مجلهٔ بلورشناسی و کانی شناسی ایران، سال دهم، شمارهٔ ۲، پاییز و زمستان ۱۳۸۱ از صفحهٔ ۱۷۹ تا ۱۹۵

پژوهشی

فشار، حرارت و ترکیب سیالات در هاله دگرگونی کلیبر، شمال غرب ایران؛ استفاده از تعادلات کانی شناسی در سنگهای رسی و کالک-سیلیکات

محسن مؤذن و رباب حاجی علی اوغلی

گروه زمین شناسی، دانشگاه تبریز، کد پستی ۵۱۶۶۴ ، تبریز

(دریافت مقاله ۸۱/۵/۲۰ دریافت نسخه نهایی ۸۱/۹/۴)

چکیده: با نفوذ توده آذرین نفلین سینیت کلیبر به داخل سنگهای رسوبی رسی و آهکی کرتاسه، هاله‌ی دگرگونی به ضخامت حدود یک کیلومتر ایجاد شده است. شش زون دگرگونی با کانیهایی چون کردیریت، آلکالی فلدسپار، سیلیمانیت و کروندوم در سنگها تشکیل شده است. سنگهایی که ترکیب شیمیایی مناسب داشته‌اند به علت حرارت توده به صورت بخشی ذوب شده‌اند. در سنگهای کالک-سیلیکات نیز پنج زون با کانیهایی چون ترمولیت، دیوپسید، گارنت، اسکاپولیت، وولاستونیت و وزوویانیت تشکیل شده است. برای تخمین فشار دگرگونی در سنگهای رسی از پتروژنتیک گرید استفاده شد. تقاطع منحنی‌های مربوط به واکنش‌های شناخته شده در سنگها بر روی پتروژنتیک گرید، فشاری حدود ۳ کیلوبار را نشان می‌دهد. محاسبهٔ محل منحنی‌های واکنشی مربوط به کالک-سیلیکات‌ها با فرض اکتیویته مساوی یک برای تمام فازها و رسم آنها بر روی نمودار حرارت-کسر مولی دی اکسید کربن، نشان می‌دهد که کسر مولی دی اکسید کربن هنگام اوج دگرگونی برابر با ۲٪ بوده است که این مقدار تقریباً مستقل از فشار دگرگونی است. محاسبه محل منحنی‌ها بر روی نمودار حرارت-کسر مولی دی اکسید کربن با فرض انحلال جامد کانیها و اکتیویته‌های غیر از یک، نتیجه مشابهی را می‌دهد و مشخص می‌کند که ترکیب واقعی سیال در اوج دگرگونی مجاورتی با ترکیب معادل کسر مولی دی اکسید کربن برابر ۲٪ بسیار نزدیک بوده است. گرمای اوج دگرگونی برای زون سیلیمانیت در سنگهای رسی ۷۰۰-۷۵۰°C و برای زون وولاستونیت-وزوویانیت در سنگهای کالک- سیلیکات برابر ۶۰۰-۷۰۰°C بوده است.

واژه‌های کلیدی: *سیلیماتیت، کالک سیلیکات، فشار، دما، ترکب سیالات.*

Pressure, temperature and fluid composition in the Kalaybar aureole, NW Iran; Mineral equilibria in metapelitic and calc-silicate rocks

Moazzen, M. and Hajialioghli, R.
Department of Geology, Tabriz University, 51664, Tabriz, IRAN
Email: moazzen@tabrizu.ac.ir

Key words: *pelites, calc-silicate, pressure, temperature, fluid composition, Kalaybar aureole*

Abstract: Intrusion of the Kalaybar nepheline syenite into the Cretaceous pelitic and calcareous sediments has produced a thermal aureole up to 1km thick. Six mineralogical zones are developed in the pelitic rocks with minerals such as cordierite, K feldspar, sillimanite and corundum. Chemically suitable rocks are partially melted in response to the heat from the pluton. Five mineralogical zones are developed in the calc-silicate rocks with minerals such as tremolite, diopside, garnet, scapolite, wollastonie and vesuvianite. A petrogenetic grid was used for pelitic rocks to put constraints on pressure of metamorphism. Intersection of the reaction curves on the grid indicates a pressure of ca. 3 kbar for the contact metamorphism in the Kalaybar aureole. Calculation of the positions of the reaction curves for the calc-silicate rocks assuming unit activity for all phases, and plotting them on T-X_{CO2} diagrams shows that the X_{CO2} is about 0.2 and it is almost independent of pressure. Calculation of the position of the reaction curves assuming dilution of the phases due to solid-solution gives the similar results indicating that the actual composition of the fluid had a X_{CO2} about 0.2 during peak metamorphic condition. The temperature was 700-750°C for sillimanite zone in pelites and 600-700°C for wollastonite-vesuvianite zone in the calc-silicates.

Introduction

Contact metamorphic aureoles are natural laboratories that can demon-strate the phase relations and meta-morphic reactions with little comp-lexity [8]. This is because pressure is almost constant during contact metamorphism, and contact meta-morphic aureoles do not experience complex multiple tecton-othermal events as regional metamorphic rocks. Estimation of pressure of contact metamorphism can provide information about depth of intrusion of plutons which itself can give valuable information about condition of the earth crust during intrusion and contact metamorphism (e.g. [2]). Fluids play an important role in metamorphism and assessing their composition is very important for explaining some aspects of contact metamorphism. Presence or absence of fluids with different compositions, during metamorphism in one hand controls the rate and grade of metamorphism and in other hand influences the phase relations in the metamorphic rocks [2, 12, 18]. Fluids help heat coduction within the thermal aureoles. Differ-ence in permeability of the country rocks may cause disturbances in distribution of metamorphic isograds [8]. The main factors in controlling the composition of fluids are dehyd-ration and decarbonation because of metamorphic reactions, infiltration of an external fluid and exertion of fluids from the crystallising pluton. Study of calc-silicate rocks can help to understand the nature of fluids during metamorphism [18]. The main fluid during metamorphism of pelitic and basic rocks is H_2O whereas the fluids in metamorphism of calc-silicates are H_2O-CO_2 mixture [18]. Pressure and temperature (P-T) of contact metamorphism is addressed in this paper. Mineral equilibria in pelitic and calc-silicate rocks are employed to elucidate the P-T condition of the Kalabar aureole.

