

## Mineralogical and Chemical Composition of Tourmaline from Najmabad, Gheshlagh, Hired and Maherabad-Khopik, and their relationship with types of mineralization, Eastern Iran

M. H. Karimpour<sup>1</sup>, C. R. Stern<sup>2</sup>

1. Research Center for Ore Deposits of Eastern Iran, Ferdowsi University of Mashhad  
2. Dept. of Geological Sciences, University of Colorado, CB-399, Boulder, CO, USA

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**Abstract:** Tourmaline is present as alteration and mineralization at Maherabad and Khopik Cu-Au prospecting areas, Najmabad Sn-W-Au prospecting areas, Hired Au-Sn prospecting area, and within Gheshlagh pegmatite dikes. Based on X-ray diffraction graphs, Maherabad, Gheshlagh and Hired tourmaline are schorl, but Najmabad and Khopik are dravite type. Based on chemical composition, all of tourmalines belong to alkali group. The Mg/(Mg+Fe) ratio in Gheshlagh tourmaline is 0.21-0.29, in Hired is 0.32-0.47 and in Maherabad is 0.44-0.5 and in Najmabad and Khopik are Mg/(Mg+Fe)= 0.55-0.82. Khopik tourmaline contains considerably higher Mg (1.9-2.3) compared with the Maherabad (Mg = 1.4-1.9). The average TiO<sub>2</sub> content of Maherabad tourmaline is 0.35 and Khopik is 0.19. At Khopik, deeper portion of the porphyry Cu-Au is exposed. Najmabad tourmaline contains the highest Mg (Mg= 2.2) and Gheshlagh the lowest Mg (Mg=0.5-0.7) and highest Fe (Fe= 1.9-2.3). Najmabad tourmaline contains the highest TiO<sub>2</sub> (0.48%) and other tourmaline contains less than 0.3 % TiO<sub>2</sub>. In general, there is a reverse correlation between CaO and Na<sub>2</sub>O. Gheshlagh has the lowest CaO and highest Na<sub>2</sub>O. The CaO and Na<sub>2</sub>O content of tourmaline from Hired are very variable.

**Keywords:** *Tourmaline, Najmabad, Maherabad, Gheshlagh, Hired*

### Analytical Techniques

All elemental analyses of Tourmaline were obtained from polished thin sections using a JEOL JXA-8900R electron microprobe at the University of Colorado Boulder (USA). Element determinations (Si, Al, Fe, Mg, Ti, Mn, Total Ba, Na, K, F and Cl) were carried out using a beam size of 1-2  $\mu$ m, an accelerating potential voltage of 15 kV, a probe current of 5-10 nA, and a counting time of 20 s for each element analyzed. Well-characterized synthetic and natural silicates were used as standards. Data were corrected online using a modified Bence-Albee correction procedure. On the basis of replicate analyses of

several secondary standards, analytical precision associated with counting statistics for selected oxides is estimated to be  $\pm 0.21\%$  SiO<sub>2</sub>,  $\pm 0.13\%$  Al<sub>2</sub>O<sub>3</sub>,  $\pm 0.06\%$  FeO,  $\pm 0.11\%$  MgO,  $\pm 0.02\%$  CaO, and  $\pm 0.03\%$  Na<sub>2</sub>O. Tourmaline formulae were normalized on the basis of 15 cations exclusive of Na, Ca and K, which assumes no vacancies in the tetrahedral or octahedral sites and insignificant Li contents [1]. X-Ray Diffraction Analysis (XRD) was done by Kansaran Binaloud (Mashhad).

### Introduction

Tourmaline from four plutons, including Gheshlagh (1), Najmabad (2), Maherabad (3), and Hired (4), are selected for this study (Fig. 1).

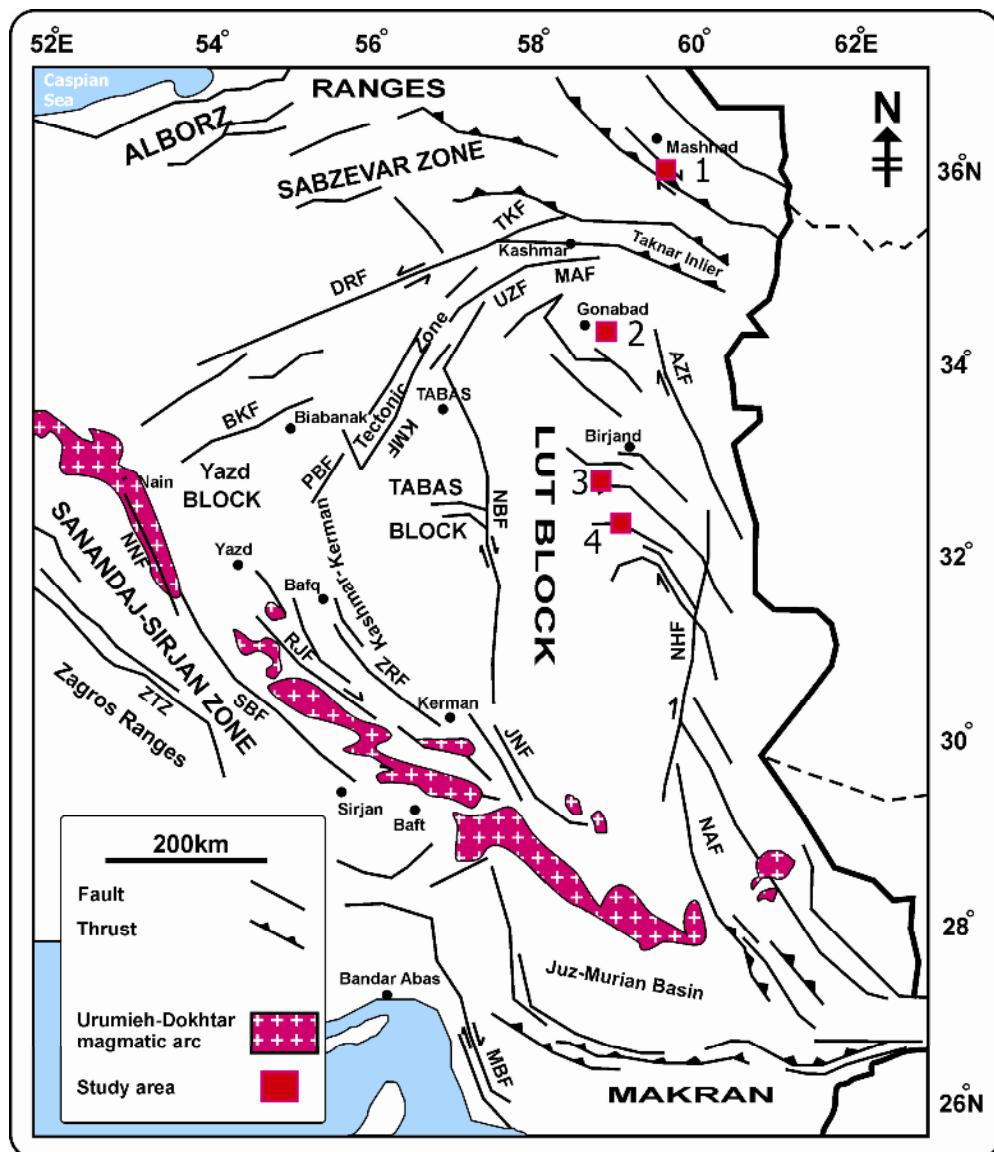
<sup>x</sup>Corresponding author, Telefax: +98 (0511) 8797275, Email: mhkarimpour@yahoo.com

