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Estimation of Pressure and Temperature of Intrusive Rocks Crystallisation: A Case Study of Naqadeh, Pasveh and Delkeh Plutons, W Iran

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Abstract: The Naqadeh, Pasveh and Delkeh plutons of North Sanandaj-Sirjan Zone, W Iran, are medium to high potassium calc-alkaline intrusive rocks composed of mafic and felsic rocks. Six samples were selected as representative of different units of these plutons for estimation of pressure and temperature of magmatic crystallisation. Al-in-hornblende barometry and crosstie contents of amphiboles suggest <4.5 kbar (1.6-4.5 kbar) pressure for emplacement depth of intrusives. Different thermometer methods indicate various stages of magmatic evolution from near liquidus to sub-solidus temperatures. The highest temperature resulted from orthopyroxene-clinopyroxene solvus thermometry which is more than 1100°C, reflecting initial crystallisation of pyroxene from dioritic magma. Hornblende-clinopyroxene thermometry show another hyper-solidus crystallisation phase during magmatic cooling. The temperature come from hornblende-plagioclase thermometer (695-760°C) probably refer to late stage crystallisation of the magma near solidus condition. Calculated temperature of feldspar thermometry show scatter results (281-1086°C) implies sub-solidus re-equilibration of the feldspar during magmatic and post-magmatic evolution.

Key words: Naqadeh, Pasveh, Delkeh, Sanandaj-Sirjan zone, thermometery, barometery, pluton

INTRODUCTION

Determination of pressure and temperature of a pluton has an important role in the definition of petrogenesis history and regional tectonism. Common procedure for retrieval physical conditions relates to application of thermobarometric mineral equilibrations. Unfortunately, use of this way for intrusive rocks is difficult. Igneous minerals crystallise over a range of P-T conditions and remain in contact well into subsolidus realm, there can be no assurance that mineral phases have locked in solidus compositions. It would be rare to find a granitic rock, for example, that did not have compositionally zoned minerals and much of the zoning can be related to mineral growth above the solidus. Other minerals easily change their compositions during subsolidus cooling. Therefore, petrologists should be careful to interpret resulted data of mineral equilibration in plutonic rocks. How accurate any one thermobarometer measures solidus conditions remains an open question. Thus it should be clear that researchers should use different thermometers to assess the crystallisation temperatures of magmas. It should also be recognized that a given thermobarometer may be providing information about only a portion of liquidus to subsolidus temperature range experienced by a pluton. Most studies emphasis on limited thermobarometers, for example Stone (2000) used only Al-in-hornblende method. Anderson (1996) presented a summary about various thermometry methods capability in granitoid rocks and Moazzen and Droop (2005) considered application of mineral thermobarometers for Etive complex, W Scotland. In this paper is tried to assess crystallization conditions of calc-alkaline plutons of Naqadeh, Delkeh and Pasveh in Sanandaj-Sirjan zone, W Iran. For this target, new mineral composition data for these plutons are presented and temperature and pressure of crystallisation are estimated by different published thermobarometric methods and finally mineral crystallisation revolution from liquidus to sub-solidus have been deduced.

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GEOLOGICAL BACKGROUND AND FIELD RELATION

The Zagros orogen, which resulted from the opening and closure of the Neo-Tethys Ocean, consists of three NW elongated parallel tectonic zones (Alavi, 1994), which from the Arabian Plate to Central Iran are: (1) the Zagros Simply Folded Belt, to the SW (2) the Sanandaj-Sirjan Zone (SSZ), in the middle (3) the Urumieh-Dokhtar magmatic arc, to the NE (Fig. 1). The Sanandaj-Sirjan Zone consists of staked metamorphosed and non-metamorphosed Phanerozoic materials of the Afro-Arabian passive continental margin, some obducted ophiolites and numerous granite plutons of different sizes and composition.

The age, nature and origin of these plutons are still poorly known, despite they can provide important information about the geological history of the zone. Until the present, it is generally believed that they mostly consist of arc-related calc-alkaline granitoids formed during the subduction of Neo-Tethys to Iranian plate (Sepahi Garow, 1999; Ghalamghash, 2002; Ahmadi Khalaj *et al*., 2006). Nonetheless, our studies in the Northern part of the Sanandaj-Sirjan Zone reveal a more complicated picture, because the age of intrusive bodies spans from ca. 300 Ma to ca 40 Ma (Unpublished data).