Fluid composition during metam-orphism of calc-silicates in the Kalaybar aureole is demonstrated using fluid-present reactions in these rocks. The method of investigation and the results are discussed.

Geology of the studied area

According to the geological subdi-vision of Iran, Kalaybar area is located within the western Alborz-Azarbaijan zone [13]. The oldest rocks in the Kalaybar area are Pre-Cretaceous regionally metamor-phosed rocks with a lithology of phyllite and chlorite schist. Calc-silicate and pelitic rocks of Cretaceous are exposed at the northern and eastern parts of the aureole. Quaternary sediments cover the older rocks. Magmatism in the Kalaybar area can be divided into five main episodes. These are clinopyroxenite Plutonism, Cretace-ous basic volcanics, analcime-bearing tephritic volcanism, neph-eline syenite plutonism and Quaternary basaltic volcanism [1, 3, 10, 20]. The Kalaybar nepheline syenite pluton with an area of about 70 km^2 is the largest feldspathoid-bearing rock body in Azarbaijan and probably in Iran. Intrusion of this pluton is the main cause of thermal metamorphism in the Kalaybar area, which is studied here. This pluton is not homogenous and consists of variety of rocks including nepheline syenite,

syenite, nepheline gabbro, microdiorite, diorite and monzonite [1]. The intrusion of the rocks is related to the Eocene-Oligocene magmatism of Azarbaijan [10]. This intrusion has developed a thermal aureole up to 1km thick in the Cretaceous clac-silicate, pelitic and basic rocks (Fig. 1).

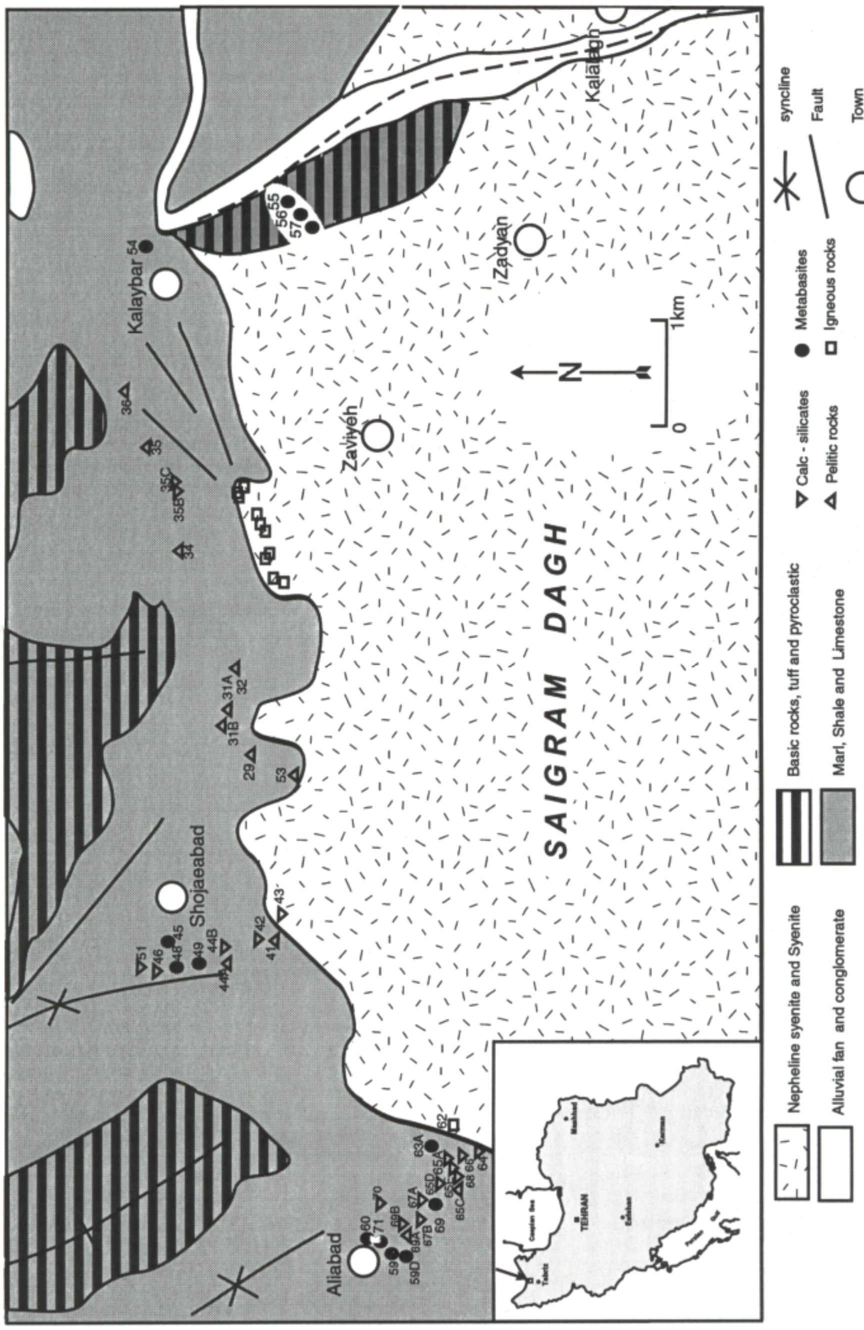

Fig. 1 Geological map of the northern part of the Kalaybar aureole with sample localities.

Metamorphism of the pelitic rocks

Pelitic rocks are the most suitable rock types for metamorphic studies because they are very sensitive to pressure and temperature changes and produce new mineral phases due to changes in the metamorphic grade. Nineteen thin sections from the pelitic rocks within the Kalaybar aureole were studied in detail using, XRD and scanning electron microscope. Fig.1 illustrates the distribution of samples collected from the aureole. The following mineral parageneses were distinguished in the pelitic rocks (all parageneses include plagioclase and ilmenite as non-AFM minerals; abbreviations from Kretz [9]).

