

ELECTRON MICROPROBE STUDY OF TURQUOISE-GROUP SOLID SOLUTIONS IN THE NEYSHABOUR AND MEYDOOK MINES, NORTHEAST AND SOUTHERN IRAN

ELAHE MANSOURI GANDOMANI AND NEMATOLLAH RASHIDNEJAD-OMRAN[§]

Department of Geology, Tarbiat Modares University, Nasr Bridge, Jalal Ale-Ahmad Highway, Tehran, Iran

AMIR EMAMJOMEH

Department of Earth Science, Faculty of Natural Sciences, University of Tabriz, Tabriz, 29 Bahman Boulevard, Tabriz, Iran

PIETRO VIGNOLA

CNR-Institute of Environmental Geology and Geoengineering, via Mario Bianco 9, 20131 - Milan, Italy

TAHEREH HASHEMZADEH

Department of Geology, Tarbiat Modares University, Nasr Bridge, Jalal Ale-Ahmad Hwy, Tehran, Iran

ABSTRACT

Turquoise, $\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$, belongs to the turquoise group, which consists of turquoise, chalcociderite, aheylite, faustite, planerite, and UM1981-32-PO:FeH. In order to study turquoise-group solid solutions in samples from the Neyshabour and Meydook mines, 17 samples were selected and investigated using electron probe microanalysis. In addition, their major elements were compared in order to evaluate the feasibility of distinguishing the provenance of Persian turquoises. The electron microprobe data show that the studied samples are not constituted of pure turquoise (or any other pure endmember) and belong, from the chemical point of view, to turquoise-group solid solutions.

In a turquoise–planerite–chalcociderite–unknown mineral quaternary solid solution diagram, the chemical compositions of the analyzed samples lie along the turquoise–planerite line with minor involvement of chalcociderite and the unknown mineral. Among light blue samples with varying hues and saturations from both studied areas, planerite is more abundant among samples from Meydook compared with samples from Neyshabour. Nevertheless, not all the light blue samples are planerite. This study demonstrates that distinguishing the deposit of origin for isochromatic blue and green turquoises, based on electron probe microanalysis method and constitutive major elements, is not possible.

Keywords: turquoise, solid solution, planerite, chalcociderite, EPMA, Neyshabour, Meydook, Iran.

INTRODUCTION

Historically, turquoise was known as a precious gemstone. The history of its usage in jewelry and as personal decoration goes back 70 centuries to ancient Egypt (Fritsch *et al.* 1999, Branson 1975, Murthy 1989). Archaeological excavations in the city of Firouzeh (10 km southeast of the Neyshabour mine) indicate that the turquoise was cut at least 3000 years BC (Garazhian & Lotfi-Gharae 2015, Basafa 2016).

Turquoise has many mineral simulants. Some of these, such as faustite, chalcociderite, and planerite, belong to the turquoise group (Foord & Taggart 1998, Murthy 1989), but others, such as variscite, amazonite (a variety of microcline), chrysocolla, brochantite, and chalcantite, are only visually similar to turquoise (Murthy 1989). Since turquoise-group minerals usually occur in massive form or microcrystalline aggregates, a comprehensive bibliography of XRD data including structure determination of single-crystal

[§] Corresponding author e-mail address: Rashid@modares.ac.ir

turquoise does not exist (Cid-Dresdner 1965, Giuseppetti *et al.* 1989, Kolitsch & Giester 2000).

Within recent years, comprehensive studies have been done on the turquoise group in order to build a comprehensive reference database; most of these studies are based on spectroscopic techniques such as Raman, FTIR, and Mossbauer spectroscopies (Frost *et al.* 2006, 2013, Čejka *et al.* 2015, Nikbakht *et al.* 2017, Qiu *et al.* 2017, Wang *et al.* 2017, Rossi *et al.* 2017, Schwarzingner & Schwarzingner 2017).

Turquoise is a hydrated copper aluminum phosphate, $\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$, belonging to the turquoise group; it crystallizes in the triclinic system and mostly appears in cryptocrystalline form (Foord & Taggart 1998). The turquoise group includes endmembers with the general formula $\text{A}_{10}\text{B}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$ (Foord & Taggart 1998, Abdu *et al.* 2011) in which Zn^{2+} , Cu^{2+} , and Fe^{2+} occur at the A site and Al^{3+} , Fe^{3+} , and Cr^{3+} occur at the B site (Foord & Taggart 1998); however, Ca^{2+} and Zn^{2+} can also occur at the A site in some of the rare members of the group (Foord & Taggart 1998). Members of the turquoise group are listed in Table 1 (Foord & Taggart 1998). The color of turquoise usually ranges from light green to dark blue. Differences in Fe and Cu proportions are mentioned by Clark *et al.* (1979) and Crespo-Feo *et al.* (2010) as the reason for the variety of color in turquoise. Abdu *et al.* (2011) attributed the cause to various contributions of Al, Cu, and Fe. Blue turquoises contain Cu^{2+} at the A site and Al^{3+} at the B site, whereas in green samples Fe^{3+} substitutes for Al at the B site (Foord & Taggart 1998). In general, the A site can substitute common cations, such as Cr^{3+} , Mn^{2+} , Mn^{4+} , and rarer ones, such as Ti^{4+} (Crespo-Feo *et al.* 2010).

Since Persian deposits are among the most important and ancient resources of turquoise in the world, the main purpose of this study is to investigate the solid solutions of the turquoise group and related elemental substitutions at the A and B sites, as well as color agents, in turquoise from the Neyshabour and Meydook mines. Based on EPMA non-destructive analysis of the studied samples, accurate major element compositions of turquoise samples from both mines were determined. The present study is expected to form a basis for further research on distinguishing Persian turquoises using major and trace elements.

