Journal of Earth & Statistics
Journal homepage: http://www.Jes.arakut.ac.ir
Doi: 10.22034/jes.2022.253086

Investigation of mineral chemistry and geothermobarometry of Gabbro-diorite rocks southeast of Arak (zone Sanandaj-Sirjan)

Saeed Naeemi[1], Elham shahosini[2]

[1] Department of geology, faculty of science, North Tehran Branch, Islamic Azad University, Tehran, Iran.

[2] North Tehran Branch, Islamic Azad University, Tehran, Iran

Article Info

Keywords: Thermobarometry; Clinopyroxene; Plagioclase; Arak, Iran.

*Corresponding Author's Email Address:saeednaemi38@gmail.com

Abstract

The gabbroic rocks in the southeast of Arak of the zone Sanandaj-Sirjan in are intruded into the Middle and Upper Cretaceous sedimentary units. The main gabbroic rocks varieties include olivine gabbro, monzogabbro, diorite, and monzodiorite. The main minerals phases in the rocks are plagioclase and pyroxene and the chief textures are sub-hedral granular, porphyritic, intergranular and poikilitic. Electron microprobe analyses on minerals in the rock samples shows that plagioclase composition ranges from labradorite to bytonite, with oscillatory and normal chemical zonings. Clinopyroxene is diopside, augite and salite in composition and characterized with alkaline nature. Thermometry calculations indicate temperatures of 750˚C to 950˚C for plagioclase crystallization and 950˚C to 1120˚C for pyroxene crystallization. According to tectonic diagrams and mineral chemistry studies, the rocks of the region were formed in an intercontinental environment(rift).

Introduction

Mineralogical composition is one of the most effective parameters in classifying and describing intrusive rocks (Streckeisen 1976, Streckeisen and Le Maitre 1979, Pearce et al. 1984, Barbarin 1990). Introduction Sanandaj-Sirjan Zone (SSZ) is a belt in the southwest of central Iran, which is located in the immediate northeast of the main Zagros thrust. The rock and structural features of this zone represent a deep trough or middle rift block in the Precambrian shield of Iran and Saudi Arabia. Therefore, its geological features are distinct from the adjacent areas. The special differences of this zone have attracted geologists for a long past. The length of SSZ is about 1500 and its width is 150 to 250 km. The zone starts from the west of Urmia Lake and continues in a northwest-southeast direction to the Minab fault, north of Bandar Abbas. Lake Urmia, Tuzlugol, Gavkhouni, and Jaz Murian are the boundary area between Sanandaj-Sirjan and Middle Iran (Stocklin, 1968). The SSZ is indeed a part of the Zagros orogenic belt, which is the result of the opening and closure of the Neotethys Ocean. From northeast to southwest, it has three parallel tectonic zones including the Urmia-Dokhtar magmatic complex, the Sanandaj-Sirjan zone, and the folded Zagros belt (GhSemi and Talbot, 2005; Ullah et al. 2021, Jafari et al. 2021). The boundary of SSZ with the Urmia-Dokhtar magmatic complex toward the east is formed by a series of structural embayments that are the result of compression. This zone is a pair of metamorphic bands mainly in the form of greenschist, amphibolite, and Eclogite facies, which has risen at the end of the Cretaceous due to the continental collision between the African-Arab continent and the Central Iranian subcontinent (Mohajjel and Fergusson, 2000; Barahouei et al. 2021; Pourabdollahi et al. 2021). The most important metamorphic events that affect the SSZ are related to the tectonic events of the opening and closure of the Neotethys Ocean (Alavi, 1994; Mohajjel et al., 2003; Aghanabati, 2004; GhSemi and Talbot, 2005; Morovati et al. 2021). Indeed, the tectonic zone of the Zagros Orogen is the result of subduction and collision of the Arabian plate and Central Iran subcontinent during the Late Cretaceous to Tertiary (Laramid orogenic phase) (Mohajjel et al., 2003; Mohajjel and Fergusson, 2000; Rajabi et al. 2021). The northwest-trending folds partly overturned to the south and southwest, southwest-verging thrusts, and northwest-trending high-angle reverse faults, which resulted in thickening of the crust and Tertiary uplift of the Sanandaj-Sirjan zone (Stöcklin, 1968; Braud and Ricou, 1971; Berberian and King, 1981; Mohajjel and Fer-gusson, 2000; Mohajjel et al., 2003; Agard et al., 2005;Ghasemi and Talbot, 2006). Tertiary

calc-alkaline magmatismin the adjacent Urumieh-Dokhtar magmatic belt (Fig. 1A;Förster, 1974; Berberian and Berberian, 1981; Berberian and King, 1981; Berberian et al., 1982) is interpreted by Ghasemi and Talbot (2006) to have resulted from slab break off during the middle Eocene.

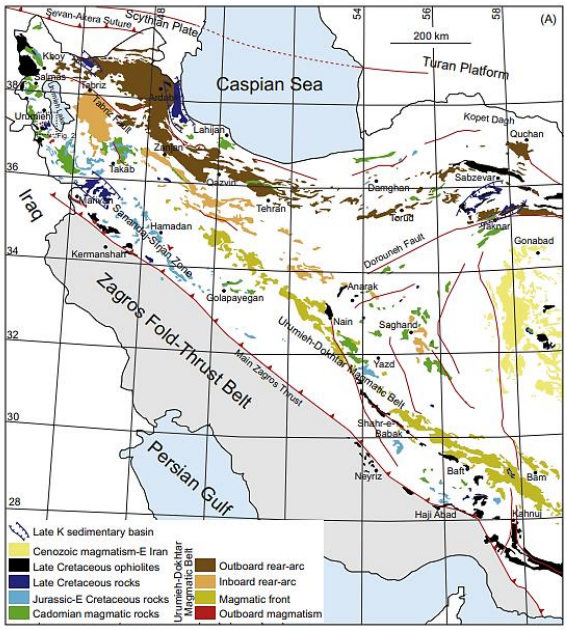


Fig 1. Simplified geological map of the Sanandaj-Sirjan Zone (SaSZ) and its Jurassic granitoid plutons in Iran (modified after Bayati et al. 2015; Azizi et al. 2019b).

