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ABSTRACT

Deposits of semi-gemstones tourmaline, beryl, and garnet associated with Jurassic granites are found in the northern Sanandaj–Sirjan Zone (SaSZ) of western Iran, defining a belt that can be traced for about 400 km. Granitic magmas strongly interacted with or were derived from melts of continental crust and/or sediments. Based on morphologies, size, mineral assemblage, and contact relationships with host granite and associated metamorphic aureoles, these deposits are categorized into six types: (1) garnet in skarns, (2) tourmaline, beryl, and garnet in pegmatite and aplite dikes, (3) disseminations and patches of tourmaline in leucogranites, (4) quartz-tourmaline veins in granite, (5) tourmaline and garnet in metamorphic aureoles, and (6) tourmaline orbicules in aplite. Tourmalines are mostly schorl and dravite, and garnets are mostly almandine, spessartine, and grossular. Tourmaline, beryl, and garnet from pegmatites in the contact aureole of Jurassic granites reflect segregations of Be, B, Mn, and Al bearing melts from the Jurassic peraluminous granites. Quartz-tourmaline veins and hydrothermal garnets in skarns reflect fluids exsolved from the surrounding metasediment and pegmatite melt. In contrast, tourmaline patches and orbicules developed from boron-rich aqueous fluids exsolved from cooling granitic magma. Distribution of semi-gemstones in the SaSZ shows that these are mostly related to pegmatites associated with Jurassic granitic intrusions. Mineral equilibrium considerations indicate that SaSZ semi-gemstones crystallized at $P = 3.5–7.5$ kbar ($11.5–25$ km deep) and temperatures of $550–650^\circ C$. SaSZ pegmatites fall in the muscovite (MS) and MS-rare element classes. They are Lithium Cesium Tantalum (LCT)-type pegmatites. Fluids responsible for gem mineralization were exsolved from cooling granite bodies and released by metamorphosed sediments. Further studies are needed to better understand the northern Sanandaj–Sirjan tourmaline–garnet–beryl semi-gemstone Province.

1. Introduction

The geology of Iran reflects diverse tectonic events and magmatic episodes (Stöcklin 1968; Berberian and Berberian 1981; Berberian et al. 1982; Alavi 1994; Mohajjel and Ferguson 2000; Mohajjel et al. 2003; Golonka 2004; Ghasemi and Talbot 2006; Davoudian et al. 2008; Azizi et al. 2011; 2017; Chiu et al. 2013; Moghadam et al. 2016); consequently, there are a wide range of lithologies and minerals, including semi-gemstones. Iranian people have mined and used gemstones and semi-gemstones throughout its >7000-year history. In ancient times, before humans learned how to cut hard minerals, rough gemstones and semi-gemstones were valued for their magical properties in addition to their material value and possessing them was considered lucky (Ghorbani 2003).

The jewellery and gem industry in Iran has a history of several thousand years, and Iranian interest in gems and jewellery is deeply rooted in this history (Meen and Tushigham 1968; Ghorbani 2003). About 200 regions in Iran are identified as gemstone and semi-gemstone regions (Ghorbani 2003; Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009, 2017; Sheikhli et al. 2012; Salami et al. 2013; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014; Alipour et al. 2015; Ahmadi Khalaji et al. 2016). Iran has diverse gemstones and semi-gemstones such as opal, turquoise, beryl, fluorite, kyanite, garnet, agate, peridot, and jasper (Ghorbani 2003; Kievelenko 2003; Groat and Laurs 2009, 2014; Huong et al. 2012; Clark et al. 2016). But realizing this potential is hampered because of the lack of systematic scientific study beyond studies of individual deposits (Ghorbani 2003; Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009, 2017; Sheikhli et al. 2012; Salami et al. 2013; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014).
Esfahani and Khalili 2014; Tahmasbi 2014; Alipour et al. 2015; Ahmadi Khalaji et al. 2016). What is especially needed is a better understanding of related deposits that can be considered together as manifestations of gemstone and semi-gemstone – forming episodes that can be defined in space and time. Similar episodes affecting similar rocks under similar conditions are likely to produce similar mineral suites, making it useful to consider defining gemstone and semi-gemstone provinces wherever possible and interpreting these as gemstone and semi-gemstone-forming systems. Such an effort requires an interdisciplinary approach involving field geology, mineralogy, geochemistry, geochronology, and isotopic studies. Similar approaches have proved to be useful for systematic study of hydrocarbons (hydrocarbon provinces) and metals (metallogenic provinces) (Worden et al. 2000; Somarim 2004; Bordenave and Hegre 2005; Zhou et al. 2007; Bernard et al. 2012).

Here we use the geoprovince approach to study semi-gemstones of the Sanandaj–Sirjan zone (SaSZ). The SaSZ is a well-defined geologic terrane that experienced pervasive magmatism, metamorphism, and deformation, and has abundant pegmatites, metamorphic aureoles, and migmatites, environments that sometimes produce pockets of semi-gemstones. There are many short reports on SaSZ deposits of tourmaline (Nezam abad, Haji abad, Astaneh, and Mangavi), garnet (Boroujerd, Molatalab, Abaru, Kamari-Zaman Abad, and Seranjik), and beryl (Ebrahim Atar and Kamari-Zaman Abad) (Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Sheikh et al. 2012; Salami et al. 2013; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalilli 2014; Tahmasbi 2014; Ahmadi Khalaji et al. 2016), but there is no systematic overview of SaSZ semi-gemstone deposits. This study aims to help overcome this shortcoming by summarizing what is known about semi-gemstones of the SaSZ of Southwest Iran, with special emphasis on its tourmaline, beryl, and garnet deposits.

2. Geological setting

The SaSZ is a distinctive terrane that is 50–150 km wide, 800 km long and trends southeast–northwest across Southwest Iran (Figure 1). The SaSZ has been part of the Iran active margin since Middle Jurassic time (Stöcklin 1968; Berberian and Berberian 1981; Berberian et al. 1982; Mohajel et al. 2003; Gholonka 2004; Ghasemi and Talbot 2006; Davoudian et al. 2008; Nadimi and Konon 2012) and helps define the southwest margin of the Iranian microcontinent (Stöcklin 1968; Berberian and Berberian 1981; Mohajel et al. 2003; Hassanzadeh et al. 2008; Azizi et al. 2016). A variety of marine sediments were deposited in Paleozoic and Mesozoic time. Igneous activity was concentrated in Jurassic time (Azizi and Moinevaziri 2009; Mahmoudi et al. 2011; Azizi and Ashara 2013; Mohajel and Fergusson 2014). SaSZ sedimentary rocks are regionally metamorphosed, especially around Jurassic plutons (Berberian and Berberian 1981; Sepah and Athari 2006; Ahmadi-Khalaji et al. 2007; Sepah 2007; Azizi et al. 2011; Maanijou et al. 2011; Aliani et al. 2012; Azizi and Ashara 2013; Yajam et al. 2015; Deesvalar et al. 2017). SaSZ basement consists of Ediacaran-Cambrian (Cadamian) igneous and metamorphic rocks (Stöcklin 1968; Berberian and Berberian 1981; Berberian et al. 1982; Mohajel et al. 2003; Golonka 2004; Ghasemi and Talbot 2006; Davoudian et al. 2008; Hassanzadeh et al. 2008; Malek-Mahmoudi et al. 2017; Shabanian et al. 2017). Codomian (~550 Ma) basement is exposed in the northern SaSZ (Moghadam et al. 2015, 2016; Honarmand et al. 2017; Shabanian et al. 2017) but Jurassic metamorphic rocks cut by Late Jurassic granitoids make up most outcrops (Berberian et al. 1982; Baharifar et al. 2004; Esmaeily et al. 2005; Sepah and Athari 2006; Arvin et al. 2007; Mazhari et al. 2009; Shahbazi et al. 2010, 2014; Azizi and Ashara 2013; Azizi et al. 2011, 2015a; b, 2016; Zhang et al. 2018). Major plutonic rocks of this area are granites, diorites, and gabbros which are intruded by aplite-pegmatitic and silicic veins. Both I-type and S-type granitic rocks are encountered.