Tourmaline is the most important and common accessory borosilicate mineral in granitic rocks and their pegmatites, associated metallic hydrothermal deposits. It is stable over a wide range of temperature in hydrothermal alteration. It occurs in the volcanic-rock-hosted massive sulfide deposits [2], in porphyry-copper deposits [3-5] in metamorphosed stratabound Pb-Zn deposits [6, 7], in medium-temperature hydrothermal gold [8, 9] and tin deposits [10], in greisen deposits [11], and schist-type emerald deposits [12, 13]. Substitutions are thus widespread in tourmaline-group minerals, whose structural formula is  $XY_3Z_6(T_6O_{18})(BO_3)_3V_3W$  [13].

- X = Ca, Na, K or vacant;
- Y = Li, Fe<sup>2+</sup>, Mg, Mn, Al, Cr<sup>3+</sup>, Fe<sup>3+</sup>, V<sup>3+</sup>, Ti<sup>4+</sup>;

- Z = Mg, Al, Fe<sup>3+</sup>, V<sup>3+</sup>, Cr<sup>3+</sup>;
- T = Si, Al, B;
- B = B, (vacant);
- V = OH, O;
- W = OH, F, O.

Hawthorne and Henry [13] proposed a classification scheme for the tourmaline group minerals based on the chemical composition and ordering at the different sites of the tourmaline structure. Consequently, limited computer programs written in Microsofts QuickBasic [14, 15]; appeared in literature to calculate and classify the tourmaline group minerals. However, Tindle et al. [16] referenced tourmaline calculation program under Microsofts Excel based on 31 anions.



**Figure 1.** Map shows location of the study areas Gheshlagh (1), Najmabad (2), Maherabad (3), and Hired (4).

## Petrography and Whole rock geochemistry

### Hired Au prospecting

Hired the largest gold prospect is located 150 km south of Birjand, in eastern Iran. Two suites of Oligocene-Miocene granitoids, one relatively oxidized (magnetite-series) and the other relatively reduced (ilmenite-series), were identified at Hired, Eastern Iran [17]. Au-Sn mineralization is associated only with the relatively reduced ilmenite-series suite. The magnetic susceptibility of the magnetite-series granitoids is greater than  $300 \times 10^{-5}$  SI. This suite includes metaluminous, medium-K to high-K series gabbros to diorites containing magnetite, hornblende and biotite. The magnetic susceptibility of the ilmenite-series granitoids are less than  $60 \times 10^{-5}$  SI. This suite includes meta-aluminous, high-K to shoshonitic diorites to granites, containing, biotite, muscovite and tourmaline. Both the ilmenite and magnetite series suites are strongly enriched in large ion lithophile elements (LILEs = K, Th, Rb, Ba) and depleted in high field strength elements (HFSE = Nb, Sr, Ti, Hf). Chondrite-normalized Rare Earth Element (REE) plots indicate strong enrichments of light relative to heavy REE, with  $(La/Yb)_N$  between 7-24 [17]. Ilmenite suite granitoids have pronounced negative europium anomalies. Stockwork mineralization is found within and nearby the relatively reduced ilmenite-series granites. Based on their mineral assemblages (arsenopyrite, pyrrhotite, tourmaline, pyrite, gold and quartz), the ore-bearing fluids that generated these stockwork veins was also reduced. This and the spatial relationship of mineralization with the ilmenite suite granitoids, indicates that the ore fluids originated from reduced granitoid magmas. Hired Au-Sn deposit is a reduced-intrusion related gold system.

### Maherabad & Khopik

The Maherabad & Khopik porphyry copper-gold prospect areas are located 70 km SW of Birjand city (center of South Khorasan province), eastern Iran. It is located in the eastern part of Lut block. Fifteen intrusive rocks (Upper Eocene) range in composition from diorite to monzonite have been distinguished [18, 19].