Study method

A total of 40 samples were taken during field visits, of which 20 thin sections were prepared and studied. Thermobarometric studies were conducted on 6 thin-polished sections prepared from the gabbro of the study area. In this regard, pyroxene, and plagioclase minerals were microproped through 15 point analyses. Point analyses were performed on minerals using an XPMA microprobe electron analyzer in Binalood Kansaran (HORIBA model, XGT-7200). The device operates at an accelerator voltage of 50 kV and current intensity of 1 Am. The analyses were performed on points with a diameter of 10 μm in 80 s for each point. The structural formula was calculated using Excel spreadsheets prepared for the minerals of these rocks.

Geology of the region

According to the 1:100,000 geological map of Varcheh, in the south and southeast of Arak, 30 small outcropped intrusive masses in the dimensions of 0.5-5 km2 have exposure between latitudes 49°45′ to 50°00′ E and 33°45′ to 34°00′ N (Figure 1).

The intrusive rocks in the study area are pyroxene gabbro, gabbro-diorite, diorite gabbro, pyroxene diorite, diorite, Luco-diorite, and monzodiorite. At the point of contact of the intrusive masses with the host rocks, there is often no specific phenomenon other than the presence of limited alteration zones. Most of these rocks are in the form of small stocks or sills. The studied intrusive mass has penetrated the Middle and Upper Cretaceous sedimentary rocks including limestone shale, marl, and siltstone. In the study area, the presence of various rocks with heterogeneous origins has created different morphologies in different parts of the study area. In addition to the type of rocks, regional tectonics and volcanic eruptions have played a determining role in the shaping these areas. The most important rocks in the study area include gabbro, monzogabbro, diorite, gabbro diorite, pyroxene diorite, diorite, and luco-diorite. In these studies, the shape and size of the hand specimens of the rock are massive and gray to dark green. Also, in terms of texture, they are holocrystalline and medium to coarse crystal and sometimes have ophitic and sub-ophitic textures. Intergranular, ophitic, and sub-ophitic textures suggest simultaneous crystallization of plagioclase and clinopyroxene (Vernon, 2004). The presence of ophitic tissue also indicates greater nucleation of plagioclase than clinopyroxene (Wager, 1960).

Petrography

These rocks have a relatively simple mineralogical composition including plagioclase, clinopyroxene, opaque minerals, and ilmenite with ophitic and sub-ophitic textures. Plagioclase is the most important and abundant mineral in these rocks with a frequency of about 20% and is often euhedral to subhedral and in the form of fine to large blades with repetitive polysynthetic twins. Clinopyroxene is the second major mineral of these rocks with a frequency of about 42%. Accessory and altered minerals include opaque minerals (iron oxide and titan), chlorite (from the decomposition of clinopyroxene), amphibole (from the decomposition of clinopyroxene), and calcite. The main marked alterations in this mass are sericitic, sussoritic, and chloritic in plagioclase and clinopyroxenes (Figure 2).

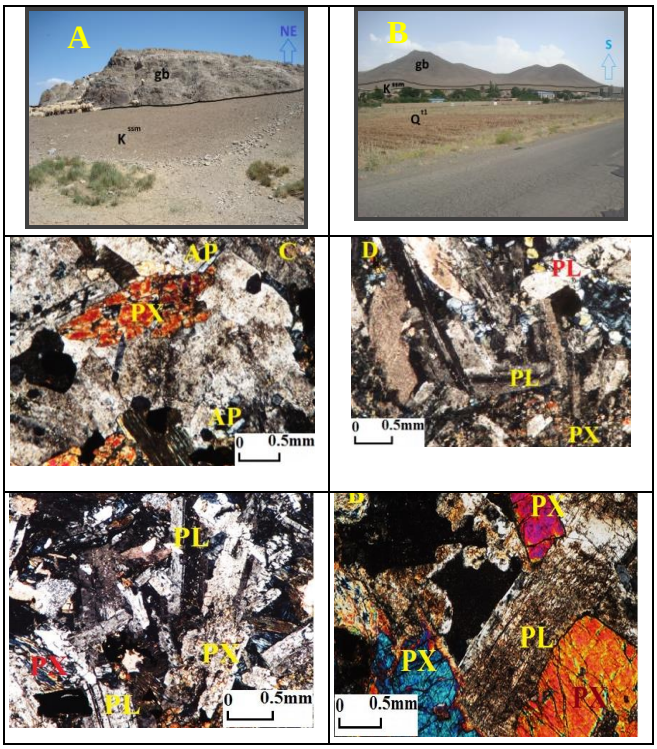


Fig 2. a,b-A view of gabbroic rocks in the studied area. c-Granular subhedral texture in gabbro-diorite; (d) Anti-perthitic plagioclase and clinopyroxene in the luco-diorite sample. e-Granular subhedral texture in gabbro pyroxene; f-View of gabbro with granular texture.

Plagioclases

Plagioclases have been mostly decomposed into sericite, chlorite, and clay minerals. Plagioclase, with an abundance of about 17 to 25%, is the second abundant mineral of these rocks. This mineral is often euhedral to subhedral in the form of fine to large blades with polysynthetic twins. These minerals sometimes show sericitization alteration. This alteration, which is mainly in the center of the crystal, shows the normal zonation of plagioclase and the higher Ca-rich core of the crystals compared to their margins.