The Jurassic volcano-sedimentary complex is an important part of the SaSZ. Jurassic volcanics and volcaniclastics are associated with marble, black shale, pelite, psammitic, mafic volcanics, calc-pelrite, and calc-silicate rocks. Pelitic rocks are the most abundant lithology. The pelitic sequence has been variably metamorphosed to slate, phyllite, mica schist, garnet schist, garnet andalusite schist, garnet staurolite schists, cor-dierite hornfels, mica hornfels, garnet hornfels, and garnet andalusite hornfels. Metamorphic rocks were overprinted by dynamic deformation (Mohajel et al. 2003; Baharifar et al. 2004; Davoudian et al. 2008). Metamorphic rocks are locally unconformably overlain by Cretaceous marble (Eftekharnejad 1981; Kazmin et al. 1986; Alavi 1994; Hosseiny 1999; Baharifar et al. 2004).

3. Semi-gemstone districts in the SaSZ

Table 1 lists and Figure 1(b) shows the main SaSZ semi-gemstone deposits, from northwest to southeast. Below we discuss these deposits and their host rocks based on geographic location. We subdivide the SaSZ semi-gemstone province into three districts, each on the order of
50–200 km across. From northwest to southeast, the three SaSZ semi-gemstone districts are (1) Ghorveh, (2) Hamedan, and (3) Boroujerd (Figure 1(b)). These are further outlined below.

### 3.1. Ghorveh semi-gemstone district

The Ghorveh semi-gemstone district is the most important one in the SaSZ and consists of two principal semi-gemstone areas: Ebrahim Atar S-type pegmatite and Seranjic skarn (Figure 1(b)). These are located near the Moshirabad (I-type granite) and Ghalaylan (A-type granite) plutons (Azizi et al. 2011, 2015b, 2016; Mahmoudi et al. 2011; Salami et al. 2013; Yajam et al. 2015). These deposits are associated with the Jurassic Hamedan-Ghorveh metamorphic complex, a suite of slate, phyllite, schist, marble, and quartzite that is interbedded with submarine metavolcanic rocks and associated with abundant pegmatites (Hosseiny 1999; Baharifar et al. 2004; Azizi and Asahara 2013). Outcrops of the Moshirabad granitoid define a sigmoidal form of medium- to coarse-grained granites (Figure 2(a)) and metaluminous to peraluminous granitoids (Figure 2(b)) (Yajam et al. 2015). The 157 Ma Moshirabad I-type granite plots in the volcanic arc granite (VAG) field due to their low...
<table>
<thead>
<tr>
<th>District</th>
<th>Number</th>
<th>Area</th>
<th>Semi-gem</th>
<th>Colour</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghorveh</td>
<td></td>
<td>Ebrahim Atar</td>
<td>Beryl</td>
<td>Green, blue</td>
<td>1. Vein, 2. aggregate</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Seranjic</td>
<td>Garnet</td>
<td>Brown, green</td>
<td>1. Pegmatite</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Mangavi</td>
<td>Tourmaline</td>
<td>Black</td>
<td>1. Pegmatite</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Ganjnameh</td>
<td>Tourmaline</td>
<td>Black</td>
<td>1. Spot, 2. aggregate</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Kamari</td>
<td>Garnet</td>
<td>Brown, red</td>
<td>1. Spot, 2. aggregate</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Abaru</td>
<td>Garnet</td>
<td>Brown, red</td>
<td>1. Spot, 2. aggregate</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Dehgah</td>
<td>Tourmaline</td>
<td>Black to green</td>
<td>1. Pegmatite, 3. quartz-tourmaline vein, 4. metamorphic halo</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Haji-abad</td>
<td>Tourmaline</td>
<td>Black</td>
<td>1. Lobar, 2. spot</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Dare Seidi</td>
<td>Tourmaline</td>
<td>Black to green</td>
<td>1. Vein, 2. stringer</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Sangesefid</td>
<td>Garnet</td>
<td>Light reddish</td>
<td>1. Pegmatite</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Ghapanvari</td>
<td>Garnet</td>
<td></td>
<td>1. Pegmatite</td>
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<tr>
<td></td>
<td>12</td>
<td>Gharedash</td>
<td>Garnet</td>
<td></td>
<td>1. Aplitic dike, 2. hydrothermal vein</td>
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<tr>
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<td>13</td>
<td>Nezam abad</td>
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<td>1. Aplitic dike, 2. hydrothermal vein</td>
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<td>Astaneh</td>
<td>Tourmaline</td>
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<td>Sarsakhty</td>
<td>Tourmaline</td>
<td>Black to green</td>
<td>1. Nodule or lobar</td>
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<td>Molataleb</td>
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<td>Black</td>
<td>1. Pegmatite</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>Garnet</td>
<td>Garnet</td>
<td>Black</td>
<td>1. Lobar, 2. spot</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>References</th>
<th>Host rock</th>
<th>Other minerals</th>
<th>Age (Ma)</th>
<th>Method</th>
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</thead>
<tbody>
<tr>
<td>Magmatic origin</td>
<td>Salami et al. (2013)</td>
<td>Pegmatite granite</td>
<td>Quartz, alkali feldspar, muscovite, biotite, garnet, and alinite</td>
<td>134 ± 29</td>
<td>Sm-Nd</td>
</tr>
<tr>
<td>Metamorphic and metasomatic origins</td>
<td>Sheikh et al. (2012)</td>
<td>Skarn and hornfels that surrounded by granites</td>
<td>Clinopyroxene, garnet, vesuvianite, wollastonite, titanite, and epidote</td>
<td>160 ± 2</td>
<td>U-Pb</td>
</tr>
<tr>
<td>Metamorphic origin</td>
<td>Ahmadi Khalaji and Tahmasbi (2015)</td>
<td>Leucogranites and granodiorites surrounded by hornfels and Jurassic phyliteschist</td>
<td>Quartz, alkali feldspar, plagioclase, muscovite, biotite, garnet, apatite, and zircon</td>
<td>163 ± 0.88</td>
<td>U-Pb</td>
</tr>
<tr>
<td>Magmatic origin</td>
<td>Ahmadi Khalaji and Tahmasbi (2015)</td>
<td>Pegmatite veins that surrounded by granidiorite, hornfels, and Jurassic phylites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metamorphic origin</td>
<td>Ahmadi Khalaji and Tahmasbi (2015)</td>
<td>Schist and hornfels that surrounded by granites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magmatic origin</td>
<td>Ahmadi Khalaji and Tahmasbi (2015)</td>
<td>Pegmatite veins that surrounded by granidiorite, hornfels, and Jurassic phylites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magmatic origin</td>
<td>Tahmasbi (2014)</td>
<td>Aplitic dikes that surrounded by granidiorite, hornfels, and Jurassic phylites</td>
<td>Quartz, alkali feldspar, muscovite, and plagioclase</td>
<td>168 ± 0.85</td>
<td>U-Pb</td>
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<tr>
<td>Magmatic, metamorphic, and hydrothermal origins</td>
<td>Khodakarami Fard et al. (2014)</td>
<td>Leucogranitic granite surrounded by hornfels and Jurassic phylite-schist</td>
<td>Quartz, alkali feldspar, muscovite, plagioclase, amphibole, epidote, zircon, and alanite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrothermal origin</td>
<td>Gholami and Mokhtari (2014)</td>
<td>Granite and granidiorite surrounding by Jurassic phylites and schists</td>
<td>Quartz</td>
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(Continued)
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<th>District</th>
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<th>Area</th>
<th>Semi-gem</th>
<th>Colour</th>
<th>Feature</th>
</tr>
</thead>
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<tr>
<td>Magmatic origin</td>
<td>Rahmani Javanmard et al. (2018)</td>
<td>Pegmatite granite</td>
<td>Quartz, alkali feldspar, muscovite, andalusite, tourmaline, zircon, and fluorapatite</td>
<td>170 ± 1.5</td>
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<td>Magmatic origin</td>
<td>Rahmani Javanmard et al. (2018)</td>
<td>Pegmatite granite</td>
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<td>Magmatic origin</td>
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<td>Pegmatite granite</td>
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<td></td>
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<tr>
<td>Magmatic and hydrothermal origin</td>
<td>Nekouvaght Tak and Bazargani-Guilani (2009)</td>
<td>Quartz diorite and granodiorite surrounded by hornfels and Jurassic phylites</td>
<td>Plagioclase, hornblende, biotite, quartz, titanite, and zircon</td>
<td>167 ± 1.0</td>
<td>U-Pb</td>
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<td>Hydrothermal fluids for nodules and metasomatism at the contact of plutonic and hornfels</td>
<td>Tahmasbi et al. (2009)</td>
<td>Monzogranite surrounded by Jurassic phylites and schists</td>
<td>Muscovite, biotite, quartz, plagioclase, and alkali feldspar</td>
<td>169 ± 1.0</td>
<td>U-Pb</td>
</tr>
<tr>
<td>Magmatic origin and reaction with fluids derived of metapelitic host rock</td>
<td>Tahmasbi (2014)</td>
<td>Monzo granite</td>
<td>Quartz, alkali feldspar, plagioclase, zircon, and apatite</td>
<td>169 ± 1.0</td>
<td>U-Pb</td>
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<td>Metasomatism at the contact of intrusive body and pelitic hornfels</td>
<td>Mansouri Esfahani and Khalili (2014)</td>
<td>Pegmatic veins that surrounded by micaceous granodiorite and metapelites</td>
<td>Quartz, alkali feldspar, plagioclase, zircon, and apatite</td>
<td>165 ± 5</td>
<td>U-Pb</td>
</tr>
<tr>
<td>Magmatic origin</td>
<td>Mansouri Esfahani and Khalili (2014)</td>
<td>Two mica granite and metapelitic rocks</td>
<td></td>
<td>165 ± 5</td>
<td>U-Pb</td>
</tr>
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<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Temperature</th>
<th>Pressure</th>
<th>References</th>
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<tbody>
<tr>
<td>35°08’</td>
<td>47°40’</td>
<td>450–587°C</td>
<td>&lt;3 kbar</td>
<td>Sheikhi et al. (2012)</td>
</tr>
<tr>
<td>35°09’</td>
<td>47°47’</td>
<td>48°44’</td>
<td>48°24’</td>
<td>568–586°C</td>
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<tr>
<td>34°38’</td>
<td>48°32’</td>
<td>48°50’</td>
<td>49°14’</td>
<td>33°45’</td>
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</tbody>
</table>
concentrations of Nb and Ta (Figures 3 and 4(a)) (Yajam et al. 2015). The Ghalaylan granite differs from other Jurassic intrusions in the Ghorveh area, which have moderate contents of SiO\textsubscript{2} (62–68 wt%; Figure 2(a)) and are mainly metaluminous to peraluminous (Figure 2(b)). Ghalaylan is A-type, ferroan and has a composition similar to adakite and tonalite–trondhjemite–granodiorite (Azizi et al. 2015b). In the tectonic discrimination diagram of Pearce et al. (1984), the Ghalaylan granitoid plots within the transitional area between the field of VAG and within-plate granite (Figure 3). It has a zircon U-Pb age indicating an age of 157 Ma (Figure 4(a)) (Azizi et al. 2015).