GEOLOGICAL BACKGROUND

The studied samples were collected from two of the world's most well-known turquoise deposits, the Meydook and Neyshabour mines (Fig. 1). According to Gübelin (1966) and other gemologists, the world's

TABLE 1. TURQUOISE GROUP ENDMEMBERS AND THEIR CHEMICAL FORMULAE (FOORD & TAGGART 1998)

Mineral	Chemical formula	Color	Luster	Hardness
Aheylite	$\text{Fe}^{2+}\text{Al}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4(\text{H}_2\text{O})$	Pale blue, green, and blue-green	Vitreous, dull	5–5.5
Chalcosiderite	$\text{CuFe}^{3+}\text{Al}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4(\text{H}_2\text{O})$	Apple green, dark green	Vitreous, glassy	4.5
Faustite	$(\text{Zn,Cu})\text{Al}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4(\text{H}_2\text{O})$	Apple green	Chalky, earthy, dull	5.5
Planerite	$\text{Al}_6(\text{PO}_4)_2(\text{PO}_3\text{OH})_2(\text{OH})_8 \cdot 4(\text{H}_2\text{O})$	Green, pale blue, green and blue-green, white, olive	Vitreous, dull	5
Turquoise	$\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4(\text{H}_2\text{O})$	Pale green, blue-green, turquoise blue	Waxy	5–6
UM1981-32-PO:FeH	$\text{Fe}^{2+}\text{Fe}^{3+}_6(\text{PO}_4)_4\text{[PO}_3(\text{OH})]_x(\text{OH})_8 \cdot 4\text{H}_2\text{O}$	No information	No information	No information

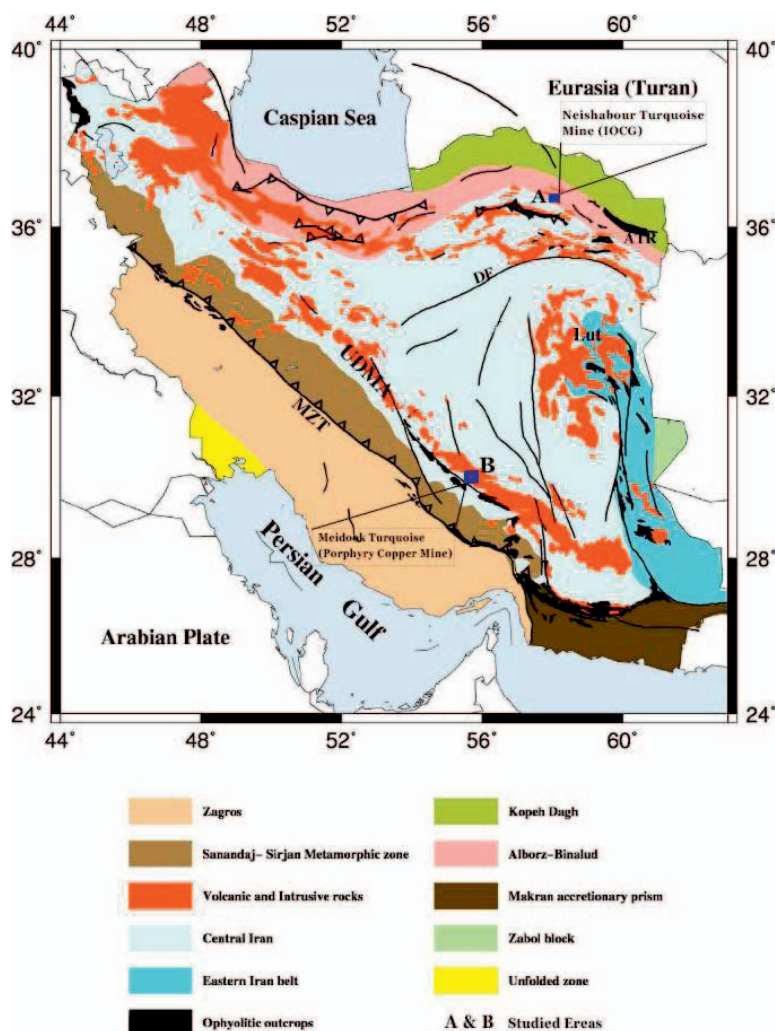


FIG. 1. Geological map of Iran showing the study areas (Aghanabati 2006)

best turquoise in terms of color, quality, and popularity is Persian turquoise derived from the Neyshabour mine, 40 km northwest of Neyshabour, Khorasan Razavi province, northeastern Iran. In this mine, turquoise is extracted from several localities, including those accessed by the Main (Abdar), Zack, and Ghardoum shafts, located in an intrusive-volcanic belt with a northwest–southeast trend (Figs. 2 and 3). The intrusive-volcanic belt can be divided into three lithological units, including (Baumann *et al.* 1984) (1) Eocene trachyte, trachyte-latite, and latite volcanic units in addition to volcanic breccia; (2) porphyry monzodiorite, monzonite, and syenite sub-volcanic intrusive units which are attributed to the post-Eocene due to their intrusion into Eocene volcanic units; (3)

hydrothermal and fault breccias which we know are younger than the other units because volcanic and intrusive fragments are found in the fault breccia. Turquoise occurs as veins and small nodules in all three units (Mansouri-Gandomani 2016). Figure 3 illustrates the geology of the mine area (from Karimpour *et al.* 2012).

Turquoise is being mined as a side product at the Meydook porphyry copper mine, located 132 km north of Shahr-e-Babak, Kerman province, southern Iran (Fig. 1). The mine is located in an area of volcanic and pyroclastic rocks which are intruded by several intrusive bodies. The three main groups of rocks in the area are (Taghipour *et al.* 2008): (1) volcanic rocks, mainly andesite and andesite-basalt; (2) pyro-

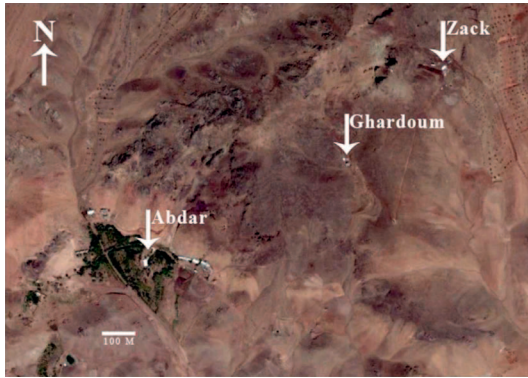


FIG. 2. Satellite image of the Neyshabour turquoise mine illustrating the entrances of the Main, Zack, and Ghardoum shafts.

clastic rocks consisting of gray tuff and agglomerate; and (3) granodioritic igneous intrusive rocks with dikes (Fig. 4). Both volcanic and intrusive rocks have been altered by hydrothermal fluids over an extensive area (Taghipour *et al.* 2008). Turquoise occurs in the supergene enrichment zone, as disseminations (1 to 30 mm) and open space fillings (OSF) in fractures. Satellite and panoramic images of the Meydook porphyry copper mine are shown in Figure 5a and b.

