 1 semi-ductile phase and 1 brittle phase of deformation, each associated with the shear zone progression. Gold mineralization via each deformation phase is relevant with the precipitation of new pyrites and shearing/rotating of old pyrites.

1. Introduction

The Sanandaj-Sirjan Zone (SSZ) is a metamorphic–magmatic belt, associated with the Zagros Orogen and part of the Alpine-Himalayan orogenic system in Iran (Mehdipour Ghazi & Moazzen, 2015). The rocks of SSZ, encompassing the 1500-km-long, 150 to 200-km-wide area, were separated mainly from central Iran during of the Mesozoic (Sengor, 1990). They share the NW-SE trend of surrounding structures (Berberian, 1995; Azizi & Jahangiri, 2008). The geodynamic evolution of the SSZ was controlled by the opening and subsequent closure of the Neotethys Ocean at the northeastern margin of Gondwana (Alavi, 1994; Fig. 1). The SSZ is subdivided into two parts in the Golpayegan area (Eftekhar-Nezhad, 1981): 1) the southern part (South SSZ) consists of rocks deformed and metamorphosed in the Middle to Late Triassic; 2) the northern part (North SSZ), known as the Sanandaj-Mahabad zone, deformed in the Late Cretaceous and contains many intrusive felsic rocks. Based on the recognition of the Late Mesozoic continental margin arc which was formed during northwestward subduction of Neotethys Ocean beneath the Iranian Continent, the SSZ is subdivided into five subzones from southwest to northeast (Mohajjel & Sahandi, 1999): 1) the radiolarite sub-zone; 2) the Biston sub-zone; 3) the ophiolite sub-zone; 4) the marginal sub-zone, and 5) the complexly-deformed subzone.

The SSZ from the Paleozoic to Eocene eras have produced several styles of gold deposits in the contemporaneous metamorphic belt. Gold deposits in the SSZ are classified into three distinct metallogenic provinces which are respectively named as northern, central and southern provinces. They include orogenic (e. g. Qolqoleh, Kervian, Qabaqhlujeh, Pir Omaran, Kharapeh, Mirgeh Naghshineh, Hamzeh Gharanain, Sheikh Chupan, Zaveh Kouh, Sardeh Kouhestan and Shoy), epithermal (e. g. Aghdarreh, Sari Gunay and Guzal Bolaqh), Carlin-type (e. g. Zarshuran and Akhtarchi), intrusion-related (e. g. Muteh, Astaneh and Zartorosht) and gold-rich volcanic-associated massive sulfide (e. g. Barika) deposits (Aliyari et al., 2012; Tajeddin et al., 2006; Fig. 2).

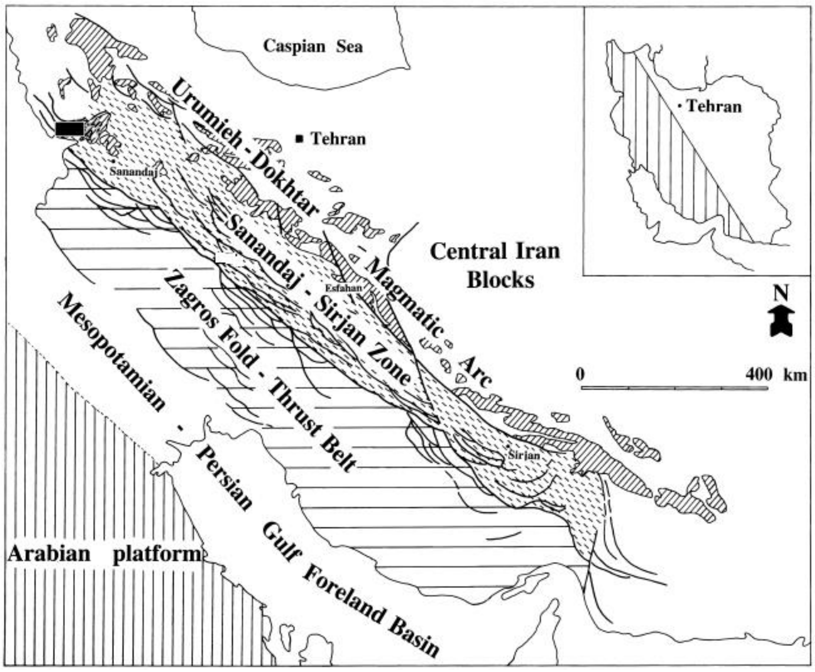

Fig. 1. The structural division of the Zagros orogeny belt (Alavi, 1994). The study area location (black rectangle) at the north-western part of the Sanandaj-Sirjan zone.