The Ebrahim-Atar pegmatite contains alkali feldspar, quartz, plagioclase, muscovite (MS), and biotite (Salami et al. 2014; Azizi et al. 2016). It is characterized by high SiO\textsubscript{2} (72.81 wt%) (Figure 2(a)) and Rb (140–440 ppm) contents and low contents of MgO (<0.12 wt%), Fe\textsubscript{2}O\textsubscript{3} (<0.68 wt%), Sr (mainly <20 ppm), Ba (<57 ppm), Zr (10–53 ppm), and rare earth elements (REE; 3.88–94.9 ppm; mean = 21.2 ppm). Chemical compositions and mineral parageneses show that the Ebrahim Atar pegmatite is peraluminous and was generated by partial melting of...
samples plot in the field for VAG but extend into fields for syn-collision and within-plate granite (Figure 3).

Deposits of beryl (Salami et al. 2013), tourmaline, and garnet (Sheikhi et al. 2012) of this district have magmatic and metasomatic origins, including the Ebrahim Atar beryl and Seranjic garnet deposits (Sheikhi et al. 2012; Salami et al. 2013) (Table 1). Rb-Sr whole rock and Sm-Nd dating indicate that the Ebrahim Atar pegmatite crystallized at 134 ± 29 Ma (Figure 4(a)) (Azizi et al. 2016), significantly younger than the ages of the Moshirabad and Ghalignyan plutons. The $^{87}\text{Sr}/^{86}\text{Sr}$ (i) = 0.7081 and $\varepsilon\text{Nd}(i)$ values range from −5.8 to −1.6, indicating the involvement of older continental crust and/or sediments (Azizi et al. 2016) (Figure 4(b)).

### 3.2. Hamedan semi-gemstone district

The Hamedan semi-gemstone district is located around the Alvand plutonic complex and deposits are concentrated in four areas: Mangavi, Ganjnameh, Kamari-Zaman Abad, and Abaru (Figure 1(b)). These deposits are mostly of magmatic and metamorphic origins. The Alvand pluton is dominated by gabbro and coarse porphyritic granite (Figure 2(a)) with metaluminous to peraluminous compositions (Figure 2(b)) which intruded 164–162 Ma ago (Figure 4) (Shahbazi et al. 2010). In the discrimination diagram of Pearce et al. (1984), all Hamedan granitoids plot close to fields for within-plate granite and VAG. Aplitic and pegmatite rocks cross-cut plutonic and metamorphic rocks in the Hamedan-Alvand region. Gabbroic rocks are calc-alkaline with low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7023–0.7037) and positive $\varepsilon\text{Nd}(i)$ to +3.3. In contrast, the granites show high to low K calc-alkaline signatures with A-type affinity and have intermediate to high initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.707–0.714) and negative $\varepsilon\text{Nd}(i)$ = −1.0 to −3.4 (Figure 4(b)) (Shahbazi et al. 2010), showing evidence for involvement of sediments or older crust. Alvand granites intrude Triassic-Jurassic phyllites, schists, metavolcanics, and dolomitic limestone (Bahrainfar et al. 2004; Shahbazi et al. 2010, 2014). Mohajjel and Izadikian (2007) reported evidence for deformation in the area. In this region, aplites and pegmatites are common inside and around the border of the pluton, cross-cutting different lithologies including granite, hornfels, and schist. Chemically, the aplites and pegmatites are peraluminous (Figure 2(b)) and highly fractionated, related to S-type granite (Sepahi et al. 2018) with high silica and alkali element contents and Light Rare Earth Elements (LREE) and High Field Strength Elements (HFSE) enrichment (Ce >103 ppm, La >125 ppm, and Nb >134 ppm), and some Large Ion Lithophile Elements (LIL) enrichment (K, Rb, Ba).

