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# U-Pb geochronology and petrogenesis of intrusive rocks: Constraints on the mode of genesis and timing of Cu mineralization in SWSK area, Lut Block



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## ABSTRACT

The South-West Sorkh-Kuh (SWSK) area, part of the Tertiary volcanic-plutonic rocks in the Lut Block, eastern Iran, comprises volcanic rocks intruded by intrusive rocks of hornblende diorite and biotite guartz monzonite compositions. Biotite quartz monzonite has been intensively affected by quartz-sericite-pyrite, argillic and silicification alterations and hornblende diorite shows weak propylitic and carbonate alterations. Disseminated, stockwork and vein-type styles of mineralization are associated with intrusive rocks. The vein-type mineralization with NW-SE trend is hosted by hornblende diorite. The ore in vein-type mineralization consist of quartz, chalcopyrite, pyrite, and secondary Cu-Fe minerals. Disseminated and stockwork mineralizations consist of quartz, pyrite, chalcopyrite, and secondary minerals replacing biotite quartz monzonite and hornblende diorite intrusive rocks. The highest grades in terms of Cu (3%), As (1.3%), Mo (150 ppm), Pb (362 ppm), Zn (743 ppm), and Au (278 ppb) are associated with vein-type mineralization. Intrusive rocks causing mineralization, are of metaluminous to peraluminous types with calc-alkaline to high-K calc-alkaline affinity formed in a volcanic arc setting. The enrichment of LILE (Ba, K, Cs, Sr), depletion of HFSE (Nb, P, Ti) and enrichment of LREE relative to HREE indicate the formation of source magmas above a subduction zone. The results of zircon U-Pb dating give constraints on the timing of emplacement of biotite quartz monzonite and hornblende diorite bodies at 40.16  $\pm$  0.72 and 20.1  $\pm$  2.1 Ma, respectively. The younger date extends the time span of mineralizations in the Lut Block from Middle Eocene to Early Oligocene (42-33 Ma.) reported by previous researchers to more recent Early Miocene times. The initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios and ɛNd values of both biotite quartz monzonite and hornblende diorite reside in the restricted ranges of 0.7055–0.7066 and -0.33 to +1.88, respectively, consistent with an origin above a subduction zone followed by crustal contaminations of the initial magma compositions, especially with regard to biotite quartz monzonite. The zircon U-Pb ages as well as geochemical and radiogenic isotope data for the intrusive bodies associated with mineralization in this study are in accordance with previous studies on intrusive bodies related to porphyry copper deposits in the Lut Block. In contrast to previous studies, this study further extends the span of mineralization events to at least Early Miocene times.

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## 1. Introduction

The SWSK area belongs to the Lut Block of eastern Iran between 32°12′ and 32°14′ north latitude and 58°20′ and 58°23′ east longitude and is 120 km south-west of Birjand city (Fig. 1). The Lut Block covers over 900 km in a NS direction from Doruneh fault in the north to the Juz-Morian basin in the south (Stocklin and Nabavi, 1973). However,

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it is only 200 km wide in an EW direction from Nayband fault in the west to East-Iranian range and Nehbandan fault in the east.

The geology of the Lut Block is not very well-known. Some generalized studies have been done on the tectonics and magmatism of Lut Block (Berberian & King, 1981; Camp & Griffis, 1982; Scotese, 2001; Golonka, 2004; Walker et al., 2009; Karimpour et al., 2011, 2012, Richards et al., 2012, Pang et al., 2013). Approximately 65% of the exposed rocks within the Lut Block are represented by volcanic-plutonic rocks. The volcanic rocks are Tertiary in age with andesitic to basaltic compositions. These rocks are not normally the source of any mineralization events in the Lut Block, although they may host some mineralizations. The earliest plutonic activities in the region are represented by Middle Jurassic (165–162 Ma) Klateh Ahani and Shah Kuh granitoids.



Fig. 1. Modified geological sketch map of Iran after Berberian and King (1981). The point indicates the location of SWSK.

These rocks were formed in a continental collision tectonic setting and the magma originated from melting of continental crust. The next episode of magmatism was in the Late Cretaceous. Granitoids are reported at three localities with ages within the short time interval of 76.6 to 74 Ma. The most significant episode of magmatism in the Lut Block is Middle Eocene to Early Oligocene comprising diorite, monzonite, quartz monzonite, and granodiorite reported in different parts of the Lut Block. According to mineralogy, magnetic susceptibility, and low initial value of <sup>87</sup>Sr/<sup>86</sup>Sr < 0.7057, they are classified as magnetite-series of oxidized I-type granitoids. These magmas originated from a subduction zone (Karimpour et al., 2012). The east of Iran, and particularly the Lut Block, has a great potential for various kinds of mineralization which include porphyry Cu-Au (such as Gazu (Mahdavi et al., 2016), Khopik (Malekzadeh Shafaroudi et al., 2015), Maherabad (Malekzadeh Shafaroudi et al., 2012), Chah-Shaljami (Arjmandzadeh et al., 2011), Dehsalm (Arjmandzadeh, 2011), Kuh-Robat-Shur and Aghol Kuh (Jung et al., 1983)), Au-Ag epithermal (e.g., Khunik (Samiee et al., 2016), Kooh-Shah (Abdi and Karimpour, 2013), Shurab (Lotfi, 1982), Fe-skarn (e.g., Bisheh (Nakhaei et al., 2015), Sangan (Golmohammadi et al., 2015; Malekzadeh Shafaroudi et al., 2013)) and IOCG deposits (e.g., Taherabad (Najafi et al., 2014), Qaleh Zari (Karimpour, 2005). Recent exploration and petrologic studies on the Lut Block volcanic–plutonic belt show that the episode of Middle Eocene to Early Oligocene (42–33 Ma.) was very important in terms of magmatism and mineralization (Karimpour et al., 2012).

Previous studies in the SWSK area were mainly limited to 1:100,000 map of south Sechangi (Blurian, 2004) and 1:250,000 map of Naybandan (Kluyver et al., 1981).

In this paper, we present geochemical, radiogenic isotopes as well as age data for intrusive rocks host to mineralization in SWSK prospect area as constraints on the mode of genesis and timing of Cu mineralization with an emphasis on using the data obtained as exploration keys to prospect for new mineral deposits in the region.

## 2. Geological setting

The Lut Block has acted as a rigid continental block since at least the early Mesozoic, when it was one of the Cimmerian continental fragments which drifted north from the Gondwana margin during the opening of the Neo-Tethys Ocean (Dercourt et al., 1986; Hooper et al., 1994; Scotese, 2001).

Upper crustal rocks in the Lut Block predominantly consists of Mesozoic shales and carbonates with fault-bounded Late Cretaceous ophiolitic belts, followed by Cenozoic volcanic and intrusive rocks and terrestrial sediments which indicate emergence. The area is now moderately uplifted, with typical elevations from 1500 to 2000 m. Quaternary desert sands cover a broad area of the block, particularly in the south (Dasht-e-Lut desert).

Magmatic activity in the Lut Block began in the middle Jurassic and reached its intensity in the Tertiary. Volcanic and subvolcanic rocks of Tertiary age cover over half of the Lut Block with up to 2000 m thickness and were formed as a result of subduction before the collision of the Arabian and Asian plates (Camp & Griffis, 1982; Tirrul et al., 1983).