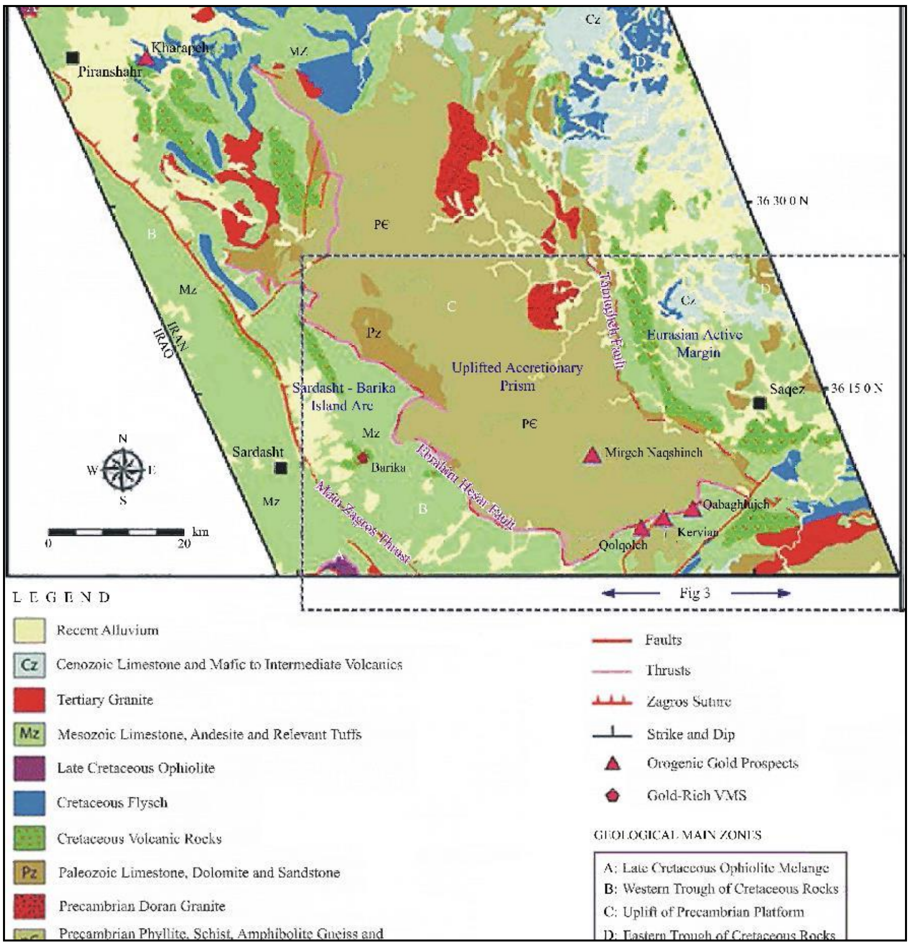

Fig. 2. Simplified geological map of the Saqez-Sardasht–Piranshahr area (Eftekhar-Nezhad, 1973) showing the distribution of various types of gold deposits and prospects in the northern SSZ. Gold occurrences are shown associated whit metamorphic and plutonic rocks and various structural settings (revised from Aliyari et al., 2012). The rectangular-shaped study area is restricted by the dashed boundary.

The first recorded gold districts within SSZ confined Muteh and Zartorosht goldfields at the central and southern parts of this belt, respectively (Aliyari et al., 2012); nonetheless north of SSZ has been considered as a potentially gold-bearing zone for the last two decades. This part of SSZ, especially concerning orogenic gold deposits, is comparable to other Phanerozoic orogens that were formed by the accretion of continental crust along the complex subduction zone of Gondwana, e. g. New Zealand and South America (Bierlein et al., 2001; Goldfarb et al., 2001) and the Lachlan Orogen (Hough et al., 2007). The Saqez–Baneh zone comprises a NE-trending goldfield belt hosted by mafic to intermediate metavolcanic and metasedimentary rocks, which are situated at the northern part of the SSZ (Aliyari et al., 2012). This area, embodying the main orogenic gold deposits (Qolqoleh, Kervian, Qabaqhlujeh, Hamzeh Gharanain and Mirgeh Naghshine), is located at 45 36 34.1 - 46 51 45.4 E and 35 53 13.3 - 36 25 37.7 N; west of the North SSZ (mainly encompassing Kurdistan Province; Fig. 3).

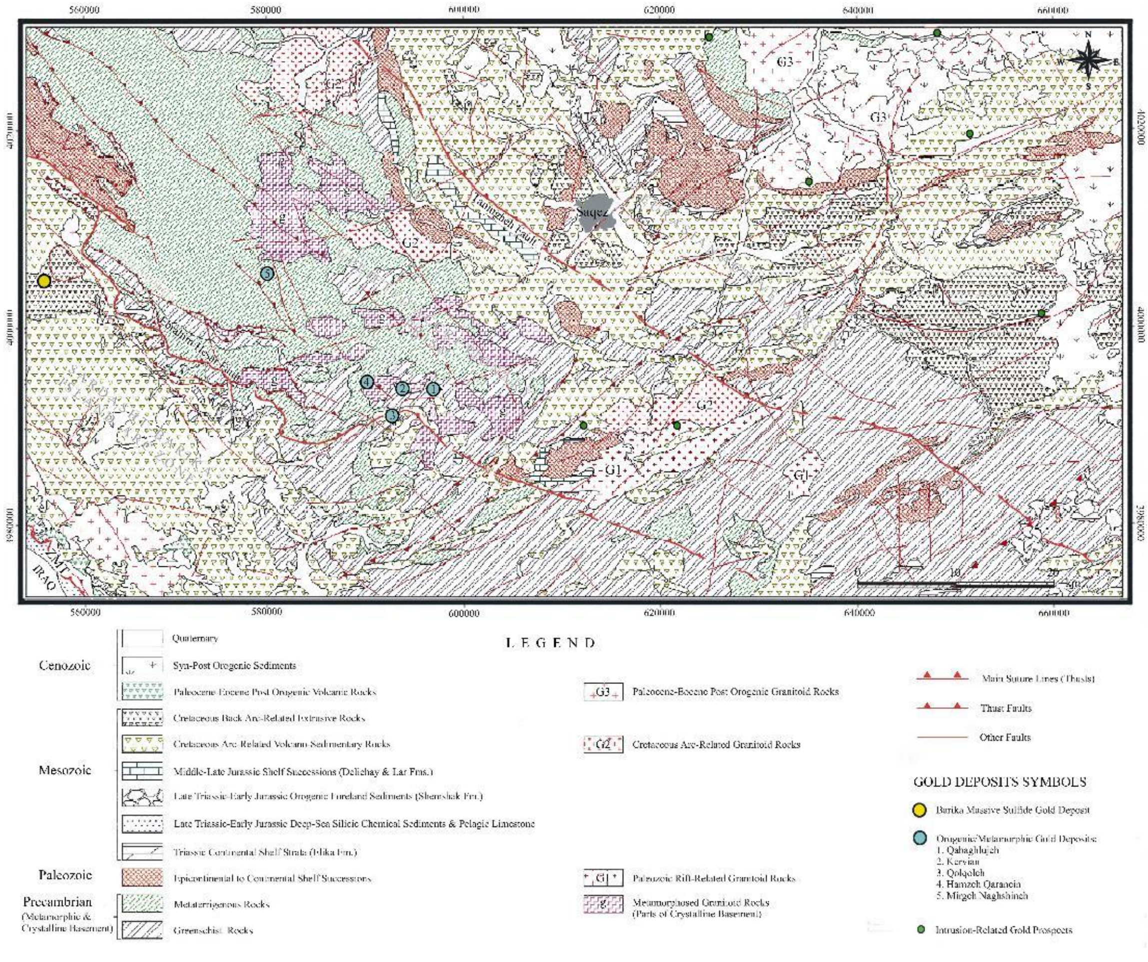

Fig. 3. Detailed geological map of the study area (Kholghi khasraghi, 1999; Fonoudi & Sadeghi, 2000; Omrani and Khabbaznia, 2003; Hariri and Farjandi, 2003; Shah Pasandzadeh & Gurabjiri, 2006; Sabzehi et al., 2009) with orogenic and massive sulfide gold deposits and intrusion-related gold indices. Granitoid bodies are revised according to Sepahi and Athari (2006-a & b), Athari et al. (2006), Hassanzadeh et al. (2008), Mahmoudi et al. (2011), Arian et al. (2011), Rashidnejad Omran et al. (2013), Abdullah et al. (2013) and Azizi et al. (2017); faults are extensively revised based on Haji et al. (2016).