Qtz+Chl (1)
Qtz+Chl+Ms (2)
Qtz+Chl+Ms+Bt+Crd (3)
Qtz+Ms+Bt+Crd (4)
Qtz+Ms+Bt+Crd+Kfs (5)
Qtz+Bt+Kfs+Crd (6)
Qtz+Bt+Kfs+Crd+melt (7)
Qtz+Bt+Kfs+Crd+Sil+melt (8)
Bt+Kfs+Crd+Spl+Crn (in quartz absent rocks) (9)
Qtz+Crd+Kfs+Opx+melt (10)

These parageneses can be divided into six main groups. These groups are studied with more details below.

1) Parageneses without biotite and cordierite (unmetamorphosed rocks)

These rocks are fine-grained and dark coloured in hand specimen. There is no thermal effect on the rocks and they are fissile and are consisted of quartz, plagioclase, chlorite, muscovite and graphite.

2) Parageneses with biotite and cordierite

These rocks appear as dark coloured, hard hornfelses in the field and show fine-grained hornfelsic texture under the microscope, occasionally with porphyroblasts of biotite and cordierite in a matrix of fine-grained muscovite, plagioclase and cordierite. Biotite is the first contact metamorphic mineral in the rocks. The modal proportion of chlorite decreases and the modal proportion of biotite and cordierite increases as the distance from the contact decreases (the grade of contact metamorphism ioncreases). The main mineral paragenesis in the lower grade rocks of this category is Qtz+Ms+Bt+Crd. As the grade of metamorphism increases alkali feldspar replaces muscovite and the paragenesis is Qtz+Bt+Crd±Ms+Kfs. Alkali feldspar appears as fine-grained crystals.

3) Parageneses with sillimanite

The main texture of these rocks is porphyroblastic with porphyroblasts of cordierite and sillimanite in a finer ground of quartz, biotite and alkali feldspar. The main paragenesis of the sillimanite-bearing rocks is Qtz+Bt+Crd+Kfs+ Sil.

4) Parageneses with corundum and spinel and without quartz

These rocks show coarse and even-grained textures and appear as xenoliths within the nepheline syenite or very close to the contact. The main minerals are alkali feldspar, cordierite, spinel and corundum. Spinels are green coloured and have hercynitic composition [3].

5) Parageneses with orthopyroxene

These rocks occur in the vicinity of the igneous rocks, at the contact. Cordierite can be distinguished as dark spots on the rocks in the hand specimen. The main texture of the rocks under the microscope, is porphyroblastic with porphyroblasts of orthopyroxene and cordierite. The main paragenesis is Qtz+Crd+Bt+Kfs+Opx+melt.

6) parageneses with melt

Chemically suitable pelitic rocks are partially melted within the Kalaybar aureole [3]. Melted parts include light domains (mesosomes) and dark domains (paleosomes). The main minerals in the mesosome parts are quartz and alkali feldspar with an igneous texture specially interstitial texture of quartz crystals and idiomorph to sub-idiomorph texture of alkali feldspars. Structural characteristics of the light domains (vein and droplet like features), textural differences between light domains and dark domains (light domains have igneous texture whereas the dark domains have hornfelsic texture and existence of granophyric texture within the light domains) and mineralogical compo-sition of the light domain (mainly quartz and alkali feldspar) all agree that the light domains are actually partially melted mesosomes and the dark domains are unmelted paleoso-mes. Mineral parageneses of partia-lly melted rocks are:

Qtz+Kfs+Crd+Bt+melt (11)

Qtz+Kfs+Sil+Crd+Bt+melt (12)

Qtz+Kfs+Bt+Crd±Opx+melt (13)

Table 1 includes mineral assem-blages in the studied pelitic and semi-pelitic hornfelses from the Kalaybar aureole. Considering min-eral parageneses, pelitic hornfelses in the Kalaybar aureole define six mineralogical zones, which are (I) biotite-cordierite zone, (II) and-alusite–K-feldspar zone, (III) sill-imanite zone, (IV) spinel-corundum zone (in the quartz absent rocks), (V) melt zone, and (VI) orthop-yroxene zone. KFMASH minerals in the studied samples from the different zones of the Kalaybar aureole are plotted on the AFM diagrams in Fig. 2. Considering tie line arrangements on these diagr-ams, a set of metamorphic reactions can be written for the pelitic rocks. These reactions are summarised in Table 2.

Metamorphism of calc-silicates

These rocks are fine-grained grey coloured in the Kalaybar aureole. Porphyroblasts of scapolite and garnet can be distinguished in the hand specimens in the rocks close to the contact. The first effect of thermal metamorphism is recrystallisation of calcite grains. Tremolite is developed in the outer aureole, which is replaced by diopside in the higher grades.

Table 1 Minerl assemblages in the pe;itic rocks of the Kalaybar ureole. × = Mjor phase, O = Minor phase, ∗ = XRD, L = Partial melting.

Sample No.	G.R.	Chl	Bt	Ms	Qtz	Crd	Kfs	Sil	Crn	Spl	Opx	L	Pl	Zrc	Tur	Ore	Gr	Apa
RH36	47003851	×			×								O			O	O	
RH26	47033846	×		×	×													
RH69A	46563849	×	×	×	×	×							O	O		O		
RH35	47003851		×	×	×	×								O				
RH67Ab	46563849		×	×	×	×								O		O	O	
RH67Bb	46563849	O	×	×	×	×							O		O	O	O	
RH44A	46573851		×	×	×	×	×						O			O	O	
RH19 ∗	47033846		×		×	×	×						O	O	O	O	O	O
RH65C ∗	46563849		×		×	×?	×											
RH20B	47033846		×		×	×?	×								O	O		
RH34	47003851		×		×	×	×							O	O		O	
RH18B	47033846		×		×	×	×					L	O	O	O	O		O
RH29 ∗	46583851		×		×	×	×	×?					O			O	O	
RH31A	46593851		×		×	×	×	×					O	O	O	O	O	O
RH31B	46593851		×		×	×	×	×					O	O	O	O	O	O
RH32	46593851		×		×	×	×	×				L	O	O	O	O	O	O
RH41 ∗	46573851		×			×	×		×	×			O	O		O	O	O
RH22B	47033846				×	×	×				×?	L		O	O	O		O
RH53 ∗	46583851		×		×?	×	×				×?	L		O		O		