MATERIALS AND METHODS

The samples used in the present study were collected from the Meydook porphyry copper and Neyshabour turquoise mines. The provenances of the samples are given in Table 2. Attempts were made to select samples covering the entire blue to green color range from each of the provenances in order to make comparisons. Eleven samples were acquired as small blocks of turquoise and six others were prepared as thin and polished sections (Fig. 6).

All 17 samples were sent to the University of Milan to be characterized by electron probe microanalysis (EPMA). The analyses were done on the homogeneous portions of small blocks and polished thin sections, avoiding host-rock minerals and sulfide grains as well as inclusions or color zoning based on backscattered electron (BSE) images. Backscattered electron imaging was done with a JEOL JSM 5500 LV scanning electron microscope equipped with an IXRF EDS 2000 microprobe (20 kV excitation voltage, 10 pA beam current, 0.5 μm beam diameter) in the Department of Chemistry at the University of Milan. Quantitative electron microprobe analyses were obtained from carbon-coated polished sections using a JEOL JXA-8200 electron microprobe in wavelength-dispersion mode (EPMA-WDS). The system was

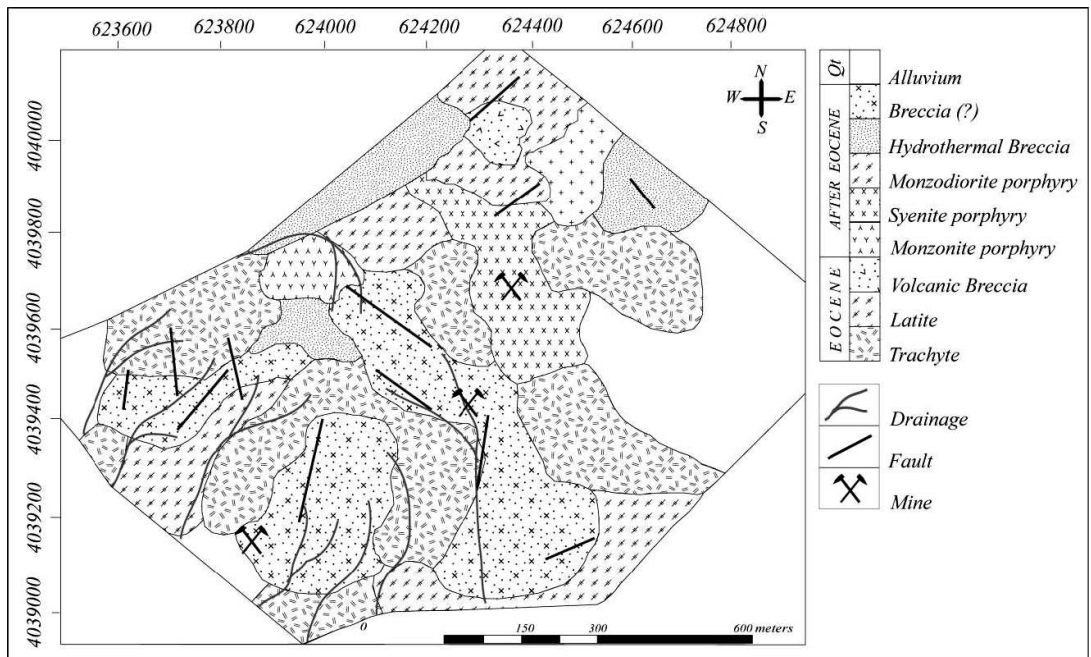


FIG. 3. Geological map of the Neyshabour turquoise mine area (modified after Karimpour *et al.* 2012).

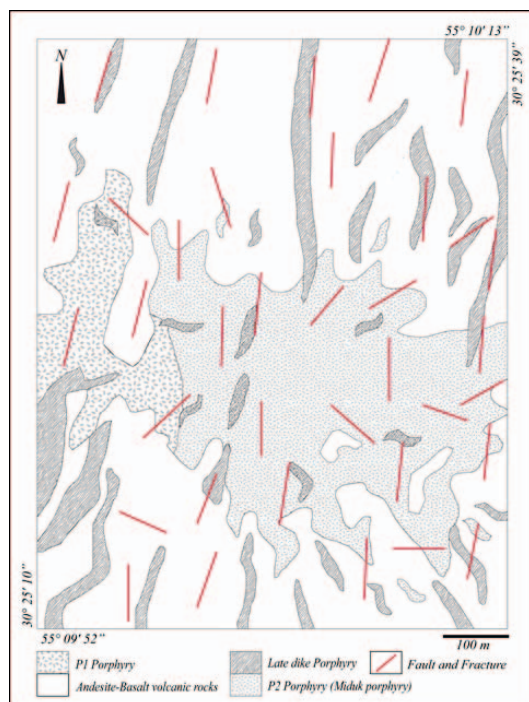


FIG. 4. Geological map of the Meydook porphyry copper deposit (Outomec 1992, modified by Taghipour *et al.* 2008).

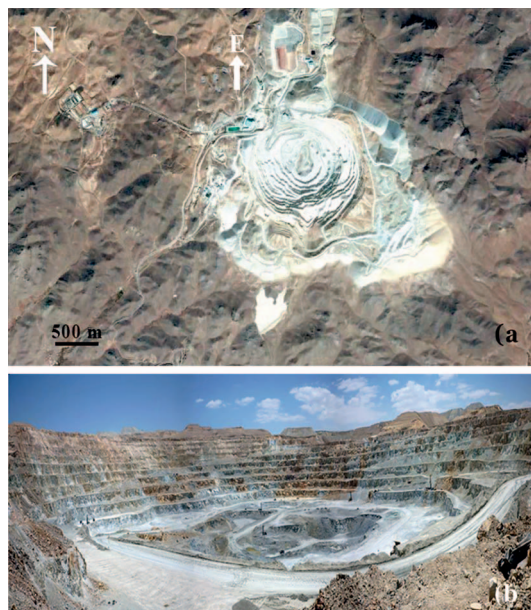


FIG. 5. Satellite (a) and panoramic (b) images of the Meydook porphyry copper mine.