The SWSK region is a NW–SE trending volcanic–plutonic Lut Block complex covering 25 km<sup>2</sup> (Fig. 2). The country rocks of these intrusions consist of andesitic and basaltic volcanic rocks, intruded by hornblende diorite, hornblende microdiorite, hornblende diorite porphyry, hornblende quartz diorite porphyry and biotite quartz monzonite which have cause extensively alteration and mineralization in volcanic rocks. These volcanic rocks have been affected by quartz-sericite-pyrite (QSP) and argillic alterations and disseminated mineralization. The final stage of magmatism is the formation of diorite intrusive rocks in the central part of the area which cross-cut the older rocks. These intrusive rocks have disseminated mineralization and are also the origin of vein-type mineralization in the northern part of the area.

The structural features of the region such as fractures and faults as well as the strike of some intrusions follow the NW–SE and NE–SW directions and the NW–SE series are younger than others.



Fig. 2. Geological map of SWSK area.

## 3. Analytic methods

#### 3.1. Optical microscopic studies

After field work, 220 of thin sections and polished slabs from the intrusive rocks and ore samples were studied using an optical microscope.

## 3.2. Geochemical analysis

Twenty-three samples were analyzed for multi-element geochemistry, using inductively coupled plasma-mass/optical emission spectroscopy (ICP-OES) for 35 trace elements at Zarazma Mineral Studies Co., Tehran, Iran. After crushing, pulverization and homogenization of the original samples, a sub-sample aliquot of 1 g was digested in aqua regia and analyzed by ICP-OES. The Au content of the samples was analyzed by fire assay. The precision and accuracy of the geochemical analyses have been checked against duplicate and international CRM samples, respectively (Table 1).

## 3.3. Major and trace elements

After field work, 120 samples of intrusive rocks, related to mineralization, were collected for petrographic studies. Eighteen of these unaltered samples were selected to determine major and trace elements. Major elements were analyzed by wave-length dispersive X-ray fluorescence using fused disks, and by a Phillips PW 1480 XRF spectrometer at Kansaran Binalud Lab., Tehran, Iran. Trace and rare earth element analyses were done by inductively coupled plasma-mass spectrometry (ICP-MS) at the ACME Analytical Laboratories Ltd., Canada. Powdered samples (0.2 g) were fused with lithium metaborate/tetraborate flux and digested by nitric acid before measurement by ICP-MS.

#### Table 1

#### 3.4. Geochronology

Two rock samples from hornblende diorite porphyry and biotite quartz monzonite were selected for zircon U-Pb age dating. Approximately 5 kg of rock was crushed to the grain size of  $<400 \,\mu\text{m}$ . The zircons were handpicked from the heavy mineral concentrate under the microscope after hand magnet. The selected crystals were placed on double sided sticky tape and epoxy glue was then poured into a 2.5 cm diameter mound on top of the zircons. The analyses were performed on an Agilent 7500cs quadruple ICP-MS with a 193 nm Coherent Ar-F gas laser and the Resonetics S155 ablation cell at the University of Tasmania, Australia. The downhole fractionation, instrument drift and mass bias correction factors for Pb/U ratios on zircons were calculated using 2 analyses on the primary zircons (91,500 standard of Wiedenbeck et al., 1995) and checked by 1 analysis on each of the secondary standard zircons (Temora standard of Black et al. 2003; JG1 of Jackson et al. 2004) analyzed. Zircons were sampled on 32 µm spots using laser at 5 Hz and a density of approximately 2  $I/cm^2$ . A flow of He carrier gas at a rate of 0.35 l/min carried particles ablated by the laser out of the chamber to be mixed with Ar gas and carried to the plasma torch. Isotopes measured were <sup>49</sup>Ti, <sup>56</sup>Fe, <sup>90</sup>Zr, <sup>178</sup>Hf, <sup>202</sup>Hg, <sup>204</sup>Pb, <sup>206</sup>Pb, <sup>207</sup>Pb, <sup>208</sup>Pb, <sup>232</sup>Th and <sup>238</sup>U with each element being measured every 0.16 s with longer counting time on the Pb isotopes compared to the other elements. The results of these analyses are listed in Table 3.

## 3.5. Rb-Sr and Sm-Nd isotopic analysis

Three samples of intrusive rocks were selected for Rb–Sr and Sm–Nd isotopic analysis on the basis of lack of alteration. They were crushed several times and then powdered in agate mortar. Sr and Nd isotopic compositions were determined at the Laboratório de Geologia Isotópica da Universidadede Aveiro, Portugal. The selected powdered samples were dissolved with HF/HNO<sub>3</sub> in Teflon Parr acid digestion bombs at 200 °C for three days. After evaporation of the final solution, the samples

Element	Х	Y	Au (ppb)	Ag (ppm)	As (ppm)	Sb (ppm)	Cu (ppm)	Mo (ppm)	Pb (ppm)	Zn (ppm)
SC-1	58°22′52″E	32°12′04″N	6	0.29	19.5	1.33	41	14.7	19	20
SC-6	58°21′47″E	32°13′41″N	7	0.17	32.6	1.45	24	25.2	7	13
SC-8	58°20′57″E	32°13′48″N	5	0.19	158.2	1.52	71	53.7	48	16
SC-10	58°21′45″E	32°13′21″N	6	0.2	88.2	1.43	75	1.54	16	14
SC-17	58°21′36″E	32°12′47″N	9	0.21	6.2	1.41	25	4.3	8	96
SC-21	58°20′45″E	32°13′11″N	5	0.55	3.9	1.34	24	1.1	4	11
SC-30	58°21′59″E	32°12′18″N	9	0.2	7.8	1.08	13	1.34	8	11
SC-32	58°20′51″E	32°14′13″N	11	0.16	5	1.2	53	3.6	21	24
SC-34	58°21′53″E	32°12′58″N	5	5.7	2.6	1.32	35	4.4	7	16
SC-42	58°21′46″E	32°12′34″N	5	0.16	10.8	1.22	18	2.16	6	8
SC-43	58°22′13″E	32°13′42″N	6	0.18	7.1	1.18	32	5.5	27	146
SC-47	58°21′51″E	32°13′47″N	26	1	150.7	1.82	9	53.2	180	51
SC-61	58°21′36″E	32°13′22″N	14	0.22	44.3	1.68	107	2.25	22	81
SC-67	58°22′17″E	32°12′47″N	5	0.16	6.1	1.18	7	1.59	27	11
SC-69	58°20′42″E	32°12′42″N	8	0.22	6.2	1.12	18	1.81	8	41
SC-72	58°21′57″E	32°13′55″N	6	0.15	29.9	1.22	10	1.63	27	10
SC-75	58°22′12″E	32°13′19″N	5	0.17	12.9	1.11	7	2.19	7	7
SC-80	58°20′27″E	32°14′33″N	278	1.3	13,220	75.9	14,829	149.6	362	743
SC-81	58°20′55″E	32°14′29″N	39	0.61	1010.3	1.42	5000	54	38	312
SC-82	58°20′24″E	32°14′30″N	210	0.52	4462	1.57	7965	46.1	294	233
SC-83	58°20′13.2″E	32°14′35″N	47	0.47	1271.9	1.94	31,976	59.2	96	375
SC-84	58°20′01.5″E	32°14′11″N	82	0.65	1114	3.4	21,256	74	129	422
Sc-85	58°19′41.7″E	32°14′18″N	119	1.25	1765	6.4	15,567	57	168	349
DUP 10	-	-	9	0.2	90.3	1.45	76	1.51	16	13
DUP 83	-	-	53	0.48	1264.7	1.95	31,968	60.5	94	372
STD BLANK	-	-	< 0.005	< 0.01	<0.1	< 0.05	<0.2	< 0.05	<0.2	<2
STD BLANK	-	-	< 0.005	< 0.01	<0.1	< 0.05	<0.2	< 0.05	<0.2	<2
STD OREAS 24b	-	-	< 0.005	0.07	8.1	0.48	36.2	4.17	8.7	101
STD GBM908-10	-	-	0.435	2.93	53.8	1.04	3380.5	66.42	2022	999