Epidote in low-grade rocks and anorthitic plagioclase in the higher-grade rocks are other minerals. Garnet appears as isotropic minerals both in form These rocks are fine-grained grey coloured in the Kalaybar aureole. Porphyroblasts of scapolite and garnet can be distinguished in the hand specimens in the rocks close to the contact. The first effect of thermal metamorphism is recry-stallisation of calcite grains. Trem-olite is developed in the outer aureole, which is replaced by diopside in the higher grades. Epidote in low-grade rocks and anorthitic plagioclase in the higher-grade rocks are other minerals. Garnet appears as isotropic minerals both in form of bands and as idioblastic crystals. Fig. 3 illustrates Back Scattered Electron images (BSE) from garnet, pyroxene and anorthite in the Kalaybar calc-silicates. Semi-quantitative analyses of the minerals using an EDS analyser, combined with SEM, indicates that garnets are mainly grossularite-rich, pyroxenes are essentially diopside, plagioclases are An-rich and scaploites are meionite-rich. As it is clear from these images, none of the minerals shows compositional zoning. Scapolite shows poikiloblastic texture with inclusions of calcite, garnet and diopside. Wollastonite is formed in the rocks close to the igneous contact and has an acicular to tabular texture Vesuvianite (idio-crase) app-ears in the rocks adjacent to the contact. Quartz is present almost in all studied calc-silicates. The main mineral assemblages in the calc-silicates of the Kalaybar aureole are as follows (abbreviations from Kretz [9]:

Cal+Qtz+Ep (14)

Cal+Qtz+Ep+Tr (15)

Table 2 metamorphic reaction pelitic rocks. Mineral assemblages are shown with regular font and reactions are shown in bold. Non-AFM minrals (e.g. plagioclase) are not include.

Mineralogical Zones	Metamorphic assemblages and reaction	Lihology
Ms Zone	Qtz+Chl+Ms	**Quartz-bearing rocks at all grades**
Bt Zone	Qtz+Chl+Ms+Bt+Crd Qtz+Ms+Bt+Crd	
	Ms+Chl+Qtz=Crd+Bt+H_2O	
Kfs Zone	Qtz+Bt+Kfs+Crd	
	Ms+Bt+Qtz=Kfs+Crd+H_2O Qtz+Bt+Kfs+Crd+L **Crd+Kfs+Qtz+H_2O=L**	
Sil Zone	Qtz+Bt+Crd+Kfs+Sil	
	Ms+Qtz=Kfs+Als+H_2O **Sil=And** **Bt+Sil+Qtz=Crd+Kfs+L** **Qtz+Kfs+Crd+Sil+H_2O+L**	
Opx Zone	Qtz+Crd+Kfs+Opx+L	
	Qtz+Bt+H_2O=Opx+L **Qtz+Bt=Opx+Kfs+Crd+L**	
Spl-Crn Zone	Crd+Bt+Kfs+Crn+Spl	**Quartez-absent rocks at high grades**
	Bt+Sil=Spl+Crn+Crd+Kfs+H_2O	

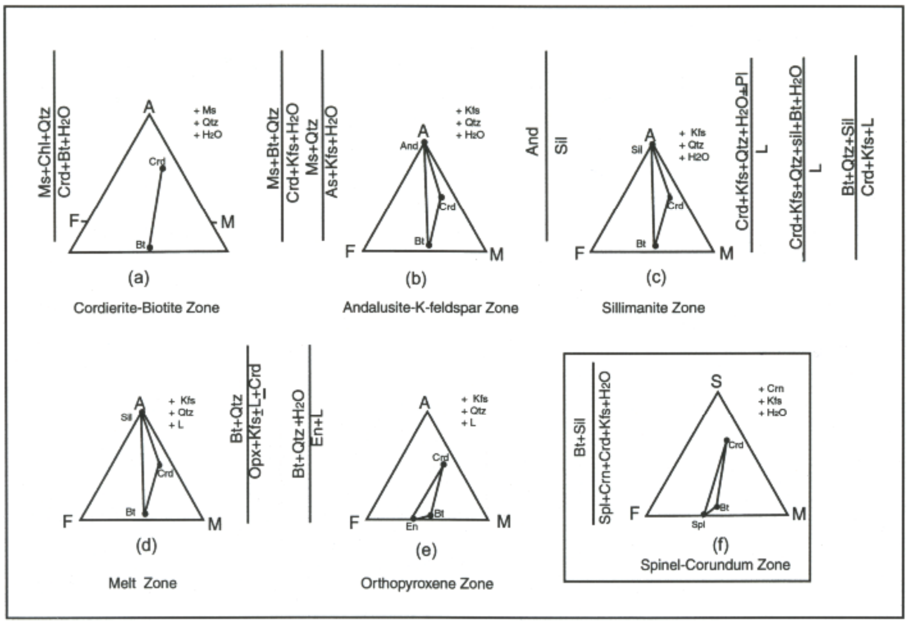

Fig 2 Phase relations and metamorfic reaction for pelitic rocks of the Kalaybar aureole. SFM diagram is used for quartz-bsent rocks.