Calc-alkaline granitoids are spread in all of the north SSZ and spans from Jurassic to Paleocene (Valizadeh and Cantagral, 1975; Ghalamghash, 2002; Ahmadi Khalaj *et al*., 2006). This study considers 3 plutons of North Sanandaj-Sirjan zone located between 45°17′-45°30′ E and 36°40′-36°55′ N and have ca. 109Ma age (Rb-Sr dating, unpublished data of the authors). Country rocks are sedimentary rocks related to different times (Fig. 2) and involve Permian limestone and dolomite

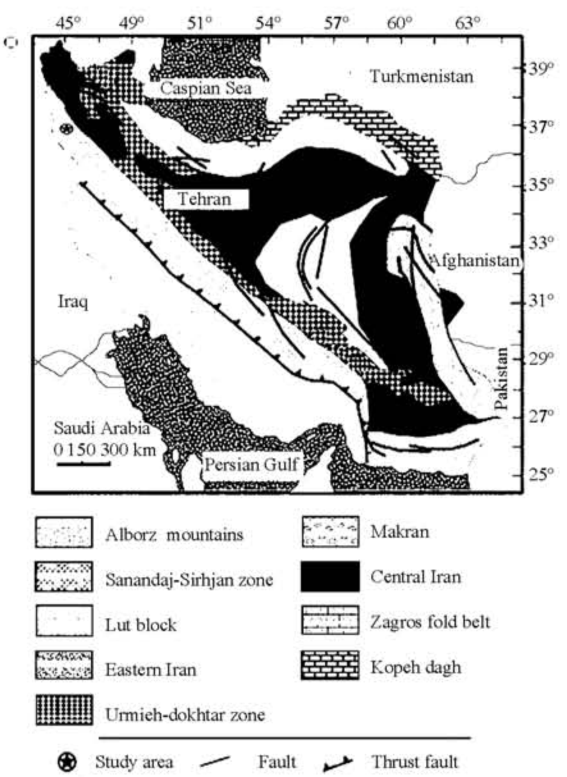

Fig. 1: Geological map of Iran which defines Sanandaj-Sirjan zone and study area with respect to major tectonic units (modified after Stöcklin and Setudinia, 1972)

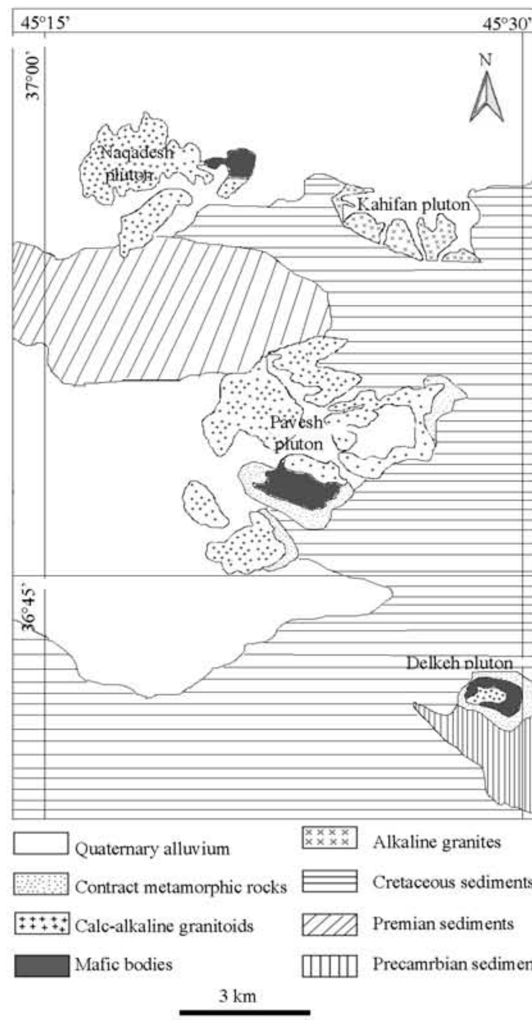

Fig. 2: Simplified geological map of study area. Khalifan pluton is an A-type granitic pluton with different age (275 Ma) and other petrogenetic conditions (unpublished data of the authors) that won't be discussed in the study

in Naqadeh pluton, Precambrian deposits in Delkeh pluton and Cretaceous formation (includes carbonate, shale andesite and related tuffs) that compose broader lithological unit in the whole region. They are high to medium-k calc-alkaline (unpublished data of the authors) similar to other calc-alkaline plutons in Sanandaj-Sirjan zone and consist of two distinct intrusive rocks of felsic and mafic. Interaction zones between these two phases are clear and there are a lot of enclaves especially MMEs that can be seen in more mafic sections of felsic rocks. The volume of mafic rocks is minor except of Delkeh pluton that is a small body with major mafic constitutes (Fig. 2). Aplitic and evolved granitic dikes and veins cross some occurrences of these bodies and magmatic or structural foliation is absent. In spite of some alteration areas, most of intrusive rocks are fresh and it is possible to get profit samples for petrologic studies.