TABLE 2. SAMPLE PROVENANCE

Provenance	Samples
Neysabour	EN1, EN5, EN6, EN7, EN9, MN55, MN59, MN87
Meydook	MM7, MM8, MM16, MM29, MM108a, MM109a_01, MM109a_02, MM115d, MM115p, MM116c

operated with an accelerating voltage of 15 kV, a beam current of 5 nA, a counting time of 30 s on the peaks and 10 s on the backgrounds, and a beam diameter of 10 μm . A large beam size was adopted in order to avoid sample sublimation under the electron beam. Standards used were as follows: graffonite for P, Fe, and Mn; grossular for Si, Al, and Ca; K-feldspar for K; forsterite for Mg; omphacite for Na and chalcopryite for Cu. The raw data were corrected for matrix effects using the $\Phi\rho Z$ protocol, as implemented in the JEOL suite of programs.

RESULTS

BSE images of the surfaces of the samples show that all of the specimens except MM115 are more or less homogeneous (Fig. 7). A BSE image of MM115 (Fig. 7) shows that clear (pale gray in BSE) inclusions correspond to the composition MM115d and the matrix to MM115p.

The average (six spots per specimen) chemical composition and proportional formulae of the investigated specimens are summarized in Table 3. The chemical formula of the phosphates under investigation was calculated using the general turquoise-group formula (Foord & Taggart 1998), with H_2O wt.% calculated assuming $(\text{OH}) = 8 + x$ and $4\text{H}_2\text{O}$ (Table 3):



where, Cu^{+2} , Fe^{+2} , and (K^+) occur at the A site and Fe^{3+} and Al^{3+} occur at the B site (see Table 3). Mg^{2+} , Zn^{2+} , and Na^+ were below detection limit.

As shown in Table 3, samples MM115 and MN87 have rather different elemental contents, with CuO significantly less than 6 wt.% in these samples, while the average CuO in other analyzed samples is approximately 6–8 wt.%.

In Table 4 the results of the analyses are normalized to H_2O and OH; also shown are possible elemental contents at the A and B sites, based on the turquoise chemical formula suggested by Foord & Taggart (1998). The percentages of turquoise, planerite, and chalcosiderite in each of the samples, based on the compositions determined by EMPA, are reported in Table 5.

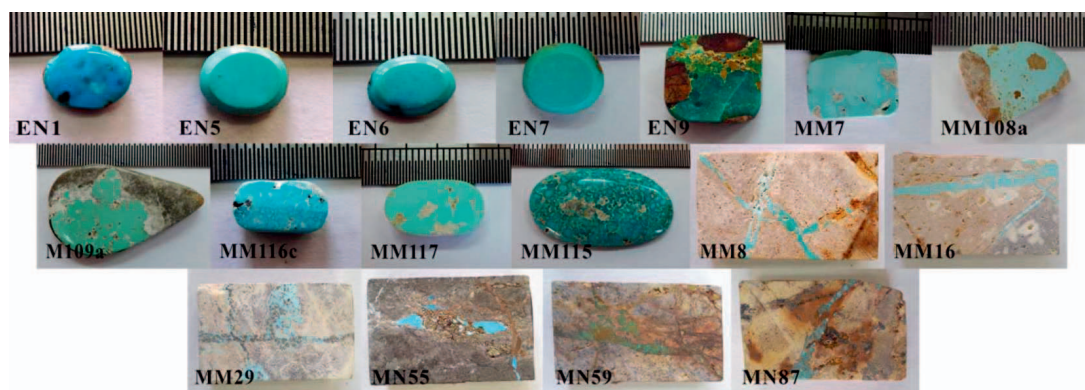


FIG. 6. Turquoise samples analyzed in this study. The numbers refer to the descriptions given in Table 2.

Figures 8 and 9 are turquoise–planerite and turquoise–chalcosiderite diagrams, respectively. Figure 10 shows the chemical compositions of all samples plotted on a quaternary diagram. The unknown mineral UM1981-32-PO:FeH (from Smith & Nickel 2007) is used as the fourth endmember in this diagram. The four endmembers are: (1) turquoise $[\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}]$, planerite $[\text{Al}_6(\text{PO}_4)_2(\text{PO}_3\text{OH})_2(\text{OH})_8 \cdot 4\text{H}_2\text{O}]$, chalcosiderite $[\text{CuFe}^{3+}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}]$, and UM1981-32-PO:FeH $[\square\text{Fe}^{3+}_6(\text{PO}_4)_2(\text{PO}_3\text{OH})_2(\text{OH})_8 \cdot 4\text{H}_2\text{O}]$.

Figure 11 illustrates alteration of the studied samples using the diagram of Abdu *et al.* (2011).

DISCUSSION

Electron probe microanalysis results show that the analyzed samples are not pure turquoise. As is clear in Figure 8, which shows the variation of A^{2+} (*apfu*) as a function of $(\text{PO}_3\text{OH})^{2-}$, all of the samples lie along the ideal line connecting the endmember compositions of the turquoise and planerite series. According to the diagram, sample MM115p and sample MN87 (Fig. 8), collected from the Meydook and Neyshabour mines, respectively, show the most tendency towards the planerite endmember. In addition, according to the $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ diagram (Fig. 9) as used by Abdu *et al.* (2011), all the analyzed samples lie along the ideal line connecting endmember compositions of turquoise and chalcosiderite. Sample MM109a-01 (collected from Meydook) and sample MN59 (from Neyshabour) are the samples with the greatest chalcosiderite component. Sample MM8, which significantly departs from the ideal line, indicates an altered turquoise. Altered turquoise contains less Fe compared to unaltered turquoisees (Abdu *et al.* 2011).

