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Origin and significance of tourmaline-bearing rocks in Boroujerd region, Sanandaj-Sirjan zone, western Iran

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Abstract

Tourmaline minerals are a main petrogenetic tool because of their refractory nature, chemical variability, and extensive occurrence in various geological settings. The Middle-Jurassic Boroujerd igneous rocks are one of the largest bodies that located in the middle part in the Sanandaj-Sirjan Magmatic Arc (SSMA) that introduced into regional metamorphic rocks. They are mostly composed of granitoids (granodiorite, quartz-diorite, and monzogranite) and contain apatite, zircon and tourmaline as abounadant accessory minerals. Tourmalines occur in varying types of mineral assemblages, chemical compositions and individual forms including tourmalinite, quartz-tourmaline vein, as accessory mineral in the more evolved granitoids, and schists. Tourmaline crystal sizes in these rocks varies from very fine to coarse-grained. The colour is brown to black and some crystals displaying a finescale chemical zonation. Tourmaline crystals commonly exhibit cellular features. Based on electron probe microanalysis (EPMA) analyses, schorl is the most abundant type of tourmaline in granitoids but foitite and dravite are common compositions in the pegmatite and schist, respectively. Presence of several tourmaline generations and their compositional trend may indicate time-varying relatively acidic boron-bearing fluids and reflects an anatexic melts influence in their crystallization.

Keywords: *Iran, Sanandaj-Sirjan, Boroujerd, Granitoid, Tourmaline*

1. Introduction

The tourmaline nature with variable compositions and its resistance against weathering made it as a vigorous stable mineral in a wide range of pressures, temperatures and compositions (e.g., Dutrow and Henry 2011; van Hinsberg 2011). Due to its crystallographic structure, most environment components (coexisting phases) and volatiles could be potentially exchanged with tourmaline. Type of these transactions are related to the bulk composition of the host rock, fluid chemistry, the composition of coexisting minerals, and the p-T-fO2 conditions (e.g., Henry and Guidotti 1985; London and Manning 1995; Garba 1996; Keller et al. 1999). Therefore, the chemical and mechanical stability of tourmaline made each tourmaline grain to record and preserved important information on the history of the rock in which it is found (e.g., Henry and Guidotti 1985; van Hinsberg et al. 2011). Furthermore, tourmaline chemistry can be used to provide a clearer understanding of ore-forming processes, related depositional environments, and the location of prospective exploration targets (Collins, 2010). In general, tourmaline formation requires the effective concentration of boron (~3 wt% B2O3) which is mostly controlled by fluid-dominated processes and magmatic differentiation (Demirel et al. 2009). Depends on this processes, tourmaline could locally be concentrated as a main constituent in tourmalinite (Slack et al. 1984), granitoids and pegmatite (Trumbull and Chaussidon 1999), quartz–tourmaline breccias (e.g., London and Manning 1995; (e.g., Altherr et al. 2004; Marschall et al. 2006).

Yang et al. (2015) discussed about trace, minor and major elements incorporated in tourmaline and their complex interactions, which can change results. The zonation of tourmaline could falsify extracted conclusions as well. Although the potential of tourmaline for recording of its geological history has been mentioned in some works, the available trace elements studies are few (e.g., Jiang et al. 2004; Galbraith et al. 2009; Klemme et al. 2011; Novák et al. 2011; Gadas et al. 2012; Bacík et al. 2012, Roda-Robles et al. 2012; Marks et al. 2013; Drivenes et al. 2015; Hazarika et al. 2015; Duchoslav et al. 2017; Yazdi et al. 2022;).

This study is concerned on the textural and compositional variation of tourmaline including major, minor and trace elements to evaluate geological conditions of its growth and Magmatic-Hydrothermal processes involved in tourmaline formation from the Boroujerd region, Sanandaj-Sirjan Magmatic Arc (SSMA), NW Iran.

2. Geological setting

Iran is a part of Alpine-Himalayan orogenic system and consists of several oceanic and continental terranes with different geological features (Stöcklin 1968). The Iranian various continental blocks is believed to have been situated along the Paleotethyan margin of Gondwana prior to Permian rifting. Then, opening of Neotethys oceanic basin in its wake separated Iran from Gondwana (e.g., Ramezani and Tucker 2003, Hassanzadeh et al. 2008) and left the Iranian fragments situated between one expanding ocean and one consuming ocean (Berberian

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and King 1981). The Neotethys thus widened as Iran pulled away from Gondwana by the subduction of Paleotethys beneath the southern margin of Eurasia. A regional unconformity separating rocks as young as Middle Triassic from overlying strata as old as Rheatic-Liassic is generally interpreted as marking the Middle to Late Triassic closure of Paleotethys (e.g., Stöcklin 1968, Horton et al. 2008). Neotethys opened during the Triassic to Late Jurassic and closed in the Late Cretaceous to Miocene (Şengöra and Yilmaz 1981; Ghasemi and Talbot 2006). The arc magmatism is one of the main consequences of the subduction of oceanic slab under the Central Iran, which began in the latest Triassic/Early Jurassic time and peak at ~170 M (Yazdi et al. 2016; Hassanzadeh and Wernicke 2016).