2. Material and Methods

Geological Setting

The oldest rocks of the Saqez-Baneh area are Precambrian phyllite, schist and gneiss. These rocks have been underlain by the Paleozoic metamorphosed detrital and chemical sediments, Mesozoic (Cretaceous dominated) phyllite, crystalline limestone, dolomite, quartzite and mafic to felsic volcanic rocks and eventually Tertiary deposits and intrusions (Kholghi khasraghi, 1999; Fonoudi & Sadeghi, 2000; Mohajjel, 2002; Omrani and Khabbaznia, 2003; Babakhani et al., 2003;

Hariri and Farjandi, 2003; Shah Pasandzadeh & Gurabjiri, 2006; Sabzehi et al., 2009; Fig. 3). Most of the study area, containing the orogenic/metamorphic gold deposits, is situated in the complexly-deformed subzone. This includes the Late Paleozoic-Mesozoic passive margin succession formed at the northeastern side of Neotethys, as well as the subzone being overlain by a convergent margin assemblage.

Magmatism

In the northern Sanandaj-Sirjan zone, numerous granitoids are exposed within extensive realms of sheared lower greenschist-facies rocks with Precambrian protolith ages. Most of them have been assigned to the so-called Doran-type granite by Eftekhatnejad (1973). The ages of these plutons have been revised by latter authors (e. g. Omrani and Khabbaznia, 2003; Rashidnejad Omran et al., 2013).

The oldest granitoid bodies, marked as “g”, dated by Hassanzadeh et al. (2008) with U-Pb zircon geochronology are the Sheikh Chupan and Bubaktan batholiths. They are situated at the west of Saqez; aged as 551 and 544 Ma Respectively. These Late Precambrian–Early Cambrian granites have not intruded the metamorphic rocks and are assigned as their protolithic. This demonstrates the Gondwanan affinity of Iranian plate (Hassanzadeh et al., 2008).

The foregoing bodies are the two largest outcrops of a series titled as Alut granites, which are spread in a vast terrain of the study area, exclusively among the central-western parts.

The other main intrusive body, located southwest of Saqez city (central southern parts of the study area) is the Hasan Salaran granitoid complex. It is composed of two distinct granitic rock suits that have various petrological and geochemical characteristics. They also have different origins and petrogenesis. The southern smaller body (Talijar Granite), known as “G1” is an A-type granite and the northern one named as “G2” is an I-type one (Sepahi and Athari, 2006-a & b; Athari et al, 2006; Abdullah et al., 2013).

Azizi et al. (2017) using the zircon U-Pb method, ascribe the G1 body to Late Carboniferous (360 Ma). The northern G2 granite body has been assigned to 109 to 110 Ma (Mid Cretaceous) using the U-Pb dating method by Mahmoudi et al., 2011.

Metamorphism

The complexly deformed subzone is distinguished from other subzones by the abundance of metamorphic rocks. Earlier reports of Hercynian and older orogenies in Paleozoic rocks of the southeastern complexly deformed subzone have been disputed by Alavi (1994) and much of the orogenic activity in the SSZ is now related to the closing of Tethys (Mohajjel et al., 2003). However, based on some other works, the older metamorphic phases have not been completely obliterated.

The oldest metamorphic rock units are associated with Precambrian-Cambrian in age (equivalent to Kahar and Sultanieh formations). These spread over the northwest to southeast and embody the large primary granites of Alut (Omrani and Khabbaznia, 2003; Hariri and Farjandi, 2003). Moreover, some newer, less abundant metamorphic rocks have been reported at north of Saqez to north of Takab. These are assigned to lower to Mid-Paleozoic (Babakhani, 1997).

Evidence for Jurassic–Early Cretaceous convergent deformation and metamorphism is provided by unconformities in the marginal and complexly deformed sub-zones and the metamorphic clasts in the conglomerate in Cretaceous rocks of the marginal subzone. Deformation accompanying this uplift in the complexly deformed sub-zone is poorly documented due to the intensity of the overprinting of Late Cretaceous deformation (Mohajjel et al., 2003). This progressive regional metamorphism has been developed to various degrees of greenschist facies via a thermodynamic phase and has produced mylonitic schistosity of S1, representing a succession of dark-light bands (Aliyari et al., 2005; Heydari et al., 2006; Nosratpour and Hassanzadeh, 2007; Shahrokhi et al., 2009; Tajeddin et al., 2012).

The next generation of metamorphism which has been regarded as the most important phase by many authors has led to the greatest deformation event. It developed the dominant schistosity of S2, the commonplace folds, mylonitic and ultramylonitic structures related to ductile shear zone in the Late Cretaceous (Mohajjel and Shamsa, 2001; Aliyari et al., 2005; Heydari et al., 2006; Nosratpour and Hassanzadeh, 2008). This event was followed by retrograde metamorphism as a ductile-brittle transition phase of deformation, waning to lower greenschist facies in the Early

Paleocene (Nosratpour and Hassanzadeh, 2008).
Finally, some hornfels aureoles (especially in the northeast of Saqez) due to contact metamorphism of Paleocene Ghalegah granite bodies, can be considered as the last metamorphic event (Arian et al., 2011).

Deformation

Except for the events that occurred on the Gondwanan plate via the very old orogenic phases (mainly postulated as Katangan), the main orogenic events in SSZ are parts of the opening/closure of the Neotethian Ocean, which is a perfect set of the Wilson cycle. The tectonic evolution of the Sanandaj–Sirjan Zone has involved the Permian generation of an arm of the Tethys. This led to a renewed extension along both passive margins in the Late Triassic, followed by Jurassic–Miocene subduction along the northeastern margin and Late Cretaceous ophiolite obduction along the southwestern margin (i.e., the northeastern margin of the Arabian platform). Eventually, Miocene collision of the northeastern margin of Arabia with Central Iran took place (Mohajjel et al., 2003). Hence, deformation commenced in the Zagros Basin during Permian period (Koop and Stoneley, 1982; Sengor, 1990; Kazmin, 1991; Grabowski and Norton, 1994; Stampfli et al., 1991, 2001). This was a phase of rifting, which flanked the SSZ and was associated with the Upper Permian (Ghasemi and Talbot, 2006).