#### Figure 4.

(a) Simplified age diagram for granitoids and pegmatites from N-SaSZ. Age data for Ghorveh from Azizi et al. (2011), Azizi et al. (2015a), (2015b), (2016), Mahmoudi et al. (2011) and Yajam et al. (2015), Hamedan from Shahbazi et al. (2010), Deevsalar et al. (2017), and Sepahi et al. (2018). Boroujerd from Ahmadi-Khalaji et al. (2007), Esna-Ashari et al. (2012), Shakerardakani et al. (2015), and Deevsalar et al. (2017). (b) Sr and Nd isotopic data for granitic rocks from Ghalignyan, Hamedan, Ebrahim Atar, and Boroujerd (Sr and Nd isotope data from Ahmadi-Khalaji et al. (2007), Shahbazi et al. (2010), Tahmasbi et al. (2010), Esna-Ashari et al. (2012), Azizi et al. (2015b), (2016)). These granitic rocks have a strong crustal component, derived from continental crust, metasediments, or both.

siliciclastic to pelitic rocks (Figure 2(b)); it is an S-type leucogranite pegmatite (Azizi et al. 2016). The pegmatite and its associated granite differ from other SaSZ Jurassic granites. The initial Sr-Nd isotopic compositions of Ebrahim Atar granites are pointedly different from those of Ghalignyan and Moshirabad granites having positive $\varepsilon\text{Nd}(i)$ values, whereas Ebrahim Atar granites display negative $\varepsilon\text{Nd}(i)$ values. A further difference is that Ghalignyan granite is post-tectonic; moreover, the low REE content infers that partial melting produced the Ebrahim Atar granites from rocks with low REE content, such as siliciclastic or metapelitic rocks (Azizi et al. 2015b, 2016). In the Pearce et al. (1984) diagram, most Ebrahim-Atar
(LILEs) including Sn (>10,000 ppm), Rb (>936 ppm), and Ba (>706 ppm) (Valizadeh and Torkian 1999; Sepahi 2007; Sepahi et al. 2018). Sepahi et al. (2018) suggest that these pegmatites originated from melting of metasedimentary rocks (Figure 3), whereas Masoudi (1997) infer metamorphic to magmatic sources for some pegmatites in the Alvand complex. U-Pb dating of monzonite and zircon from apliteitic and pegmatic rocks indicates an age of 154–172 Ma (Figure 4(a)) (Sepahi et al. 2018), overlapping the age of the Alvand pluton. Gem deposits are found both within the Alvand granitoid and in the surrounding metamorphic complex. Deposits of garnet and beryl are found in pegmatites and metamorphic rocks (Abaru and Kamari-Zaman Abad) (Ahmadi Khalaji and Tahmasbi 2015). Deposits with coexisting tourmaline and garnet occur in pegmatites and aplite in metamorphic rocks (Mangavi) and in garnitoid hosts (Ganjnameh) (Ahmadi Khalaji et al. 2016) (Table 1).

3.3. Boroujerd semi-gemstone district

The Boroujerd gem field near the Boroujerd granitic complex consists of ten main areas: Dehgah, Sangesefid, Ghapanvari, Gharedash, Hajiabab, Dare Seidi, Nezam abad, Astanen, Sarsakhthi and Molataleb. A significant amount of tourmaline and garnet has been produced from the Dehgah, Sangesefid, Ghapanvari, Gharedash, Hajiabab, Dare Seidi, Nezam abad, Astanen, Sarsakhthi and Molataleb sites. A significant amount of tourmaline and garnet has been produced from the Astanen, Nezam abad, Hajiabab, Molataleb, and Sar Sakhti sites (Nekouvaght Tak and Bazargani-Guilani 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014; Rahmani Javanmard et al. 2018) (Table 1). These deposits are mostly metasomatic and rarely metamorphic in origin. The Boroujerd complex consists of metagranitic rocks and garnitoids (Ahmadi-Khalaji et al. 2007; Tahmasbi et al. 2009; Deevsalar et al. 2017). Metamorphic rocks are low- to high-grade metavolcanics and metasediments (such as meta-tuffs, metachert, schist, and phyllite). Contact metamorphic rocks such as spotted schists, cordierite-andalusite, and cordierite-sillimanite hornfels outcrop in the northern part of the district. The Boroujerd granitoid complex consists of three main units including voluminous granodiorite, small stocks of quartz diorite, and small outcrops of monzogranite in the southern Boroujerd district. These granitoids have large ranges in SiO₂ contents (52–73 wt %; Figure 2(a)). NW-trending pegmatites and aplite dikes cross-cut the granodiorite and its metamorphic halo. Geochemically, the Boroujerd granitoid complex is metaluminous to slightly peraluminous (Figure 2(b)) I-type granite belonging to the medium to high K calc-alkaline series. The granitoids usually have low HFSE contents (Nb, Ta, and Hf) and have widely ranging Sr and Ba contents (66–484 ppm and 38–1150 ppm, respectively). They have initial ⁸⁷Sr/⁸⁶Sr of 0.7035–0.7110 and εNd(⁴⁰) of −0.7 to −6.13 that are consistent with generation by partial melting of crustal protoliths or sediments (Ahmadi-Khalaji et al. 2007; Deevsalar et al. 2017) (Figure 4(b)). U-Pb zircon dating indicates an age range of 158–173 Ma (Figure 4(a)) for Boroujerd granitoids (Ahmadi-Khalaji et al. 2007; Deevsalar et al. 2017). Three SaSZ pegmatites have been dated: two are the same age as associated granite but pegmatite in the Ghorveh district is much younger.

Boroujerd pegmatites are LREE-enriched and their geochemical characteristics suggest that these were produced by differentiating peraluminous to slightly metaluminous (Figure 2(b)) I-type granitic magma. In contrast, Masoudi (2009) suggest that pegmatites reflect partial melting of metasedimentary host rock. Ahmadi-Khalaji et al. (2007) proposed that the Boroujerd pegmatite was generated about the same time as the Boroujerd granitoid (Figure 4) in a volcanic arc to syn-collision setting (Figure 3).

4. SaSZ semi-gemstone mineralization styles

Understanding how Sanandaj–Sirjan semi-gemstone deposits formed must be first understood based on relationships with their host rocks. Tourmaline, beryl, and garnet occur in six main settings, including (1) garnet in skarns; (2) tourmaline, beryl, and garnet in pegmatite and aplite dikes related to granodiorite and hornfels; (3) disseminations and patches of tourmaline in leucogranites; (4) quartz-tourmaline veins in granite; (5) tourmaline and garnet in metamorphic aureoles; and (6) tourmaline orbicules in aplite (Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Salami et al. 2013, 2014; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014; Ahmadi Khalaji and Tahmasbi 2015; Ahmadi Khalaji et al. 2016). These occurrences are discussed further below.

4.1. Garnet in skarn

The skarns (Figure 5(a,b)) contain carbonate (calcite), clinopyroxene (diopside) (Figure 7(a)) garnet (grosoular-andradite), vesuvianite, wollastonite, titanite and epidote. (calcite), clinopyroxene (diopside). Calcite is both primary and secondary. Clinopyroxene, wollastonite, and titanite are almost euhedral and clinopyroxene inclusions in garnet.
suggests replacement of pyroxene by garnet (Figure 7(b)). Most garnets show atoll texture and have distinct resorbed margins. Garnets are partially altered and some have been pseudomorphed by chlorite, calcite, and quartz. Garnetiferous rocks are granoblastic (Sheikhi et al. 2012). Some skarns produce good tourmaline and garnet gems.

4.2. Tourmaline, beryl, and garnet in pegmatite and aplitic dikes

Pegmatites up to tens of centimeters thick (Figures 5(c, d) and 6(a-c)) consist of quartz, plagioclase, K-feldspar, muscovite, tourmaline, beryl and garnet. Pegmatites are equigranular, medium- to coarse-grained rocks. Pegmatites are equigranular, medium- to coarse-grained rocks. Plagioclase forms subhedral to euhedral crystals which commonly have sericitized cores where they border tourmaline. Anhedral to subhedral K-feldspars and MSs enclose small plagioclase and quartz. Quartz is anhedral, polycrystalline and shows undulose extinction. Tourmalines are columnar, up to 1 cm long, oriented perpendicular to the pegmatite margins. They are colour zoned with homogenous cores surrounded by narrow rims. Pleochroism changes from light to dark blue in the core to olive brown in narrow rims. Tourmalines are usually segmented (Figure 7(c)) by cracks filled with quartz and K-feldspar. In some cases, tourmaline is replaced by quartz. Garnets in pegmatites are sparse (Figure 7(d)) and are subhedral to euhedral with red to red brown colour and some parts contain abundant inclusions of quartz and feldspar. Fractures in the garnets are filled by quartz. Elongated beryls are widely distributed but are only abundant in the Ghorveh district where most crystals are large and fractured (Figure 7(c)). Beryl is light green, yellowish green, blue, pale yellow, or nearly white, these beryls would be classified as green beryl, aquamarine, heliodor, and goshenite varieties. Some contain MS and opaque minerals. They occur in the intermediate zone of pegmatites and typically range in size from a few millimetres to centimetres. The middles of pegmatites produce the best beryl, tourmaline, and garnet gems (Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Salami et al. 2013, 2014; Khodakarami Fard et al. 2014; Tahmasbi 2014; Ahmadi Khalaji and Tahmasbi 2015; Ahmadi Khalaji et al. 2016).