The Sanandaj-Sirjan Magmatic Arc (SSMA) is the Neotethys' arc that mainly consists of Mesozoic metasedimentary rocks, Middle Tertiary to Middle Jurassic intrusive rocks and related contact metamorphic aureoles, and pegmatites. This zone was accreted with Eurasia in the Late Triassic. The SSMA subsequent incorporation into the Zagros orogeny is caused by the collision of Eurasia (including Iranian microplate) with the northern margin of Gondwana (Arabia) during the Cenozoic (Fig 1).

The Zagros Main Thrust and Tabriz and Nain-Baft Faults separated the SSZ from Zagros and Central Iran, respectively (Şengör 1979). The main trend of the faults, fractures and other structural features of the area is NW-SE. The Sanandaj-Sirjan regional metamorphism in the area has reached a peak of greenschist facies, but further metamorphism has occurred locally, associated with granitoid emplacement. The P-T gradient of this subduction zone is high due to the intrusion of mantle-derived mafic magma into the crust or local thickening of continental crust (Yeganehfar and Deevsalar 2016). Magmatism has produced large felsic to intermediate intrusive bodies along a general northwest trend, which is intruded into regional metamorphic rocks.

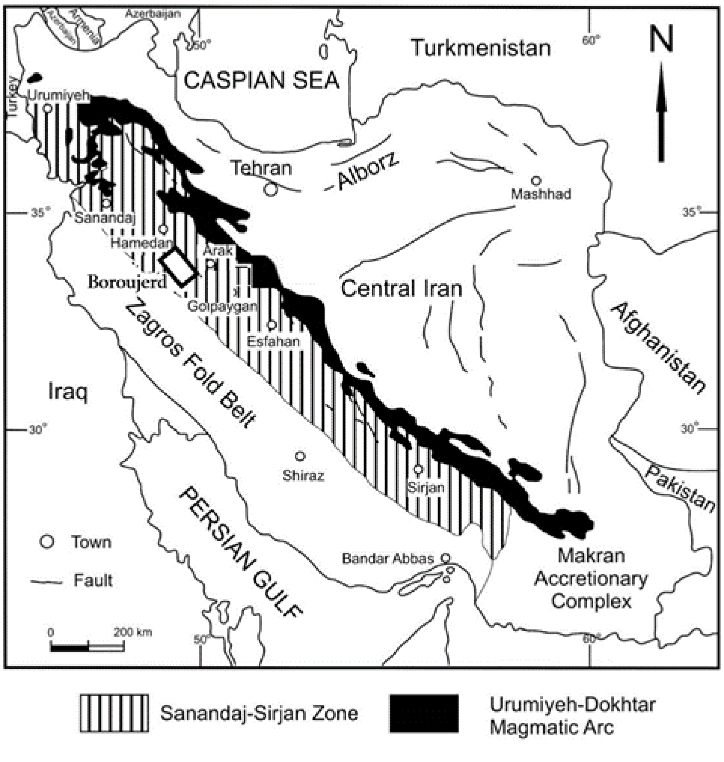

Fig 1. The main geological structures of Iran (after Stöcklin 1968; Alavi et al. 1977). The white square shows location of the Boroujerd area.

3. Materials and methods

3.1. Field relations and petrography of tourmaline-rich rocks

Tourmaline is widespread in more felsic types of granitoids, pegmatites and quartz veins, and surrounding regional metasedimentary rocks (mainly phyllite and schist). The Middle Jurassic Boroujerd granitoid complex (BGC) as the main lithologic unit in the study area extends over 600 km2 and forms one of the largest igneous complexes in the middle part of the SSMA (Fig 2a). It mostly consists of granodioritic, quartz-dioritic, monzogranitic units that accompanied by several small outcrops of quartz veins and pegmatites. Fine- to medium-grained quartz-diorite typically exhibits a porphyritic texture with average modal composition: quartz 12-15, K-feldspar 8-10, plagioclase 45-50 and biotite 20-25 (all in vol %) (Fig 2b). The low concentration of litophile metals (e.g. Cs-Ta) may indicates weak to moderate degree of differentiation (Nekouvaght Tak and Bazargani-Guilani 2009). Granodiorite is the most abundant facies, shows medium to coarse-grained textures with modal mineralogy of: quartz 28–30, plagioclase 35–40, K-feldspar 12-15, and biotite 15–20 (all in vol %) (Fig 2c). The small and separate monzogranitic units display both granular and porphyritic textures. Their minerals are composed of quartz 33–30, plagioclase 32–35, K-feldspar 35-38, and biotite 8–10 (all in vol %) (Fig 2d).