The next phase of deformation, titled as D1 compressional event by many authors, has been compatible with the S1 metamorphic phase in Jurassic-Early Cretaceous (Heydari et al., 2006; Aliyari et al., 2005; Nosratpour and Hassanzadeh, 2007; Shahrokhi et al., 2009).

The most intense and pervasive deformation, the D2 phase, which has been associated with the peak of the convergence event in the Late Cretaceous (Mohajjel et al., 2003), is ascribed to the contemporaneous S2 regional metamorphism. Yet this phase was ductile (shear zone-bounded) in type; causing the general orientation and features of the outcrops (Heydari et al., 2006; Aliyari et al., 2005; Nosratpour and Hassanzadeh, 2007; Shahrokhi et al., 2009). The D3 deformation phase postulated as the main factor of the present morphology of the study area. It is distinctive from the previous phases due to being on the onset of brittle deformation in Paleocene. So the dominated structures resulting from D3 are fractures. This deformation phase coincides with the retrograde metamorphism across the region (Heydari et al., 2006; Aliyari et al., 2005; Nosratpour and Hassanzadeh, 2007; Shahrokhi et al., 2009). The fault sets of this final phase have been classified by Haji et al. (2016) into 3 sets: 1) the oldest fault set is oriented N135 and is dextral-reversed; 2) the younger set is N70 with both sinistral and reverse slipping, and 3) the youngest one has a mean direction of N15 with a sinistral movement. The third juvenile set occurred for the first time; but the first two older sets were reactivated during the brittle phase in Paleocene (Haji et al., 2016).

The 3 main aforementioned deformation phases are recorded again via this work at both mesoscopic and microscopic scales by the researchers of this study. The consecutive strain generations have been marked on the outcrop rocks (Fig. 4), exploratory drilling cores (Fig. 5) and thin sections (Fig. 6) of the gold districts. Based on microscopic observations, there have been 1 or 2 ductile deformation/s in Qolqoleh, Qabaghlujeh, Kervian and Mirgeh Naghshineh areas. The second one has had an acute angle to the first one whenever present (in Mirgeh Naghshineh both the sub-phases are oriented parallel with each other). Moreover, the second ductile sub-phase has affected the rocks in Kervian by folding the previous structures; but in other areas, the general remnant features of this strain are the numerous sigmoidal shapes (mica fish structures) over the former foliation. These sigmoids are sinistral in Qolqoleh and Mirgeh Naghshineh, and dextral in Qabaghlujeh. The semi-ductile deformation phase is unique in all above districts, except for the Qabaghlujeh, which occasionally can be divided into 2 generations. This phase has had an acute angle in relation with the last phase in Mirgeh Naghshineh; 45° to 60° in Qolqoleh and Qabaghlujeh and 60° to 90° in Kervian. Also, this phase has had a dextral sense, except for Qolqoleh with the sinistral condition. The last strain phase, detected as brittle, has impacted all the districts just once. Its angle in respect with the last phase in Kervian is 45° to 90°. For other areas, it is approximately perpendicular. These fractures have had sinistral movements in Qabaghlujeh and Kervian, dextral movements in Mirgeh Naghshineh and no obvious movements in Qolqoleh (Fig. 6).

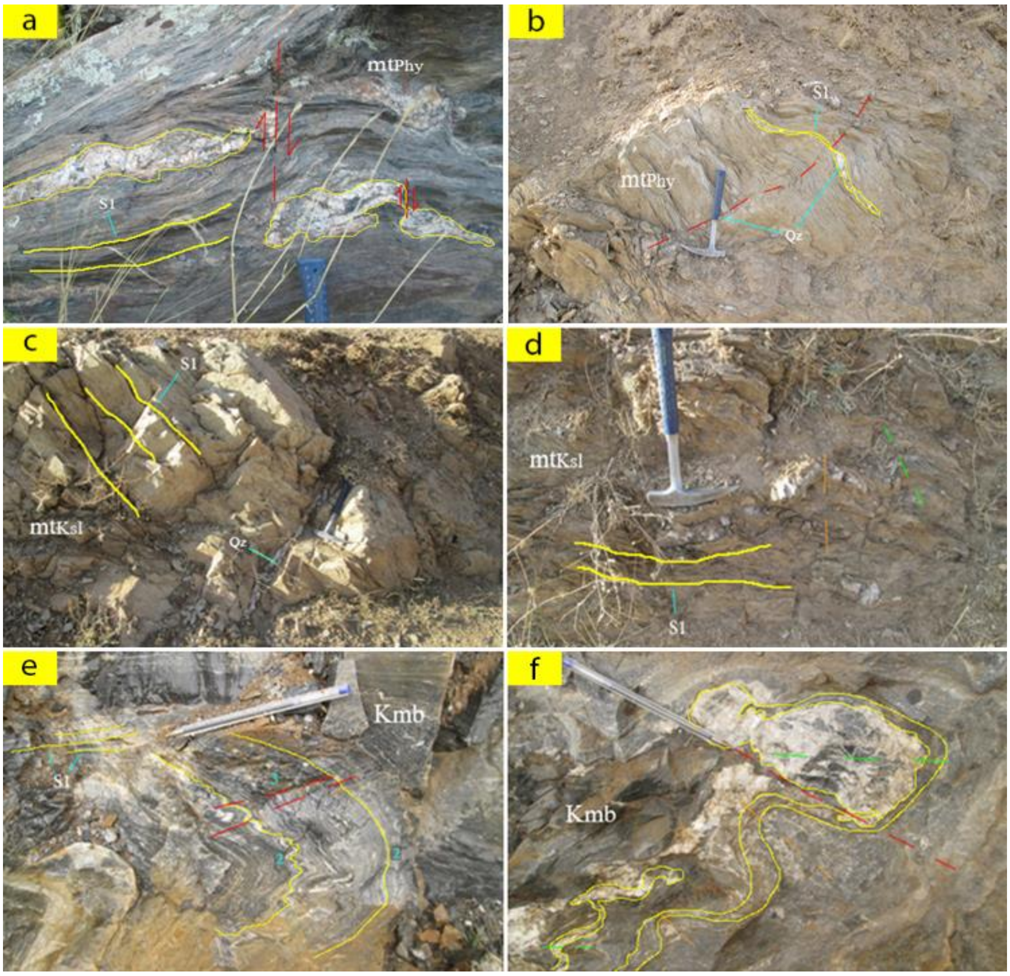

Fig. 4. Differentiation of the deformation phases by their generation order at the outcrops of Qolqoleh (a and b), Qabaghlujeh (c and d) and Kervian (e and f) gold districts; all rocks have been initially exfoliated by S1 metamorphism (yellow foliation lines), then folded/bounded in a ductile environment (green/orange dashed lines are the fold axes) and eventually cut by fractures/faults (red dashed lines) in the brittle condition.