Based on mineralogy and high values of magnetic susceptibility [ $(300$  to  $2000) \times 10^{-5}$  SI], these intrusive rocks are classified as belonging to the magnetite-series of I-type granitoids. Chemically

they are met-aluminous, high-K calc-alkaline to shoshonic intrusive rocks which were formed in island arc setting. These rocks are characterized by average of  $SiO_2 > 59$  wt%,  $Al_2O_3 > 15$  wt%,  $MgO < 2$  wt%,  $Na_2O > 3$  wt%,  $Sr > 870$  ppm,  $Y < 18$  ppm,  $Yb < 1.90$  ppm,  $Sr/Y > 55$ , moderate LREE, relatively low HREE and enrichment LILE (Sr, Cs, Rb, K and Ba) relative to HFSE (Nb, Ta, Ti, Hf and Zr) [18, 19]. They are chemically similar to some adakites, but their chemical signatures differ in some ways from normal adakites, including higher  $K_2O$  contents and  $K_2O/Na_2O$  ratios and lower  $Mg\#$ ,  $(La/Yb)_N$  and  $(Ce/Yb)_N$  in Maherabad rocks [18, 19]. Maherabad intrusive rocks are the first K-rich adakites that can be related to subduction zone.

### Najmabad

Najmabad is located 15 Km southeast of Gonabad. An east-west trending biotite granodiorite porphyry pluton,  $26 \times 4$  km<sup>2</sup> in size, intruded Jurassic slates and quartzites. The granodiorite has porphyry texture with 35 to 55 percent phenocrysts. The mineral content based on the phenocrysts are: 15%–20% plagioclase, 10%–15% K-feldspar, 10%–15% quartz, 5%–10% biotite and less than 2% accessory phases. Based on mineralogy and low values of magnetic susceptibility [ $(5$  to  $11) \times 10^{-5}$  SI], this granodiorite is classified as belonging to the ilmenite-series of reduced S-type granitoids. Chemically it is met-aluminous, with relative enrichment in LILE = Rb, Ba, Zr, Th, Hf, K and LREE, and depletion in Sr, P, Ti and HREE. Based on REE content and low  $(La/Yb)_N = 7$ -11.5, this pluton originated from melting of continental crust during the Jurassic-Cretaceous orogeny that caused regional metamorphism [20].

### Gheshlagh Pegmatites

Gheshlagh pegmatites are exposed in the southeastern plutonic belt of Mashhad. It lies between Longitude  $59^{\circ}35'E$  to  $59^{\circ}51'E$  and Latitude  $36^{\circ}N$  to  $36^{\circ}10'N$ . Pegmatites are the youngest intrusive rocks in this belt. Numerous pegmatite dykes crosscut the older units like a network. Pegmatites are most commonly dyke like or lensoid. Most pegmatites dykes are small, but dimensions vary from 1 cm to as much as 25 meters in width [21].

Pegmatite dykes are encountered throughout the whole biotite-muscovite leucogranite plutonic complex and in the feldspar monzogranite. Microcline, a single crystal measuring up to 40 centimeters long is formed.

Pegmatites on their mineral content can be classified, based into 4-group: Type-1 contains 60-90% pink microcline with minor albite as perthite (up to 20 cm long), 5-20% clear quartz, 5-20% muscovite (plates are 2-8 cm long). Type-2 contains 70-80% pink microcline with some albite as perthite (up to 15 cm long), 10-15% quartz, 5% muscovite (up to 3 cm long) and 5% tourmaline (up to 12 cm long). Type-3 is less common and

contains Microcline, quartz, muscovite, albite, almandine-type garnet and  $\pm$  tourmaline. Type-4 is very rare and it contains microcline, quartz, muscovite, albite and beryl [21].

Pegmatites are being mined for feldspar. Feldspars are in general K-rich type some Na-K feldspars are found in Khajehmourad area.

### Mineralogical composition

X-ray diffraction graph of tourmaline are shown in Figs. 2a-d. Najmabad tourmaline is Dravite (Fig. 2a). Based on X-ray diffraction graphs, Maherabad, Gheshlagh and Hired tourmaline are schorl (Figs 2b-d).

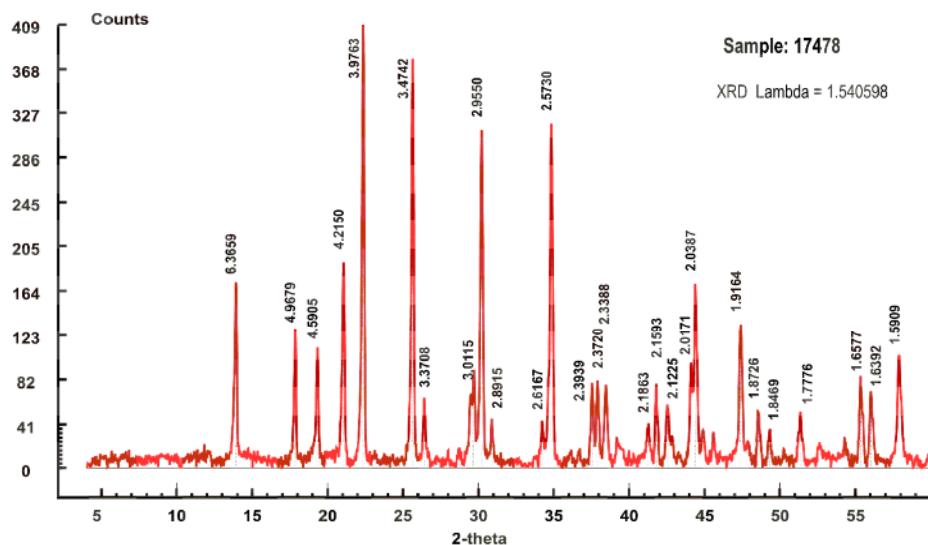


Figure 2a X-ray diffraction graph of Najmabad tourmaline.