All the mentioned unites have tourmaline, zircon, allanite, and apatite as accessory minerals. Most of feldspars in granitoids have undergone some degree of argillic and phyllic alterations. This is documented by clay minerals and serecite and chlorite occurrences. These alterations imply permeability of rocks that has been affected by circulation of hydrothermal fluids. This spectrum of granitic rocks can be explained by fractional crystallization of upper crustal magmas. The geochemical signatures of BGC (e.g. Ti, Nb, Sr and P depletion) imply a typical of volcanic arc tectonic conditions (Ahmadi-Khalaji et al. 2006). The contents of initial Strontium and Neodymium (Sri = 0.7062 - 0.7074 and εNdt = –3.02 to –3.62, respectively) imply a crustal protolith (Ahmadi-Khalaji et al. 2006). Deep accretion that occurred at the base of crust followed by under-plating melted lower crustal rocks and mafic rocks (i.e. gabbro) were crystallized from these magmas. Deevsalar et al. (2017) assigned high-Ti gabbros to a largely derived from asthenospheric magma followed by higher degrees of melting at a shallower depth. Magnetic fabrics and microstructural studies show a continuum from magmatic to (sub) mylonitic deformations fabrics (Rasouli et al. 2012). Furthermore, the petrographic study shows biotite and amphibole as the main paramagnetic contributors which is common in the S-type granitoids. The overall magnetic fabrics of the pluton display sub-horizontal lineations and steep NW-SE striking foliations that have plunge toward the both northwest and southeast that imply a NW-SE stretching during intrusion of the pluton (Rasouli et al. 2012).

Pegmatites appear as veins of variable thickness ranging from several centimeters to 3 m. They occur as dikes and mostly are hosted by several large granitic rocks (Fig 3a). The thickness of quartz veins varies from a few millimeters to several decimeters (Fig 3b).

The metamorphic rocks are mainly phyllite and schist and hornfels (Figs 3c and 3d), however the high-grade metamorphic rocks such as gneiss and migmatite are exist in the study area. High grade metamorphism followed by temperatures (up to 750°) that are appropriate for partial melting and anataxis (Saki et al. 2012). The regional metamorphic rocks are mainly composed of quartz, muscovite, biotite, and K-feldspar. The garnet, andalusite and tourmaline are the main porphyroblasts in the mentioned rocks. Slate and phyllite have lepidoblastic and lepidogranoblastic texture, respectively. Their mineralogy, field relations and geochemistry imply that they are originated from sedimentary rocks (Berberian and Alavi-Tehrani 1977; Baharifar et al. 2004).

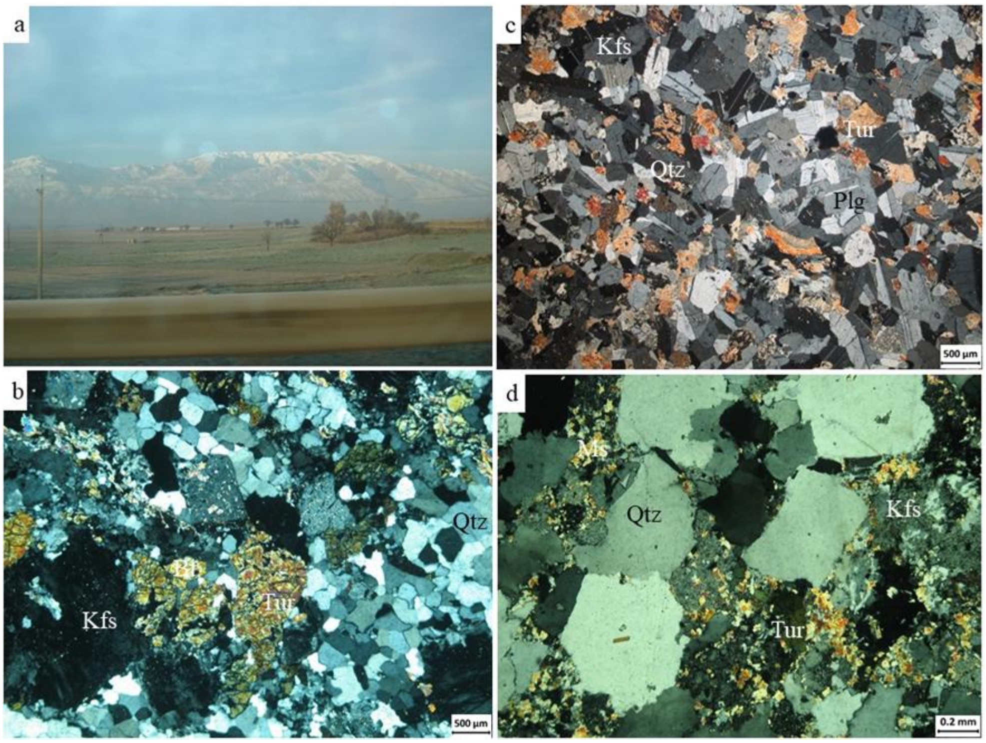

Fig 2. (a) Boroujerd batholite; Photomicropgraphs (XPL) of tourmaline in (b) Quartz Diorite, (c) Granodiorite and (d) Granite. Mineral abbreviations: Bt biotite, K-fs K-feldspar, Ms muscovite/white mica, Plg Plagioclase, Qz quartz, Tur Tourmaline

Tourmaline occurrences are observed as diverse types and include: as the dominant mineral in massive tourmalinite are associated with quartz-feldspar crystals in veins (Fig 4a), fine to medium acicular grains and euhedral columnar crystals in mozogranites (Fig 4b), disseminated crystals in quartz veins, small to large platy crystals in schists (Fig 4c), and large crystals in pegmatitic rocks (Fig 4d).