Water vapor pressure, the sudden magma rising, and the creation of unbalanced magmatic conditions reduce the amount of anorthite and increase Fe and Mg concentrations in plagioclase, respectively (Ahmadi et al., 2017).

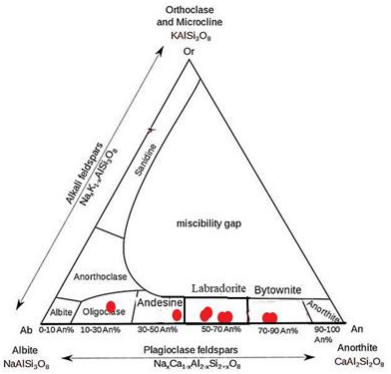


fig 3. Plagioclase composition in Ab-An-Or ternary diagram Deer (1991)

The Or-Ab-An diagram of Deer (1991), the plagioclases of the study area are plot in the andesine, labradorite, and bytownite fields (Fig. 4A). Zoning in plagioclase mineralization has formed for two reasons. First, plagioclase has been crystallized in a melt that undergoes continuous variations in temperature, water vapor pressure, and composition (magmatic mixing and change in magma chemical composition during magma crystallization) (Humphreys et al., 2006). Decreased pressure due to sudden magma ascension and increased oxygen escape are other factors changing the amount of anorthite plagioclase from the center to the edge (Blundy et al., 2006). The oxygen escape change due to successive injection of magma from the mantle into the magmatic chamber changes the chemical composition of the melt, so crystals in the magmatic chamber can lead to zoning. Second, increased growth rate at the crystal-melt interface in response to equilibrium conditions (Ginibre et al., 2002a) is the other explanation for this mineralization.

Pyroxene

Clinopyroxene appeared as subhedral to euhedral with a frequency of about 42%, and is the most important and abundant mineral. Sometimes, they have been euralitized and is seen with cavities filled with chlorite. Morimoto et al. (1988) classification diagram was used to determine the type of pyroxenes. As shown in Fig. 5B, in the Q-J diagram, the studied pyroxenes are in the range of Fe-Mg-Ca type pyroxenes. Also, according to the Polderwaart-Hess diagram (Fig. 5b), the pyroxenes are in the composition range of diopside, augite and salite(Fig. 5b).

Olivine

The composition of analysed olivines are mainly hyalosiderite (Figure.6) according to Wager and Deer (1939). Primary olivine minerals certainly have a higher magnesium content but the edingzitation and oxidation of these minerals has led to the stabilization of Fe in place of Mg and the placement of Olivine's to the Faylite pole.

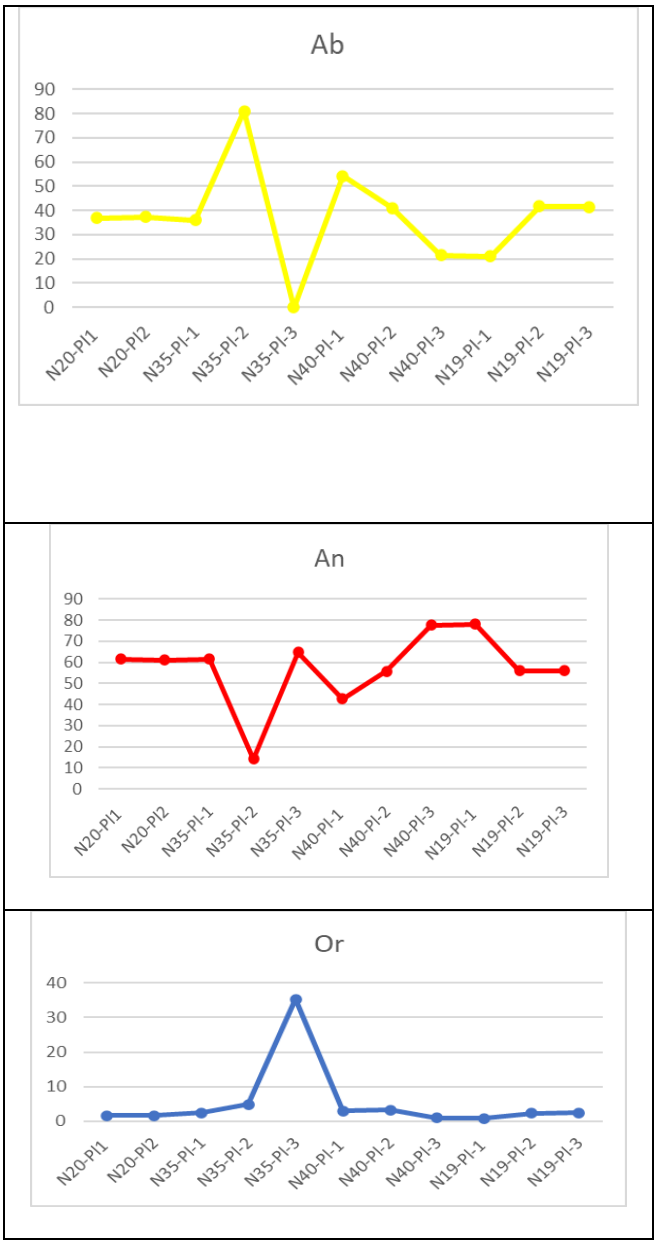
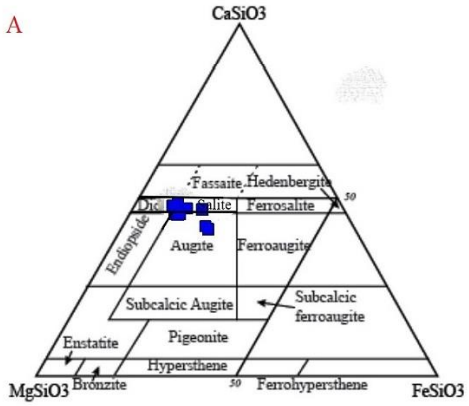


fig 4. Changes in the amount of anorthite, orthose and albite in three plagioclase minerals.