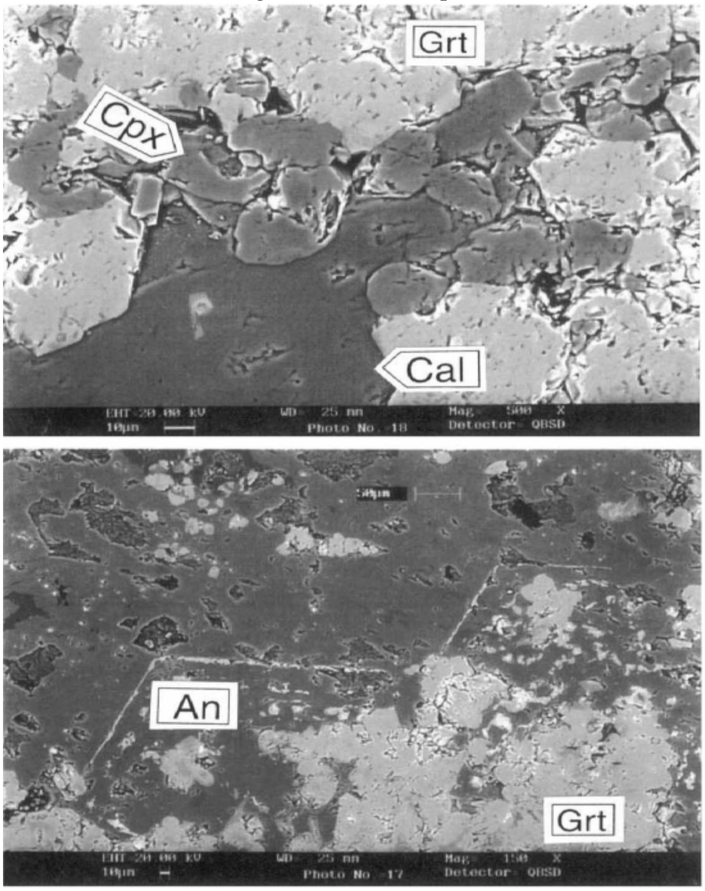

Fig 3 Back scattered images from calc-silicates of the kalaybar aureole. a) Minerals in sample RH64, garnet (Grt), clinopyroxene (Cpx) and clacite (Cal). b) Minerals in sample RH42, Garnet (Grt) and anorthite (An).

Cal+Qtz+Cpx (16)
Cal+Qtz+Cpx+Pl (17)
Cal+Qtz+Cpx+Grt (18)
Cal+Qtz±Grt+Scp (19)
Cal+Qtz+Cpx±Grt+Scp (20)
Cal+Qtz±Pl+Cpx+Grt+Scp (21)
Cal+Qtz+Cpx+Scp+Ves+Wo (22)
Cal+Qtz±Pl+Cpx+Grt+Wo+Scp (23)

Table 3 includes the mineral assemblages in the studied calc-silicates. These mineral assemblages define five mineralogical zones in the calc-silicates, which are: (I) epidote-tremolite zone, (II) diopside zone, (III) garnet-scapolite zone, (IV) wollastonite zone and (V) wollastonite vesuvianite zone. Fig. 4 illustrates the mineral parageneses in the calc-silicates from the kalaybar aureole plotted on the ACM diagram indicate a set of metamorphic reactions, witch are summarised in table 4.

Table 3 Mineral assemblages in the calc-silicate rocks of the Kalaybar aureole. × = Major phase, ○ = Minor phase, ⊗ = Xenolith in the igneous rocks, ∗ = Analysed by XRD, • = Studied by SEM.

Sample No.	G.R.	Dol,Cal	Qtz	Pl	Cpx	Grt	Wo	Scp	Ves	Ep	Tr	Zrc	Ttn	Ore	Gr
RH74B	46563849	×	×							×	×	○		○	
• RH42	46573851	×	×	×?	×	×	×	×						○	
RH25	47033846	×	×							×		○			○
RH22D	47033846	×	×		×	×						○			
RH35B	47003851	×	×		×	×		×					○	○	
RH35C	47003851	×	×		×	×		×					○		
RH43A∗⊗	46573851	×	×	×?	×	×		×				○			
RH44Bb	46573851	×	×		×										○
• RH64	46563849	×	×		×	×	×	×		○				○	
RH65D	46563849	×	×		×			×				○	○		
RH66 ∗	46563849	×	×		×		×	×	×	○		○			○
RH67A	46563849	×	×	○	×?					×			○	○	
RH67B	46563849	×	×	○	×?					×			○		
RH68 ∗	46563849	×	×	×	×	×	×	×							
RH69B	46563849	×	×		×										

Geothermometry, geobarometry and X_{CO2} calculations

In order to estimate the pressure and temperature of contact metam-orphism, and calculation of fluid composition (X_{CO2} and X_{H2O} in the fluid), mineral equilibria approach was applied to the pelitic and calc-silicate rocks of the Kalaybar aureole.

Estimation of pre*ssure using the pelitic rocks:*The estimation of pressure of contact metamorphism was carried out in the pelitic rocks using a petrogenetic grid. There are three possible melting reactions for the pelitic rocks, which are labeled as reactions 2, 5 and 6 on the petrogenetic grid presented in Fig. 5. Reaction 2 is proposed by Tuttle and Bowen [19], reaction 5 is studied by Seifert [16] and reaction 6 is suggested by Shaw [17]. These melting reactions intersect two other reaction curves on the grid (reactions 3 and 4), which their position on the P-T grid is calculated by the means of THERMOCALC software [6, 7, 14]. These reactions are confirmed by mineral parageneses and AFM diagrams (Table 2 and Fig. 2). All melting reactions occur in the sillimanite zone of the Kalaybar aureole (marked with small arrows on the Ky = Sil and And = Sil curves on Fig. 5). The positions of aluminosilicate reaction curves are calculated using THERMOCALC. Also position of the curves proposed by Holdaway [4] and Richardson et al. [15] are provided for comparison. Interse-ction of curves 3, 4, 5 and 6 on the P-T grid of Fig. 5 indicates a pressure of ca. 2.5 –3 kbars for the Kalaybar aureole. This pressure is marked with a large arrow on Fig.5 (pressure is constant during contact metamorphism). Because of errors

Table 4 Metamorphic reactions in calc-silicates oh the Kalaybar aureole.

Metamorphics grade	Mineralogical Zone	Metamorphic assemblages and reaction
Low	Epidote-tremolite Zone	Cal+Qtz+Pl+Ep Cal+Qtz+Tr+Ep
		Chl+Cal+Qtz=Tr+Ep+H_2O+CO_2 **Cal(Dol)+Qtz+H_2O=Tr+Cal+CO_2**
Medium	Diopside Zone	Cal+Qtz+Ep+Cpx Cal+Qtz+Cpx+Pl
		Ep+CO_2=An+Cal+H_2O **Tr+Cal+Qtz=Dol+Di+CO_2+H_2O**
	Garnet-scapolite Zone	Cal+Qtz+Cpx+Grt+Scp
		An+Cal+Qtz+Di=Grt+CO_2 **Cal+An+Qtz=Scp**
High	Wollastonite Zone	Cal+Qtz+Cpx+Pl+Wo+Scp+Grt
		Grt+Cal+Qtz=Scp+Wo **Grt+Qtz=An+Wo** **Qtz+Scp=Wo+An+CO_2**
	Wollastonite-vesuvianite Zone	Cal+Qtz+Cpx+Ves+Wo+Scp
		Di+Grt+Cal+H_2O=Wo+Ves+CO_2

in thermodynamic data used for construction of the internally consistent thermodynamic dataset [6], the concluded pressure is subjected to about ±1 kbar uncertainty.