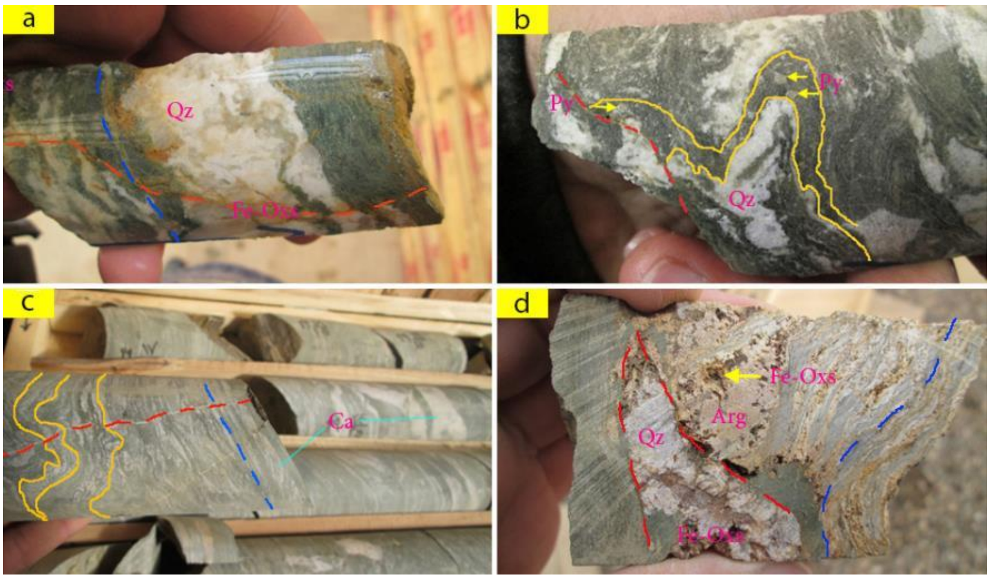

Fig. 5. Differentiation of the deformation phases according to their generational order on the drilling core samples of Qolqoleh (a), Qabaghlujeh (b), Kervian (c) and Hamzeh Gharanein (d) gold districts; blue dashed lines are the foliation planes (S1≈D1), yellow lines indicate the folds (D2 ductile phase), and red dashed lines show the fractures (D3 brittle phase). Quartz/calcite veins have formed both along the foliation planes and the fractures, and automorphic pyrite crystals/Fe-Oxides at the nose of the folds and along with the fractures (tensional areas).

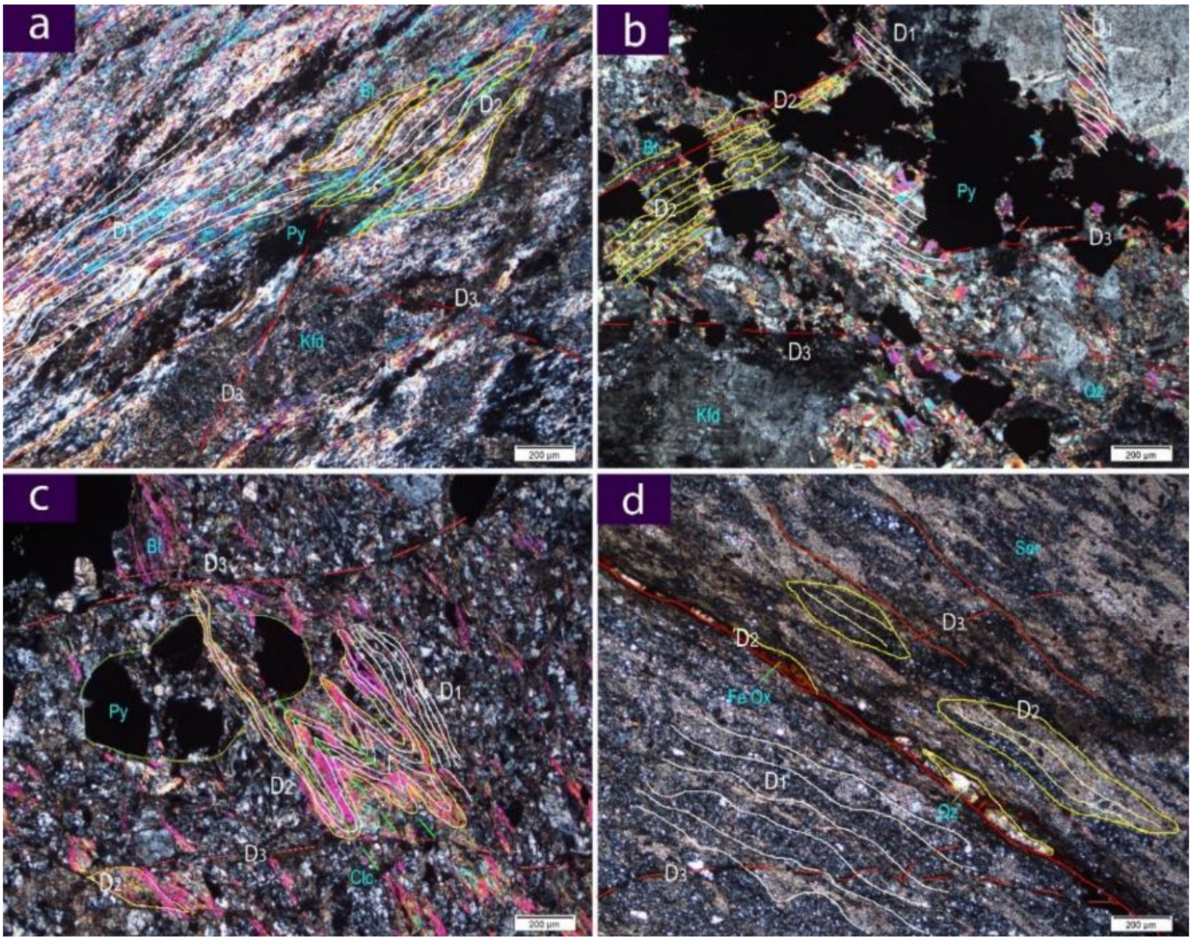

Fig. 6. Differentiation of the deformation phases according to their generational order on the thin sections of Qolqoleh (a), Qabaghlujeh (b), Kervian (c) and Mirgeh Naghshineh (d) gold districts via the XPL images. D1 ductile phase is equivalent to the regional metamorphism demonstrated as white lines; delineating the foliation traces (elongated micas) and/or the mylonitic trends of the crushed minerals. D2 is ductile to ductile-brittle; in the ductile form, it is seen as microfolds (yellow lines; c) or in sigmoidal sheared (mica fish) structures (yellow boundaries; a); in ductile-brittle form D2 is observed as the sigmoidal forms and the synchronous fractures (red lines) together (b and d). The final D3 brittle phase of deformation has overprinted the former structures just by fracture development (red dashed lines).