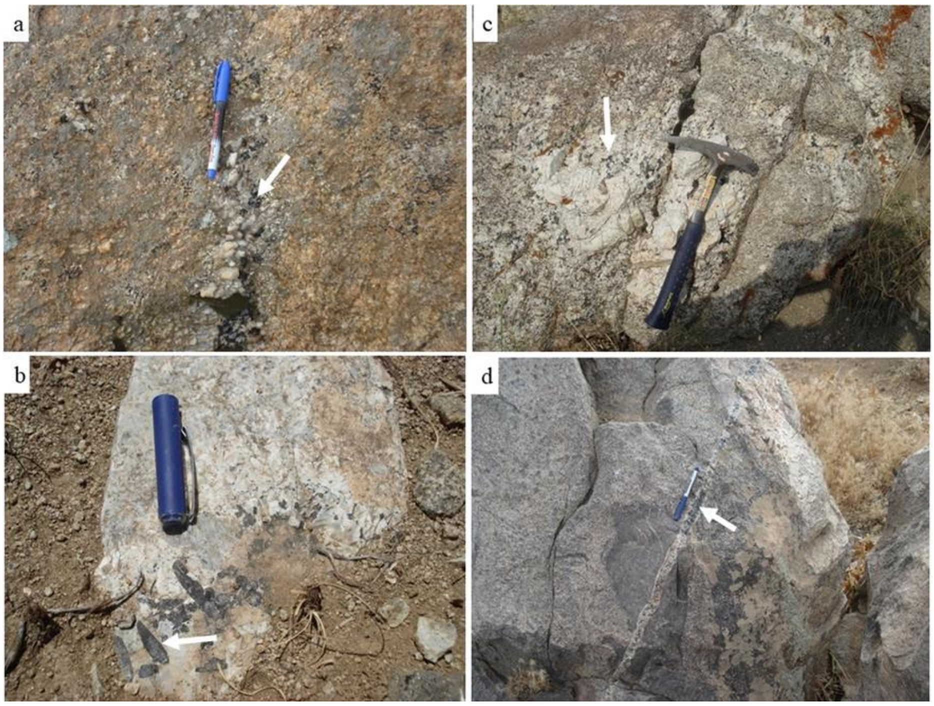

Fig 3. The various tourmaline-bearing rock types in Boroujerd. Tourmalines are shown by white arrows. (a) quartz-tourmaline-feldspar assemblage in coarse-grained granite.(b) Quartz vein containing tourmaline crystals, (c) Schist with tourmaline patchs and (d) Quartz-tourmaline vein cross-cutting both granite and hornfels patch which is included inside the granite.

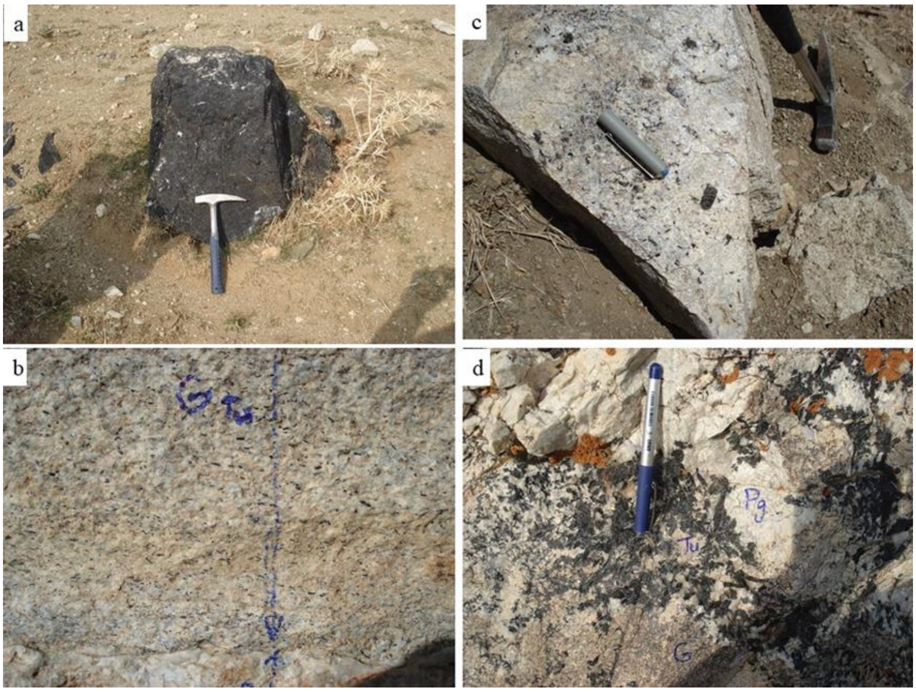

Fig. 4. Field images of tourmaline types. (a) a tourmalinite vein with minor quartz (~ 60 cm), (b) monzogranite with acicular and oriented tourmalines (c) tourmaline minerals with different sizes in schist, (d) tourmaline-bearing pegmatite