Estimation of X_{CO2} and temperature using calc-silicate rocks. In order to undertake geothermometry and X_{CO2} calculations, multiple equilibrium approach was employed. Sample RH68 from the calc-silicates of the Kalaybar aureole contains the largest number of minerals in textural (and thermodynamical) equilibrium (paragenesis 22). Three or four reactions can be written for the end-members of these minerals (depending on T-X_{CO2} window). The reactions, which are determined using THERMOCALC are as follows:

Cal+Di+Wo+Scp+H_2O = Ves+CO_2 (a)

Cal+Qtz+Di+Scp+H_2O = Ves+CO_2 (b)

Cal+Qtz = Wo+CO_2 (c)

Qtz+Ves+CO_2 = Di+Wo+Scp+H_2O (d)

Assuming unit activity for all end-members, the positions of the equilibrium curves for the above reactions were calculated for three nominal pressures 2, 4 and 6 by THERMOCALC. The results are plotted on T-X_{CO2} diagram in Fig. 6. As it is obvious from this figure, intersection of the equilibrium curves defines the X_{CO2}. The X_{CO2} is about 2.5 and it is almost independent of pressure (i.e. in all three pressures the X_{CO2} is about 2.5). Microprobe analyses of phases in calc-silicates of Kalaybar aureole are not available, therefore the calculation of the exact activities of the end-members is not possible. Among the phases in sample RH68, clinopyroxene and scapolite may show solid-solution. The positions of the reaction curves were calculated for diopside activities of 0.8 and 0.5 and scapolite activities (meionite) of 0.8 and 0.5 at pressure of 3 kbar.

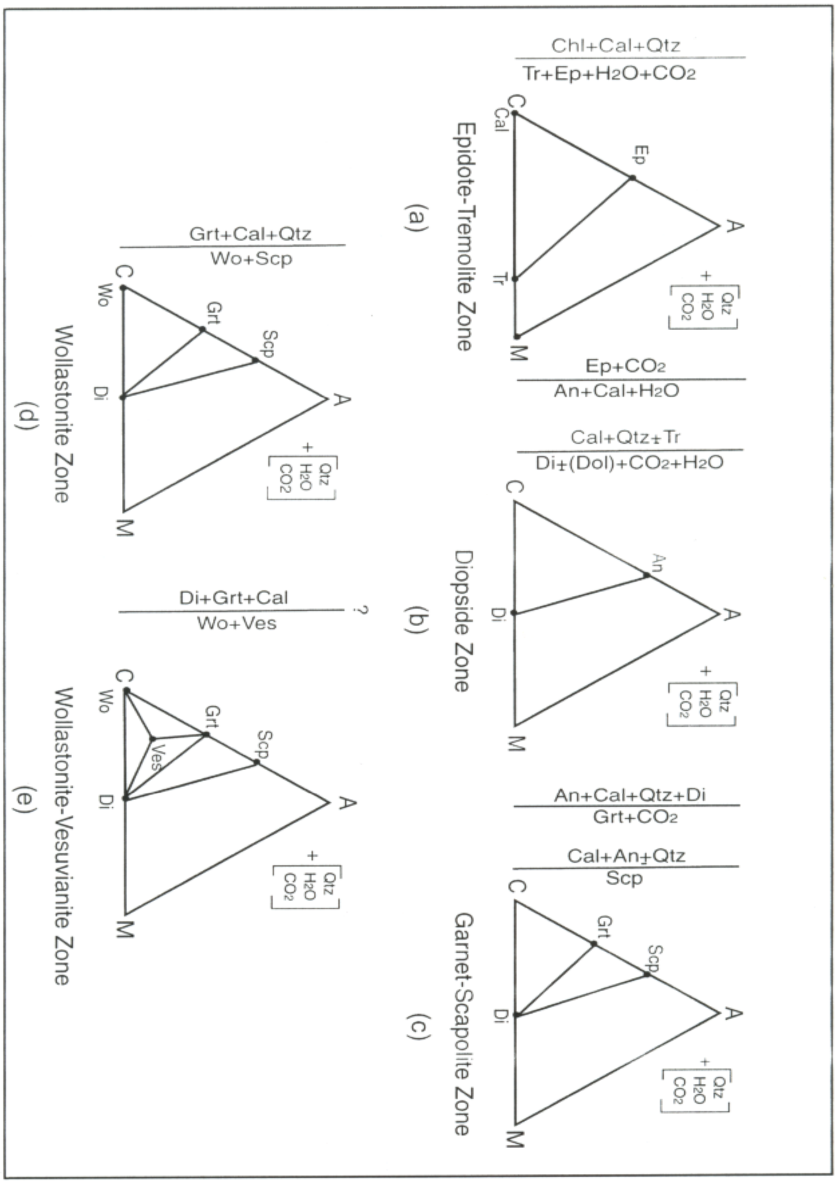

Fig 4 Phase relation and metamorphic reaction for calc-silicates of the Kalaybar aureole.