PETROGRAPHY

As it is mentioned earlier, Naqadeh, Pasveh and Delkeh plutons are composed of two distinct zones of felsic and mafic rocks. Felsic rocks have broad petrographic range of diorite-quartz diorite-granodiorite and granite (hereafter are called granitoids) and mafic rocks in Naqadeh and Delkeh plutons are restricted to monzodiorite-diorite and quartz diorite (named as diorites), but Pasveh complex has cumulate gabbroic rocks with >80% modal diopside+ plagioclase. There is not any sign of mineral preferred orientation or deformational textures in these intrusives. Textural and mineralogical features of these plutons are discussed below in three categories: granitoids, Naqadeh diorites and Pasveh gabbros.

Granitoids: These rocks have equigranular texture (Fig. 3a) but some samples, especially in Delkeh pluton, are porphyritic (Fig. 3b). They are massive medium to coarse grained (1-5 mm diameter) rocks which are composed mainly of quartz (3-20% modal), plagioclase (10-60), K-feldspar (5-55), biotite (3-25) and amphibole (0-30). Modal difference of these major minerals causes the variation of petrographic and chemical composition in different granitoid rocks and yields the range of diorite to granodiorite and granite. Amphibole is the major mafic mineral in diorites and quartz diorites; the abundance of amphibole and biotite is relatively equal in granodiorites, but amphibole is absent in the more evolved biotite granites. Plagioclase occurs as prismatic, euhedral to subhedral phenocrysts, ~1-2 mm long (some examples are up to 2.5 mm long). Except of more felsic biotite granites, large plagioclase crystals show oscillatory and discontinuous zoning. K-feldspar occurs in some samples as subhedral phenocrysts but usually show interstitial texture along with quartz. Abundance of K-feldspar and quartz increases in more evolved rocks. Biotite occurs as euhedral to subhedral crystals, generally less than 2 mm long. They show red-brown pleochroism. Amphiboles are euhedral to subhedral and zoning and twinning are not observed under polarized light. Clinopyroxene appears as minor mineral in some samples that rimmed by amphibole (Fig. 3c) or occurs as relicts that exhibit exsolution texture of clinopyroxene (Cpx) and orthopyroxene (Opx) (Fig. 3d). Other minor minerals in granitoids include ilmenite, magnetite, titanite, apatite, zircon and rarely allanite, thorite and monazite. There are a lot of enclaves in granitoids which are more frequent in the quartz diorites and granodiorites. Most of enclaves are fine grained which appears as MMEs (mafic microgranular enclaves, Fig. 3e) or fine grained enclaves with similar composition of host granite. MMEs consist of 80-90 % amphibole+ biotite with plagioclase and rare pyroxenes that K-feldspar and quartz filled matrix as interstitial texture. Nevertheless, some enclaves have the same size and composition of host granitoids.

Naqadeh and delkeh diorites: Major mineral constituents in dioritic rocks are plagioclase (25-45% modal), clinopyroxene (10-25), biotite (3-10), K-feldspar (2-10) and amphibole (2-8). Different percentage of these minerals results in various rocks for this phase. K-feldspar and quartz are rare in diorites which increase their modal percentage in monzodiorite and quartz diorites. Modal volume of quartz never exceeds 5%. Plagioclase is the main mineral and occurs as normal and oscillatory zoning. They are euhedral to subhedral and unzoned crystals can be occurred, too. Pyroxenes exist as subhedral to anhedral in the forms of clinopyroxene and orthopyroxene (Fig. 3f). Amphibole is formed as haloes around pyroxene (magnesio-hornblendes) or resulted by subsolidus reactions (actinolites). Minor minerals include titanite, ilmenite, magnetite, apatite and pyrite.

Pasveh gabbros: These gabbros are cumulative rocks composed of Cpx and plagioclase. Plagioclases are large euhedral to subhedral phenocrystals with labradorite-bitonite composition. Clinopyroxene appears as large anhedral grains or interstitial texture. There are two different types Cpx in gabbros: (1) high Ti diopside and (2) low Ti diopside. Textural relations suggest that high Ti diopside is replaced by low Ti diopside and pargasitic amphibole. Low Ti Cpx has light colour while high diopsides have pink appearance. Amphiboles are brown