were dissolved with HCl (6.2 N) and with acid digestion bombs and were dried again. The elements to be analyzed were purified using conventional ion chromatography technique in two stages: (a) separation of Sr and REE elements in ion exchange column with AG8 50 W Bio-Rad cation exchange resin; (b) purification of Nd from other lanthanides elements in columns with Ln Resin (ElChrom Technologies) cation exchange resin. Sr was loaded with H<sub>3</sub>PO<sub>4</sub> on a single Ta filament, whereas Nd was loaded with HCl on a Ta outer-side filament in a triple filament arrangement. <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd isotopic ratios were determined using a Multi-Collector Thermal Ionization Mass Spectrometer (TIMS) VG Sector 54. Data were acquired in dynamic mode with peak measurements at 1-2 V for <sup>88</sup>Sr and 0.5-1.0 V for <sup>144</sup>Nd. Sr and Nd isotopic ratios were corrected for mass fractionation relative to  ${}^{88}$ Sr/ ${}^{86}$ Sr = 0.1194 and  $^{146}$ Nd/ $^{144}$ Nd = 0.7219. During this study, the SRM-987 standard gave an average value of  ${}^{87}\text{Sr}/{}^{86}\text{Sr} = 0.710261 \pm 17$  (*N* = 13; conf. lim = 95%) and the JNdi-1 standard gave an average value of  $^{143}$ Nd/ $^{144}$ Nd = 0.5121000  $\pm$  86 (N = 12; conf. lim = 95%). The Rb–Sr and Sm–Nd isotope compositions are listed in Tables 4 and 5.

## 4. Petrography

#### 4.1. Biotite quartz monzonite

This rock has a granular texture. The main minerals are 45 vol% plagioclase, nearly 20 vol% biotite, 10–15 vol% K-feldspar, 10–15 vol% quartz and <5 vol% hornblende (Fig. 3a). Its accessory minerals are magnetite (3 vol%), apatite and zircon. Biotite quartz monzonite altered to QSP and argillic in a widespread range and non-altered outcrops only existed in the eastern part of the area where the samples were taken. In non-altered rocks low amounts of sericite, epidote and calcite exist as secondary minerals. Plagioclase is partially altered to small amounts



**Fig. 3.** Microphotographs of thin section of intrusive rocks; (a) Biotite quartz monzonite with granular texture. (b) Hornblende and plagioclase with granular texture in hornblende diorite. (c) Hornblende and plagioclase phenocrysts and magnetite microphenocrysts in hornblende diorite porphyry. (d) Plagioclase and hornblende phenocrysts in groundmass of quartz, plagioclase in hornblende quartz diorite porphyry. (e) Hornblende phenocryst with poikilitic texture in a microlitic groundmass of hornblende microdiorite porphyry. Pl, plagioclase; Hbl, hornblende; Bt, biotite; Kfs, K-feldspar; Qtz, quartz; Ep, epidote, Mgt, magnetite. (mineral abbreviations from Whitney and Evans, 2010).



Fig. 4. Alteration map of SWSK area.

	Early Late											
Minerals	QSP Alteration		Disseminated (diorite group)	Vein-type mineralization	Oxidized zone							
	Disseminated Stockwork											
Pyrite												
Chalcopyrite												
Quartz			-									
Sericite		-	-									
Clay M.												
Carbonate M.												
Chlorite												
Epidote												
Chalcocite												
Covellite												
Hematite												
Goethite												
Malachite												
Azurite												
Mn-oxide												

Table	2
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Whole-rock major and trace element compositions of SWSK intrusive rocks.

Sample no.	S-16	S-22	S-23	S-25	S-26	S-33	S-35	S-38	S-46
Х	58°21′51.7″E	58°22′0″E	58°21′53″E	58°20′21″E	58°22′25″E	58°20′35″E	58°20′24″E	58°21′52″E	58°20′16″E
Y	32°12′18″N	32°12′44″N	32°12′41″N	32°13′33″N	32°13′21″N	32°13′44″N	32°13′59″N	32°13′11″N	32°14′18″N
Rock type	5	2	3	3	4	5	4	2	2
Wt%									
SiO <sub>2</sub>	60.01	59.39	60.58	59.85	60.57	59.61	60.24	58.75	56.12
TiO <sub>2</sub>	0.618	0.551	0.501	0.686	0.474	0.639	0.457	0.669	0.523
Al <sub>2</sub> O <sub>3</sub>	17.76	18.24	17.91	17.64	17.83	18.12	17.81	18.13	18.24
FeOt	5.89	5.28	5.18	5.74	5.68	5.98	5.41	5.95	6.72
MnO	0.18	0.11	0.12	0.115	0.087	0.214	0.05	0.088	0.14
MgO	2.19	2.19	2.57	2.92	2.98	2.33	2.86	2.64	4.28
CaO	6.14	6.34	5.63	6.02	5.56	6.17	4.21	6.68	6.11
Na <sub>2</sub> O	3.12	3.07	2.89	2.62	2.72	2.89	3.57	3.01	3.25
K <sub>2</sub> O	1.68	2.11	1.89	1.53	2.18	1.84	2.42	2.19	1.15
P <sub>2</sub> O <sub>5</sub>	1.69	0.000	2.45	0.071	1.84	0.075	2.61	0.074	0.074
Total	99.86	99.67	99.8	99.6	100.0	1003	99.7	100 7	99.5
Total	55.00	55.07	55.0	55.0	100.0	100.5	55.7	100.7	55.5
ppm									
Ba	533	579	515	534	603	582	759	568	337
Co	1/	16	15	16.3	15.2	17.6	12	17.2	13.8
Cs Ca	2	4.9	3.Z	4.1	2.0	2.3	10.5	4.3	3.1 147
Ga Hf	35	3.8	15	14.5	28	14.0	3	3 1	14.7
Nb	5.8	73	59	62	53	61	54	68	57
Rb	53	77	71	72.8	69.3	51.3	72	76.3	48.6
Sr	491	471	399	404.2	544.6	493.7	678	474.9	498.6
Та	0.4	0.6	0.6	0.5	0.3	0.5	0.4	0.5	0.3
Th	6	7.5	7.6	7.9	6.3	5.8	7.3	7.8	5.2
U	1.8	2.9	2.1	2.6	2.2	2.1	2.5	2.7	1.8
V	178	149	135	139	142	183	141	153	173
W	1.5	1.8	1.4	0.8	1.1	1.3	< 0.5	1.7	0.5
Zr	139	152	152	144.2	109.5	136.3	117	150.3	116.5
Y	23	23	22	21.7	16.4	22.7	17	22.9	18.1
Ld	17	20	19	10.9	17.1	15.4	17	19.7	15.3
Pr	3.65	432	4	4 12	3 28	3 72	31	4 15	3 11
Nd	15.5	17.1	15.3	16.7	13.4	14.9	12.6	16.8	11.8
Sm	3.54	3.84	3.31	3.44	2.27	3.62	2.61	3.65	2.62
Eu	1	1.15	0.92	0.86	0.85	1.06	0.81	1.37	0.95
Gd	3.96	4.11	3.62	3.14	2.75	3.68	2.82	4.06	2.68
Tb	0.61	0.61	0.57	0.45	0.52	0.63	0.43	0.54	0.37
Dy	3.86	3.72	3.8	4.06	3.07	3.71	2.9	3.58	3.22
Но	0.76	0.77	0.76	0.73	0.65	0.78	0.54	0.69	0.61
Er	2.32	2.32	2.24	2.62	1.93	2.38	1.7	2.57	1.72
lm Vh	0.33	0.33	0.35	0.36	0.28	0.31	0.24	0.35	0.34
YD Lu	2.25	2.2	2.14	2.37	0.24	2.27	1./	2.05	1.88
Lu	0.50	0.57	0.54	0.52	0.24	0.52	0.27	0.20	0.57
Ratio									
K <sub>2</sub> O/Na <sub>2</sub> O	0.54	0.69	0.65	0.58	0.8	0.64	0.68	0.73	0.35
Eu/Eu*	0.82	0.89	0.81	0.8	1.04	0.89	0.91	1.09	1.1
$(Ld/YD)_N$ $(Ce/Yb)_N$	5.03 3.76	0.28	0.05	4.81	0.95 5.08	4.57	0.08	0.48 5.02	5.49 3.01
Sample no	S-49	4.55 S-63	4.58 S-67	S-84	S-102	S-104	4.38 S-105	S-119	S-127
	50°20/21 15″F	50°22/21//F	50000000	500/22//5	50021/10//5	50821/22//5	50°21/40″E	50°22/10″F	50°22/16//F
X	58 20'21.15"E 32°13/33"N	58 22'21"E 32°13/33"N	58 22'26"E 32°13/27"N	58 20'32"E 32°13/30"N	58 21/18"E 32°12/42"N	58 21'32"E 32°12/24"N	58 21/48″E 32°12/34″N	58 22' 10"E 32°13/06"N	58 22'16"E 32°13/31"N
Rock type	2	1	1	3	4	5	3	3	5
Wt%	57.01	c2 7 1	62.00	50.75	61.05	50.61	60.07	50.50	CO 1 1
S10 <sub>2</sub>	57.21	63./4	63.88	59.75	61.37	59.61	60.87	59.58	60.14
	18 /3	0.372	0.403	0.484	17 00	0.470	0.433	0.512 1814	0.463
FeO.	6.42	5.23	5.83	5.61	5.31	5.45	5.21	5.47	5.93
MnO	0.06	0.28	0.216	0.128	0.1	0.17	0.10	0.128	0.17
MgO	3.89	0.93	1.17	3.14	2.68	3.24	3.15	3.27	3.08
CaO	5.24	3.78	3.72	4.58	5.24	3.83	4.78	5.12	3.62
Na <sub>2</sub> O	3.67	3.85	3.75	3.34	2.88	3.15	3.11	2.99	3.19
K <sub>2</sub> O	0.89	1.65	1.59	2.03	2.11	2.42	2.41	2.56	2.63
$P_2O_5$	0.067	0.055	0.058	0.059	0.059	0.064	0.051	0.062	0.058
L.O·I	2.25	3.12	2.96	2.74	1.45	2.82	1.85	2.08	1.61
Total	99.63	99.61	97.8	99.9	99.65	99.75	99.83	99.9	98.57
ppm									
Ва	359	2514	1745	684	558	600	582	567	546