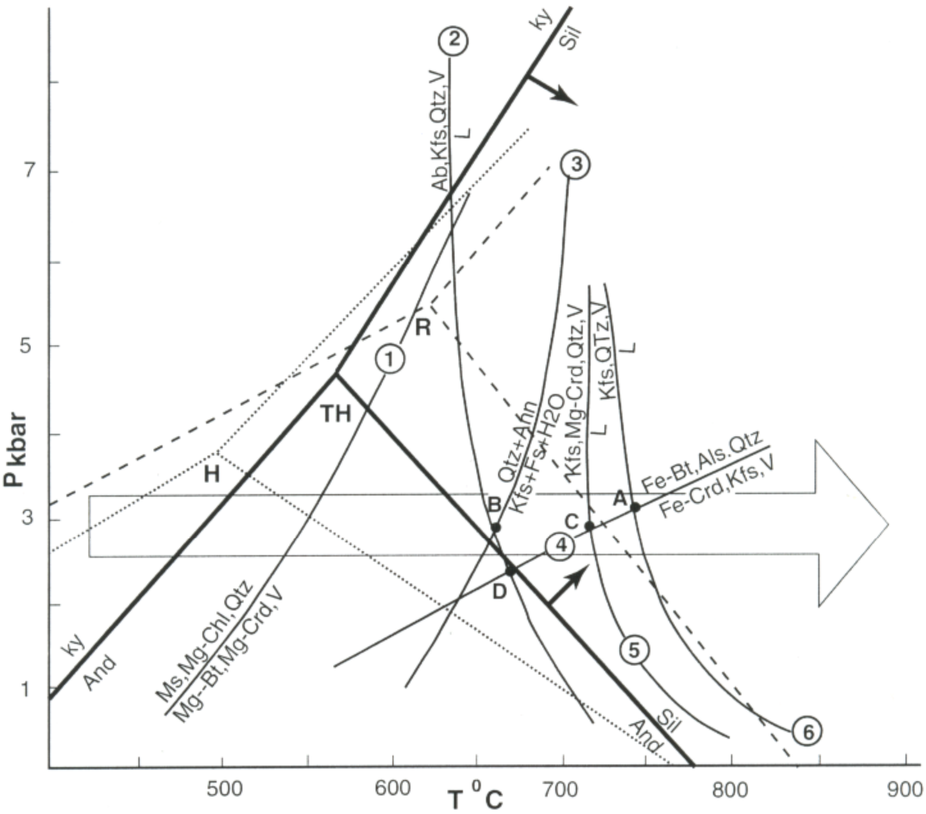

Fig 5 Estimation of presure of contact metamorphic in the Kalaybar aureole using petrogenetic. The pressure is about 3 kbars.

H: Holdaway (1971); R: Richardsonet al., (1969); TH: THERMOCALC (version 4.2);

(1): Seifert (1970); (2):Tuttle and Bowen (1958); (3): Thermocalc (version 4.2); (4): Holdaway and Le (1977); (5): Seifert (1976); (6): shaw (1963)

Fig. 7 illustrates the results. In both cases (a_{Di} = 0.8 and 0.5; a_{Mie} = 0.8 and 0.5) the X_{CO2} is about 0.2, which is very close to the mole fraction calculated for pure phases (unit activities). The temperature for sample RH68 is 650-700ºC. temperature for sample RH68 is 650-700ºC.

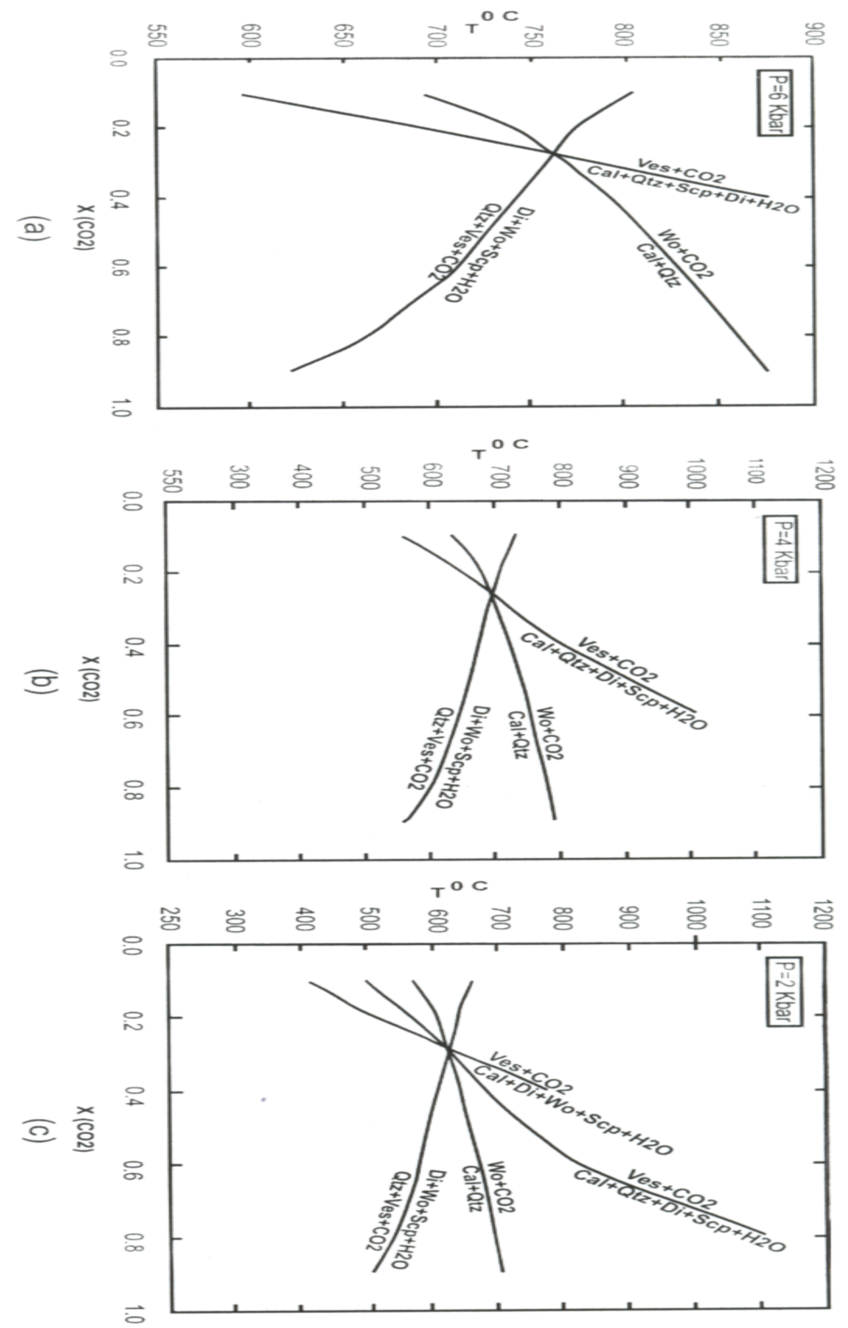

Fig 6 Estimation of X_{CO2} and temperature of metamorphism in wollastonite-vesuvianite zone of the Kalaybar aureole (Sample: RH68). The equilibrium curves for the reactions intersect at X_{CO2} about 0.25, witch is independent of pressure. Assuming a pressure of 2-4 kbars, the temperature for this zone is 600-700°C.