Most tourmalines are dark to dark blue in hand samples. Some granites show most of mentioned types of tourmaline (i.e. sizes and shapes), which may imply that these rocks were affected by hydrothermal tourmaline-precipitating events.

Petrographically, several tourmaline types show variable grain sizes (<50μm to 10 cm) with different relationships of overgrowth, crosscutting, and replacement. There are very rare tourmalinite veins with fine-grained that occur as dark brown to black and significant amounts of tourmaline (70-90% by volume). Their petrography demonstrates a layering alternating by tourmaline-rich laminae with quartz-rich laminae (Fig 5a). In some granite samples, biotite diminishes with increasing degree of tourmalinization (Fig 5b). There are vast of quartz-tourmaline veins that cross-cut with both granitoids and metamorphic rocks (Figs 4d, 5c, and 5d). This indicate a late and multiple stages activity of hydrothermal fluids which has affected all rock types of the studied area

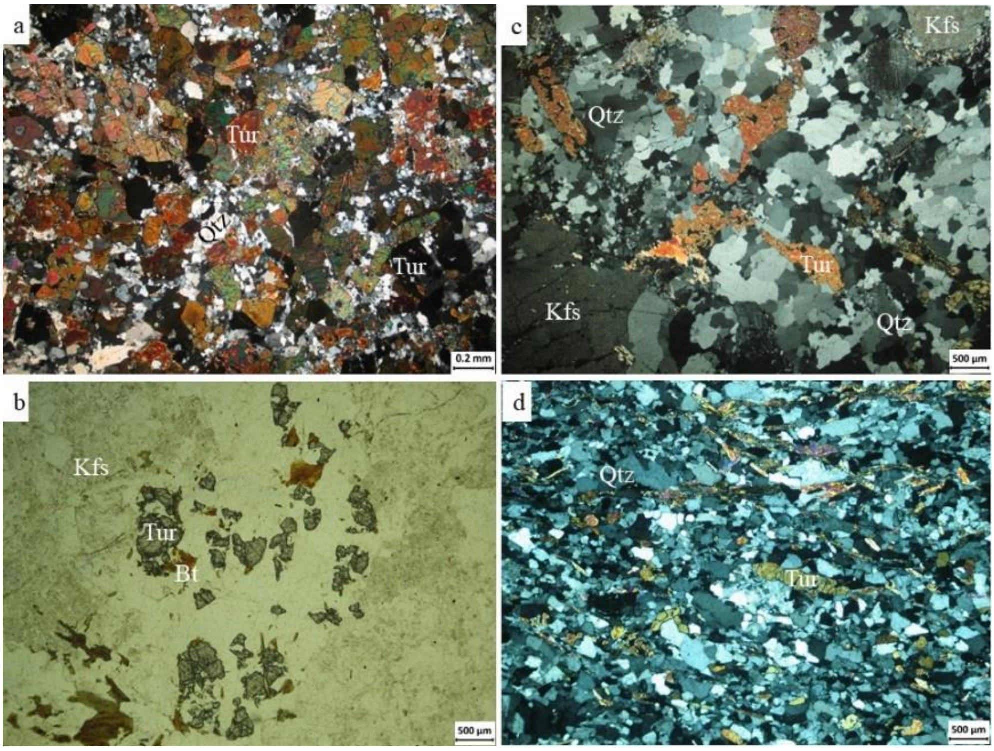

Fig. 5. Photomicrographs (XPL except for b) of tourmaline in (a) tourmalinite vein that mainly composed of tourmaline (70-90%) and quartz, (b) biotite is replaced by tourmaline in monzogranite (c) quartz vein that crosscuts granitoid (d) tourmaline-bearing schist. Bt (Biotite).

The petrographic studies show considerable variation in tourmalines. Optically, Boroujerd tourmalines are zoned and sometimes spectacularly, varying from concentric to highly irregular. This zoning in tourmaline readily responds to changes in its chemical environment. The color change can be either gradational or sharp. Cores range from irregular (common) to euhedral with euhedral to corroded rims. Zoning in studied tourmalines range from concentric to discordant that may indicative of open-system behavior. Unzoned tourmalines are brown or black. The complexity of zoning is reflected in the compositional variation of tourmalines from even one thin section. Furthermore, several fine-scale zonation was seen in the thin sections, which is indicative of rapid growth in a changing chemical environment (London and Manning 1995). Discordant zoning patterns indicate a dissolution as a result of changing conditions.