4.3. Disseminations and patches of tourmaline in leucogranites

Host leucogranites (Figure 6(d,e)) are typically equigranular and locally porphyritic tourmalines occur as
anhedral interstitial grains (Figure 7(f)) with angular and dendritic morphologies. Tourmaline is generally unzoned. Well-developed microscopic tourmaline ‘suns’ are sometimes encountered in the leucogranitic host rock from Khaku (Hamedan semi-gemstone district). (e) Patches of tourmaline in aplite dikes (Hamedan semi-gemstone district). (f) Tourmaline-quartz vein (Hamedan semi-gemstone district). (g) Tourmaline-quartz (Qz) veins from Dehno, south of Khomein (Boroujerdi semi-gemstone district) (Darvishi 2012). (h) Layers of tourmaline in metamorphic halo from Dare-Simin (Hamedan semi-gemstone district). (i) Layers of tourmaline in hornfels from Astaneh (Boroujerdi semi-gemstone district) (Tahmasbi et al. 2009). (J) Tourmaline orbicules in granites (Hamedan semi-gemstone district). (k) Tourmaline orbicules in aplite dikes from Dehgah (Boroujerdi semi-gemstone district) (Tahmasbi 2014). (l) Tourmaline orbicules in dikes from Dehgah (Boroujerdi semi-gemstone district) (Mirsepahvand et al. 2012).

4.4. Quartz-tourmaline veins in granite

Quartz-tourmaline veins (Figure 6(f,g)), ranging from a few centimetres to more than 1 m thick, cross-cut the granitic rocks and are often associated with pegmatites. These veins are mostly dark (tourmaline-rich) but sometimes light coloured (quartz-rich). Vein mineralogy is simple consisting of quartz and tourmaline with medium- to fine-grained mosaic textures and small amounts of opaque minerals. In the veins, hair-like aggregates and needle crystals of tourmaline form stripes up to 2 mm thick. Typically, quartz is
milky white and shows no sign of deformation. Tourmalines may be unzoned, irregularly zoned, or have two sharply defined zones. Tourmaline with two zones forms small crystals associated with pyrite and magnetite.

4.5. Tourmaline and garnet in metamorphic aureoles

This type of tourmaline is very fine grained (<1 mm) and is associated with hornfels and metapelites (Figure 7(h)) within the contact aureole of a granitoid intrusion (Figure 6(h,i)). Tourmaline-rich zones are found along the boundary between a granitic pluton and its contact aureole. Tourmaline crystals are prismatic-acicular in shape and show strong pleochroism, with colour ranging from brown, dark green to very pale bluish-green, frequently with numerous quartz inclusions. Garnet occurs as isolated grains or clusters and euhedral grains (Figure 7(i)) that are characteristically associated with coarse- to fine-grained chlorite, andalusite, and cordierite. Tourmaline is often replaced by other minerals such as chlorite, albite, and Fe oxides (Khodakarami Fard et al. 2014; Ahmadi Khalaji and Tahmasbi 2015).

4.6. Tourmaline orbicules in aplites

Tourmaline orbicules (Figure 6(j-l)) are particularly well developed within aplitic dikes, which consist mainly of quartz, plagioclase, K-feldspar, biotite, and tourmaline (Tahmasbi et al. 2009; Tahmasbi 2014). Tourmaline orbicules typically have spherical to elliptical shapes and are 20–40 mm across.

5. Mineral chemistry

In the following sections, we summarize the mineral chemistry of semi-gemstone crystals: (1) garnet, (2) tourmaline, and (3) beryl.

5.1. Garnet chemistry

Garnets from the Ghorveh, Hamedan, and Boroujerd semi-gemstone districts have been analysed for
chemical composition (Figure 8(a)) (Sheikhi et al. 2012; Mansouri Esfahani and Khalili 2014; Ahmadi Khalaji and Tahmasbi 2015; Rahmani Javanmard et al. 2018). Garnets are generally almandine-rich, less commonly

![Diagram of garnet compositions](image)

**Figure 8.** (a) Garnet compositions of SaSZ deposits (Einaudi et al. 1981). Data for garnets from Hamedan (Ahmadi Khalaji and Tahmasbi 2015), Molataleb (Mansouri Esfahani and Khalili 2014), Ghorveh (Sheikhi et al. 2012), and Boroujerd (Rahmani Javanmard et al. 2018). (b) Ca-K + Na-X-site vacancy ternary diagram for classifying tourmalines (Hawthorne and Henry 1999). (c) Mg/Mg + Fe versus X-vacancy/(X-vac + Na) for classifying tourmalines from Hamadan-Ghorveh metamorphic rocks (Hawthorne and Henry 1999; Nekouvaqht Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014; Ahmadi Khalaji et al. 2016; Sepahi et al. 2018).
grossular- or spessartine-rich. The composition of garnet from the Ghorveh skarn is almandine 0.28, grossular 0.71, pyrope 0.00, and spessartine 0.01 (Table 1 in Sheikhi et al. 2012), whereas garnet from Hamedan pegmatites is almandine 0.70, grossular 0.00, pyrope 0.01, and spessartine 0.28 (Table 1 in Ahmadi Khalaji and Tahmasbi 2015). Garnets from the Boroujerd region are predominantly almandine-spessartine with less pyrope and grossular components (Alm_{48.85-79.83}, Sp_{17.16-50.06}, Py_{0.08-3.53}, Gr_{0.00-0.85}) (Table 2 in Mansouri Esfahani and Khalili 2014; Table 2 in Rahmani Javanmard et al. 2018). Pegmatitic garnets from Hamedan and Boroujerd are homogenous, with almandine slightly increasing while spessartine decreases from core to rim. Schist-hosted garnets in the Hamedan metamorphic halo contain less almandine (0.63) and pyrope (0.07) component than do garnets with hornfels host (almandine 0.80 and pyrope 0.13) (Table 1 in Ahmadi Khalaji and Tahmasbi 2015). Despite the modest effect of temperature on garnet morphology, temperature gradients may control crystal morphologies so that most garnet crystals with varying CaO and MnO in hornfels and aplites are trapezohedrons rather than dodecahedrons. Dodecahedrons may be produced under low-temperature gradients in schists, but trapezohedrons are produced with high-temperature gradients (Sepahi 2007).

Thermobarometric studies of SaSZ metamorphic rocks show that garnet schists formed at 4.3 ± 0.5 kbar (14 km deep in the crust) and 568–586°C, whereas garnet hornfelses formed at 2.5 ± 0.1 kbar (9 km) and 539–569°C (Baharifar 1997). In contrast, Ghorveh garnets formed at <3 kbar (<10 km) and 450–587°C (Sheikhi et al. 2012) (Table 1).

### 5.2. Tourmaline chemistry

Five types of tourmaline have been distinguished based on field geology and mineral assemblages (Nekouvaught Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Gholami and Mokhtari Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014; Ahmadi Khalaji et al. 2016): (1) tourmaline in pegmatite and aplitic dikes related to granodiorite and hornfels; (2) disseminations and patches of tourmaline in leucogranites; (3) quartz-tourmaline veins in granite; (4) tourmaline in metamorphic aureoles; and (5) tourmaline orbicules in aplite.