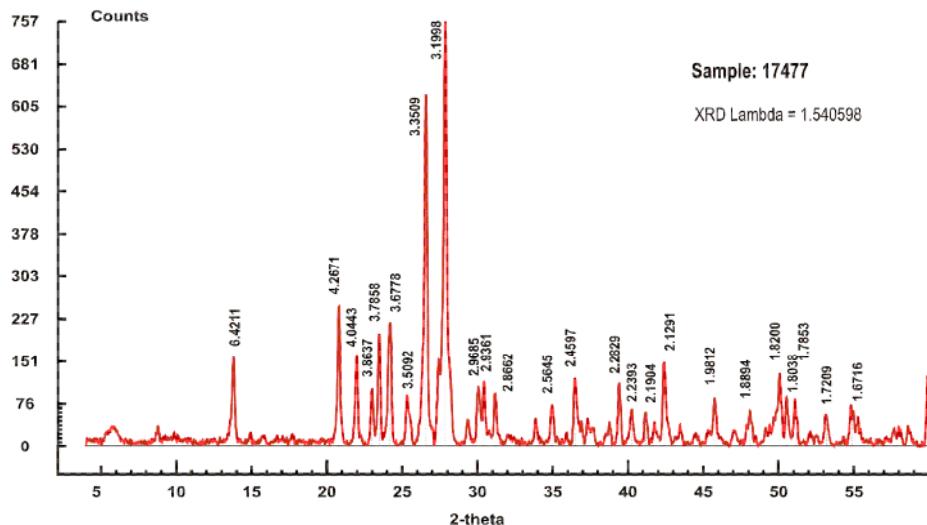


Figure 2b X-ray diffraction graph of Gheshlagh tourmaline.

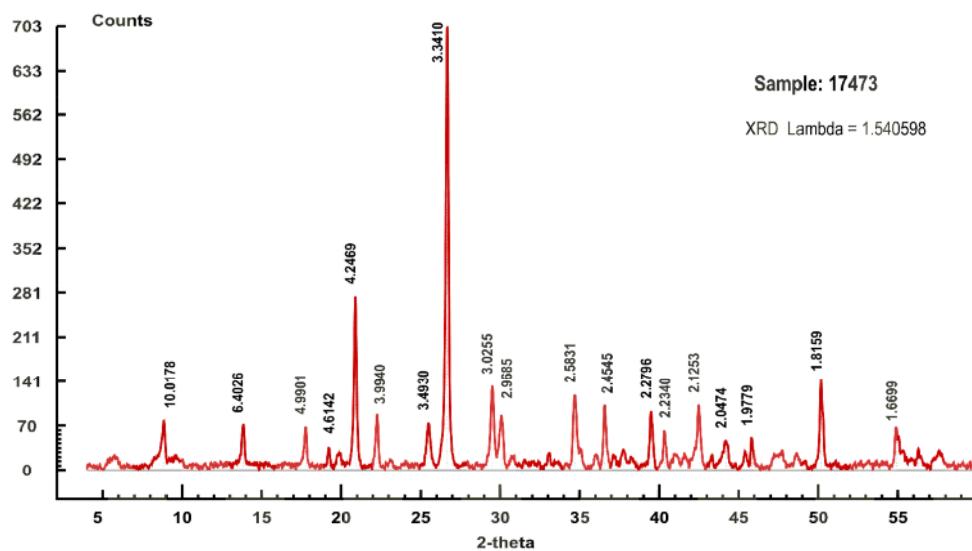


Figure 2c X-ray diffraction graph of Hired tourmaline.

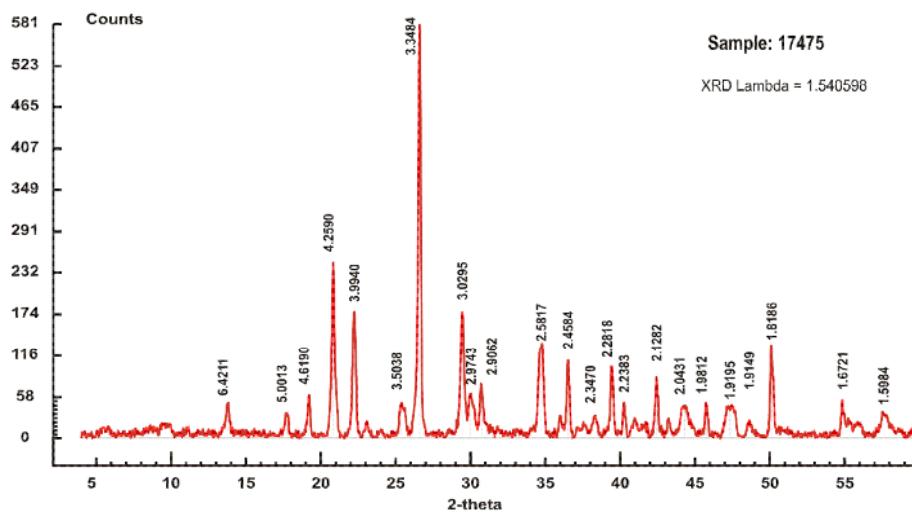


Figure 2d X-ray diffraction graph of Maherabad tourmaline.

### Tourmaline Chemistry

Electron microprobe analyses of tourmaline from Najmabad, Hired, Gheshlagh and Maherabad are listed in Table (1a-e). Tourmaline is a complex borosilicate with a general formula of  $XY_3Z_6(T_6O_{18})(BO_3)_3V_3W$  [13], where X = Na, Ca, K, vacancy; Y = Mg,  $Fe^{2+}$ , Mn, Al, Li,  $Fe^{3+}$ ,  $Ti^{4+}$ ,  $Cr^{3+}$ ,  $V^{3+}$ ; Z = Al, Mg,  $Fe^{3+}$ ,  $Cr^{3+}$ ,  $V^{3+}$ ; T = Si, Al, (B); B = B, vacancy; V = OH, O; W = OH, F, O. Several normalization procedures for tourmaline are possible [1]. In this paper, structural formulae were calculated on the basis of 15 (T + Z + Y) cations, assuming that boron has a stoichiometric value of 3 apfu (Table 1a-e).

Tourmaline species include 13 end-member compositions (dravite, schorl, chromdravite,

povondraite, buergerite, elbaite, olenite, magnesiofoitite, foitite, rossmanite, uvite, feruvite, and liddicoatite).