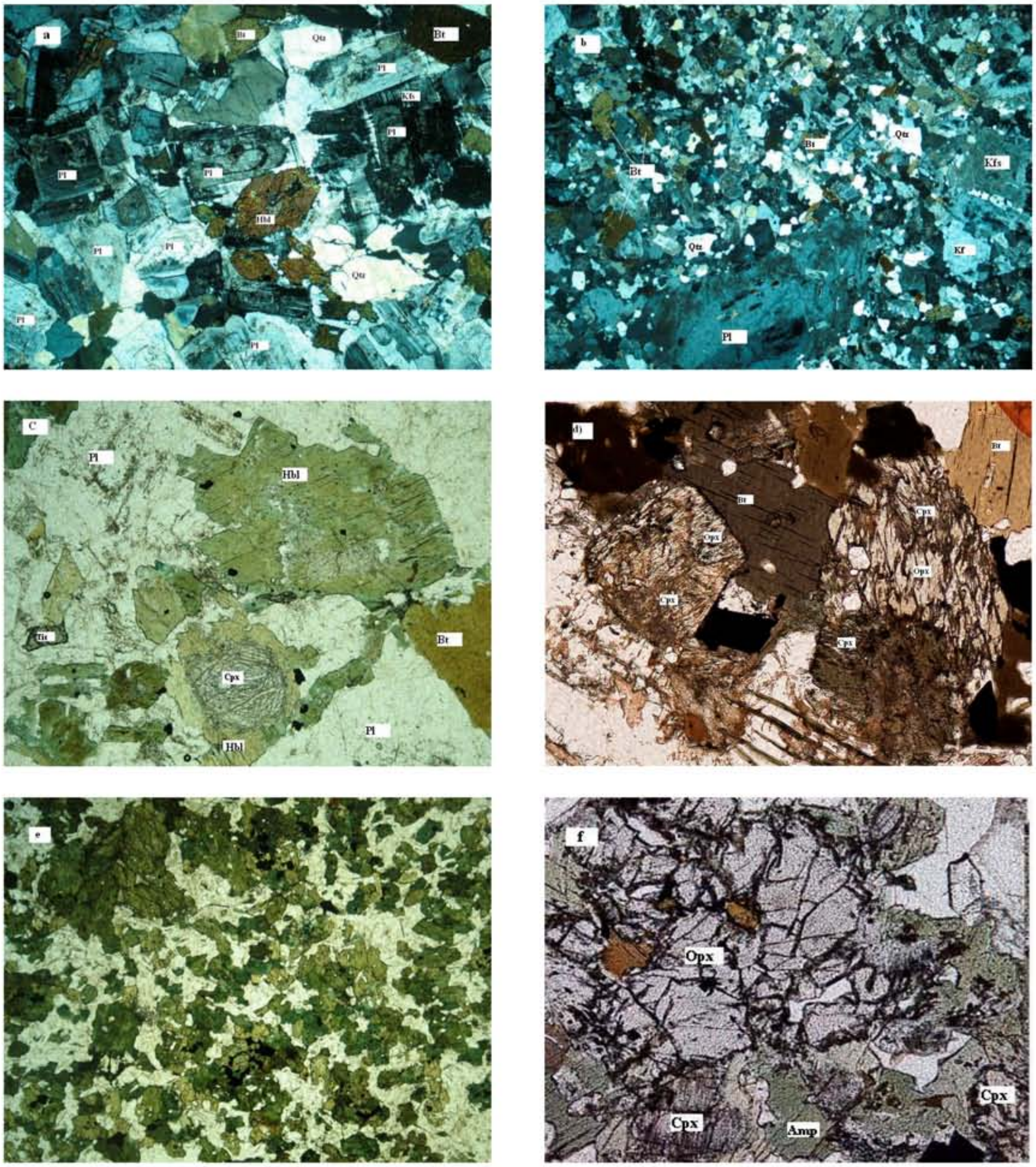

Fig. 3: a: Hornblende granodiorite of Naqadeh pluton includes hornblende, plagioclase, quartz, biotite and K-feldspar, XPL

b: Porphyritic texture in biotite granite of Delkeh. Feldspar porphyric crystals in the groundmass of grained quartz and biotite, XPL

c: Clinopyroxene enclosed by amphibole in quartz monzonite of Pasveh pluton, PPL

d: Exsolution texture of Opx and Cpx in the relict crystals of Delkeh granite, PPL

e: Mafic microgranular enclaves (MMEs) in Pasveh quartz diorite consist of high content amphibole and biotite in the matrix of feldspars, PPL

f: Cpx+ Opx in dioritic gabbros. Amphibole forms haloes around pyroxenes, PPL, base of photo in all pictures is 12 mm except (f) Which is 6 mm. Mineral name abbreviations from Kertz (1983) clots surrounded by low Ti pyroxenes. Pasveh gabbros don't have amenable mineral composition to apply for thermobarometric estimation. Therefore, they won't consider in next sections.