The altered turquoise also shows a negative correlation between P_2O_5 and $\text{SiO}_2 + \text{SO}_3$, which may indicate P exiting the turquoise structure and its substitution by Si and S during alteration (Abdu *et al.* 2011, Rossi *et al.* 2017). Figure 11 shows that the studied samples are not altered, except samples EN7 and EN59, which show minor alteration. Rossi *et al.* (2017) noted that, although the presence of a high amount of Ca in turquoise is related to Cu deficiency, it is unlikely that Ca substitutes for Cu at the A site, and that it is more likely caused by microcrystalline impurities of other minerals. Nevertheless, among samples from the present study, sample MN59, which contains the highest CaO (0.35 wt.%), possess a normal proportion of CuO (6.28 wt.%); in addition, this sample is among the less-altered turquoisees and is low in P_2O_5 (32.91 wt.%). The presence of Ca in turquoise can be attributed to alteration. Determining the cause of Ca substitutions in turquoise requires further investigation.

Samples MN87 and MM115p show a low population at the A site, which is accompanied by increasing PO_3OH content. This low population, which is an A-site defect and involves an extra H_2O molecule, was attributed by Foord & Taggart (1998) to $(\text{PO}_4)^{3-}$ group protonation resulting in planerite $(\text{Al}_6(\text{PO}_4)_2(\text{PO}_3\text{OH})_2(\text{OH})_8 \cdot 4\text{H}_2\text{O})$.

As seen in a quaternary solid solution diagram (Fig. 10), created by combining Figures 8 and 9, the chemical compositions of the samples lie along the turquoise–planerite line, with slight involvement of chalcosiderite and UM1981-32-PO:FeH. As can be seen from Table 5, which shows the percentages of turquoise, planerite, and chalcosiderite contents in each sample, the majority of samples contain 18–25% planerite, 0–18% chalcosiderite, and 60–80% tur-

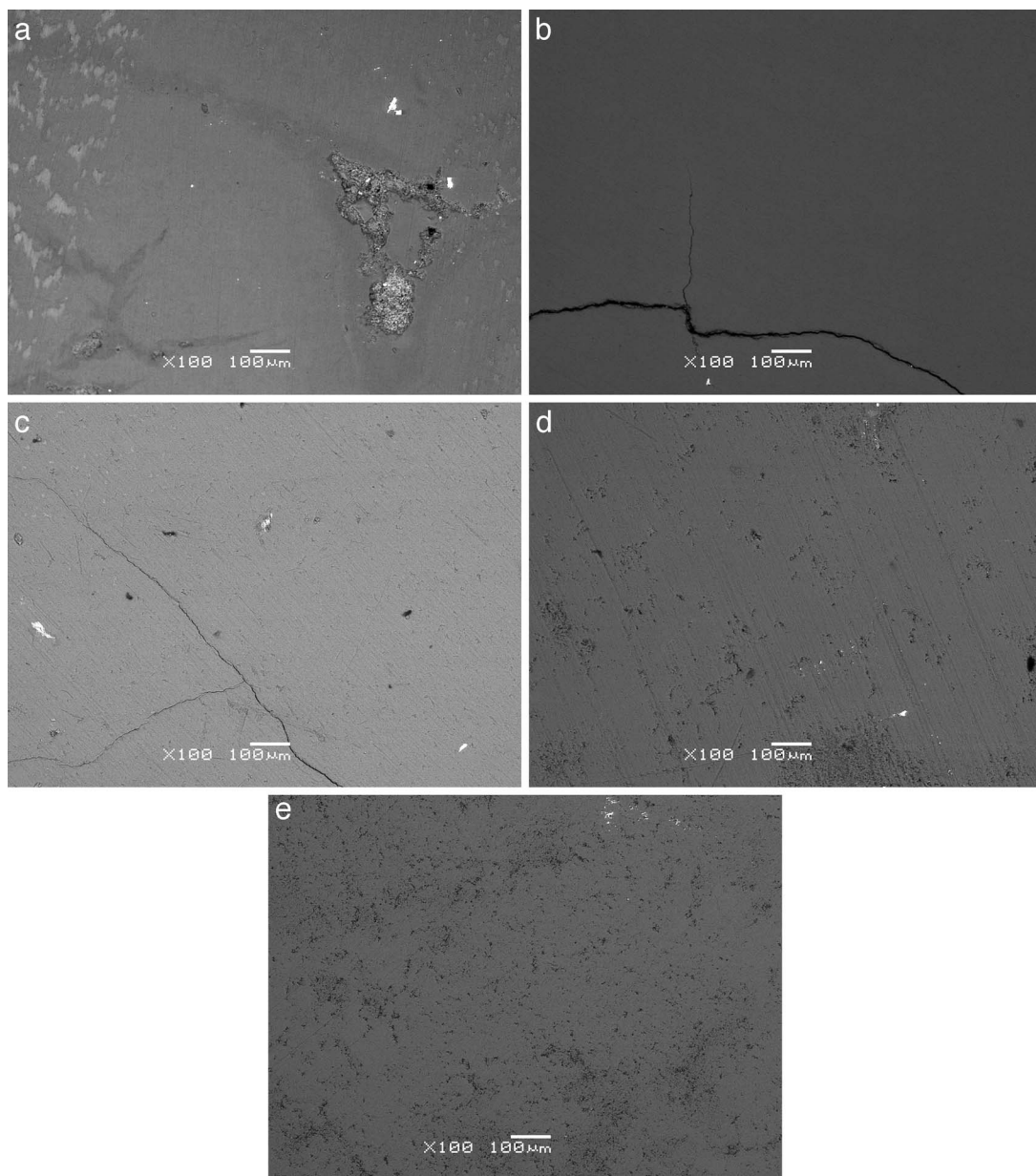


FIG. 7. BSE images of some samples; all the samples studied are homogenous, except for MM115. (a) Sample MM115 showing a turquoise matrix with planerite inclusions. (b) EN01, (c) EN05, (d) MM108A, and (e) MM116C illustrate the homogeneity (turquoise) of the analyzed spots.

quoise. These amounts are consistent with Figures 8, 9, and 10.