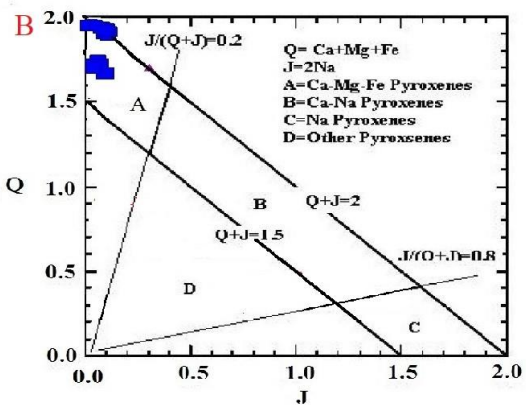


Fig5. A-Composition of clinopyroxenes on the ternary diagram of enstatite (En), wollastonite (Wo) and ferrosilite (Fs) (Deer et al., 1992). b-J versus Q diagram (Morimoto et al., 1988). The studied clinopyroxenes are in the range of Fe + Mg + Ca pyroxenes;

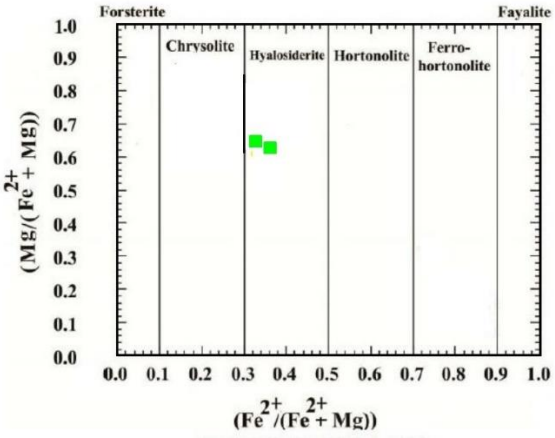


Fig 6. Chart for determination of olivine composition.

Magmatic nature and tectonic setting

Chemistry of clinopyroxene is used to find out the magmatic nature and tectonic setting for the studied gabbros (e.g Moazzen and Oberhänsli, 2008). Al and Ti content in clinopyroxene depends on silica content of magma and the ratio of these elements in tholeiitic, alkaline and calc-alkaline magmas (Kushiro,1960; Le Bas, 1962). The analysed pyroxenes plot on and above the saturation line of diagram in Fig. 7. This shows that the tetrahedral site is occupied by Si and AlIV (Schweitzer et al., 1979). Ti content in clinopyroxene is related to the alkalinity of parental magma. Clinopyroxenes in alkaline basalts contain higher amount of Ti, compared to sub-alkaline basalts (Gill, 2010). Our samples plot in the Calc-alkaline field of SiO2 versus Al2O3 and Al2O3 versus TiO2 diagrams of Le Bas (1962) in Fig. 8a and b. Clinopyroxene compositions in diagrams by Leterrier et al (1982) indicate calc-alkaline nature for the parental magma of the gabbroic rocks and a volcanic arc tectonic setting (Fig. 8c, d and e).

Ti-Ca criteria of Leterrier et al. (1982), confirms an orogenic setting for the gabbros (Fig. 8e).
According to some researchers, regardless of the influence of cooling rate and differential crystallization, the chemical composition of clinopyroxene is highly related to the composition and type of magma that produced it (Beccaluva et al., 1989). The amount of TiO2 and TiO2/Al2O3 in clinopyroxene has an inverse relationship with the amount of SiO2 and has a direct relationship with the Zr/Y ratio of its host rock. are specified Pearce and Cann, 1973; Floyd and Winchester, 1975; (Pearce and Norry, 1979). According to the diagram of Beccaluva et al., 1989, with the increase of TiO2 and Na2O and the decrease of SiO2, the composition of clinopyroxenes tends from andesitic basalts to islands, mid-oceanic ridge arcs and OIB type basalts respectively in the diagramTiO2 - SiO2-Na2O in Figure 9 B, the position of clinopyroxenes in the samples shows the nature of OIB type. As a result, by studying the chemical content of minerals such as clinopyroxenes, useful information can be obtained in the field of rock petrogenesis.