(continued on next page)

Table 2	(continued
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Sample no.	S-49	S-63	S-67	S-84	S-102	S-104	S-105	S-119	S-127
Со	13	5	9.3	14.2	15	17	15	16.5	15.1
Cs	2.3	80	76.7	12.3	2.2	6.1	5.6	4.2	8.3
Ga	15	12	12.4	14.8	15	16	15	15.3	15.6
Hf	3.2	3.8	3.5	3.6	3.1	3	3.2	3.6	3.4
Nb	5	6.6	6.9	4.7	5.7	5.8	5.7	5.2	6.1
Rb	46	34	31.4	68.3	66	90	82	77.6	83.4
Sr	492	916	906.7	683.8	531	555	559	538.6	542.5
Та	0.4	0.3	0.3	0.3	0.4	0.4	0.5	0.3	0.5
Th	5.9	4.2	3.9	6.9	6.7	6.1	6.4	5.1	6.7
U	2.3	1.6	1.7	2.3	2.4	2.2	2.2	1.9	1.8
V	165	50	47	154	136	147	154	166	134
W	0.8	0.5	0.5	0.6	1	1.1	0.8	1.3	1.6
Zr	120	179	173.6	114.5	117	125	127	122.3	129.2
Y	17	14	13.2	16.7	17	17	17	15.4	16.1
La	14	24	22.1	16.9	16	17	18	30.7	30.4
Ce	24	42	41.7	33.2	30	30	32	16.2	17.3
Pr	2.81	4.38	4.12	3.24	3.19	3.22	3.44	3.18	3.28
Nd	11.5	15.7	16.08	12.19	12.1	13	13.1	12.04	12.5
Sm	2.79	2.56	2.37	2.78	2.63	2.8	2.78	2.66	2.71
Eu	0.86	1.32	1.34	0.75	0.83	0.81	0.85	0.93	0.86
Gd	2.93	2.55	2.68	2.69	2.88	2.93	2.91	2.97	2.67
Tb	0.46	0.36	0.34	0.41	0.45	0.45	0.47	0.44	0.43
Dy	2.98	2.26	2.45	3.13	2.89	2.96	2.92	3.01	2.86
Но	0.59	0.47	0.54	0.49	0.61	0.56	0.6	0.57	0.58
Er	1.8	1.42	1.45	1.78	1.85	1.64	1.72	1.73	1.57
Tm	0.28	0.22	0.26	0.21	0.27	0.26	0.25	0.29	0.29
Yb	1.86	1.49	1.37	1.61	1.75	1.71	1.75	1.68	1.67
Lu	0.28	0.23	0.21	0.31	0.27	0.28	0.28	0.23	0.26
Ratio									
K <sub>2</sub> O/Na <sub>2</sub> O	0.24	0.42	0.42	0.6	0.73	0.76	0.77	0.85	0.82
Eu/Eu*	0.92	1.51	1.63	0.84	0.92	0.86	0.91	1.1	0.98
(La/Yb) <sub>N</sub>	5	9.63	10.88	7.08	6.32	6.66	6.78	6.18	6.5
(Ce/Yb) <sub>N</sub>	3.38	6.69	7.87	5.33	4.43	4.52	4.76	4.73	4.71

of sericite and calcite. Also biotite and hornblende is altered to small amounts of epidote.

## 4.3. Hornblende diorite porphyry

# 4.2. Hornblende diorite

The hornblende diorite has a granular texture containing up to 65 vol% plagioclase and 30 vol% hornblende (Fig. 3b). Its accessory minerals are commonly euhedral to subhedral magnetite (3 vol%) and zircon. Plagioclase and hornblende are replaced by minor chlorite and calcite.

The hornblende diorite porphyry has a porphyritic texture (0.1–0.3 mm) with medium-grained groundmass and 50 vol% phenocrysts, including 35 vol% plagioclase and 15 vol% hornblende (Fig. 3c). The same minerals are also present in the groundmass. Its accessory minerals are quartz, zircon and magnetite (2–3 vol% and 0.2 mm). There was no alteration in hornblende diorite porphyry but in some places,



Fig. 6. Geochemical classification of SWSK intrusive rocks (Middlemost Eric, 1985), according to  $Na_2O + K_2O$  vs. SiO<sub>2</sub> that plot on diorite and granodiorite field.