In terms of tourmaline classification (Hawthorne and Henry 1999), most are alkali type with minor X-site vacancies and Ca substituting for Na (Figure 8(b)). They are mostly schorl and dravite, with minor foitite (Figure 8(c)) (Nekouvaught Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014; Ahmadi Khalaji et al. 2016). Nearly all samples of SaSZ tourmaline do not have enough Si to fill the tetrahedral sites. The six octahedral Z sites are occupied by Al but the three octahedral Y sites contain a variety of divalent cations. In fact, the main compositional variable of tourmaline is the occupancy of Y site. The sum of T + Z + Y cations in the tourmaline ideal formula is 15. The X-site ranges from 0.63 to 1.12 and the X-site vacancy is smallest in hornfels and schist tourmaline and the largest in pegmatite tourmaline. Na is dominant over Ca and K in X-sites in all samples. Ca contents are low, ranging from 0.0 to 0.24 apfu. B_{2}O_{3} ranges from 9.90 to 12.92 wt%. Fe^{2+} content varies a lot (0.80–1.96 apfu.), whereas Al varies less, between 5.83 and 7.02 apfu (Table 1 in Ahmadi Khalaji et al. 2016). In all samples, FeO contents are greater than MgO. Pegmatite tourmaline has the highest Fe/Mg value (Table 1 in Ahmadi Khalaji et al. 2016), whereas tourmalines from leucogranite, country rocks, quartz veins, and metamorphic haloes show the lowest Fe/Mg value (Nekouvaught Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014). Pegmatite tourmalines have higher concentrations of Fe and lower concentrations of Mg (Nekouvaught Tak and Bazargani-Guilani 2009; Ahmadi Khalaji et al. 2016) than those in the granite, quartz veins, and country rock.

Major and trace element abundances of tourmalines were controlled by their pegmatite host. Pegmatitic tourmalines that do not coexist with garnet have elevated contents of Ga, Zn, Sn, and Zr; large ion lithophile elements like Sr; and REEs relative to those associated with garnet (Ahmadi Khalaji et al. 2016). This conclusion is in agreement with statement that tourmaline chemistry mostly reflects the compositional nature of its host melt and or fluid (Van Hinsberg et al. 2011).

### 5.3. Beryl chemistry

Analysed beryls show a slight excess of Si. This is attributed to high silica activity in the crystallizing melt, which is assigned to the Be tetrahedron. Beryls in Ebrahim Atar pegmatite have very low contents of MnO, TiO_{2}, CaO, and K_{2}O (Table 1 in Salami et al. 2013); the low amount of alkali element minerals indicates direct crystallization from magma because hydrothermal beryl contains more alkali elements (Markl and Schumacher 1997; Wang et al. 2009; Salami et al. 2013). Beryls in Ebrahim Atar pegmatite contain 108–123 ppm Cs and 9–12 ppm V. Elevated Cs contents can be explained by enrichment of this
element in the pegmatitic siliceous and hydrous fluid (Salami et al. 2013).

Evensen et al. (1999) demonstrated that the solubility of Be is strongly affected by differing fluid concentrations of SiO$_2$, Al$_2$O$_3$ (i.e. beryl saturation), and F (Wood 1992). They explained that F-related complexes can carry a lot of Be in aqueous fluids (Barton and Young 2002). Wood (1992) showed how low Ca contents in fluids are essential for Be movement, because elevated Ca contents will crystallize fluorite, so preventing the complexing of Be with F. Silica and alumina activities are also important because low SiO$_2$ activity in the fluid favours precipitation of chrysoberyl, phenakite, and bromellite (Barton and Young 2002). Very high Al$_2$O$_3$ contents favour precipitation of chrysoberyl or euclase, whereas very low Al$_2$O$_3$ contents favour formation of phenakite or bertrandite (Barton and Young 2002). Thus, the peraluminous nature of the Ghorveh pegmatite (Azizi et al. 2016) may have favoured precipitation of Be-alumosilicates such as chrysoberyl and euclase.

6. Boron and oxygen isotopic constraints

The two main isotopic constraints for SaSZ semi-gemstone genesis come from B and O isotopes. B isotopes are especially useful for understanding the origin of tourmaline, because this mineral contains so much B, typically ~10 wt% B$_2$O$_3$ (Foit et al. 1989). Figure 9(a) summarizes what we know about the $\delta^{11}$B isotopic composition of SaSZ semi-gemstone deposits, based on 41 analyses (Esmaeily et al. 2009). The $\delta^{11}$B values of tourmaline in hydrothermal quartz veins range from -2.3‰ to -11.7‰ (Esmaeily et al. 2009), broadly similar to many igneous rocks and typical continental crust (Nekouvaght Tak and Bazargani-Guilani 2009). The mantle range in B isotopes is from -4‰ to -10‰ (Dixon et al. 2017). Sediments and crust vary between +5‰ and -5‰ depending on lithology and degree of seawater alteration (Ishikawa and Nakamura 1993; Smith et al. 1995). This overlap is consistent with the hypothesis that semi-gemstone-mineralizing fluids were largely sweated out of SaSZ metasediments.

The $\delta^{18}$O values of five quartz samples from hydrothermal quartz-tourmaline veins are in the range of +11.9‰ to +13.8‰ (average 13.4‰) (Figure 9(b)) (Nekouvaght Tak and Bazargani-Guilani 2009). These O isotopic compositions are similar to metamorphic or magmatic-metamorphic waters (Rollinson 1993; Hoefs 2004), indicating that semi-gemstone-mineralizing fluids formed through dehydration of hydrous minerals during metamorphism (Hoefs 2004).

7. Discussion

Here, we explore two related topics concerning the Sanandaj–Sirjan semi-gemstone province: (1) types of SaSZ pegmatites and (2) geological conditions of gem mineralization.

7.1. Types of SaSZ pegmatites

Whole rock analyses of pegmatites from the Ghorveh, Hamedan, and Boroujerd regions show that these contain ~75 wt% SiO$_2$ and ~16 wt% Al$_2$O$_3$ as well as highly variable Na$_2$O (1.58–7.64 wt%) and K$_2$O (0.70–6.68 wt%). These compositions indicate a very evolved magma, perhaps reflecting the final expulsion of hot fluid- and silica-rich melt(s) from the solidifying granite. Pegmatites show peraluminous to slightly metaluminous natures, and based on Alumina Saturation Index (ASI) these types of pegmatites are commonly related to orogenic S- and I-type granitic magmas (Sepahi 1999; 2008; Azizi et al. 2016; Ahmadi-Khalaji et al. 2007; Rahmani Javanmard et al. 2018; Sepahi et al. 2018).

Pegmatites are classified based on their depth of emplacement and relationship to metamorphism and associated granitic plutons. Ginsburg et al. (1979) identified five classes (byssal, MS, muscovite-rare element (MSREL), rare-element, and mioraltic) (Figure 10). Abyssal pegmatites form in granulite facies metamorphic terranes (lower crust, >15 km deep) and display no direct relationship with granitic bodies. Mioraltic pegmatites form 1.5–3.5 km deep (Černý 1982; Černý and Erict 2005) and are the shallowest of the pegmatites (Černý 1982; Černý and Erict 2005). REE pegmatites crystallize 3.5–7 km deep. These are interpreted to be fractionation products of differentiated granites (Černý 1982; Černý and Erict 2005). Mica-bearing pegmatites crystallize 7–11 km deep and are hosted by amphibolite-facies metamorphic rocks (Černý 1982; Černý and Erict 2005). These mica-rich, rare-element poor magmas represent direct products of sediment anateksis or are magmas separated from anatectic, autochthonous granites (Černý 1982).

SaSZ pegmatites fall in the MS and MSREL classes (Salami et al. 2014; Azizi et al. 2016; Rahmani Javanmard et al. 2018; Sepahi et al. 2018), although they formed a bit shallower than most MS pegmatites. Figure 10 shows that SaSZ pegmatites formed at 3.5–7.5 kbar and 550–650°C, corresponding to 10–25 km deep in the crust, suggesting an elevated temperature gradient of 22–65°C/km.