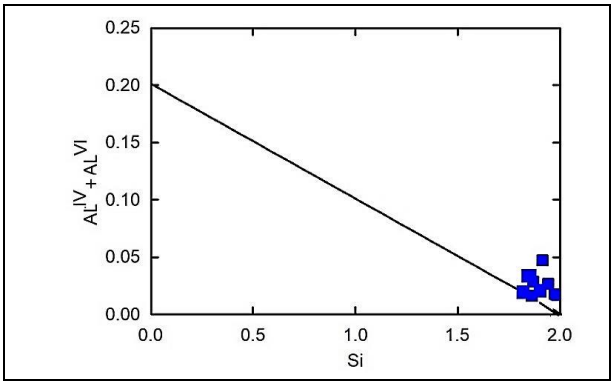


Fig 7. The diagram of Si against the sum of Aliv+Alvi

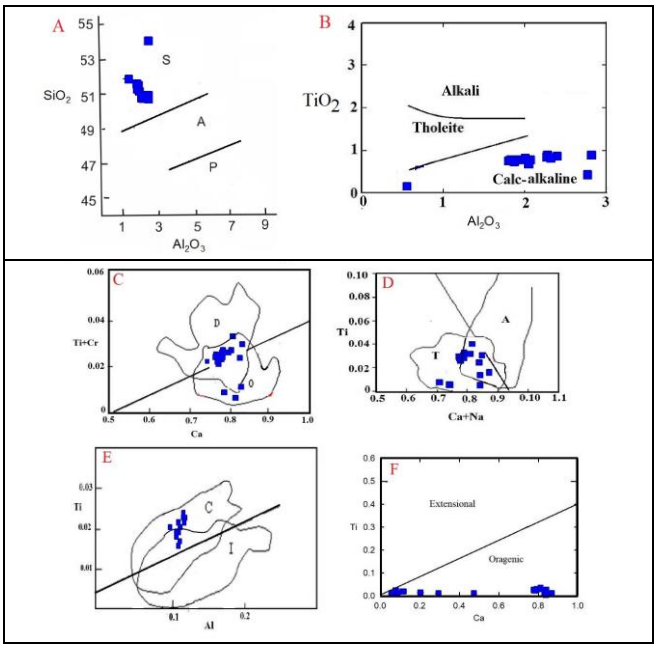


fig 8. Plotting of pyroxene analyses on Al_2O_3 versus SiO_2 and Al_2O_3 versus TiO_2 diagrams (Le Bas, 1962) (A and B) for distinguishing the nature of the parental magma. C, D and E: diagrams from Leterrier et al. (1982) for magma type and tectonic setting (T= Island arc tholeiitic basalt, A= Alkali basalt, O= volcanic arc basalt, D= MORB, I+ Island arc tholeiite, C= Calc-alkaline basalt. F: Ca versus Ti diagram showing tectonic setting after Leterrier et al. (1982)

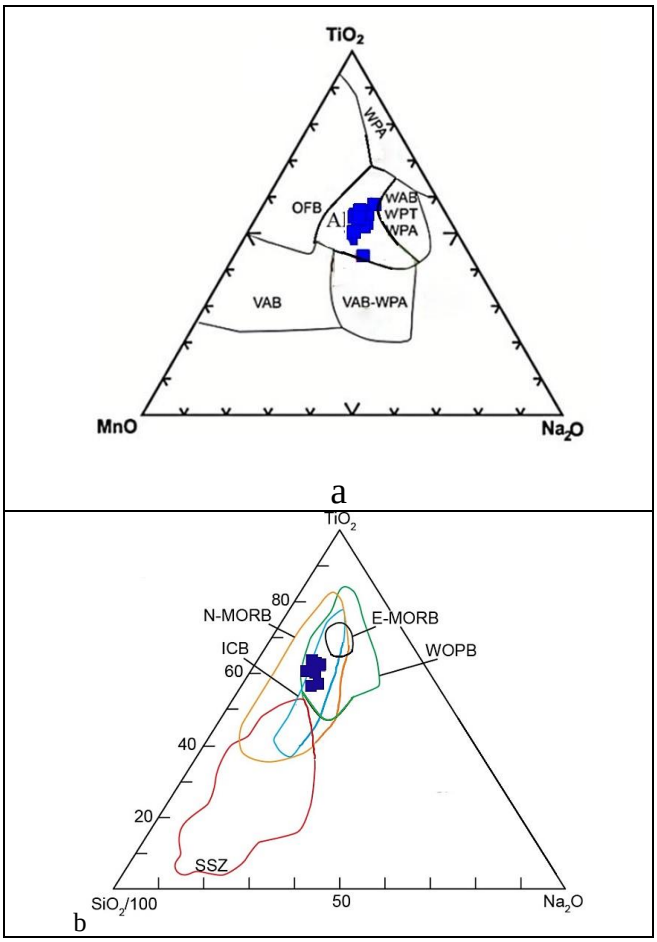


Fig 9. a-diagram of (Nisbet and Pearce,1997). b-diagram of Beccaluva et al., 1989.
Abbreviations, E-MORB: enriched mid-ocean ridge basalt; N-MORB: normal mid-ocean ridge basalt; WOPB: within oceanic plate basalts; ICB: Iceland basalts; SSZ: supra-subduction zone basalts.

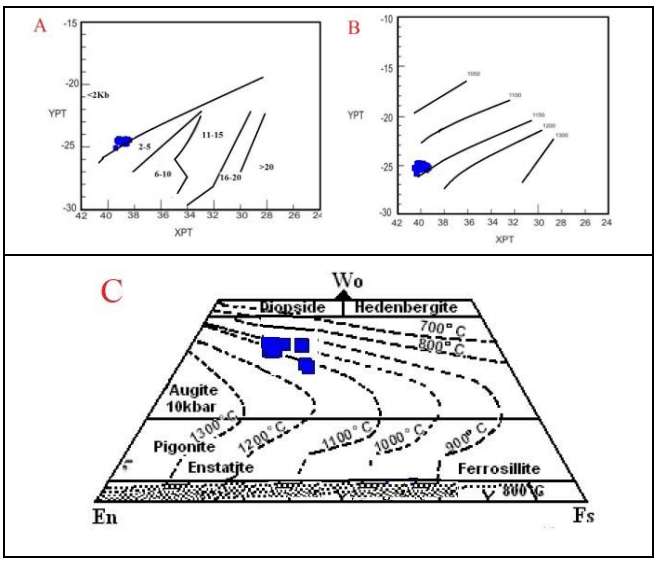
Also, in the chart of Nisbet and Pearce, 1997, the samples of the region are placed in the range between different tectonic environments (volcanic arc basalt, ocean floor basalt and intraplate zone). When melting part of the mantle, sodium and titanium elements are incompatible and prefer the molten phase. Therefore, the lower concentration of TiO2 in the melt is attributed to the origin of the depleted mantle and its higher amounts to the origin enriched or less depleted to the deep mantle (OIB) (Davis et al., 2011) or altered subcontinental mantle (McKenzie & Onions, 1995) is attributed. According to the chemistry of the rocks of the area, there has been a cafitation event in the area, but this event was local.