Tourmaline can be separated into principal groups based on ternary X-site-vacancy–Na–Ca [13, 22], respectively] on the dominant occupancy of the X site, the alkali-, calcic- and vacant-tourmaline groups. In general, the microprobe data indicate that most of the tourmalines are Al-saturated and belong to the alkali group (Fig. 3). Gheshlagh tourmaline has the lowest amount of Ca and Maherabad has the highest Ca content (Fig. 3). Based on the ternary Al–Fe–Mg plots [13, 22] tourmaline from Najmabad are plotted next to Dravite and tourmaline from Gheshlagh is schorl (Fig. 4).

**Table 1-a.** Representative electron-microprobe analyses of tourmaline from Hired Au prospecting areas (Structural formula based on 31 anions (O, OH, F)).

| Sample No.                     | T2-DDH9-1 | T2-DDH9-2 | T2-DDH9-3 | T2-DDH9-4 | T2-DDH9-5 | T2-DDH9-6 | T2-DDH9-7 | T2-DDH9-8 |
|--------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| SiO <sub>2</sub>               | 33.77     | 32.89     | 33.50     | 34.32     | 33.78     | 32.97     | 33.89     | 34.39     |
| TiO <sub>2</sub>               | 0.15      | 0.19      | 1.19      | 0.21      | 0.14      | 0.20      | 0.17      | 0.19      |
| Al <sub>2</sub> O <sub>3</sub> | 28.85     | 22.95     | 23.19     | 28.12     | 28.45     | 23.89     | 23.45     | 26.23     |
| FeO                            | 12.19     | 18.60     | 17.18     | 12.42     | 12.21     | 17.78     | 18.21     | 13.45     |
| MgO                            | 5.40      | 4.99      | 5.77      | 6.26      | 5.34      | 5.10      | 5.69      | 6.19      |
| CaO                            | 1.77      | 2.05      | 2.85      | 2.45      | 1.79      | 2.11      | 2.79      | 2.39      |
| MnO                            | 0.03      | 0.01      | 0.03      | 0.03      | 0.03      | 0.02      | 0.03      | 0.03      |
| Na <sub>2</sub> O              | 1.79      | 1.82      | 1.35      | 1.55      | 1.79      | 1.82      | 1.38      | 1.65      |
| K <sub>2</sub> O               | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      |
| B <sub>2</sub> O <sub>3</sub>  | 10.50     | 10.50     | 10.50     | 10.50     | 10.50     | 10.50     | 10.50     | 10.50     |
| H <sub>2</sub> O*              | 3.48      | 3.33      | 3.40      | 3.52      | 3.47      | 3.36      | 3.41      | 3.47      |
| Li <sub>2</sub> O*             | 0.22      | 0.03      | 0.09      | 0.14      | 0.27      | 0.04      | 0.00      | 0.19      |
| Total*                         | 98.15     | 97.36     | 99.05     | 99.52     | 97.77     | 97.79     | 99.51     | 98.68     |
| T: Si                          | 5.82      | 5.93      | 5.91      | 5.85      | 5.84      | 5.89      | 5.97      | 5.95      |
| Al                             | 0.18      | 0.07      | 0.10      | 0.15      | 0.16      | 0.11      | 0.03      | 0.05      |
| B                              | 3.12      | 3.27      | 3.20      | 3.09      | 3.14      | 3.24      | 3.19      | 3.14      |
| Z: Al                          | 5.68      | 4.81      | 4.72      | 5.51      | 5.64      | 4.93      | 4.83      | 5.30      |
| Mg                             | 0.32      | 1.19      | 1.28      | 0.49      | 0.36      | 1.08      | 1.17      | 0.71      |
| Y: Al                          | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      |
| Ti                             | 0.02      | 0.03      | 0.16      | 0.03      | 0.02      | 0.03      | 0.02      | 0.03      |
| Mg                             | 1.07      | 0.15      | 0.24      | 1.10      | 1.02      | 0.28      | 0.32      | 0.89      |
| Mn                             | 0.00      | 0.00      | 0.00      | 0.01      | 0.00      | 0.00      | 0.01      | 0.00      |
| Fe <sup>2+</sup>               | 1.76      | 2.80      | 2.53      | 1.77      | 1.77      | 2.66      | 2.68      | 1.95      |
| Li*                            | 0.16      | 0.02      | 0.07      | 0.10      | 0.19      | 0.03      | 0.00      | 0.14      |
| YY                             | 3.00      | 3.00      | 3.00      | 3.00      | 3.00      | 3.00      | 3.03      | 3.00      |
| X: Ca                          | 0.33      | 0.40      | 0.54      | 0.45      | 0.33      | 0.40      | 0.53      | 0.44      |
| Na                             | 0.60      | 0.64      | 0.46      | 0.51      | 0.60      | 0.63      | 0.47      | 0.55      |
| r                              | 0.08      | 0.00      | 0.00      | 0.04      | 0.07      | 0.00      | 0.00      | 0.00      |
| OH                             | 4.00      | 4.00      | 4.00      | 4.00      | 4.00      | 4.00      | 4.00      | 4.00      |
| F                              | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      |
| Cl                             | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      | 0.00      |
| Mineral                        | Schorl    | Schorl    | Feruvite  | Schorl    | Schorl    | Schorl    | Feruvite  | Schorl    |

**Table 1-b.** Representative electron-microprobe analyses of tourmaline from Hired Au prospecting areas (Structural formula based on 31 anions (O, OH, F)).

**Table 1-c.** Representative electron-microprobe analyses of tourmaline from Gheshlagh (Structural formula based on 31 anions (O, OH, F)).