Gold Mineralization

Many of the Iranian orogenic gold deposits hosted in the Carboniferous to Cretaceous metamorphic rocks occur along ductile to brittle-ductile shear zones. In general, the mineralized structures exhibit ductile deformation that is overprinted by later brittle faulting; both appear to be gold-related (Aliyari et al., 2012).

The oldest gold mineralization event in the study area is Barika VMS goldfield (18 km east of Sardasht), which its first stage is associated with the Lower Cretaceous (Tajeddin et al., 2004; Yarmohammadi and Rastad, 2006). Barika rocks are a complex of volcano-sedimentary units (metamorphosed in Cretaceous; Omrani and Khabbaznia, 2003) which the metavolcanic rocks are originated from an enriched mantle (compared with MORB) relating to a continental arc system, above a subduction zone (Tajeddin et al., 2010).

Other occurrences, such as the orogenic goldfields of Qolqoleh, Qabaghlujeh, Kervian, Hamzeh Gharanein and Mirgeh Naghshineh (situated 25 to 30 km SW of Saqez), have been considered as Mid-Upper Cretaceous as their mineralization commenced. The younger gold deposition/enrichment phases are assigned to Tertiary (Shamsa, 1998; Aliyari et al., 2007; Nosratpour and Hassanzadeh, 2007; Heydari et al., 2006) and precisely associated to Paleocene (Aliyari et al., 2007; Nosratpour and Hassanzadeh, 2007; Heydari et al., 2006) and Oligo-Miocene (Abolmaali et al., 1999; Hasani Pak, 2000; Geological Survey of Iran, 2014).

3. Results and discussion

The ore-forming fluids of the Saqqez-Sardasht orogenic gold mineralization are mainly derived from metamorphic fluids, with some contributions of magmatic fluids in mesozonal goldfields (e. g. Qolqoleh, Qabaghlujeh and

Kervian) and some meteoric water in the relatively shallow epizonal environments (e. g. Mirgeh Naghshineh and Sheikh Chupan). These have localized along with suitable structural traps; namely shear zones and faults. The Mesozonal gold deposits are larger and economically more significant than epizonal districts (Tajeddin, 2012).

The Qolqoleh goldmine is composed of phyllite (with intercalations of marble), schist and gneiss which have been penetrated by the later granite bodies (Hariri and Farjandi, 2003). These intruded bodies (with the age of Upper Cretaceous; Aliyari et al., 2005) are displaced reversely several times; exacerbating the tectonic complexity of the area (Moinevaziri et al., 2017). The Qabaghlujeh gold district is located within Precambrian gneiss, granite-gneiss (Ghazanfari, 2009) and Cretaceous metasedimentary rocks; containing schist, phyllite and marble (Hariri and Farjandi, 2003). Lithological units of the Kervian gold district are composed of metavolcano-sedimentary rocks which are affected by the NE-SW trending, NW dipping shear zone. This complex contains phyllite and crystallized limestone, dolomite, quartzite and metamorphosed felsic and mafic volcanic rocks with Late Mesozoic age (Mohajjel, 2002; Hariri and Farjandi, 2003). Granitic masses in this area are noteworthy. In the Mirgeh Naghshineh goldfield, the Precambrian schist, phyllite, slate and gneiss rock units form the most dominant lithology (Hariri and Farjandi, 2003). The Hamzeh Gharanein district rocks are metavolcano-sedimentary units of the Cretaceous age (Hariri and Farjandi, 2003).

Gold occurrences of the Saqez-Baneh region are described by their attributed timelines as follows.

3.1. Ductile Deformation

The first orogenic mineralization event in the Saqez-Baneh area has occurred in the Late Cretaceous. These mineralization events are considered as shear zone-related reservoirs localized within Phanerozoic metamorphic rocks (Yarmohammadi, 2006). In Qolqoleh, intruded granitoids, host rock lithology, structural characteristics and tectonic events have been affecting gold mineralization. Mylonitic and ultra-mylonitic fabric with lenticular foliation-concordant geometry, are the common features of this phase. The first generation of the sulfides in Qolqoleh, precipitating in this stage are the automorphic and coarse-grained pyrites; formed individually or alongside the quartz boundaries (Aliyari et al., 2005; Shahrokhi et al., 2009). They have developed and oriented parallel to the mylonitic foliation and the C planes in company with the first generation quartz grains (Shahrokhi et al., 2009). Because of the frequent oriented stresses and increasing temperatures during the ductile phase, rocks of the Qabaghlujeh gold district are deformed to mylonite and ultramylonite (Nosratpour and Hassanzadeh, 2008).

The first opaque minerals have been formed parallel to the foliation of mylonitic rocks (Mir et al., 2014). Kervian deformed rocks due to the ductile shearing phase, are of various types, from proto- to ultramylonites. Ore-accompanying pyrite and quartz crystals range from moderate sizes to coarse-grained ones. These pyrite crystals are automorphic and have been oriented in shape during deformation (Heydari et al., 2006). Rocks of Mirgeh Naghshineh are deformed to mylonite and ultramylonite. Gold mineralization has occurred in silicic zones and veins (Mohammadpour et al, 2012). Veins are bedded parallel, laminated and are quartz-rich. They have occurred embodying kinds of sulfide minerals such as pyrite, arsenopyrite and chalcopyrite. Microscopic studies demonstrate that the majority of the ore related phases, coexist with pyrite in the Mirgeh Naqshineh area. Pyrite is the principal mineral of the sulfide phase which occurs in several generations (Asghari et al., 2018). In Hamzeh Gharanein the rocks have folded at least 3 times during the ductile deformation phase (Zarnab Ekteshaf Co., 2008).