Geothermometry and geobarometry

Mineral chemistry of clinopyroxene and plagioclase used to determine the P -T conditions during the crystallisation of the gabbroic rocks.

Calibration by Soesso (1997) gives temperatures of 1100 ˚C to 1150 ˚C and pressures of 1 to 3 kbar for pyroxene crystallization (Figure. 10 a and b). Two pyroxene thermometry of Lindsley et al. (1983) gives temperatures of 950˚Cto 1130˚C (Figure.10c), which is in good agreement with results from thermometer of Soesso (1997). In the following, various models have been used to measure the temperature of the rock in the area. Using the Or-Ab-An ternary system, the temperature was estimated to be around 650 to 750 ∘c for different rocks (Fig. 5a).

1) XPT = 0.446 SiO2 + 0.187 TiO2 – 0.404 Al2O3 + 0.346 FeO – 0.052 MnO + 0.309 MgO + 0.446 CaO- 0.446 Na2O
2) YPT = - 0.369 SiO2 + 0.535 TiO2 – 0.317 Al2O3 + 0.232 FeO + 0.235 MnO – 0.516 MgO – 0.167 CaO – 0.153 Na2O



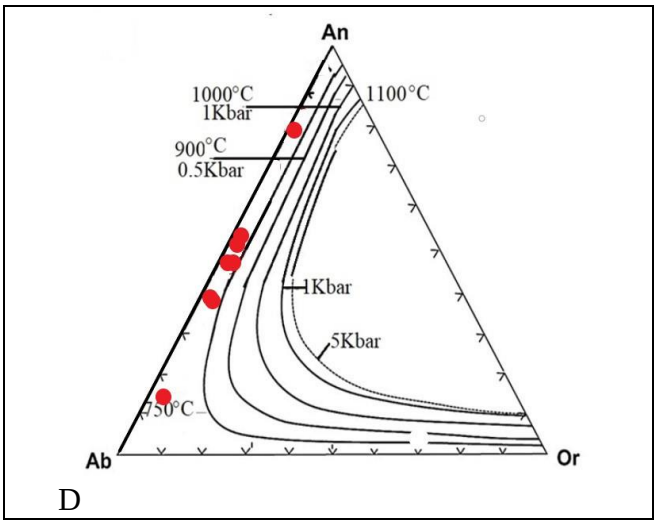


Fig 10. a , b-Position of plagioclase of the studied samples in the diagram (Soesso, 1997). C- diagram of (Lindsley et al 1983). D- the Ab-An-Or diagram of (Seck, 1971).

Oxygen fugacity is an important controlling factor for liquidus temperature and melt/crystal composition (France et al., 2010) and magmatic processes (Kilinc et al., 1983; Kress and Carmichael, 1991; Ottonello et al., 2001; Botcharnikov et al., 2005; Moretti, 2005).

Using AlIV+Na versus AlVI+2Ti+Cr, which is a function of Fe^{3+} content of pyroxene, oxygen fugacity during pyroxene crystallization can be estimated. A diagram is constructed (Schweitzer et al., 1979) based on Al in tetrahedral and octahedral crystallographic sites. Fe^{3+} can substitute for AlVI, Ti and Cr in the octahedral site. Therefore Fe3+ content in pyroxene is a AlVI content. Data plotting above the Fe3+=0 line in the diagram (Figure. 11) are for pyroxenes crystallized at high fO2. Papike and Cameron (1981) pointed out that samples plotting away from the line show higher fO2.Our samples plot below the Fe^{3+}=0, indication low fO_2 during crystallization (Figure.11). Wass (1979) suggested that the ratios of AlVi/AlIv, Ti + AlIV/Si, and TiO2/(Mg + Mg + Fe) in pyroxenes could be used as a barometer. According to AlVi/AlIv diagrams in Fig. 13, the samples fall in the medium pressure range. Also, in the structure of clinopyroxenes, Cr is in equilibrium with AlVI, and the Cr * 100/Cr + AlVI ratio in pyroxenes is directly related to pressure (Nimis and Taylor, 2000). In this respect, aluminum content of clinopyroxenes is controlled by reactions $NaAlSi3O8 = NaAlSi_2O_6 + SiO_2$ and $CaAl_2Si_2O_6 = CaAl_2SiO_6 + SiO_2$ at high and low pressures, respectively (Green and Ringwood, 1967). The first reaction occurs at a depth of about 120 km (containing garnet peridotite), and the second reaction occurs at a depth of less than 40 km. The depth of the magmatic reservoir was determined using the aluminum concentration in the structure of pyroxenes. Researchers, including Helz (1983), have emphasized that the distribution of aluminum in both quadrilateral and octahedral situations of clinopyroxenes is a good measure of magma water and pressure in the environment of igneous rock formation. With this model, pyroxenes have been crystallized at the pressure of 5 kbar, and magma water content is less than 10% (Fig. 13).