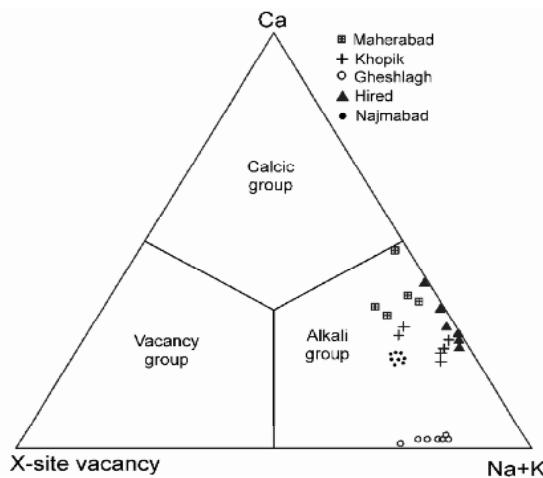
**Table 1-d.** Representative electron-microprobe analyses of tourmaline from Najmabad (Structural formula based on 31 anions (O, OH, F)).

**Table 1-e.** Representative electron-microprobe analyses of tourmaline from Maherabad Cu-Au porphyry prospecting areas (Structural formula based on 31 anions (O, OH, F)).

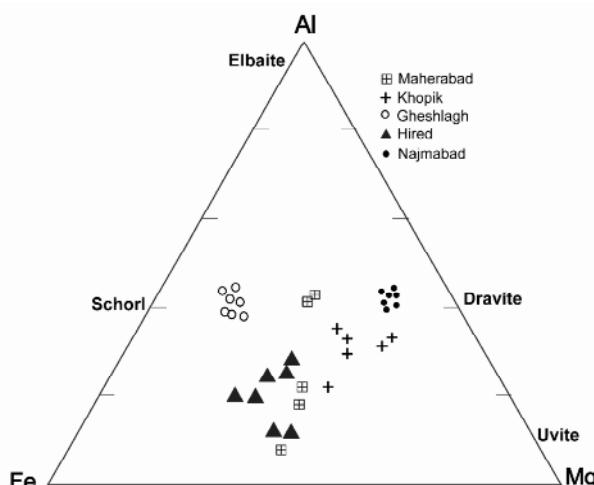
| Sample No.                     | T2-87-1 | T2-87-2 | T2-87-3 | T2-87-4 | T2-87-5 | T2-87-6 | T2-87-7 |
|--------------------------------|---------|---------|---------|---------|---------|---------|---------|
| SiO <sub>2</sub>               | 33.73   | 34.30   | 34.67   | 35.79   | 33.73   | 34.28   | 35.79   |
| TiO <sub>2</sub>               | 0.35    | 0.64    | 0.22    | 0.18    | 0.33    | 0.57    | 0.18    |
| Al <sub>2</sub> O <sub>3</sub> | 26.85   | 24.18   | 31.78   | 32.52   | 27.89   | 24.89   | 32.67   |
| FeO                            | 12.18   | 15.59   | 9.73    | 9.65    | 12.19   | 15.49   | 9.69    |
| MgO                            | 7.03    | 7.01    | 5.34    | 5.30    | 7.11    | 7.09    | 5.35    |
| CaO                            | 2.01    | 2.58    | 1.26    | 1.35    | 2.01    | 2.34    | 2.02    |
| MnO                            | 0.03    | 0.01    | 0.18    | 0.18    | 0.03    | 0.09    | 0.17    |
| Na <sub>2</sub> O              | 1.79    | 1.46    | 1.70    | 1.65    | 1.78    | 1.35    | 1.48    |
| K <sub>2</sub> O               | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    |
| B <sub>2</sub> O <sub>3</sub>  | 10.50   | 10.50   | 10.50   | 10.50   | 10.50   | 10.50   | 10.50   |
| H <sub>2</sub> O*              | 3.46    | 3.46    | 3.57    | 3.64    | 3.50    | 3.47    | 3.66    |
| Li <sub>2</sub> O*             | 0.05    | 0.00    | 0.19    | 0.17    | 0.00    | 0.00    | 0.23    |
| Total*                         | 97.99   | 99.72   | 99.14   | 100.93  | 99.07   | 100.07  | 101.74  |
| T: Si                          | 5.85    | 5.95    | 5.82    | 5.90    | 5.78    | 5.92    | 5.86    |
| Al                             | 0.15    | 0.05    | 0.18    | 0.10    | 0.22    | 0.08    | 0.14    |
| B                              | 3.14    | 3.14    | 3.04    | 2.99    | 3.11    | 3.13    | 2.97    |
| Z: Al                          | 5.33    | 4.89    | 6.00    | 6.00    | 5.42    | 4.98    | 6.00    |
| Mg                             | 0.67    | 1.11    | 0.00    | 0.00    | 0.58    | 1.02    | 0.00    |
| Y: Al                          | 0.00    | 0.00    | 0.11    | 0.21    | 0.00    | 0.00    | 0.17    |
| Ti                             | 0.05    | 0.08    | 0.03    | 0.02    | 0.04    | 0.07    | 0.02    |
| Mg                             | 1.15    | 0.71    | 1.34    | 1.30    | 1.24    | 0.80    | 1.31    |
| Mn                             | 0.01    | 0.00    | 0.03    | 0.03    | 0.01    | 0.01    | 0.02    |
| Fe <sup>2+</sup>               | 1.77    | 2.26    | 1.37    | 1.33    | 1.75    | 2.24    | 1.33    |
| Li*                            | 0.04    | 0.00    | 0.13    | 0.11    | 0.00    | 0.00    | 0.16    |
| VY                             | 3.00    | 3.05    | 3.00    | 3.00    | 3.03    | 3.13    | 3.00    |
| X: Ca                          | 0.37    | 0.48    | 0.23    | 0.24    | 0.37    | 0.43    | 0.35    |
| Na                             | 0.60    | 0.49    | 0.56    | 0.53    | 0.59    | 0.45    | 0.47    |
| r                              | 0.03    | 0.03    | 0.22    | 0.23    | 0.04    | 0.12    | 0.18    |
| OH                             | 4.00    | 4.00    | 4.00    | 4.00    | 4.00    | 4.00    | 4.00    |
| F                              | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    |
| Cl                             | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    | 0.00    |
| Mineral                        | Schorl  |

**Table 1e.** Representative electron-microprobe analyses of tourmaline from Khopik Cu-Au porphyry prospecting areas (Structural formula based on 31 anions (O, OH, F)).