**Fig. 7.** Molecular A/CNK [ $Al_2O_3/(Ca + CNa_2 + CK_2O)$ ] vs SiO<sub>2</sub> (wt%) diagram (Shand, 1974) of SWSK plot in metaluminous to peraluminous field.



Fig. 8.  $K_2O$  vs. SiO<sub>2</sub> diagram of SWSK intrusive rocks (Rickwood, 1989) with boundaries by for high-K, and medium-K series.

especially in contact to biotite quartz monzonite, plagioclase and hornblende were replaced by sericite, calcite and epidote.

## 4.4. Hornblende quartz diorite porphyry

The hornblende quartz diorite porphyry has a porphyritic texture (0.15–0.2 mm) with a fine-grained groundmass. This rock consists of 30 vol% phenocrysts including 15 vol% plagioclase, 8–10 vol% hornblende and 5–7 vol% quartz (Fig. 3d). Its groundmass consists of quartz and hornblende. Its accessory minerals are biotite and magnetite (2 vol% and 0.02 mm). Plagioclase phenocrysts have been partially altered to small amounts of sericite and carbonate minerals.

## 4.5. Hornblende microdiorite

This rock has a porphyritic and poikilitic texture (0.5–3 mm) with micro granular groundmass and 35–37 vol% phenocrysts, including 25 vol% plagioclase, 10 vol% hornblende and 2–3 vol% clinopyroxene. Plagioclase (Fig. 3e), hornblende and magnetite are also present in the groundmass. Its accessory minerals are apatite and zircon. Hornblende diorite had no alteration but in mineralization zone plagioclase altered to carbonate minerals and hornblende altered to chlorite and epidote.

## 5. Alteration and mineralization

#### 5.1. Alteration

Based on field and petrography results, the alteration intensity of the biotite guartz monzonite and diorite intrusive bodies host to mineralization has been represented by three groups of strongly (>50%), moderately (~10-50%), and weakly (<10%) altered rocks. The same hydrothermal alteration effects are also manifest in all exposed volcanic and subvolcanic rocks at SWSK prospect area covering an extent of ca. 25 km<sup>2</sup>. The main alteration types include propylitic, argillic, carbonate, QSP alterations as well as silicification (Fig. 4). QSP is the most widespread alteration type intensely affecting biotite quartz monzonite so that a very small amount of the original rock has been preserved in some sparse outcrops. The QSP alteration minerals, i.e. sericite and pyrite, are in turn extensively replaced at the surface by supergene argillic alteration minerals dominated by guartz and clay minerals in addition to Fe-oxyhydroxides. Where there is a local dominance of quartz over clay minerals, the argillic alteration grades turn into silica alteration. The propylitic alteration consists of chlorite and epidote as the major minerals overprinting the QSP alteration but is mainly associated with diorites and volcanic rocks in the area. As is explained in detail elsewhere in this paper, the diorite bodies post-date the biotite guartz monzonite and the associated OSP alteration which is in turn preceded by the formation of volcanic rocks as the oldest lithological units in the study area. All of the alteration types described show an association with carbonate minerals, largely calcite, selectively replacing plagioclase and hornblende in dioritic and volcanic rocks.

## 5.2. Mineralization

The three main mineralization styles include disseminated, stockwork and vein. According to polished and thin section examinations, the disseminated and stockwork mineralization types in QSP alteration in altered biotite quartz monzonite consist mainly of quartz (15-20 vol%) and pyrite (2-3 vol%) in addition to hematite and goethite (5-7 vol%). The results of ICP-OES analysis of the disseminated mineralization in these rocks show a minor Cu anomaly up to 100 ppm. Considering that no detectable Cu minerals were recognized by ore microscopy, the copper anomaly is presumed to be present as Fe substitutions in Fe-oxyhydroxides. However, the presence of submicroscopic chalcopyrite is not rejected. Disseminated mineralization in hornblende diorite contains pyrite (2–3 vol%) and chalcopyrite (1–2 vol%). The veintype mineralization cross-cuts the disseminated mineralization with NW-SE trend. The vein-type mineralization includes quartz, chalcopyrite, pyrite, and secondary Cu-Fe minerals such as chalcocite, covellite, malachite, azurite, hematite, and goethite. Fig. 5 shows the paragenetic mineral assemblages in SWSK.



Fig. 9. Chondrite-normalized REE (a) and primitive-mantle-normalized multi-element (b) diagrams for biotite quartz monzonite in SWSK. Normalizing values are from Boynton (1984) and Sun and McDonough (1989), respectively.



Fig. 10. Chondrite-normalized REE (a) and primitive-mantle-normalized multi-element (b) diagrams for diorite group in SWSK. Normalizing values are from Boynton (1984) and Sun and McDonough (1989), respectively.

#### 6. Results

#### 6.1. Ore geochemistry

The results of 23 samples of alteration and mineralized zone analyzed for 35 trace elements by ICP-OES are listed in Table 1. Out of the 35 elements reported, only the 8 target elements of Au, Ag, As, Sb, Cu, Mo, Pb and Zn are discussed here. Apart from the major oxide forming the structure of silicate and oxide minerals, these target elements are going to be the most abundant trace elements in the mineralized samples. This constitutes the economic metals of Au, Ag and Mo found with Cu along with the associated path finder elements As, Sb, Pb and Zn.

The Cu contents (Table 1) reach up to 3% in vein-type mineralization. In contrast, the disseminated mineralization associated with QSP alteration has Cu contents up to 100 ppm. Au contents are negligible in both mineralization types ranging from 5 and 278 ppb with vein-type mineralization bearing the highest concentrations at a minimum of 39 ppb. The highest value in disseminated mineralization is 26 ppb. A high degree of correlation was observed between Cu and Au (0.7) indicating a co-genetic relationship. Au is most probably hosted by chalcopyrite as submicroscopic inclusions requiring a close examination in BSE images for confirmation. Some samples from the vein-type mineralization also show high values in terms of such elements as Ag (0.16-5.7 ppm), Mo (1–150 ppm), As (3 ppm-up to 1%), and Sb (1–75 ppm). Similar to QSP alteration disseminated mineralization, the vein-type mineralization has relatively high values of Pb (4–362 ppm) and Zn (7-743 ppm) in comparison with disseminated mineralization in diorite.

#### 6.2. Geochemistry of the host intrusive rocks

18 whole-rock samples from the SWSK pluton-subvolcanic rocks were analyzed for their major and trace element contents (Table 2). SiO<sub>2</sub> contents of intrusive rocks are from 55 to 63.7 wt% and have been plotted mainly in the fields of granodiorite, and diorite of the Middlemost (1985) diagram (Fig. 6). In the molecular diagram of Al<sub>2</sub>O<sub>3</sub>/(CaO + K<sub>2</sub>O + Na<sub>2</sub>O), i.e. A/CNK, versus that of SiO<sub>2</sub> (Fig. 7), the compositions mostly plot into the metaluminous to peraluminous domains of Shand (1974). The plot of K<sub>2</sub>O vs. SiO<sub>2</sub> (Rickwood, 1989) indicates that intrusive rocks plot in the field of high-K calc-alkaline and calc-alkaline magmas (Fig. 8). The K<sub>2</sub>O/Na<sub>2</sub>O ratio is from 0.24 to 0.86 (Table 2).

The chondrite-normalized (Boynton, 1984) rare earth element samples are characterized by relatively flat heavy rare earth elements (HREE) and there is a significant enrichment in light rare earth elements (LREE), with  $(La/Yb)_N$  values of 4.57–7.08 in diorite group and 9.6–10.9 in biotite quartz monzonite.