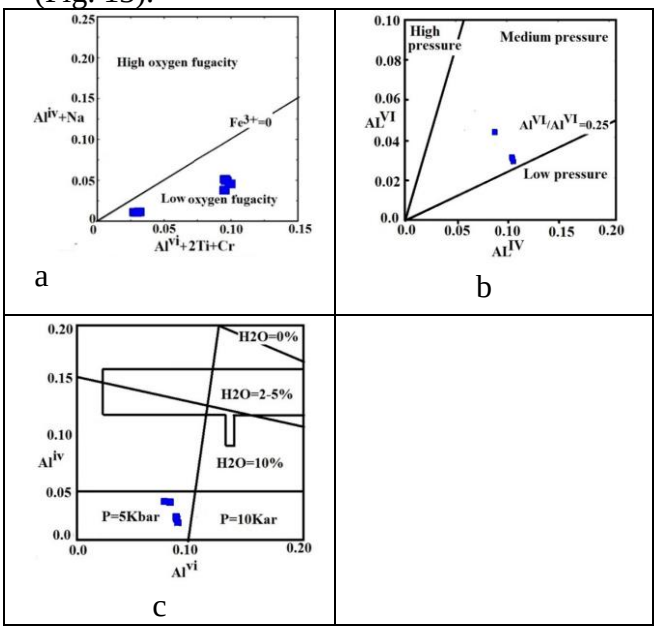


Fig 11. a) Al^{IV} versus Al^{VI} barometry diagram of clinopyroxene) (Schweitzer *et al*., 1979). b) Al^{IV} versus Al^{VI} barometry diagram of clinopyroxene (Aoki and Shiba, 1993); c) Barometry and hydrometry diagrams of clinopyroxene (Helz, 1973).

Conclusion

The gabbroic rocks of the region include gabbroporphyry, olivine gabbro, olivine dolerite and olivine monzogabbro. Plagioclase, olivine and

pyroxene are the main minerals of these rocks. Based on the results of microprobe analysis, the plagioclase composition of the igneous rocks of the andesine region is labradorite-bitonite and they have fluctuating or normal zoning. The composition of clinopyroxenes is augite and diopside, and the composition of olivine is hyalosiderite. Thermometric calculations of plagioclase minerals show that these minerals are formed in the range of 650 to 750 degrees Celsius. The pyroxene rocks of the region have also crystallized in the temperature range of 950 to 1150 degrees Celsius. The composition of clinopyroxenes are those that are placed on the diagrams of determining the magmatic series in the alkaline range and the tectonomagmatic position in the rift or intracontinental tension range.

References

Agard, P., Omrani J., Jolivet, L., Mouthereau, F., 2005, Convergence History Across Zagros (Iran): Constraints from Collisional and EarlierDeformation, Int J Earth Sci (GeolRundsch), 94: 401–419.

Aghanabati, A., 2004. Geology of Iran geological survey of iran. Theran, Iran, 586pp.

Alavi, M., and Mahdavi, M.A., 1994, Stratigraphy and structures of the Nahavand region in western Iran and their implications for the Zagros tectonics: Geological Magazine, v. 131, pp. 43–47.

Aoki, K. & Shiba, I., 1973- Pyroxenes from lherzolite inclusions of Itinome-gata, Japan. Lithos, 6, 41–51.

Azizi, H., Stern, R.J., Topuz, G., Asahara, Y., Moghadam, H.S., 2019. Late Paleocene adakitic granitoid from NW Iran and comparison with adakites in the NE Turkey: Adakitic melt generation in normal continental crust. Lithos 346, 105151.

Bayati, M., Esmaeily, D., Maghdour-Mashhour, R., Li, X.H., Stern, R.J., 2017. Geochemistry and petrogenesis of Kolah-Ghazi granitoids of Iran: Insights into the Jurassic Sanandaj-Sirjan magmatic arc. Chemie der Erde-Geochemistry 77 (2), 281–302. https://doi.org/10.1016/j.chemer.2017.02.003.

Beccaluva, L., Macciotta, G., Piccardo, GB., and Zeda, O., 1989. Clinopyroxene composition of ophiolite basalts as petrogenetic indicator, Chemical Geology 77, pp,165-182.

Berberian, F. & Berberian, M., 1981. Tectono-plutonic episodes in Iran.In: Gupta HK, Delany FM (eds) Zagros, Hindukosh, Himalaya Geodynamic Evolution. American Geophysical Union, Washington DC: 5–32.

Berberian, F., I. D. Muir, R. J. Pankhurst, and M. Berberian., 1982, Late Cretaceous and early Miocene Andean-type plutonic activity in northern Makran and central Iran, J. Geol. Soc., 139, 605–614.

Berberian, M., King, G.C.P., 1981. Towards a Paleogeography and Tectonic Evolution of Iran. Can. J. Earth Sci. 18, 210–265.

Blundy J., Cashman K., Humphreys M., 2006."Magma heating by decompression-driven crystallization beneath andesite volcanoes", Nature, Vol: 443, p: 76-80.

Botcharnikov, R.E., Koepke, J., Holtz, F., McCammon, C., Wilke, M., 2005. The effect ofwater activity on the oxidation and structural state of Fe in a ferro-basaltic melt. Geochim. Cosmochim. Acta 69, 5071–5085.

Braud, J., and Ricou, L.-E., 1971, L'accident du Zagros ou Main Thrust, un charriage et un coulissement: Comptes Rendus de l'Académie des Sciences de Paris, v. 272, p. 203–206.

Cameron M., Papike J. J., 1981. structural and chemical variations in pyroxenes ", American minerals, 66, pp. 1 - 50.

Cameron, M., Papike, JJ., 1981. Structural and chemical variations in pyroxenes. Am Min 66: 1–50.

Davies, M. H., Mix, A. C., Stoner, J. S., Addison, J. A., Jaeger, J., Finney, B., Wiest, J., 2011. The deglacial transition on the southeastern Alaska Margin: Meltwater input, sea level rise, marine productivity, and sedimentary anoxia. Paleoceanography. Volume 26, Issue 2.

Deer, W.A., Howie, R.A., and Zussman, J., 1991. An introduction to rock forming minerals. Longman., 528p.

Deer, W.A., Howie, R.A., and Zussman, J., 2013. An Introduction to the rock-forming minerals, John Wiley and Sons, New York, 3rd ed. 549p.

Floyd, P. A., and Winchester, J. A., 1975. Magma type and tectonic setting discrimination using immobile elements. Earth and Planetary Science Letters, 27, 211–218.