SAMPLE SELECTION AND MINERAL CHEMISTRY

Six fresh samples from intrusive rocks were chosen for mineral chemistry studies. These samples are also representative of plutonic rocks in this area. Pasveh gabbros don't consider because applicable mineral assemblage for thermobarometric equations are absent in these rocks. Table 1 present mineral assemblage and modal percentage of the selection samples. The samples of N24, N41 and N54 are granites of Pasveh, Naqadeh and Delkeh plutons, respectively. N1 and N18 represent granodiorite and quartz-monzonite of granitoid plutons of Naqadeh and Pasveh. Sample of N56 is selected as representative of mafic rocks and petrographically named as monzodiorite. Furthermore, this sample can be used for two-pyroxene thermometry. Minerals were analysed in Granada University by wavelength dispersive analyses with a CAMECASX100 electron microprobe. Accelerating voltage was 20 kV and beam current was 20 nA. The precision was close to ±4% for an analyte concentration of 1 wt. %. Summary of these data is discussed below:

Feldspar: All of selected samples have fresh feldspars and alteration effects are rare. Optically defined plagioclase crystals in each sample were analysed for compositional zoning and construction of the zoning profiles. Representative analyses of feldspars are brought in Table 2 and are plotted in Or-Ab-An diagram (Fig. 4a). According to this data almost all of plagioclases are poor in orthoclase component and have composition between An_8 to An_{50} in granitoids and An_{26} to An_{79} in monzodiorite. K-feldspar crystals are poor in anorthite component in granitoids (Or_{88}-Or_{92}), except in the monzodiorite sample of N56 (An_{15-20} Ab_{38-44} Or_{35-43}). The microprobe data show oscillatory and discontinuous zoning in granitoids and normal and oscillatory zoning in the mafic rock.

Amphiboles: Table 3 presents representative amphibole analyses of different rocks in Naqadeh, Delkeh and Pasveh plutons. There is not clear compositional zoning in amphibole crystals. Amphiboles are calculated by the method of Leake *et al*. (1997) on the basis of 46 negative charges assuming 23 atoms of oxygen and a combined total of 2 OH, F and Cl anions [23O+ 2(OH+F+Cl)]. Fe^{3+} and Fe^{2+} are determined by 13eCNK method. With this method, the number of cations is calculated on the basis of 46 negative charges with the added constraints that the sum of Si+Al+Ti+Cr+Fe+Mn+Mg is 13. All of amphiboles have $(Ca+Na)_B>1$ and $Na_B<0.50$, so classified as calcic amphiboles. According to calcic subgroup classification (Leake *et al*., 1997), amphiboles are magnesiohornblende except the sample of N24 which lies in the ferrotschermakite area (Fig. 4b).

Pyroxenes: Representative analysed pyroxenes presented in Table 4. These analyses were done on three samples: N18, N54 and N56. According to the classification of Morimoto (1989), these pyroxenes are diopside with relatively high Wo component (X_{Wo}=0.4-0.48, Fig. 4c). Monzodiorite sample of N56 includes both of Opx and Cpx. Opxs are enstatite and Cpxs have diopside-augite composition (Fig. 4c).

Table 1: Modal composition of selected samples from studied plutons

Sample ID	N1	N18	N24	N41	N54	N56
Rock type	Granodiorite	Quartz monzonite	Granite	Granite	Granite	Monzodiorite
Pluton name	Naqadeh	Pasveh	Pasveh	Naqadeh	Delkeh	Delkeh
Quartz	20.0	5	20	25.0	24.0	2
Plagioclase	33.0	32	23	22.0	21.0	37
K-feldspar	12.0	24	35	30.0	37.0	10
Amphibole	15.0	24	2	15.0	0.7	5
Biotite	18.0	11	18	5.0	11.0	7
Clinoyroxene		2			1.0	20
Orthopyroxene					2.0	16
Opaque	1.5	2	2	1.7	4.0	3
Titanite	0.5	1	tr	0.2	tr	tr
Apatite	tr	tr	tr	0.1	tr	tr
Zircon	tr	tr	tr	tr	tr	tr
Epidote	tr	tr	tr	tr	tr	tr
Chlorite			tr		0.3	