Samples collected from Meydook mine tend towards planerite. In sample MM115 (Figs. 6 and 7a), which has both light and dark blue zones, the light blue parts (Fig. 7a sample matrix) are planeritic,

including 1% chalcosiderite and 28% turquoise, while the dark blue parts are a solid solution of turquoise group members, with 55% planerite, 44% turquoise, and 1% chalcosiderite. Among all studied samples, EN6 (containing 80% turquoise) (Fig. 6) and MM109a (containing 79% turquoise) (Fig. 6), collected from the

TABLE 3. AVERAGED (6 SPOTS EACH ANALYSIS) ELECTRON MICROPROBE COMPOSITIONS OF STUDIED SAMPLES (wt.%), BASED ON EMPA DATA

Neyshabour Samples								
	EN 1	EN 5	EN 6	EN 7	EN 9	MN87	MN55	MN59
P ₂ O ₅ (SD)	35.18 (0.41)	34.97 (0.26)	34.61 (0.58)	32.60 (0.31)	33.75 (0.12)	35.10 (0.22)	34.48 (0.31)	32.91 (0.56)
SiO ₂	0.02 (0.01)	0.06 (0.05)	0.01 (0.01)	3.38 (0.66)	0.03 (0.01)	0.02 (0.02)	0.04 (0.03)	1.78 (0.44)
Al ₂ O ₃	36.82 (0.21)	36.80 (0.32)	36.63 (0.11)	34.92 (0.21)	33.06 (0.20)	36.59 (0.11)	37.09 (0.23)	31.14 (1.29)
Fe ₂ O ₃	0.71 (0.04)	1.63 (0.11)	1.09 (0.04)	1.94 (0.07)	5.31 (0.20)	2.01 (0.26)	0.28 (0.06)	8.76 (1.12)
FeO	0.00	0.06	0.09	0.00	0.27	3.37	0.29	0.00
CuO	7.78 (0.25)	7.62 (0.10)	7.86 (0.09)	6.99 (0.15)	7.33 (0.13)	3.20 (0.39)	7.34 (0.12)	6.28 (0.13)
CaO	0.02 (0.01)	0.01 (0.01)	0.02 (0.01)	0.06 (0.01)	0.02 (0.01)	0.02 (0.01)	0.08 (0.01)	0.35 (0.04)
K ₂ O	0.06 (0.01)	0.07 (0.01)	0.08 (0.01)	0.12 (0.01)	0.11 (0.02)	0.08 (0.02)	0.08 (0.01)	0.09 (0.01)
H ₂ O	18.11	18.07	17.78	21.08	17.40	18.58	17.80	19.24
total	98.70	99.29	98.17	101.08	97.29	98.98	97.49	100.54

Neyshabour and Meydook mines, respectively, are closer to the turquoise endmember, whereas samples MN86 (Fig. 6) and MM115p (Fig. 6), collected from the Neyshabour (containing 66% planerite) and Meydook (containing 77% planerite) mines, respectively, approach the planerite endmember.

Based on the EPMA data, which were obtained from homogeneous points on the studied samples, element substitution in the structure lattice of turquoise group minerals plays a significant role in color determination of the members, and therefore the

turquoise color is not due to inclusions of other minerals. Substitution of Fe³⁺ at the Al³⁺ site and conversion of turquoise to chalcosiderite is accompanied by a change in color from blue (turquoise) to green (chalcosiderite). Thus, Fe³⁺ can be recognized as a chromophore causing green color in the turquoise group.

Reducing the amount of Cu²⁺ and increasing (PO₃OH)²⁺ in the lattice decreases the intensity of the blue color and turns it light blue. Nevertheless, not every light blue mineral in this group is planerite, for

TABLE 4. EPMA DATA NORMALIZED TO H₂O AND OH AT BOTH A AND B SITES (FOORD & TAGGART 1998)

		Neyshabour Samples							
		EN 1	EN 5	EN 6	EN 7	EN 9	MN55	MN87	MN59
(PO ₄) ³⁻	P ⁵⁺	3.791	3.765	3.816	2.844	3.778	3.765	3.33	3.205
	Si ⁴⁺	0.005	0.017	0.003	0.787	0.009	0.011	0.005	0.453
	sum	3.796	3.781	3.82	3.631	3.787	3.777	3.336	3.658
(PO ₃ OH) ²⁻	P ⁵⁺	0.204	0.219	0.18	0.369	0.213	0.223	0.664	0.342
	H ⁺	0.204	0.219	0.18	0.369	0.213	0.223	0.664	0.342
B	Al	5.821	5.835	5.888	4.792	5.442	5.971	5.797	4.673
	Fe ³⁺	0.072	0.165	0.112	0.17	0.558	0.029	0.203	0.839
	sum	5.892	6.000	6.000	4.961	6.000	6.000	6.000	5.513
A	Fe ²⁺	0.000	0.007	0.01	0	0.032	0.033	0.379	0.000
	Cu	0.788	0.774	0.81	0.615	0.774	0.757	0.325	0.604
	Ca	0.002	0.002	0.003	0.008	0.003	0.012	0.004	0.047
	K	0.005	0.006	0.007	0.009	0.01	0.007	0.007	0.007
	sum	0.796	0.788	0.83	0.631	0.818	0.81	0.715	0.658
OH ⁻		8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
H ₂ O		4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000

* Fe³⁺ calculated for stoichiometry up to fill the B site.

TABLE 3. CONTINUED.

Meydook Samples						
	MM 109a_01	MM 109a_02	MM 7	MM 108a	MM 116c	MM 117
P ₂ O ₅ (SD)	33.50 (0.49)	34.63 (0.62)	34.80 (0.43)	34.64 (0.46)	34.13 (0.62)	34.29 (0.50)
SiO ₂	0.04 (0.02)	0.30 (0.19)	0.02 (0.02)	0.04 (0.02)	0.03 (0.01)	0.05 (0.01)
Al ₂ O ₃	29.78 (0.36)	37.19 (0.26)	36.73 (0.19)	34.11 (0.69)	36.13 (0.14)	33.94 (0.21)
Fe ₂ O ₃	9.81 (0.24)	1.00 (0.03)	1.29 (0.18)	4.37 (0.16)	1.12 (0.11)	4.93 (0.10)
FeO	0.00	0.00	0.56	0.00	2.15	2.07
CuO	6.98 (0.20)	7.94 (0.14)	6.39 (0.13)	7.49 (0.11)	7.53 (0.15)	7.44 (0.15)
CaO	0.01 (0.01)	0.02 (0.01)	0.02 (0.01)	0.04	0.03 (0.02)	0.01 (0.01)
K ₂ O	0.04 (0.01)	0.06 (0.01)	0.05 (0.01)	0.06 (0.01)	0.06 (0.01)	0.05 (0.02)
H ₂ O	17.33	18.15	18.07	17.88	17.59	17.72
total	97.48	99.29	97.93	98.64	98.77	100.52

example, although samples MM116c and MM16 are light blue, they tend towards the turquoise endmember rather than the planerite endmember (Fig. 6).