| Sample No.                     | T2-KH3-1 | T2-KH3-2 | T2-KH3-3 | T2-KH3-4 | T2-KH3-5 | T2-KH3-6 | T2-KH3-7 |
|--------------------------------|----------|----------|----------|----------|----------|----------|----------|
| SiO <sub>2</sub>               | 35.31    | 35.06    | 34.89    | 35.34    | 35.38    | 34.89    | 34.56    |
| TiO <sub>2</sub>               | 0.22     | 0.15     | 0.08     | 0.23     | 0.18     | 0.21     | 0.19     |
| Al <sub>2</sub> O <sub>3</sub> | 30.83    | 27.83    | 31.19    | 30.82    | 29.78    | 31.19    | 31.23    |
| FeO                            | 5.55     | 10.75    | 8.56     | 6.56     | 8.98     | 8.98     | 8.58     |
| MgO                            | 9.18     | 7.88     | 7.75     | 9.23     | 7.89     | 7.68     | 6.99     |
| CaO                            | 1.29     | 1.50     | 1.46     | 1.21     | 1.26     | 1.34     | 1.59     |
| MnO                            | 0.01     | 0.01     | 0.06     | 0.01     | 0.01     | 0.01     | 0.07     |
| Na <sub>2</sub> O              | 2.20     | 1.83     | 2.21     | 2.23     | 1.88     | 2.21     | 1.72     |
| K <sub>2</sub> O               | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     |
| B <sub>2</sub> O <sub>3</sub>  | 10.50    | 10.50    | 10.50    | 10.50    | 10.50    | 10.50    | 10.50    |
| H <sub>2</sub> O*              | 3.61     | 3.53     | 3.61     | 3.63     | 3.58     | 3.62     | 3.58     |
| Li <sub>2</sub> O*             | 0.04     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.08     |
| Total*                         | 98.74    | 99.05    | 100.31   | 99.76    | 99.44    | 100.63   | 99.08    |
| T: Si                          | 5.87     | 5.95     | 5.79     | 5.84     | 5.92     | 5.78     | 5.79     |
| Al                             | 0.13     | 0.05     | 0.21     | 0.16     | 0.08     | 0.22     | 0.21     |
| B                              | 3.01     | 3.08     | 3.01     | 3.00     | 3.03     | 3.00     | 3.04     |
| Z: Al                          | 5.90     | 5.52     | 5.89     | 5.85     | 5.79     | 5.88     | 5.96     |
| Mg                             | 0.10     | 0.48     | 0.11     | 0.15     | 0.21     | 0.13     | 0.04     |
| Y: Al                          | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     |
| Ti                             | 0.03     | 0.02     | 0.01     | 0.03     | 0.02     | 0.03     | 0.02     |
| Mg                             | 2.18     | 1.51     | 1.81     | 2.12     | 1.76     | 1.77     | 1.71     |
| Mn                             | 0.00     | 0.00     | 0.01     | 0.00     | 0.00     | 0.00     | 0.01     |
| Fe <sup>2+</sup>               | 0.77     | 1.53     | 1.19     | 0.91     | 1.26     | 1.25     | 1.20     |
| Li*                            | 0.02     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.05     |
| VY                             | 3.00     | 3.06     | 3.02     | 3.06     | 3.04     | 3.05     | 3.00     |
| X: Ca                          | 0.23     | 0.27     | 0.26     | 0.21     | 0.23     | 0.24     | 0.29     |
| Na                             | 0.71     | 0.60     | 0.71     | 0.72     | 0.61     | 0.71     | 0.56     |
| r                              | 0.06     | 0.12     | 0.03     | 0.07     | 0.17     | 0.05     | 0.15     |
| OH                             | 4.00     | 4.00     | 4.00     | 4.00     | 4.00     | 4.00     | 4.00     |
| F                              | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     |
| Cl                             | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     | 0.00     |
| F content                      |          |          |          |          |          |          |          |
| Mineral                        | Dravite  | Schorl   | Dravite  | Dravite  | Dravite  | Dravite  | Dravite  |