Generally, tourmaline crystals are pleochroic that may indicate the tourmaline contain significant amounts of Fe with mixed valences (2+ and 3+), resulting in intervalence charge transfer (Mattson and Rossman 1987). If tourmaline contains monovalent iron it should exhibit weak absorption. Finally, non-pleochroic tourmaline is complexly zoned and dark in color. Almost all vein tourmalines associated with Boroujerd pluton are pleochroic. Some samples in metasedimentary rocks contain tourmalines that are nearly optically opaque in thin section, suggesting that optical opacity may be related to high Fe concentrations relative to Al. The blue tourmaline had not seen in the samples, which means there is not Fe2+ → Ti4+ charge-transfer and that Fe is the primary chromophore. Some brown color tourmalines that are exist in granitoids could be related to Mg and Ti contents, although generally the Ti contents in the Boroujerd tourmalines are highly variable.

The black colors associated with schorl to be dominantly influenced by Fe2+ → Fe3+ and O2- → Fe3+ charge-transfer processes, and the brown hues of dravite by uv-centered O2- → Fe2+ and Fe2+ → Ti4+ processes (Taylor and Slack 1984).

3.2. Analytical method

After petrographic studies of sixty-two samples, a series of twenty-seven tourmaline samples (with total of ninety-four spots) were selected from all different tourmaline-bearing rock types for analysis by electron microprobe (EPMA). The Electron probe microanalysis (EPMA) was carried out on selected polished samples using a JEOL JXA-8200 at the ETHZ, Zurich, Switzerland The beam were used at 15 kV and probe current was 20 nA. The calibration was performed by using silicate mineral and natural oxide reference. Analytical errors on for major and minor elements were 1% and 5%, respectively. In the Table 1, the analyses of representative tourmaline are summarized (Supplementary Table).

4. Results and discussion

Tourmalines from Boroujerd vary widely in chemical compositions, reflecting systematic changes associated with types of hydrothermal mineral assemblages and geologic settings. Tourmaline is a borosilicate that has a complex chemistry. The basic formula can been written as $XY_3Z_6(T_6O_{18})(BO_3)V_3W$, where X= Na, Ca, K, vacancy; Y= Fe^{2+}, Mg, Mn^{2+}, Li, Al, Cr^{3+}, V^{3+}, Fe^{3+}, (Ti^{4+}); Z = Mg, Al, Fe^{3+}, V^{3+}, Cr^{3+}; T = Si, Al, (B); B = B, (vacancy), V=OH, O; W= OH, F, O (Hawthorne and Henry 1999). B is assumed stoichiometric but other light elements such as (O, H, Li) were not determined. For Fe, the Fialin et al. (2004) methods of Fe^{+3}/Fe_{total} calculations were used. Analyses of tourmalines from tourmaline-bearing rocks of Boroujerd, mainly fall within the alkali compositional group of Hawthorne and Henry (1999) (Fig 6a). The major control on the tourmaline compositions that plot outside of the alkali compositional field is the composition of the mineral assemblage. Alkali-deficient tourmaline from schist mineral assemblage and argillic-altered granitoids contain little Ca and then plot along the base of the ternary diagram. With progressive evolution of the hydrothermal alteration, the Ca concentration increased. These tourmalines that plot into calcic group show a core-to-rim increasing of Ca. Figure 6b shows discrimination diagrams for common tourmaline end members. Tourmaline compositions of Boroujerd area have trend from schorl to dravite end members. The dravite is an accessory in metapelites and persists up to the onset of anataxis (London et al. 2011). In the most rocks, the early tourmaline compositions are intermediate schorl-dravite compositions to another tourmaline compositional end members.

Almost all tourmalines correspond to the schorl-dravite solid-solution. The majority of tourmalines that sampled from granitoids in Boroujerd occupying fields of 3 and 6 in the Al-Fe-Mg and Ca-Fe-Mg compositional diagrams of Henry and Guidotti (1985) (Fig 6c), denoting a wide hydrothermal alteration of granitic rocks. Within this diagram, some of tourmaline generations fall within field 6, representing Fe^{3+}-hydrothermally altered quartz-tourmaline within granitoids. Most samples fall below the schorl (buergerite)-dravite join that implies their Al-deficient (less than 6 apfu Al) and either Fe- or Ca-Mg-rich (Henry et al. 1999). In the Figure 6d, there is not a substantial calcic component, which could have indicated a coupled substitution of Ca and Mg or Fe^{2+} for Na and Al, and it can be inferred that Fe^{3+} is a major substituent of Al in the Z-site to maintain charge balance.