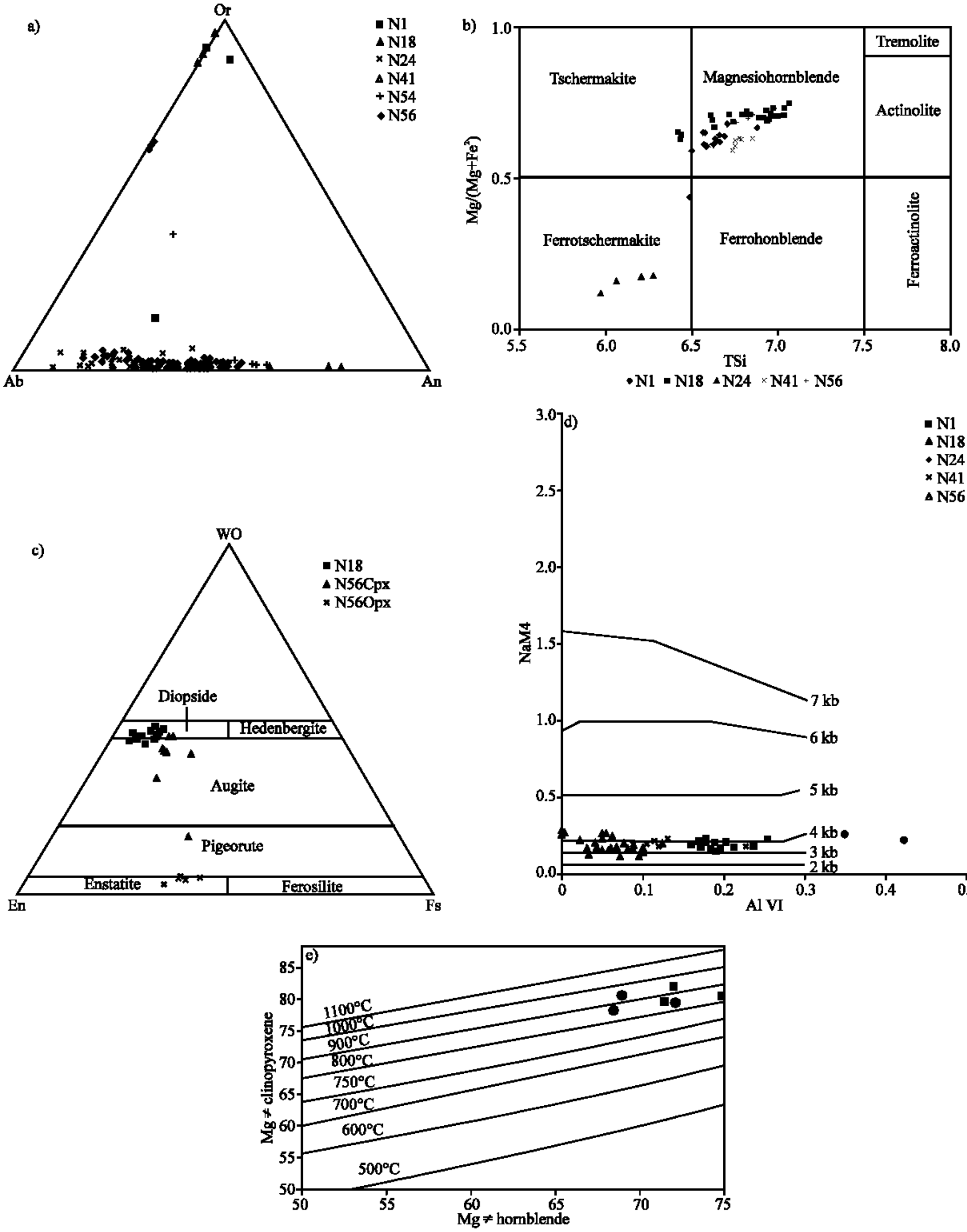

Fig. 4: a: Plot of feldspar composition on Ab-An-Or diagram
b: Amphibole composition on Ca-amphibole classification diagram (Leak *et al*., 1997)
c: Plot of pyroxene compositions on En-Wo-Fs diagram
d: Estimates of the crystallisation pressure of the igneous amphiboles based on the crosstie (NaM4) content of amphiboles (after Brown, 1977). Note that all of the amphiboles lie below the 4.5 kbar
e: Results of hornblende-clinopyroxene thermometer for the rims of contiguous minerals