3.2. Ductile-Brittle Deformation

Native gold is observed in silicic gangs and inside the sulfide (pyrite) networks; so pyrite and silica are the ore-hosting minerals in Qolqoleh. The main gold-bearing minerals are intercommunicated with sulfide, silicic and carbonate alterations (Aliyari et al., 2005; Shahrokhi et al., 2009; Taghipour and Ahmadnejad, 2012). Sulfide minerals produced via this phase, include fine-grained and amorphous pyrite and chalcopyrite crystals which are dissipated and non-deformed and found within the alteration zone (Aliyari et al., 2005; Shahrokhi et al., 2009). Pyrites are disseminated and spatially associated to the altered zones of the rock, formed alongside the S-C fabrics or set into the micro-fractures, accompanied by silicic, carbonate and micaceous fine-grained minerals (Shahrokhi et al., 2009).

The main gold concentration is correspondent to the highly deformed, silicic-sulfide alteration localities (Aliyari et al., 2005). Categories of alteration in Qabaghlujeh goldfield are of phyllic and propylitic types (pervaded over an extensive area) and the silicic type, mostly related to the mineralization zone and the dependent on frequency of sulfides and carbonates. Silicification has occurred along the mylonitic foliation in the mineralization zone (Nosratpour and Hassanzadeh, 2007). The gold is syngeneic with at least one quartz generation and two pyrite generations in the native form (Nosratpour and Hassanzadeh, 2007; Vahedi et al, 2010). The most prominent gold mineralization of Qabaghlujeh is ascribed to the final stage of ductile deformation and the first stage of the brittle deformation phase (Nosratpour and Hassanzadeh, 2008). Pyrite is the main sulfide mineral in association with gold precipitation. Opaque minerals of this phase, are amorphous and fine-grained at all (Mir et al., 2014).

Silicic, sulfide and carbonate alterations have been developed in a great affinity with the mineralization zones in Kervian. Silicic veins and laminas are formed along the mylonitic foliation (S fabric) and the general trend of the shear zone (C fabric), as well as silicification of the adjacent areas of the wall rock. The dominant sulfide minerals are disseminated and elongated pyrites, observed in the most interior sections of the alteration and mineralization zones. Pyrite and quartz crystals which accompany the gold in this considerate mineralization phase, are fine-grained. This kind of pyrites is amorphous and dispersed (Heydari et al., 2006). Gold fragments are observed in the native or dissipated forms within the sparse secondary pyrites (Heydari, 2004).

Sericitization and silicification are the major hydrothermal alterations within the metapelites and metavolcanic units in the Mirgeh Naghshineh area. These altered zones are closely correlated with the mineralization events. Free quartz is precipitated as cement, disseminations and patches. The stockwork veins contain white quartz veins and veinlets which also contain some pyrite, chalcopyrite and pyrrhotite minerals. Pyrites of this stage coexist with arsenopyrite and contain the greatest amount of the As-Au concentrations (Asghari et al., 2018). There are a variety of alterations assigned to this phase in the Hamzeh Gharanein gold district, prevailing at the mylonitic granite in sericitic and limonitic types, which are accompanied by pyrite and gold fragments (Zarnab Ekteshaf Co., 2008).

3.3. Brittle Deformation

This phase of mineralization has influenced the interior parts of the mylonitic zone in Qolqoleh in the form of concordant or discordant microfractures and brecciate textured silicic-sulfide veins and veinlets. Normal faults (illustrating the tensional condition) have had a prominent effect on the mobilization, migration and concentration of gold and the accompanying minerals (Aliyari et al., 2005). These structures have had a considerable role in the activation of hydrothermal leaching. Spatial correlation between dissipated sulfides, mylonitic texture and sulfide veinlets are considered as a key factor in gold concentration via the brittle deformation phase (Aliyari et al., 2005; Taghipour and Ahmadnejad, 2012).

The pervasive gold concentration is assigned to the cross-cutting veinlets, which occasionally include native gold fragments (Tajeddin et al., 2008). The ore-controlling large-scaled structure in Qolgoleh, as the milestone area of the gold-bearing districts, is a NE-trending oblique thrust, verging toward the southern ductile-brittle shear zone (Aliyari et al., 2012). The opaque minerals of Qabaghlujeh during this mineralization phase, have formed in the veins and fractures which have crosscut the general trend of foliations (Mir et al., 2014). Gold mineralization at this phase is associated with the silicic veins and veinlets which have intersected at the primary gold-bearing foliations (Tajeddin et al., 2008).

Pervasive silicification has occurred in the form of quartz bands, veins and veinlets and the stockwork zones among the wall rock and ore-bodies of Mirgeh Naghshineh. The veins of this stage are late stock work micro fractures, micro veins and extensional veins filled with quartz in addition to amounts of calcite-siderite or dolomite. This vein group has crosscut the previous veins and all the hydrothermally altered areas. Sulfides are generally present in the mineralized veins (Asghari et al., 2018). Main faults with the NNW-SSE trend have caused or eased the hydrothermal fluid cycling in the Hamzeh Gharanein gold district (Zarnab Ekteshaf Co., 2008).

Role of Faults

Gold districts of SSZ are spatially associated with the first and second-order fault systems of major deep-seated faults (Mohajjel et al., 2003; Aliyari et al., 2009). Gold deposits in northern SSZ have been linked to deep fault structures that could penetrate to a greater depth and therefore, cause hydrothermal fluids (Aliyari et al., 2012). The Saqez-Baneh fault zone is Late Cretaceous to Early Tertiary in age. It is a steeply dipping major reverse fault and is oriented rather perpendicularly to the Zagros thrust fault. The faults acted as regional focusing structures for crustal fluids, controlling the emplacement of intrusion bodies and the location of gold deposits in the Piranshahr-Sardasht-Saqez goldfields (Mohajjel et al., 2003). These sinistral-reverse faults, with the mean strike of N70, are the second system of the main faults which were investigated by Haji et al. (2016). The most prominent fault of this group is named as Hasan Salaran-Boeen Fault Zone at SE of Saqez, which has controlled both the intrusion of G2 felsic bodies (as the probable temperature sources) and the mineralization spatial trend in Mesozonal gold districts (Haji et al., 2016).