Samples EN1 and MM116, collected from the Neyshabour and Meydook mines, respectively, have almost the same tone and saturation in blue hue, and are plotted in Figures 8, 9, and 10. These two samples plot close to each other in an area with similar chemical compositions. Samples MN87 and MM29, originating from Neyshabour and Meydook, respectively, also have nearly the same tone and saturation in

light blue hue. However, unlike the previous samples (MM116c, EN1), despite being isochromatic, these samples are not confined to one area and plot in two chemically different regions on the same diagrams (Figs. 8, 9, and 10).

CONCLUSIONS

Based on the EPMA results, the compositions of the studied samples do not consist of pure turquoise and can be displayed using three diagrams showing the

TABLE 4. CONTINUED.

	Meydook Samples										
	MM 109a_01	MM 109a_02	MM 7	MM 108a	MM 116c	MM 117	MM 115 pale blue	MM 115 dark blue	MM29	MM8	MM16
(PO ₄) ³⁻	3.735	3.73	3.655	3.771	3.787	3.764	3.280	3.445	3.735	3.765	3.749
	0.012	0.08	0.007	0.01	0.009	0.015	0.005	0.006	0.023	0.007	0.021
	3.747	3.81	3.662	3.781	3.796	3.779	3.284	3.451	3.759	3.773	3.770
(PO ₃ OH) ²⁻	0.253	0.19	0.338	0.219	0.204	0.221	0.716	0.549	0.241	0.227	0.230
	0.253	0.19	0.338	0.219	0.204	0.221	0.716	0.549	0.241	0.227	0.230
B	4.935	5.861	5.868	5.469	5.883	5.491	5.801	5.858	6.050	5.765	5.843
	1.038	0.101	0.132	0.447	0.116	0.509	0.059	0.070	0.000	0.235	0.157
	5.973	5.961	6.000	5.916	6.000	6.000	5.860	5.928	6.050	6.000	6.000
A	0.000	0.000	0.063	0.000	0.248	0.238	0.000	0.000	0.152	0.296	0.142
	0.741	0.802	0.655	0.770	0.786	0.772	0.281	0.444	0.740	0.762	0.747
	0.002	0.003	0.003	0.006	0.005	0.002	0.001	0.001	0.013	0.004	0.017
	0.003	0.005	0.004	0.005	0.005	0.005	0.003	0.006	0.005	0.007	0.006
	0.747	0.81	0.725	0.781	1.045	1.016	0.284	0.451	0.911	1.069	0.912
OH ⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
H ₂ O	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000

TABLE 3. CONTINUED.

	Meydook Samples				
	MM 115 pale blue	MM 115 dark blue	MM29	MM8	MM16
P ₂ O ₅ (SD)	36.21 (0.37)	35.58 (0.34)	34.15 (0.73)	29.17 (0.98)	33.51 (0.63)
SiO ₂	0.012 (0.01)	0.02	0.09 (0.02)	0.02 (0.02)	0.07 (0.02)
Al ₂ O ₃	37.77 (0.17)	37.49 (0.34)	37.32 (0.30)	30.25 (1.02)	35.34 (0.15)
Fe ₂ O ₃	0.60 (0.08)	0.70 (0.09)	0.00 (0.09)	1.93 (0.16)	1.49 (0.11)
FeO	0.00	0.00	1.32	2.19	1.21
CuO	2.85 (0.16)	4.43 (0.28)	7.12 (0.22)	6.24 (0.29)	7.05 (0.20)
CaO	0.00 (0.01)	0.01 (0.01)	0.09 (0.01)	0.02 (0.01)	0.11 (0.02)
K ₂ O	0.04 (0.01)	0.08 (0.01)	0.06	0.07 (0.01)	0.07 (0.01)
H ₂ O	19.23	18.71	17.70	15.05	17.35
total	96.73	97.03	97.86	84.94	96.20

solid solutions of turquoise and three other members of turquoise group. In the A²⁺ versus (PO₃OH)₂ diagram, the samples plot along the ideal line connecting endmember compositions of turquoise and planerite. In the Al₂O₃/Fe₂O₃ diagram, the samples plot along the ideal line connecting endmember compositions of turquoise and chalcociderite. The third diagram, made by combining the two previous diagrams, is a quaternary diagram with turquoise, planerite, chalcociderite, and a fourth unknown mineral as its endmembers. In this diagram the samples plot along the turquoise–planerite line, tending to the turquoise

endmember, with two other minerals (chalcociderite and the unknown mineral) slightly involved.

The existence of Fe³⁺ in the structure lattice of turquoise is the main cause of the green color in the mineral. As Cu leaves the structure lattice and turquoise turns to planerite, the color of the mineral tends to light blue. Nevertheless, this does not mean that all light blue turquoise-group minerals are planerite.

Comparing samples with dissimilar colors from both mines, the Meydook samples tend towards the planerite composition compared with those collected

TABLE 5. PERCENTAGES OF TURQUOISE, PLANERITE, AND CHALCOSIDERITE IN THE STUDIED SAMPLES

		Samples	planerite fraction	chalcociderite fraction	turquoise fraction
Blocks	Neyshabour	EN 1	20.4	1.2	78.4
		EN 5	21.85	2.75	75.4
		EN 6	18.0	1.86	80.14
		EN 7	36.88	3.42	59.7
		EN 9	21.3	9.3	69.4
	Meydook	MM 108a	21.90	7.56	70.54
		MM 117	22.15	8.48	69.367
		MM 7	33.83	2.2	63.97
		MM 116c	20.39	1.94	77.67
		MM 115 p	71.58	1.0	27.42
		MM 115 d	54.86	1.18	43.96
		MM 109a_01	25.3	17.4	57.3
		MM 109a_02	19.0	1.69	79.31
Thin Sections	Meydook	MM29	24.13	0	75.87
		MM8	22.72	3.91	73.37
		MM16	23.0	2.62	74.38
	Neyshabour	MN87	66.43	3.39	30.18
		MN55	22.34	0.48	77.18
		MN59	34.22	15.22	50.56