Petrographic studies are indicating several stages of hydrothermal alteration for tourmaline deposition. Some tourmalines formed in crack-seal mechanisms and show elongated crystals, demonstrative of multistage development of tourmaline at the vein scale (Fig 5). Tourmaline compositions reflect both the host rock and fluid source characteristics and are strongly controlled by the mineral assemblage. Most of granitic rocks have tolerated sericitic alteration that form tourmalines range from well-formed to poorly formed with corroded grain boundaries. Their compositions vary greatly, trending mostly to schorl-dravite. Tourmalines are progressively enriched in Fe, possibly indicative of an increase of host rock control on tourmaline composition. Well-formed tourmalines in sericitic assemblages are found in the vicinity of the Boroujerd pluton.

In the aplitic veins, albite phenocrysts are intact and only display sericitic alteration in the presence of tourmaline. Changing compostions from schorl to feruvite may implies to the breakdown of magmatic pyroxene or amphibole. Tourmaline compositions influenced by the host rock and hydrothermal fluid compositions, and differences in temperature and pressure of formation (<150°C to >700°C and 1 bar to >10 kbars). Although tourmaline has a wide range of stability (Henry and Dutrow 1996), it is strongly controlled by the composition of the mineralizing fluid and associated mineral assemblage.

The concentrations of Cr are diverse; while one group (i.e. samples 1-9) has normal contents of Cr (up to 0.02 %), the other group (10-27) display high concentrations (higher than 10%) of chromium. The occurrences of Cr-bearing tourmalines (chromium-dravite of Henry et al. 2011) are relatively rare due to they need the simultaneous presence of B and Cr cations in their composition. The ultramafic rocks are source of the Cr but they have not significant outcrops in the region. Deevsalar et al. (2018) reported mafic dyke-swarms in the Boroujerd-Malayer granitoids. They are hornblende-pyroxene gabbro and their geochemical and isotopic data indicating a metasomatized mantle peridotite origin (Deevsalar et al. 2018). This confirm an ultramafic feeding of veins and metamorphic rocks which can supply Cr into granitoids and regional metamorphic rocks. The presence of Cr-bearing minerals such as rutile and titanite (not shown) in altered rocks indicates the high content of hydrothermal solutions of this element. This confirms hydrothermal-metasomatic reworking as a main factor for formation of Cr-bearing tourmalines in the studied rocks. In general, tourmaline formation is favored in strongly to weakly acidic fluids (Frondel and Collette 1957; Morgan and London 1989) and the minimum aqueous boron necessary to stabilize tourmaline increases with increasing temperature and pH. The pH higher than 6.5 and no level of boron can stabilize tourmaline. The activity of Al2O3 or equivalent aqueous species also contributes to tourmaline stability and formation Increasing fluid alkalinity increases the solubility of alumino-silicate phases and components (e.g., Al) in borate fluids (Morgan and London 1989), therefore, alkali minerals that react with water to produce alkaline solutions inhibit tourmaline growth.Boroujerd tourmalines from various localities of batholite and country rocks fall generally toward or within the Fe-rich hydrothermally altered rocks domain in the Al-Fe-Mg diagram (Fig 6d), which implies a major control of host rock of magmatic rocks. Tourmalines associated with metapelites terranes tend to have intermediate schorl-dravite. Chemically, there is a considerable inverse relationship between total Fe and Al in the most of tourmalines from the Boroujerd region (Fig 6c). Tourmalines from various schists display intermediate schorl-dravite to dravitic compositions and appear to be geochemically similar to non-hydrothermal.