Černý (1991) and Černý and Erict (2005) split pegmatites into two compositional types: NYF and LCT types. The acronyms NYF and LCT stand for the trace elements that are most enriched in the fractionation sequences of
these two families (Nb, Y, and REE, F versus Li, Cs, and Ta, also B, P, and F). Salami et al. (2014), Azizi et al. (2016), and Sepahi et al. (2018) report LCT affinity for pegmatites from the Ghorveh and Hamedan semi-gemstone districts. LCT pegmatites are peraluminous (London 1996) but are mostly associated with metaluminous granites. LCT pegmatite magma can also be generated from supracrustal metasediments and as well as lower crystal granulites

7.2. Geological conditions of gem mineral formation

Below we discuss how SaSZ gem minerals formed. First, we discuss tourmaline, then beryl, then garnet.

7.2.1 Tourmaline

Tourmaline is the earliest mineral produced from a dense silica-rich aqueous melt as it cools, assuming there is enough B, Al, Mg, and Fe for making tourmaline. Clay minerals and organic materials are potential sources for boron (Henry and Guidotti 1985; Henry and Dutrow 1990) and thus psammopelitic metasediments contain sufficient B, Al, Mg, Fe, Ca, and Na to produce tourmaline through reaction of boron-rich fluids with feldspars, phyllosilicates, and other minerals (Morgan and London 1989; Fuchs and Lagache 1994; London et al. 1996). Boron in SaSZ metamorphic rocks probably was concentrated in clay minerals with adsorbed boron (Henry and Dutrow 1996). During prograde metamorphism, B may have been released from the clays
in the pelitic protolith. Rising temperatures around a cooling pluton results in dehydration metamorphic reactions which will also mobilize boron. Released boron can mix with magmatic fluids to form tourmaline. Tourmaline compositions in SaSZ metamorphic rocks show affinities with metapelites and metapsammites (Figure 11) (Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014).

As a result, the granitoid and metamorphic hosts are widely distributed and cut by many dikes that are S- and rarely I-type pegmatites and aplites (Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014; Ahmadi Khalaji et al. 2016; Rahmani Javanmard et al. 2018; Sepahi et al. 2018) (Figure 12). SaSZ pegmatites generally reflect magmatic fluids expelled during advanced fractional crystallization of granitic magmas (London et al. 2001; Burianek et al. 2011). With progressive melt fractionation pegmatites are progressively enriched in Rb, Cs, Be, Sn, Ta, Nb and often also in B, P, and F (Salami et al. 2013; Azizi et al. 2016; Rahmani Javanmard et al. 2018; Sepahi et al. 2018). Inger and Harris (1993) emphasized that contents of Ba, Ca, and K in anatectic melts are strongly influenced by the presence of water during partial melting (Conrad et al. 1988; Holtz and Johannes 1991; Patino Douce and Harris 1998; Kawakami 2001; Burianek et al. 2011; Müller et al. 2012; Weinberg and Hasalová 2015). As granite melts cool and become more viscous (Baker and Vaillancourt 1995), boron-bearing dense hydrous fluids may separate from residual magma due to its much lower viscosity. Thus, the presence of trace amounts of boron contained in aluminosilicate minerals in the parent peraluminous magma source may be sufficient to produce tourmaline in pegmatite and aplite rocks via aluminosilicate breakdown during low degrees of partial melting (Nabelek et al. 1992). This is confirmed by tourmaline compositions in SaSZ pegmatite and aplite rocks that show affinities with granitoids and their associated pegmatites and aplites (Figure 11) (Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014). This contrasts with tourmaline compositions in SaSZ metamorphic rocks, as discussed above.

Tourmaline nodules and orbicules in the SaSZ aplites formed from post-magmatic metasomatism by boron-rich hydrothermal fluids derived from the crystallization of granite magma along cracks (Figure 11) (Rozendaal and Bruwer 1995; Burianek and Novak 2003; Hezel et al. 2011; Tabbakh Shabani et al. 2013; Tahmasbi 2014; Hong et al. 2017). Tourmaline patches and orbicules are commonly dispersed below the roof zones of aplites as scattered masses or clusters (Burianek et al. 2011; Tahmasbi 2014; Hong et al. 2017) resulting from devolatilization and phase separation of hydrous boron-rich fluid from granitic melts (Samson and Sinclair 1992; Sinclair and Richardson 1992; Jiang et al. 2003; Shewfelt 2005; Dini et al. 2007; Trumbull et al. 2008; Balen and Broska 2011). In this situation, boron will be concentrated in silicic melts, but will ultimately segregate into a bubble-rich aqueous phase (Dingwell et al. 1996; London et al. 1996; Veksler and Thomas 2002; Veksler 2004). Depending on lithostatic pressure, vapour bubbles can separate from a melt at a low degree of crystallization, and rise up between grains as bubble-laden plumes or tubules (Burianek and Novak 2003; Hezel et al. 2011; Tabbakh Shabani et al. 2013; Tahmasbi 2014; Hong et al. 2017). Increasing pressure around the pluton due to volatile degassing, together with crystallization of tourmaline and other minerals, will enlarge the deformed zone and open spaces for boron-rich fluids to occupy. As crystallization continues and magmatic viscosity increases, small bubbles may join to produce tubules channelling flow to the top of the intrusion. When the supply of vapour is reduced, bubble-laden plumes solidify, ultimately creating irregular tourmaline-rich patches among coarse-grained igneous crystals (Hong et al. 2017). Irregular

Figure 11. Average composition of studied tourmalines plotted in triangular Al-Fetot-Mg diagram (Henry and Guidotti 1985). Fields: 1 – Li-rich granitoids, pegmatites, and aplites; 2 – Granitoids and associated pegmatites and aplites; 3 – Hydrothermally altered granites; 4 – Metapelites and metapsammites coexisting with an Al-saturated phase; 5 – Metapelites and metapsammites not coexisting with Al-saturated phase; 6 – FeTi-rich quartz-tourmaline rocks, calc silicate rocks, and metapelites; 7 – Metaultramafics with low Ca; 8 – Meta carbonates and metapyroxenites.
tourmaline patches disseminated in aplites are understood to reflect small boron-rich volatile bubbles, while the spherical tourmaline orbicules and cavities solidified in the uppermost portions of granite plutons are likely to be relics of large trapped bubbles of exsolved magmatic fluid (Tahmasbi et al. 2009; Tahmasbi 2014; Hong et al. 2017).

Increasing lithostatic pressure and tectonic activity often leads to fracture of the surrounding wall rocks. Boron-rich aqueous fluids invade these fractures, hydrothermally altering the host rocks, and finally healing the fractures by mineral precipitation. Field relations indicate that quartz-tourmaline veins were the final stage of SaSZ magmatic fluid evolution (Figure 12) (Nekouvaght Tak and Bazargani-Guilani 2009; TahmasbI et al. 2009; Khodakarami Fard et al. 2014). Field evidence together with geochemical and petrographic data shows that only a minor fraction of the melt was saturated in tourmaline (Nekouvaght Tak and Bazargani-Guilani 2009; Sheikh et al. 2012; Khodakarami Fard et al. 2014). The presence of graphite in SaSZ granitoids is further evidence for metasediment assimilation (Radfar 1987; Ahmadi-Khalaji et al. 2007; Nekouvaght Tak and Bazargani-Guilani 2009). This allowed evolved B-rich fluids to infiltrate along lithological boundaries and shear zones around the pluton. On the other hand, the $\delta^{11}$B values of tourmaline-quartz veins in the Nezam abad deposit (Boroujerd semi-gemstone district; Figure 9(a)) look like those of the metamorphosed pyroclastic-sedimentary and metavolcanic terranes (Esmaeily et al. 2009). This is confirmed by tourmaline composition of quartz veins that show some affinities with metapelites and metapsammites (Figure 11) (Nekouvaght Tak and Bazargani-Guilani 2009; Tahmasbi et al. 2009; Khodakarami Fard et al. 2014; Mansouri Esfahani and Khalili 2014; Tahmasbi 2014).