Table 2: Representative analyses of feldspars

Sample ID	N1	N1	N18	N18	N24	N24	N41	N41	N54	N54	N56	N56
Minerals	Pl	Pl	KF	Pl	KF	Pl	Pl	KF	Pl	KF	KF	Pl
SiO_2	62.43	55.78	64.94	60.89	65.78	58.78	58.52	64.19	64.78	66.41	53.96	47.91
TiO_2	0.01	0.01	0.01	0.01	0.01	0	0	0	0	0.02	0.85	0.04
Al_2O_3	23.71	28.41	18.55	24.61	18.9	22.68	25.89	18.22	22.89	19.32	20.6	32.99
Cr_2O_3	0	0	0	0	0	0	0	0	0.01	0.04	0	0
NiO	0.03	0.06	0.02	0	0	0.03	0.02	0	0.06	0.06	0	0.05
FeO	0.24	0.17	0.18	0.17	0.05	1.18	0.11	0.42	0.15	0.07	7.07	0.32
MnO	0.01	0	0	0.01	0.03	0.02	0.01	0	0	0.02	0.08	0
MgO	0.01	0.01	0	0	0	0.33	0.01	0	0	0	3.03	0.01
CaO	4.71	10.2	0.02	6.32	0.23	4.45	6.97	0.03	3.59	0.24	3.44	16.36
Na_2O	8.57	5.49	1.38	8.17	4.13	7.58	7.14	0.40	9.18	4.04	4.3	2.39
K_2O	0.12	0.18	14.92	0.33	10.83	0.91	0.74	16.23	0.60	10.87	6.03	0.09
Total	99.97	100.36	100.09	100.6	99.96	96.1	99.46	99.54	101.3	101.17	99.96	100.17
Si	2.769299	2.502706	2.992048	2.70298	2.986583	2.738648	2.634043	2.991582	2.827217	2.981632	2.581732	2.197535
Ti	0.000334	0.000337	0.000347	0.000334	0.000341	0	0	0	0	0.000675	0.030588	0.00138
Al	1.239476	1.502217	1.007234	1.287474	1.011283	1.245317	1.373348	1.000719	1.177319	1.022252	1.161546	1.78329
Fet	0.008902	0.006378	0.006935	0.00631	0.001898	0.045972	0.00414	0.016368	0.005474	0.002628	0.282854	0.012273
Mn	0.000376	0	0	0.000376	0.001154	0.000789	0.000381	0	0	0.00076	0.003242	0
Mg	0.000661	0.000669	0	0	0	0.022922	0.000671	0	0	0	0.216126	0.000684
Ca	0.223831	0.49029	0.000987	0.300563	0.011187	0.22212	0.336104	0.001498	0.167855	0.011544	0.176327	0.803924
Na	0.736997	0.477543	0.123266	0.703117	0.363529	0.684675	0.623053	0.036141	0.776728	0.35165	0.398856	0.212528
K	0.00679	0.010302	0.876868	0.018686	0.627217	0.054083	0.042487	0.964853	0.033402	0.622528	0.368015	0.005266
Ab	76.16615	48.82175	12.31281	68.77347	36.28273	71.25513	62.20305	3.605131	79.42122	35.67433	42.2876	20.80104
An	23.13213	50.12504	0.09861	29.39879	1.116584	23.11642	33.5552	0.149416	17.16334	1.171114	18.69462	78.68357
Or	0.701719	1.053208	87.58858	1.827736	62.60068	5.628452	4.241757	96.24545	3.415433	63.15456	39.01778	0.515383

ESTIMATION OF TEMPERATURE AND PRESSURE

As mentioned in introduction, geothermobarometric calculations for plutonic rocks and especially granitoids are not easy. In spite of these problems, many researchers have used mineral thermobarometric methods to granitoid rocks (Vyhnal *et al*., 1991; Schmidt, 1992; Altherr *et al*., 1995; Stone, 2000; Lissenberg *et al*., 2004; Moazzen and Droop, 2005). Since there are few suitable mineral assemblages in granitoid rocks for thermobarometry, the pressure and temperature estimation in those studies is, based mainly on Al-in-hornblende barometry (Hammarstrom and Zen, 1986; Hollister *et al*., 1987; Schmidt, 1992) and amphibole-plagioclase thermometry (Holland and Blundy, 1994; Blundy and Holland, 1990). Suitable assemblage mineral in our studied plutons are rare, too. Since, it is emphasized on the use of amphibole composition to thermobarometric valuation. Furthermore, other methods are applied to consult the best interpretation of the temperature and pressure of emplacement of Naqadeh, Pasveh and Delkeh plutons.

BAROMETRY

The most useful barometric method in granitoid rocks is the estimation of pressure with Al-in-hornblende. First, Hammarstrom and Zen (1986) distinguished Al^{tot} content of magmatic hornblende correlate linearly with crystallization pressure of intrusion:

$$P\ (\pm 3\ \text{kbar}) = -3.92 + 5.03\ Al^{tot}\quad r^2 = 0.80 \qquad (1)$$

Hollister *et al*. (1987) discussed the thermodynamic basis for this barometer and refined the empirical calibration of Hammarstrom and Zen with additional hornblende compositional data from intrusives that crystallized at intermediate pressures:

$$P\ (\pm 1\ \text{kbar}) = -4.76 + 5.64\ Al^{tot}\quad r^2 = 0.97 \qquad (2)$$

Johnson and Rutperford (1989) suggested below equation:

$$P\ (\pm 0.5\ \text{kbar}) = -3.46 + 4.23\ Al^{tot}\quad r2 = 0.99 \qquad (3)$$

Schmidt (1992) defined that crystallization pressure can be fit by the equation:

$$P\ (\pm 0.6\ \text{kbar}) = -3.01 + 4.76 Al^{tot}\quad r^2 = 0.99 \qquad (4)$$

All Calibration studies have emphasized need for the assemblage hornblende+ biotite+ plagioclase+ K-feldspar+ quartz+ titanite+ Fe-Ti oxides for application of the Al-in-hornblende barometer. As discussed by Schmidt (1992), hornblende would be expected to equilibrate with this assemblage in addition to melt and a fluid phase at temperature in the vicinity of the solidus and the Al content of hornblende would be constrained by ambient pressure. Following solidification and cooling, the equilibration of hornblende with the above minerals