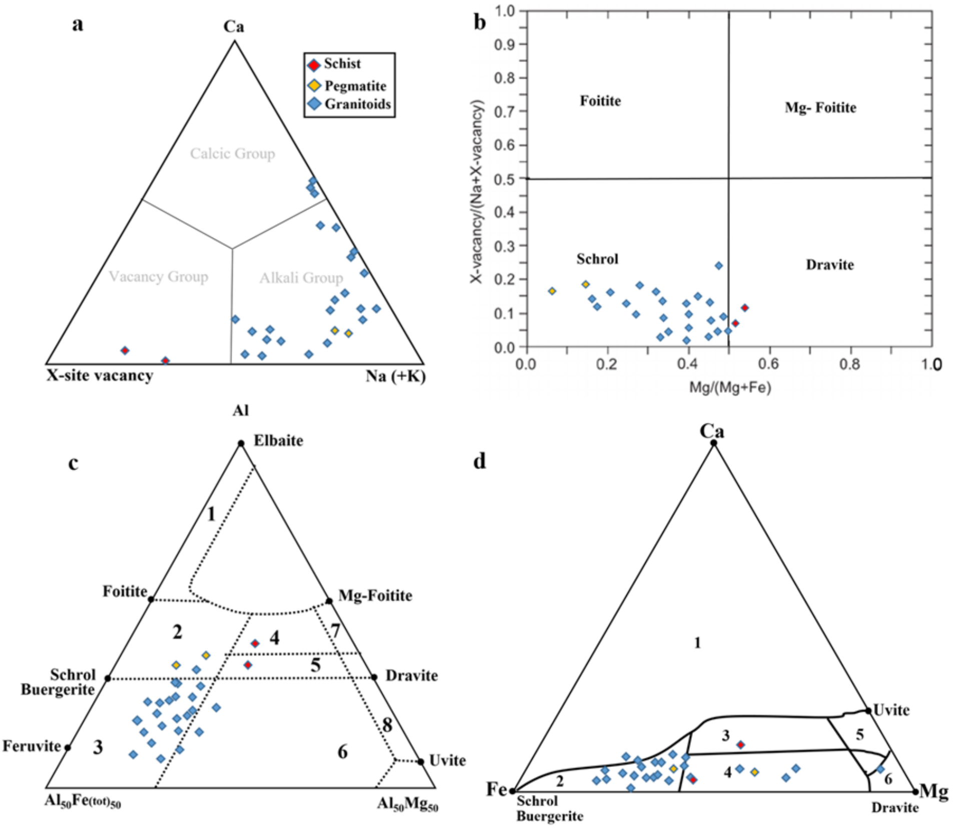

Fig 6. (a) Alkali classification diagram (Hawthorne and Henry 1999). Tourmalines from various rocks within the Boroujerd region are plotted based on their host rocks. The most tourmaline compositions fall within the alkali compositional group. Tourmalines from schists trend towards vacancy-rich compositions, whereas tourmalines of magmatic origin trend towards more Ca-rich compositions. The pegmatitic tourmalines contain low Ca but high Na. (b) Mg/(Mg + Fe) vs. X-vac/(X-vac + Na) discrimination diagram for naming tourmaline species; are mostly fall in the schrol area. This discrimination diagram shows solid solutions between Na- and vacancy-rich end members with varying Mg/(Mg+Fe). (c) Al-Fe-Mg compositional diagram (Henry and Guidotti 1985) with common end members for Boroujerd tourmaline analyses. Each field delineates various tourmaline-bearing rock types. Boroujerd tourmalines mostly cover the range of altered granitoids. (1) Li-rich granitoid pegmatites and aplites; (2) Li-poor granitoids and their ssociated pegmatites and aplites; (3) Fe^{3+} -rich quartz-tourmaline rocks (hydrothermally altered granites); (4) Metapelites and metapsammites coexisting with an Al-saturating phase; (5) Metapelites and metapsammites not coexisting with an Al-saturating phase; (6) Fe^{3+}-rich quartztourmaline rocks, calc-silicate rocks, and metapelites; (7) Low-Ca metaultramafics and Cr-, V-rich metasediments; and (8) Metacarbonates and meta-pyroxenites. (d) The Ca-Fe-Mg compositional diagram modified from Henry and Guidotti (1985) with Boroujerd tourmaline analyses. Common end members are plotted for reference. The majority of tourmaline analyses falls within field 2. Fields: (1) Li-rich granitoid pegmatites and aplites; (2) Li-poor granitoids and their associated pegmatites and aplites; (3) Ca-rich metapsammites, metapelites, and calc-silicate rocks; (4) Ca-poor metapelites, metapsammites, and quartz-tourmaline rocks; (5) metacarbonates; (6) metaultramafics.

5. Conclusions

Wide range of stability and chemical variability made tourmalines as a distinctive record of compositional variation in hydrothermal systems and their chemistry can be used to provide a clearer understanding of related formation environments. Tourmalines in the Boroujerd are formed in distinct. They are generally pleochroic and optically and chemically zoned. The composition of tourmaline is highly affected by rock/fluid ratios and chemical equilibria with coexisting phases in the hydrothermal system. The hydrothermal fluids have a main role in chemical variation of tourmalines with Fe, Mg, Al, Na, and Ca ions from this region. The substitutions of the elements are inferred by the variations of mentioned major element compositions. Most tourmalines show a negative correlation between Fe and Al and largely have sodic compositions. Magmatic tourmalines, show a negative correlation between Al and Ca, however, sericitic alteration changed this array in some samples (e.g. samples no. 6, 10, 16, 23). The sericitic hydrothermal alteration form tourmalines that display more compositional scatter which is dominated by substitution along the FeAl-1 exchange vector.

Tourmaline crystals hosted in the pegmatites and granitoids from Boroujerd region mostly belong to the alkali group, while the metasedimentary rocks -hosted tourmaline belongs to the X-site vacancy group. Magmatic tourmalines were produced by the late crystallization process of the granitoids. Occurrences of the tourmaline nodules in the Boroujerd batholite demonstrated that the boron might derived from a metapelitic host rocks. The existence of migmatite and gneiss in the region implies that the studied area had tolerated high grade metamorphism and anataxis-related crustal melts had a main role in formation of tourmalines. These melts have high contents of volatiles including iron and boron, which is ideal chemical condition for crystallization of Fe and Mg-rich shorl tourmaline. Uprising of this melt changed the temperature and pressure to tourmaline favor T-P and crystallize this mineral. The Mg, Fe and Ca were supplied by breakdown pyroxene, amphibole and biotite. Finally, the field, petrography and geochemical studies indicated that both magmatic and hydrothermal fluids sources are participating in crystallization of tourmalines in Boroujerd region.

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