Diorite group shows slightly positive Eu anomalies ( $Eu/Eu^* = 0.8-1.1$ ) and biotite quartz monzonite has clear positive Eu anomalies ( $Eu/Eu^* = 1.51-1.63$ ; Figs. 9 and 10), and these intrusive rocks contain high concentrations of Sr (400–916 ppm).

In the primitive-mantle-normalized trace-element spider diagrams (Sun and McDonough, 1989), all of the intrusive rocks are enriched in large ion lithophile (LILE, Cs, Ba, K), and are strongly depleted in high field strength elements (HFSE, Nb, P, Ti) compared to the primitive mantle (Figs. 9 and 10). These features are typical of subduction related magmas in the calc-alkaline volcanic arcs of continental active margins (Gill, 1981; Pearce, 1983; Walker et al., 2001; Wilson, 1989).



Fig. 11. Representative cathodoluminescence (CL) images of zircons from the SWSK intrusive rocks; (a) S-63 and (b) S-16.

Table 3
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Summary of zircon U-Pb ages of the intrusive rocks from the SWSK area.

Analysis	U2 <sup>38</sup>	Th <sup>232</sup>	<sup>207</sup> Pb/ <sup>206</sup> Pb	± (%)	<sup>238</sup> U/ <sup>206</sup> Pb	± (%)	<sup>206</sup> Pb/ <sup>238</sup> U	± (%)	Best age	$\pm$ (Ma)
	(ppm)	(ppm)							(Ma)	
S-16 (hornble	nde diorite por	phyry)								
S16-1	1007	628	0.0473	0.0018	336.12	2.5	0.0030	1.8	19.1	0.3
S16-2	1048	632	0.0474	0.0017	325.16	2.1	0.0031	1.6	19.8	0.3
S16-3	968	621	0.0476	0.0035	313.23	4.7	0.0032	1.7	20.3	0.5
S16-4	1084	649	0.0472	0.0049	330.77	5.9	0.0030	3.6	19.3	1.0
S16-5	734	341	0.0467	0.0021	338.52	2.6	0.0030	2.2	18.9	0.6
S16-6	983	569	0.0477	0.0036	315.91	1.9	0.0032	1.5	20.2	0.5
S16-7	421	168	0.0521	0.0045	320.65	4.5	0.0031	3.4	19.7	0.7
S16-8	1006	575	0.0477	0.0043	306.01	2.7	0.0033	1.4	21.1	0.6
S16-9	743	338	0.0493	0.0023	308.34	2.1	0.0032	1.5	20.9	0.4
S16-10	1157	720	0.0462	0.0034	325.37	2.7	0.0031	2.3	19.6	0.5
S16-11	834	372	0.0471	0.0058	328.82	3.1	0.0030	1.9	19.4	0.6
S16-12	506	212	0.0514	0.0062	292.79	4.8	0.0034	3.6	22.4	0.3
S16-13	984	476	0.0479	0.0043	301.62	3.3	0.0033	2.8	20.6	0.5
S16-14	1120	687	0.0499	0.0043	326.43	2.8	0.0031	1.4	19.6	0.5
S-63 (biotite q	uartz-monzoni	ite)								
S63-1	2119	6392	0.0468	0.0011	168.60	2.53	0.0059	1.5%	38.1	0.6
S63-2	82	74	0.0413	0.0044	164.07	5.24	0.0061	3.2%	39.2	1.3
S63-3	158	86	0.0948	0.0054	150.49	3.59	0.0066	2.4%	40.1	1.0
S63-4	227	102	0.0559	0.0029	158.14	3.36	0.0063	2.1%	40.2	0.9
S63-5	149	116	0.0474	0.0030	159.75	4.05	0.0063	2.5%	40.2	1.0
S63-6	127	105	0.0489	0.0033	158.59	3.98	0.0063	2.5%	40.4	1.0
S63-7	161	132	0.0418	0.0043	157.84	5.65	0.0063	3.6%	40.7	1.5
S63-8	117	76	0.0409	0.0030	156.89	4.16	0.0064	2.7%	41.0	1.1
S63-9	89	70	0.0534	0.0046	155.55	4.64	0.0064	3.0%	41.0	1.2
S63-10	277	211	0.0588	0.0034	154.19	3.71	0.0065	2.4%	41.0	1.0
S63-11	96	84	0.0602	0.0047	153.82	4.33	0.0065	2.8%	41.1	1.2
S63-12	77	62	0.0508	0.0041	155.35	4.60	0.0064	3.0%	41.2	1.2
S63-13	328	343	0.0572	0.0022	153.36	2.95	0.0065	1.9%	41.4	0.8
S63-14	119	77	0.0440	0.0044	153.04	4.69	0.0065	3.1%	42.0	1.3
S63-15	499	306	0.0572	0.0022	150.79	2.56	0.0066	1.7%	42.1	0.7
S63-16	130	110	0.0494	0.0048	145.08	4.92	0.0069	3.4%	44.1	1.5
S63-17	158	118	0.0484	0.0027	141.95	3.58	0.0070	2.5%	45.2	1.1

The low Nb and Ti contents of intrusive rocks are believed be due to the presence of Ti (Nb) minerals (rutile and ilmenite) in the residue left in the source area of the parental magmas (Martin, 1999; Pearce and Parkinson, 1993; Reagan and Gill, 1989). P depletion content may also be considered as the presence of apatite and enrichment of Ba due to the K-feldspar melting in the mantle source rocks (Gust et al., 1997; Woodhead et al., 1993). Zr/Nb ratios (21–24) and depletion in Nb are related to the crust contamination.

# 6.3. Geochronology

U–Pb ages of intrusive rocks from SWSK were determined on zircons separates from two representative source rock: samples (1) hornblende diorite porphyry (sample no. S-16), and sample (2) biotite quartz monzonite (sample no. S-63). In all the samples the zircon grains are fine to medium size (50–150 µm), prismatic and colorless. CL imaging indicates that most grains are not complex with only minor abundances of composite zircon crystals (Fig. 11). Average <sup>238</sup>U and Th<sup>232</sup> are 900 and 499 ppm for hornblende diorite porphyry, and 289 and 498 ppm for biotite quartz monzonite. Also the average of <sup>206</sup>Pb/<sup>238</sup>U and <sup>207</sup>Pb/<sup>206</sup>Pb ratios are 0.044 and 0.67 for hornblende diorite porphyry and 0.11 and 0.89 for biotite quartz monzonite respectively. Our preferred <sup>207</sup>Pb/<sup>206</sup>Pb ages of the hornblende diorite porphyry and biotite quartz monzonite are 20 Ma (MSWD = 1.9, n = 14 total spots) and 40 Ma (MSWD = 1.6, n = 17), respectively. A summary of ages with associated statistics is given in Table 3, and the Tera-Wasserberg U–Pb Concordia diagram and weighted mean ages are shown in Figs. 12 and 13. In addition, the U–Th–Pb zircon dating shows that biotite quartz



Fig. 12. Zircon U-Pb plots of isotopic data (10 confidence level) for hornblende diorite porphyry: (a) concordia diagram, and (b) average age plot.



Fig. 13. Zircon U-Pb plots of isotopic data (10 confidence level) for biotite quartz monzonite: (a) concordia diagram, and (b) average age plot.

monzonite intruded in the upper Eocene (Bartonian) and in the lower Miocene (Aquitanian) hornblende diorite porphyry intruded within previous plutonic and volcanic rocks.