**Figure 3** Ternary X-site-vacancy–Na–Ca [13, 22]. All of the tourmaline is plotted in the field of Alkali-type.

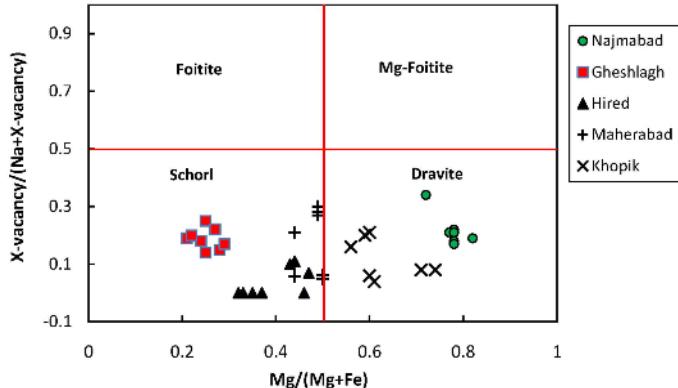


**Figure 4** Ternary Al–Fe–Mg plots showing changes in chemical composition of tourmaline [13, 22].

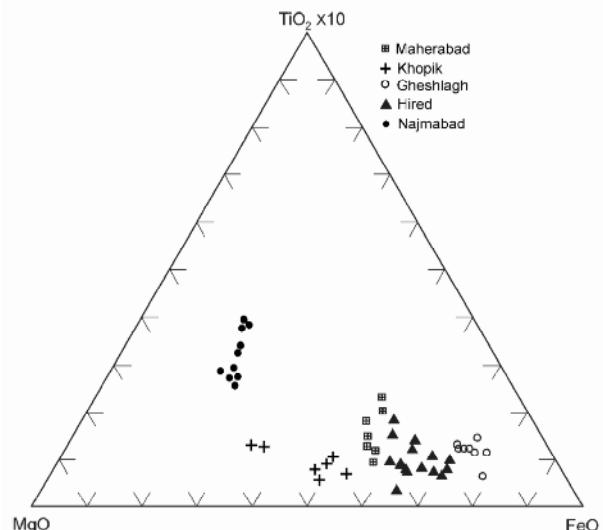
The best diagram for classification of the tourmaline species is an  $Mg / (Mg + Fe)$  vs.  $X$ -vacancy / ( $X$ -vacancy + Na) diagram (Fig. 5). Tourmaline from Najmabad and Khopik are plotted in the field of Dravite [ $(Mg / (Mg + Fe)) = 0.55 - 0.82$ ]. The  $Mg / (Mg + Fe)$  ratio in Gheshlagh tourmaline is 0.21-0.29, in Hired is 0.32 - 0.47 and in Maherabad is 0.44-0.5 (Fig. 2). In the  $X_{vac}$  vs  $Mg / (Fe + Mg)$  discrimination diagram in Fig. 5, Gheshlagh, Maherabad and Hired lie just within the Schorl field.

The  $Mg \sim$  clearly distinguishes Cu-Au deposits in terms of their distance from the granitic source (proximal to distal). More specifically, a high  $Mg \sim$  (1.9-2.3) is indicative of tourmalines associated with an endogranitic system or a proximal system. Khopik tourmaline contains considerably higher

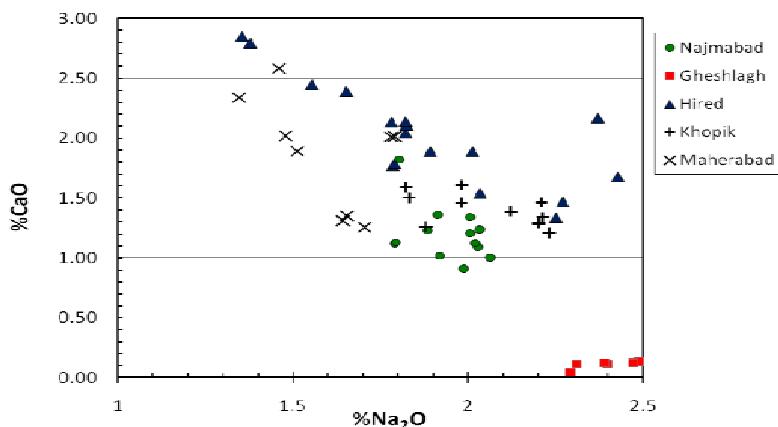
$Mg$  (1.9-2.3) compared with the Maherabad ( $Mg = 1.4-1.9$ ) (Fig. 6). This could be the level of erosion. At Khopik, deeper portion of the porphyry Cu-Au is exposed. Najmabad tourmaline contains the highest  $Mg$  ( $Mg = 2.2$ ,  $Fe = 0.45 - 0.6$ ) and Gheshlagh the lowest  $Mg$  ( $Mg = 0.5 - 0.7$ ) and highest  $Fe$  ( $Fe = 1.9 - 2.3$ ) (Fig. 6). Najmabad tourmaline contain the highest  $TiO_2$  (0.48%) and other tourmaline contain less than 0.3 %  $TiO_2$  (Fig. 6). The average  $TiO_2$  content of Maherabad tourmaline is 0.35 and Khopik is 0.19 (Fig. 6). The  $CaO$  and  $Na_2O$  content of all tourmalines are plotted in Fig. (7). In general, there is a reverse correlation between  $CaO$  and  $Na_2O$  (Fig. 7). Gheshlagh has the lowest  $CaO$  and highest  $Na_2O$  (Fig. 7). The  $CaO$  and  $Na_2O$  content of tourmaline from Hired is very variable (Fig. 7).



**Figure 5** Plot of  $Mg / (Mg + Fe)$  v.s  $X_{vac}$  for classification of tourmaline.



**Figure 6** Ternary  $MgO-FeO-TiO_2$  diagram shows the composition of tourmaline from the five study areas.



**Figure 7** Plot of %CaO v.s %Na<sub>2</sub>O.

## Conclusions

The study of tourmaline from five areas has revealed significant changes in composition. It is hoped that this will encourage more extensive studies of chemical variations within single tourmalines as a tool in mineral exploration and in petrogenetic studies. Tourmaline alteration is commonly associated with Cu, Sn, W and Au porphyries. Compositional variations are significant between Maherabad and Khopik Cu-Au porphyry prospecting areas. These two areas are nearby, but the level of erosion is higher in Khopik. The  $Mg / (Mg + Fe)$  ratio of Khopik is 0.56-to 0.74, therefore it is dravite type. The  $Mg / (Mg + Fe)$  ratio of Maherabad is 0.44-0.5,

therefore it is schorl- type. Najmabad tourmaline contains the highest  $TiO_2$  (0.48%) and other tourmaline contains less than 0.3 %  $TiO_2$ . The average  $TiO_2$  content of Maherabad tourmaline is 0.35 and Khopik is 0.19. In general, there is a reverse correlation between CaO and Na<sub>2</sub>O of tourmaline. Gheshlagh has the lowest CaO and highest Na<sub>2</sub>O. The CaO and Na<sub>2</sub>O content of tourmaline from Hired are very variable. Tourmaline from Gheshlagh (not mineralized pegmatite) has the lowest ratio of  $Mg / (Mg + Fe) < 0.3$ , highest Na<sub>2</sub>O and highest FeO.

Gheshlagh tourmaline (from pegmatite with no mineralization) has the lowest %CaO = 0.04-0.14,  $Mg/(Mg + FeO) < 0.3$  and highest %FeO (13-

14.5%), %Na<sub>2</sub>O = 2.3-2.49. Najmabad Tourmaline (reduced granitoid with low Sn-W) with minor changes in their composition contains the highest Mg/(Mg+FeO) >0.7, %TiO<sub>2</sub> = 0.48, %MgO = 8.5, %CaO = 1-1.4, and low %FeO = 3.3-4.5.

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