7.2.2 Beryl

Beryl is found in Ebrahim Atar (Ghorveh) and Zaman Abad (Hamedan) pegmatites. Crystal fractionation of pegmatic melts enriches the residual magmatic fluid in incompatible elements such as Be. It is not clear what was the source of Be for forming beryl in pegmatites. Because Be has a very small ionic radius (0.27 Å) and low charge (+2), it prefers tetrahedral coordination (Hawthorne and Huminicki 2002). Minerals such as cordierite, plagioclase, and phyllosilicates in SaSZ metamorphic rocks can contain significant non-essential Be in their mineral structures (ČErný 2002; Franz and Moretti 2002). Plagioclase and MS can have high Be concentrations (~200 and ~150 ppm respectively).
(Evensen et al. 1999; Grew 2002; London and Evensen 2002). Cordierite can contain up to \( \sim 8100 \) ppm Be (Evensen and London 2002) and staurolite contains up to \( \sim 150 \) ppm Be (Grew et al. 2001; Grew 2002). Breakdown of these minerals may be the source of Be to produce pegmatitic beryls.

Barton and Young (2002) subdivided Be mineralization based on ASI, silica saturation, and alkalinity, including (1) strongly to weakly peraluminous, (2) metaluminous and weakly peraluminous, and (3) peralkaline. Of these, peraluminous magmas are most favourable for beryl mineralization, due to their favourable SiO\(_2\) and Al\(_2\)O\(_3\) contents. The most favourable intrusions for forming beryl are ultrafrac-tionated, moderately peraluminous S- and I-type granitoid magmas with low Ca and high F concentrations, which can yield fertile epigenetic hydrothermal fluids that favour beryl precipitation. Very high Al\(_2\)O\(_3\) fluid activities favour precipitation of chrysoberyl or eucalite, whereas very low Al\(_2\)O\(_3\) fluid activities favour formation of phenakite or bertrandite. So, the main source of Be for generating beryl in Ebrahim Atar and Zaman Abad pegmatites may have been derived from breakdown of phyllosilicate minerals and feldspars associated with a strongly peraluminous granitic magma (Azizi et al. 2016). As Figure 2b shows, the Ebrahim Atar and Hamedan pegmatite is strongly peraluminous.

### 7.2.3 Garnet

SaSZ garnets are limited to pegmatites, aplites, adjacent metamorphic rocks, and other metamorphic rocks far from contact. Pegmatite and aplite garnets are all members of the almandine-spessartine solid-solution series, with igneous compositions (Miller and Stoddard 1981). They have high spessartine (17–50 mol%) and almandine (49–80 mol%) contents, whereas pyrope and andradite components are minor. The absence of reaction rims, euhedral shapes, and spessartine \( > 50 \) mol% indicates that the garnets in pegmatite and aplite crystallized at low pressure from these melts. It is suggested that an exsolved aqueous phase from the melt complexed accessible Mn and mixed with SaSZ pegmatite melts to form spessartine. Müller et al. (2012) showed that a range in MnO/(FeO + MnO) ratio of garnets reveals progressive magmatic differentiation.

The disappearance of biotite during the last stages of fractional crystallization favours formation of garnetiferous aplites and pegmatites (Abbot 1981). In extremely fractionated granitic magmas such as pegmatites (Bogoch et al. 1997), the very low abundances of Fe result in very minor little or no biotite crystallizing. In the absence of biotite, the stability of spessartine garnet increases, which may partly be reflected in Mn enrichment in rims. If and when MS crystallizes, the melt moves to the liquid-garnet-MS coticic and Fe/Mg and Mn/Fe content of the melt rises (Miller and Stoddard 1981). It is proposed that segregation of an aqueous phase from the granitic melt transported Mn and Fe to the peripheries (Figure 12), allowing garnet crystallization below 700°C (Clarke 1981; Manning 1983; Burianek et al. 2011; Moore et al. 2013). As a result, the MnO/(FeO + MnO) content of garnet rises with increasing melt fractionation, which is partly controlled by the presence or absence of coexisting Mn- and Fe-bearing minerals (Müller et al. 2012).

In this case, the MnO/(FeO + MnO) of garnet can be used to indicate the degree of fractionation of the melt from which it formed. Garnets from less fractionated pegmatites are typically Fe rich (Müller et al. 2012). Garnets from aplites and pegmatites are often Fe-Mn rich, and exhibit obvious core to rim decrease in Mn (Baldwin and von Knorring 1983; Whitworth 1992; Gadas et al. 2013), whereas garnets from granitoids are mostly Fe rich and show weak core-to-rim increase in Mn (Day et al. 1992; Harangi et al. 2001; Koepeke et al. 2003; Samadi et al. 2014). The wide variations noted above in almandine and spessartine components indicate low to moderate degrees of pegmatite evolution, suggesting that high Mn content in garnet reflects more fractionated magmas. It is therefore possible that crystallization of spessartine-rich garnets in SaSZ pegmatites reflects enrichment of the magma in volatile constituents at low pressures and temperatures. At the final steps of pegmatite development, the removal of aqueous fluids formed quartz veins and skarns rich in tourmaline and garnet (Figure 12) (Nekouvagh Tak and Bazargani-Guilani 2009; Sheikhi et al. 2012; Khodakarami Fard et al. 2014).

The formation of SaSZ skarns (Sheikhi et al. 2012) can be ascribed to the contact metamorphic effects of intrusions into limestones associated with shearing along minor faults. During metamorphism, decarbonation and dehydration reactions yield significant CO\(_2\) and H\(_2\)O which can mix with magmatic fluids and flow into faults and fractures; these processes are important for garnet mineralization in skarn.

### 8. Conclusions

We have six main conclusions from our study:

1. The SaSZ semi-gemstone province is identified and subdivided into three districts: Ghorveh, Hamedan, and Boroujerd. The SaSZ semi-gemstone province is characterized by the abundance of tourmaline and garnet, sometimes also beryl.

2. Tourmalines are concentrated in a variety of lithologies related to Jurassic intrusions: metamorphic rocks, quartz veins, patches, orbicules, pegmatites,
and granitic rocks, reflecting pervasive mobilization and concentration of B around these intrusions.

(3) SaSZ pegmatites fall in the MS and MSREL classes and formed at 3.5–7.5 kbar and 550–650°C, corresponding to 10–25 km deep in the crust, suggesting an elevated regional temperature gradient of 22–65°C/km. The geochemical and mineralogical characteristics of the pegmatites reveal high contents of silica and alkali elements, indicating extreme fractionation.

(4) Tourmalines belong to schorl-dravite solid solution, with compositions largely controlled by the composition of the wall-rock hosts. Metapelites provided the essential Fe, Mg, and Al contents for forming tourmaline, but B may be derived from granitic magma as well as metasediments. Magmatic fractionation, metamorphism, and anatectic created tourmaline-bearing pegmatite dikes along the contact between granites and metamorphic rocks. Quartz-tourmaline veins are explained as products of crystallization of fluids exsolved from the granitic melt and surrounding metasediments. In contrast, magmatic-hydrothermal volatile exsolution and fluxing of boron-rich aqueous fluids exsolved from the crystallizing granitic magma during emplacement into shallow crust was responsible for forming tourmaline patches, orbicules, and cavities.

(5) Garnets in pegmatites have igneous compositions and belong to the almandine-spessartine solid-solution series. It is suggested that exsolution of one or more aqueous phases from the granitic melt locally evolved Mn and Fe concentrations locally to allow garnet crystallization. In contrast, fractures in limestone formed by regional deformation provided channels for flow of magmatic volatiles and produced garnet, pyroxene, and wollastonite from thermal metamorphic reactions as skarn.

(6) Further research is needed to test and refine these ideas and better understand tourmaline–garnet ± beryl mineralization of the SaSZ semigemstone province.

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