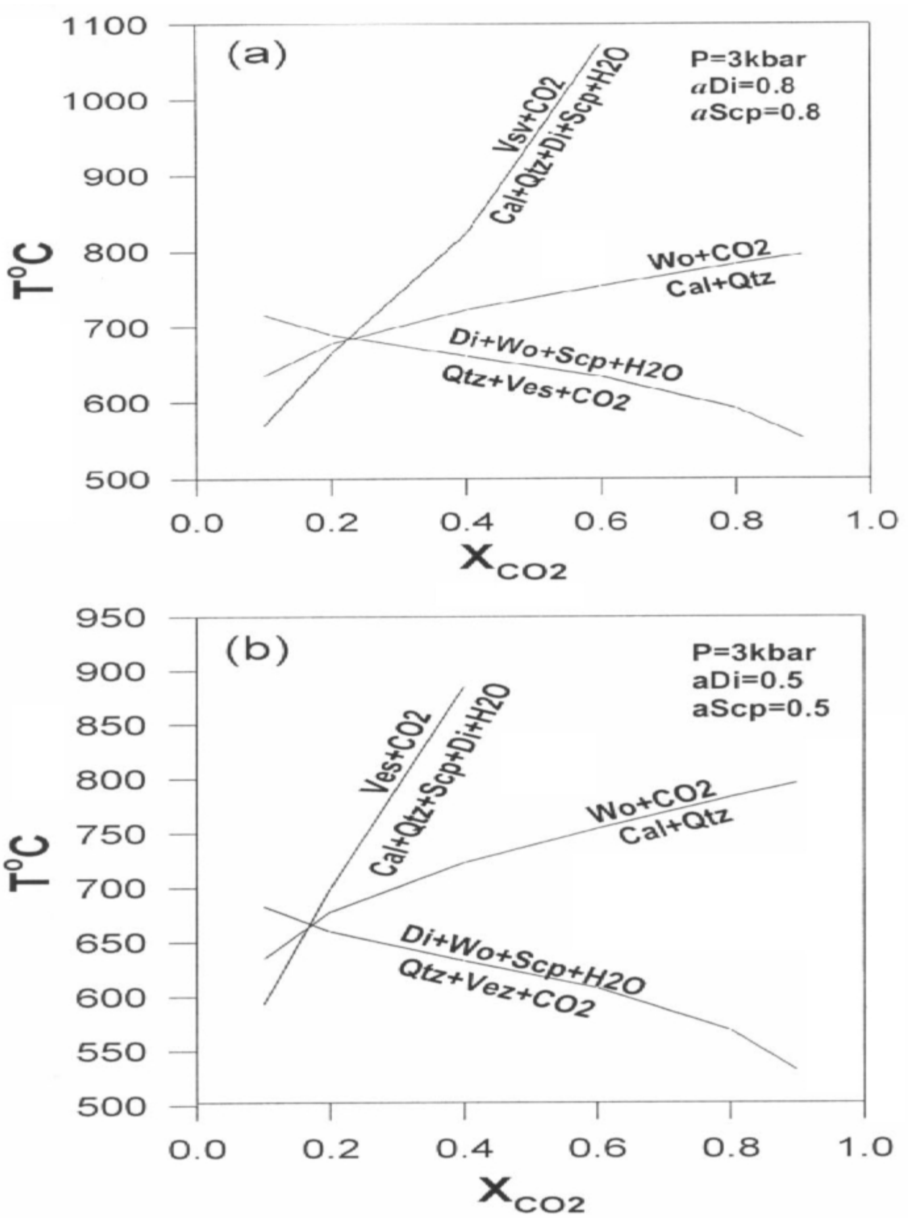

Fig 7 Estimation of X_{CO2} and temprature of metamorphism in wollastonite vesuvianite zone at 3 kbar asuming activity of 0.8 for diopside and scapolite (a) and activity of 0.5 for diopside and scapolite.

Conclusions and discussion

The pressure of contact metam-orphism in the Kalaybar aureole was calculated by means of petrogenetic grid and multiple equilibrium approach. The estimated pressure is ca. 3 kbar. This pressure is equi-valent to 9 km depth of burial. The possible error is ±1 kbars, which corresponds to ±3 km depth. The maximum temperature estimated here is 700-750ºC. The stimated temperature has a local significances because the thermal gradient in a contact aureole is very steep but the calculated pressure has a regional importance indicating that either the thickness of the continental crust in the Kalaybar aureole was about 9km during the emplacement time or there has been a tilting during the intrusion of the pluton i.e. the contact exposed in the northern part of the aureole (where the pressure estimation is done) have been deeper than contacts at the southern part. More studies are required to elucidate this point.

Considering mineral assemblages in the studied rocks, it is very likely that fluids during contact metam-orphism were of a binary composition of H_2O-CO_2. Absence of volumetric amounts of graphite and absence of Cl and F-bearing minerals demonstrate that other fluid species were not present in contact metamorphic processes in the Kalaybar aureole. Occurrence of paragenesis Cal+Qtz+Cpx+Scp+Ves+Wo in the Kalaybar aureole, defines a X_{CO2} about 0.2. In other words the fluid was rich in H_2O (X_{H2O} = 0.8). This finding has important applications in further studies on nature of contact metamorphic reactions (fluid-present or fluid-absent) and on nature of partial melting processes within the Kalaybar aureole.

Acknowledgements

We thank Dr. Kianvash from Faculty of Engineering, Tabriz University for his help in SEM studies. Comments of two anon-ymous referees of the Iranian Journal of Crystallography and Mineralogy improved the manuscript. This paper is a part of M.Sc. thesis of R. Hajialioghli and she thanks the Higher Education Department of the Tabriz University for financial supports during the course of this study.

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