France, L., Ildefonse, B., Koepke, J. and Bech, F., 2010. A new method to estimate the oxidation state of basaltic series from microprobe analysis. Journal of Volcanology and Geochemistry 69 (2008) 61-120.

Ghasemi, A., Talbot, C.J., 2006. A new tectonic scenario for the Sanandaj–Sirjan Zone (Iran). J Asian Earth Sci 26:68.

Ghasemi, A., Talbot, C.J., 2005. "A new tectonic scenario for the Sanandaj–Sirjan Zone (Iran)", Journal of Asian Earth Sciences, 24, p. 1–11.

Gill, R., 2010. Igneousrocks and processes apractical guide" Department of Earth Sciences Royal Holloway University of London, 472 pp.

Ginibre C., Kronz A., Wörner G., 2002. "High-resolution quantitative imaging of plagioclase composition using accumulated backscattered electron images: new constraints on oscillatory zoning. Contributions to Mineralogy and Petrology", 142, 436-448.-

Helz, R. T., 1983. Phase reactions of basalts in their melting rang at PH2O=5kb.

Humphreys M.C.S., Blundy J.D., Sparks S.J., 2006. "Magma evolution and opensystem processes at shiveluch volcano: insights from phenocryst zoning", Journal of Petrology, 47 (12), 2303-2334.

Kilinc, A., Carmichael, I.S.E., Rivers, M.L., Sack, R.O., 1983. The ferric-ferrous ratio ofnatural silicate liquids equilibrated in air. Contrib. Mineral. Petrol. 83, 136–140.

Kress, V.C., Carmichael, I.S.E., 1991. The compressibility of silicate liquids containingFe2O3 and the effect of composition, temperature, oxygen fugacity and pressure ontheir redox states. Contrib. Mineral. Petrol. 108, 82–92.

Kushiro I., 1960. "Si-Al relation in clinopyroxenes from igneous rocks", American Journal of Scince 258, pp. 548-554.

Le Bas, M.J., 1962. The role of aluminum in igneous. clinopyroxenes with relation to their parentage. American Journal of Science., Vol. 260, PP. 267-288.

Leterrier J., Maury R.C., Thonon P., Girard D., Marchal M., 1982. "Clinopyroxene composition as a method of identification of the magmatic affinities of paleo-volcanic series", Earth and Planetary Science Letters, Vol: 59(1), p: 139-154.

Lindsley D. H., 1983. "Pyroxene thermometry". Am. Miner 68, pp. 477-493.

McKenzie, D., Onions, R. K., (995. The source regions of ocean island basalts. Journal of Petrology, 36: 133-159.

Mohajjel, M., Fergusson, C.L., 2000. Dextral transpression in Late-Cretaceous continental collision, Sanandaj–Sirjan zone, Western Iran. J. Struct. Geol. 22, 1125–1139.

Mohajjel, M., Fergusson, C.L., Sahandi, M.R., 2003. Cretaceous–Tertiary convergence and continental collision, Sanandaj–Sirjan Zone, western Iran. J. Asian Earth Sci. 21, 397–412.

Moretti, R., 2005. Polymerization, basicity, oxidation state and their role in ionic modelling of silicate melts. Geophysics, 48(4– 5): 583–608.

Morimoto, N. (1989) Nomenclature of pyroxenes. The Canadian Mineralogist 27(1): 143-156.

Nisbet E. G., Pearce J. A., 1977. Clinopyroxene composition of mafic lavas from different tectonic settings. Contributions to Mineralogy and Petrology, 63, pp.149 -160.

Nisbet, E. G. & Pearce, J. A. 1997. Clinopyroxene composition of mafic lavas from different tectonicsettings. Contributions to Mineralogy and Petrology 63: pp. 161-173.

Ottonello, G., Moretti, R., Marini, L., Zuccolini, M.V., 2001. Oxidation state of iron insilicate glasses and melts: a thermochemical model. Chem. Geol. 174, 157–179.

Pearce, J.A., and Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses, Earth and Planetary Science Letters, 19, 290-300.

Pearce, J.A., and Norry, M.J., 1979. Petrogenetic implications of Ti, Zr, Y and Nb variations in volcanic rocks, Contribution to Mineralogy and Petrology, 69, 33-47.

Schweitzer, E. L., Papike, J. J. and Bence, A. E. 1979. Statistical analysis of clinopyroxenes from deepsea basalts. American Mineralogist 64: 502-513.

Seck H. A., 1971. Koexistierende Alkalifeldspate and Plagioklase in system NaAlSi3O8-KAlSi3O8-CaAl2Si2O8 bei Temperaturen 650 c bis 900 c.N., Jahrb. Min. Abh.,115:315-34.

Shelly, D., 1993. Igneous and metamorphic rocks under microscope classification features, microstructures and mineral preferred orientations. Chapman & Hall, London, 405 pp.

Soesoo A. A., 1974. "multivariate statistical analysis of clinopyroxene composition: empirical

Stöcklin J., Northern Iran: Alborz Mountains. In: Mesozoic–Cenozoic orogenic belts: data for orogenic studies", (Ed. Spencer, A.) Vol: 4, p: 213–234.

Vernon, R.H., 2004, A Practical guide to rock microstructure", Cambridge University Perss, United Kingdom. P. 594.

Wager, L. R., Deer, W. A., 1939. The petrology of the Skaergaard intrusion, Kangerdlugssuak, East Greenland. Meddel. om Grenland, Vol. 105, no. 4, PP. 1-352. [M.A. 8-27.]

Wager, L.R., 1960. Anote on the origin of ophitic texture in the chilled olivine gabbro of the Skaergaard intrusion", Geological Magazine. 98: P. 353 – 366.