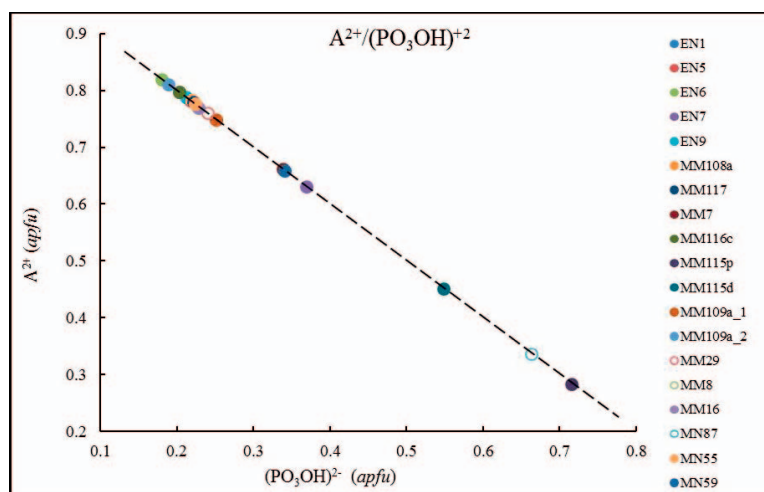


FIG. 8. $A(Fe^{2+} + Cu + Ca + K)$ versus $(PO_3OH)^{2-}$ (apfu) diagram. Note that all the studied samples lie along the turquoise–planerite line.

from Neyshabour. However, the provenances of these turquoises cannot be determined decisively based on chemistry alone.

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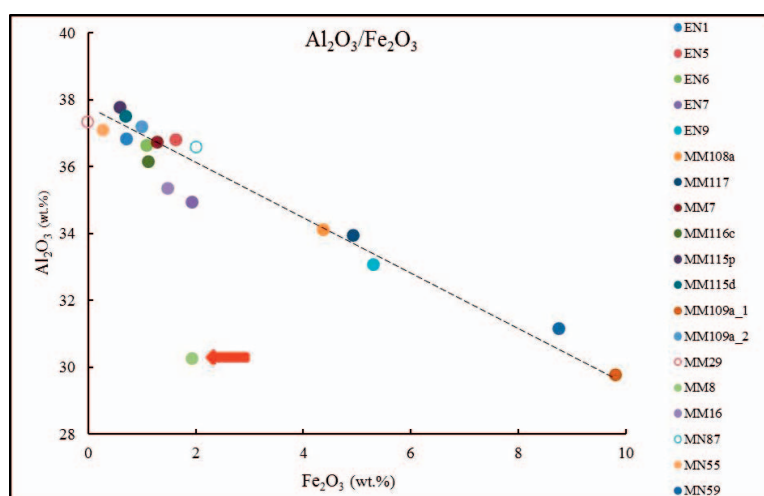


FIG. 9. Al_2O_3 versus Fe_2O_3 (wt.%) diagram (Abdu *et al.* 2011). Note that the majority of studied samples lie long the turquoise–chalcosiderite line. The red arrow indicates sample MM8, which contains the lowest amount of Fe.

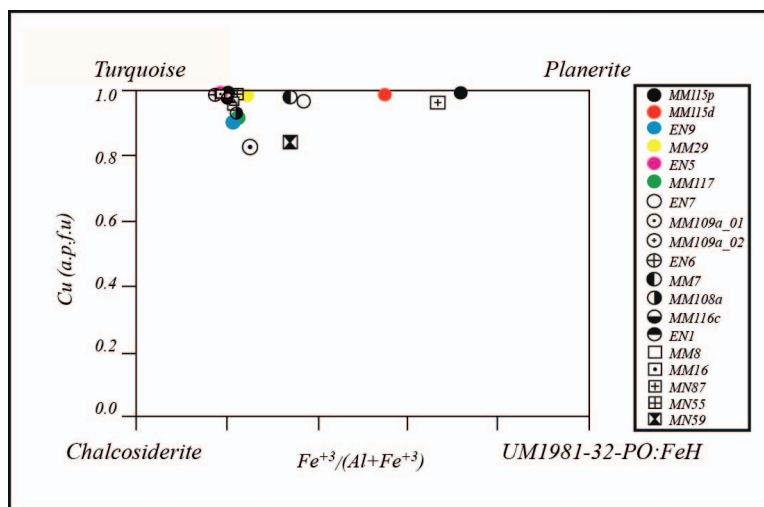


FIG. 10. Cu versus $\text{Fe}/(\text{Al} + \text{Fe}^{3+})$ diagram. Note that the studied samples lie along the turquoise–planerite line with slight involvement of chalcosiderite and the unknown mineral.

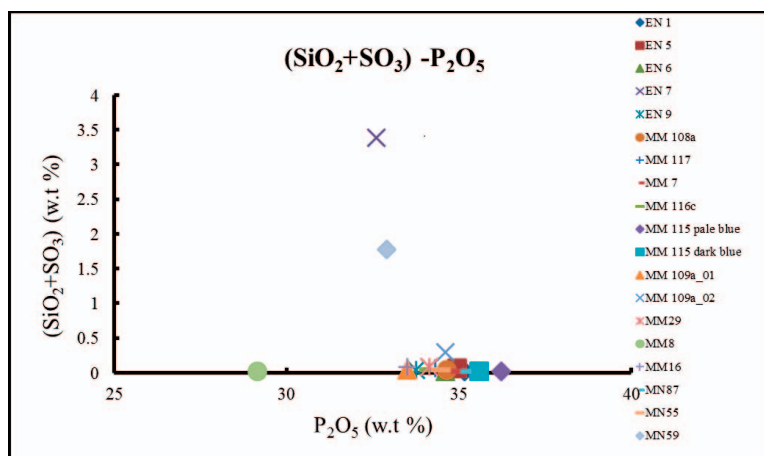


FIG. 11. $(\text{SiO}_2 + \text{SO}_3)$ versus P_2O_5 (wt.%) diagram (Abdu *et al.* 2011) with all microprobe data for samples.

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