## 6.4. Sr-Nd isotopes

The results of the Rb-Sr and Sm-Nd isotopic analyses are given in Tables 4 and 5. Present day <sup>87</sup>Sr/<sup>86</sup>Sr ratios from the hornblende diorite samples are between 0.7056 and 0.7063 and the <sup>87</sup>Rb/<sup>86</sup>Sr ratios are between 0.308 and 0.315. The Sr isotope ratio for the biotite quartz monzonite is 0.7067 with <sup>87</sup>Rb/<sup>86</sup>Sr ratio of 0.107. The <sup>143</sup>Nd/<sup>144</sup>Nd ratios for hornblende diorite samples are between 0.51268 and 0.51273, and <sup>143</sup>Nd/<sup>144</sup>Nd ratio for biotite quartz monzonite is 0.5125. Recalculated to the age of crystallization of the hornblende diorite at 20 Ma and biotite.

quartz monzonite at 40 Ma, the  $\varepsilon$ Nd values for hornblende diorite samples range from 0.97 to 1.88, and the  $\varepsilon$ Nd value for biotite quartz monzonite is -0.33 (Table 5). These values, together with the individual initial  ${}^{87}$ Sr/ ${}^{86}$ Sr values as shown in Fig. 14, have been plotted to the right part of the mantle array.

1 = Bt Quartz Monzonite, 2 = Hbl Quartz Diorite porphyry, 3 = Hbl Microdiorite, 4 = Hbl Diorite, 5 = Hbl Diorite porphyry.

## 7. Discussion

## 7.1. Mineralization in the SWSK area

Copper-gold mineralization at the SWSK prospect is spatially and temporally associated with magnetite-series subvolcanic calc-alkaline rocks i.e. biotite quartz monzonite and hornblende diorite. The biotite quartz monzonite intrusions caused extensive QSP alteration in the host volcanic rocks and the plutonic body itself which is associated with disseminated Cu mineralization largely as weak Cu anomalies consisting of secondary Cu-Fe minerals. The hornblende diorite bodies are similarly associated with disseminated Cu mineralization which is in contrast dominated by hypogene ore minerals such as chalcopyrite and pyrite.

#### Table 4

Rb-Sr isotopic compositions of the hornblende diorite and biotite quartz monzonite in SWSK.

Sample no.	Age (Ma)	Rb (ppm)	Sr (ppm)	<sup>87</sup> Rb/ <sup>86</sup> Sr	Error (2 s)	<sup>87</sup> Sr/ <sup>86</sup> Sr	( <sup>87</sup> Sr/ <sup>86</sup> Sr) <sub>i</sub>
S16	20.1	53.5	491	0.315	0.000021	0.705611	0.705521
S35	~20.1	72.3	678	0.308	0.000023	0.706315	0.706227
S63	40.16	33.8	916	0.107	0.000018	0.706692	0.706631

The vein-type mineralization clearly post-dates the QSP mineralization noting the cross-cutting relationship between the diorite and the QSP alteration and that between the vein-type mineralization and host diorites. As noted above, this mineralization is to be with relatively high Cu, As, Mo, Pb, Zn and Au contents.

The difference in metal content between the vein-type mineralization with disseminated mineralization in hornblende diorite could be explained by the concentration mechanism of ore fluids depositing the metals leached out from large volumes of low grade mineralization into fractures as structural controls for vein-type mineralization.

#### 7.2. Petrogenesis and tectonic setting of intrusive rocks in SWSK area

Based on the geochemical and U–Pb age data (Tables 2 and 3), there are two groups of magmatic activity in 40 Ma (biotite quartz monzonite) and 20 Ma (diorites) for the intrusive rocks in SWSK area. The diorite group is in turn subdivided into hornblende diorite, hornblende microdiorite, hornblende diorite porphyry, and hornblende quartz diorite porphyry. From the chemical point of view, these intrusive rocks are plotted in the fields of metaluminous to peraluminous granitoids (A/ CNK = 0.95–1.25) (Shand, 1974), and in the high-K calc-alkaline and calc-alkaline series using K<sub>2</sub>O vs. SiO<sub>2</sub> diagram (Rickwood, 1989). The high A/CNK values in the two samples can be due to the relatively little alteration effects they have received. Chemical composition of the SWSK intrusive rocks has an affiliation to the I-type granitoid series using Chappell and White (1974) diagram.

High-K, calc-alkaline, and I-type granitoids are common in the continental crust (Roberts and Clemens, 1993) and are formed in a continental collision or subduction zone tectonic setting (Pitcher et al., 1985). The SWSK intrusive rocks are plotted almost in the fields of the volcanic arc granites in the diagrams proposed by Pearce et al. (1984) (Fig. 15). Fig. 16 shows the schematic model formation of SWSK intrusive rocks in the subduction zone where the oceanic crust of Afghan block was subducted beneath the Lut Block. The first stage of intrusive magmatism was a biotite quartz monzonite formed ca. 40 Ma. The diorite group cross-cut the biotite quartz monzonite in 20 Ma. Replacement of biotite quartz monzonite has itself altered and is the cause of alteration of volcanic host rocks. The final stage of mineralization is veintype mineralization.

Enrichment in LILEs (Cs, Ba, K, and Sr) and LREE, and depletion in HFSE (Nb, P, and Ti) and HREE in these rocks hint to a subduction zone. A Ti–Nb negative anomaly associated with the SWSK rocks is typical of calc-alkaline magmas and is caused by the existence of residual hornblende and/or Fe–Ti oxides (rutile, ilmenite) in the magma source region (Reagan and Gill, 1989; Pearce and Parkinson, 1993; Martin, 1999). The phosphorous negative anomaly might be due to apatite fractionation.

Table 5
Sm-Nd isotopic compositions of the hornblende diorite and biotite quartz monzonite.

Sample no.	Age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}{\rm Sm}/^{144}{\rm Nd}$	Error (2 s)	$^{143}Nd/^{144}Nd$	$(^{143}Nd/^{144}Nd)i$	εNd
S16	20.1	3.54	15.5	0.138	0.007	0.512727	0.512709	1.88
S35	~20.1	2.61	12.6	0.125	0.007	0.512678	0.512662	0.97
S63	40.16	2.56	15.9	0.097	0.005	0.512595	0.512569	-0.33

The positive Eu anomalies in intrusive rocks, most pronounced in biotite quartz monzonite, are either due to the accumulation of plagioclase in these rocks which incorporated most of Eu as a substitute for Ca in the crystal structure; the scarcity of plagioclase in the source mantle rocks or high oxygen fugacities (i.e. oxidizing conditions) during partial melting (Rollinson, 1993).

Mantle-derived magmas are amenable to crustal contamination during ascent (Mohr, 1987). The initial <sup>87</sup>Sr/<sup>86</sup>Sr and ɛNd values of hornblende diorite, hornblende diorite porphyry and biotite guartz monzonite from the study area have been plotted in Fig. 14 indicating variable degrees of crust contamination contributing to the final magma composition responsible for these intrusive rocks. Some enrichment in radiogenic Sr may be explained by hydrothermal alteration caused by crustal derived fluids (as in sample S 63). The hornblende diorite is characterized by <sup>87</sup>Sr/<sup>86</sup>Sr ratios of 0.7056 to 0.7063 and positive εNd values (1.88 and 0.97) indicating a source not significantly enriched relative to MORB. In contrast, the Sr-Nd isotope ratios for biotite quartz monzonite show more enrichment because of the more enriched nature of the source mantle rocks relative to MORB and Bulk Earth. Thus, the Sr-Nd isotope characteristics of the SWSK intrusive rocks suggest some crustal contamination with more contamination in biotite quartz monzonite than hornblende diorite, further validated by other geochemical characteristics.