Studying Thin Sections

The presence of gold-accompanying minerals, particularly quartz and pyrite was studied using thin-polished (TP) sections of the four main gold districts. To achieve an accurate visual diagnosis of the pyrites, both the XPL and PPL images of each district were compared for any viewpoint of the associated photograph (Fig. 7). According to these observations, the first ductile phase (in 1 or 2 generation/s) has precipitated the coarse-grained automorphic pyrites that are protracted along with S1 in all regions. But the second phase (containing 1 or 2 generation/s), the ductile-brittle one, has concentrated the fine-grained amorphous pyrites. The prior pyrites have been sheared and rotated (leaving pressure shadows) via this phase in Qolqoleh and Mirgeh Naghshineh. This shearing/rotation is seen relatively sparse in Qabaghlujeh, but in Kervian the incipient pyrites concentrate in the dilational hinges of microfolds. The last phase of deformation, D3, described above as the brittle phase, has generated the finest pyrite crystals along the fractures in all districts, excluding Qolqoleh. This phase has sheared and rotated the former pyrites in Qolqoleh and Mirgeh Naghshineh, and has broken them in Kervian (Fig. 7).

4. Conclusion

1- Ductile deformation phase of the Saqez-Baneh zone can be divided into two sub-phases (generations) in the orogenic gold districts. The second sub-phase has crosscut the first one’s foliations. General remnant features of the second generation are the numerous dominant sinistral sigmoidal shapes (mica fish structures). The later semi-ductile deformation is structurally a single strain phase, which has regularly crosscut the latter one's direction with acute angles. This phase has had a dextral sense of movement. The brittle phase of deformation has overprinted the previous structures as a single-phase. It is approximately perpendicular to the latter one's direction. These fractures have had sinistral movements in most of the districts.

2- The first ductile strain phase in the orogenic gold deposits (In 1st or 2nd generation/s) has precipitated the coarse-grained automorphic pyrites that are protracted along with S1 in all regions. But the ductile-brittle phase has concentrated the fine-grained amorphous pyrites. The prior pyrites have been sheared and/or rotated (regarding the traces of pressure shadows) or coalesced into the dilatational hinges of micro-folds. The brittle deformation phase has precipitated the most fine-grained pyrite crystals inside the fractures. This phase has sheared and rotated the former pyrites or has broken them on some occasions.

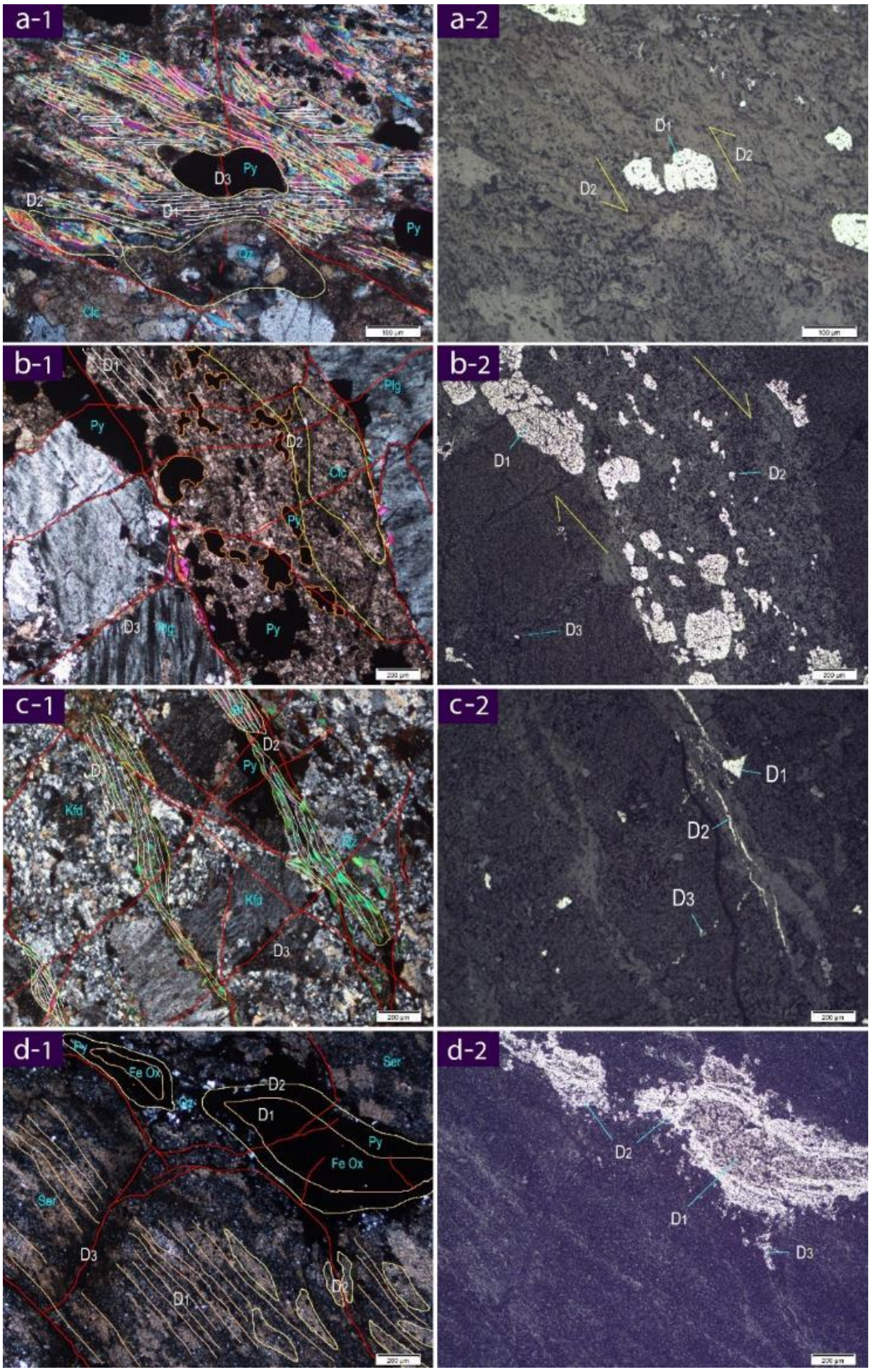

Fig. 7. Comparison of the XPL and PPL images on the thin-polished sections of Qolqoleh (a), Qabaghlujeh (b), Kervian (c) and Mirgeh Naghshineh (d) gold districts; the coarse automorphic pyrite crystals are formed by the first phase (in all images) which has been sheared to sigmoidal form (mica fish) via D2 phase. Afterwards it is broken in corollary with the matrix during D3 brittle phase (a and d); the mosaic of primary pyrite-calcite is sheared during D2 phase and broken via D3 phase (b); the secondary pyrite fragments precipitated during D2 and D3 phases are fine-grained and amorphous in shape (b, c and d); the amorphous pyrites of D2 have encompassed the primary pyrite crystals (d) as the lighter incrustations (the D1-affined older core crystals are dimmer due to the alteration).

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