## 7.3. Comparison of SWSK and the Lut Block intrusive rocks

According to previous studies, the Lut Block has a great potential for various types of mineralization due to different tectonic environments and widespread magmatism with various geochemical characteristics in Cenozoic. The composition of these intrusive rocks are diorite, monzonite, quartz monzonite and granodiorite. These intrusive rocks are classified as belonging to magnetite series of oxidant I-type granitoids. In addition they are metaluminous and high-K granitoids which were formed in the subduction zone (Karimpour et al., 2012). An interval spanning from Middle Eocene to Early Oligocene (42–33 Ma) has been suggested for the magmatism and mineralization in the Lut Block. The

Hbl Diorite Porphyry Bt Qtz-Monzonite 3 2 S16 S35 βNG CHUR **Bulk Earth** 0 S63 -1 -2 -3 -5 0.7040 0.7045 0.7050 0.7055 0.7060 0.7065 0.7070 ′Sr/<sup>86</sup>Sr)i

Fig. 14. ENd vs. (87Sr/86Sr)<sub>i</sub> diagram for SWSK intrusive rocks.

initial  ${}^{87}$ Sr/ ${}^{86}$ Sr of the intrusive rocks of the Lut Block ranges from 0.707 to 0.7047. The age and  $({}^{87}$ Sr/ ${}^{86}$ Sr)<sub>i</sub> of intrusive rocks in the Lut Block follow a descending trend southward. The geochemistry of REE and  $\epsilon$ Nd values show crust contamination in the source of magmatism (Karimpour et al., 2012).

Petrological, geochemical and REE analyses of this study are consistent with other Tertiary intrusive rocks in the Lut Block, with few differences such as peraluminous and positive Eu anomalies in SWSK area.

The zircon U-Pb dating data likewise confirms the occurrence of intrusive rocks associated with mineralization with an age around 40 Ma for biotite quartz monzonite in this part of the Lut Block. However, the zircon U-Pb age data of 20 Ma for diorites extend the span of mineralization events to Early Miocene times and significantly post-date the previously reported interval of Middle Eocene to Early Oligocene (42-33 Ma.) for magmatism and the associated mineralization events in the Lut Block. In Fig. 17 and Table 6, the locations of some of the porphyry copper and epithermal deposits in the Lut Block have been shown along with the age data and initial Sr isotopes for representative intrusive rock samples. According to these data, biotite quartz monzonite in SWSK is comparable in geochemistry, lithology and age to other intrusive rocks related to copper porphyry deposits in the Lut Block. However, this is not the case with the diorite group rocks, containing disseminated and vein-type mineralization, which show a significantly younger age.

Based on the mineralization, alteration, geochemical and isotopic data in this study for the intrusive rocks in SWSK, it can be concluded that the formation of the intrusive rocks in SWSK is approximately synchronous with the formation of major intrusions in the Lut Block (Karimpour et al., 2012). In addition, a direct relationship is presumed between the occurrence of intrusive bodies and the mineralization events. Biotite quartz monzonite bodies are largely responsible for the occurrence of alteration and mineralization in the SWSK area.



**Fig. 15.** Tectonomagmatic discrimination diagrams for the SWSK intrusive rocks (Pearce et al., 1984) WPG: within-plate granitoids; VAG: volcanic arc granitoids; ORG: ocean ridge granitoids; syn-COLG: syncollisional granitoids.



Fig. 16. Simplified schematic model of forming the intrusive rocks of SWSK area. 1) biotite quartz monzonite and 2) diorite group.

# 8. Conclusions

- The mineralization styles and the associated alterations, especially the close relationship between high Cu and related anomalies of elements with QSP alteration zones within biotite quartz monzonite bodies share many similarities with porphyry copper deposits systems.
- 2) The analysis of Zircon U-Pb dating results reveals two magmatic events. The age of biotite quartz monzonite is 40 Ma and the second stage of magmatism started with the emplacement of the younger hornblende diorite at 20 Ma. The U-Pb dating on diorite could extend the age of intrusive rocks related to mineralization in 20 Ma (Early Miocene) in the Lut Block
- 3) Geochemical data show that the SWSK intrusive rocks are metaluminous to slightly peraluminous and range from calc-alkaline to high-K calc-alkaline series. The enrichment of LILE (Ba, K, Cs and Sr), depletion of HFSE (Nb, P, Ti) and enrichment of LREE relative to HREE indicate the formation of the source magmas in a subduction zone environment. The high Eu/Eu\* ratios in the diorite group rocks (0.8–0.9) and biotite quartz monzonite (~1.5), and the enrichment of Sr, especially in biotite quartz monzonite (900 ppm), indicate the scarcity of plagioclase and lack of plagioclase in the source mantle rocks for diorite group and biotite quartz monzonite rocks, respectively.
- 4) The ranges of their initial <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd reveal that crustal contamination is the main process in the formation of the intrusive rocks. The ascent of magmas through thickened continental



Fig. 17. Map showing location of intrusive rocks related to porphyry copper deposit within Lut Block (References see Table 6).

Table 6
Lithology, Sr-Nd isotopes and age data of intrusive rocks related to copper porphyry deposits of Lut Block in comparison to SWSK.

Location	Age (Ma)	Rock type	$({}^{87}\mathrm{Sr}/{}^{86}\mathrm{Sr})_i$	$(^{143}Nd/^{144}Nd)_i$	εNd	Reference
Kuh-Robat-Shur	42	Syenite	0.7051	-		Jung et al. 1983
Aghol Kuh	-	Monzonite	0.7048	_		Jung et al. 1983
Kuh Shah	39.7	Diorite	0.7049	0.512644	1.09	Abdi and Karimpour, 2013
Khopik	39	Monzonite	0.7047	0.512662	1.45	Malekzadeh Shafaroudi et al., 2015
Maherabad	39	Monzonite	0.7049	0.512681	1.81	Malekzadeh Shafaroudi et al., 2012
SWSK	40.16	Quartz-monzonite	0.7066	0.512595	-0.33	
SWSK	20.1	Diorite	0.7055-0.7062	0.512662-0.512709	0.97-1.88	
Khunik	38	Diorite	0.7045	_	-	Samiee et al., 2016
Chah-Shaljami	33.3	Monzonite	0.7052	0.512724	2.08	Arjmandzadeh, et al., 2011
Dehsalm	33.6	Diorite-Granite	0.7050	0.51271	1.8	Arjmandzadeh, 2011

crust could have been the cause of crustal contamination resulting in higher Rb/Sr and LILE/HFSE ratios. Furthermore, geochemistry of REE and Sr-Nd isotope results show that biotite quartz monzonite has more crustal contamination and may be affected by hydrothermal alteration of crustal fluids.

5) As mentioned in previous sections, the Lut Block has a great potential for exploring porphyry Cu-Au, IOCG, Fe skarn, Au-Ag epithermal and etc. due to the tectonomagmatic setting and presence of intrusive rocks such as diorite, monzonite, quartz monzonite, and granodiorite. Considering intrusive rocks in SWSK, biotite quartz monzonite is in agreement with an important episode of magmatism and mineralization in the Lut Block (Middle Eocene to Early Oligocene), and also has similar geochemical and isotopic characteristics with other intrusive rocks related to mineralization in the Lut Block. Therefore, biotite quartz monzonite has a mineralization potential in SWSK. This scenario needs more explorations for instance geophysics and core drilling.

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