Table 3: Representative analysed amphiboles. Pressure and temperature calculations are inserted, too

Sample ID	N1	N1	N18	N18	N24	N24	N41	N41	N56	N56
Minerals	Amph	Amph	Amph	Amph	Amph	Amph	Amph	Amph	Amph	Amph
SiO_2	44.7	45.4	46.85	45.04	40.08	37.77	45.55	44.37	46.08	46.62
TiO_2	1.84	1.18	2.03	2.33	0	0	1.3	1.96	1.53	0.99
Al_2O_3	9.22	9.2	7.2	8.22	11.23	14.01	7.85	8.59	7.04	6.59
Cr_2O_3	0.06	0.04	0	0.03	0	0	0	0.02	0	0
NiO	0	0	0.03	0	0	0	0	0	0	0.05
FeO	17	17.45	14.94	15.45	30.1	29.6	18.01	17.66	17.4	16.86
MnO	0.41	0.4	0.42	0.4	0.91	0.86	0.72	0.68	0.22	0.2
MgO	11.23	11.04	13.14	12.54	2.5	1.63	10.84	10.77	12.3	12.76
CaO	11.26	11.32	11.15	11.42	10.4	10.83	11.16	11.36	10.91	11.06
Na_2O	1.32	1.05	1.34	1.43	1.54	1.52	1.21	1.54	1.56	1.31
K_2O	0.75	0.92	0.67	0.84	0.9	1.12	0.8	0.76	0.92	0.84
F	0.2	0.15	0.19	0.26	0.43	0.45	0.24	0.25	0.5	0.47
Cl	0.23	0.17	0.09	0.09	0.2	0.2	0.15	0.28	0.57	0.55
Total	98.22	98.32	98.05	98.05	98.29	97.99	97.83	98.24	99.03	98.3
TSi	6.581	6.666	6.821	6.62	6.279	5.975	6.759	6.601	6.761	6.855
TAl	1.419	1.334	1.179	1.38	1.721	2.025	1.241	1.399	1.217	1.141
TFe^{3+}	0	0	0	0	0	0	0	0	0	0.004
Sum_T	8	8	8	8	8	8	8	8	8	8
CAl	0.18	0.256	0.055	0.043	0.351	0.585	0.131	0.106	0	0
CCr	0.007	0.005	0	0.003	0	0	0	0.002	0	0
CFe3	0.754	0.78	0.698	0.657	1.23	1.077	0.771	0.641	0.854	0.911
CTi	0.204	0.13	0.222	0.258	0	0	0.145	0.219	0.169	0.109
CMg	2.465	2.416	2.852	2.748	0.584	0.384	2.398	2.389	2.691	2.797
CFe^{2+}	1.339	1.362	1.12	1.242	2.714	2.838	1.464	1.557	1.259	1.158
CMn	0.051	0.05	0.052	0.05	0.121	0.115	0.09	0.086	0.027	0.025
Sum_C	5	5	5	5	5	5	5	5	5	5
BCa	1.776	1.781	1.739	1.798	1.746	1.836	1.774	1.811	1.715	1.742
BNa	0.224	0.219	0.261	0.202	0.254	0.164	0.226	0.189	0.285	0.258
Sum_B	2	2	2	2	2	2	2	2	2	2
ACa	0	0	0	0	0	0	0	0	0	0
ANa	0.153	0.08	0.117	0.206	0.214	0.302	0.123	0.255	0.159	0.116
AK	0.141	0.172	0.124	0.158	0.18	0.226	0.151	0.144	0.172	0.158
Sum_A	0.294	0.252	0.242	0.363	0.394	0.528	0.274	0.399	0.331	0.273
Sum_cat	15.294	15.252	15.242	15.363	15.394	15.528	15.274	15.399	15.331	15.273
CCl	0.057	0.042	0.022	0.022	0.053	0.054	0.038	0.071	0.142	0.137
CF	0.093	0.07	0.087	0.121	0.213	0.225	0.113	0.118	0.232	0.219
Sum_oxy	23	23	23	23	23	23	23	23	23	23
P1(±3)	4.12297	4.0777	2.28702	3.23769	6.50216	9.2083	2.98116	3.65015	2.20151	1.81923
P2(±1)	4.25836	4.2076	2.19976	3.26572	6.92608	9.9604	2.97808	3.7282	2.10388	1.67524
P3(±0.5)	3.30377	3.2657	1.75982	2.55929	5.30456	7.5803	2.34356	2.90615	1.68791	1.36643
P4(±0.6)	4.60124	4.5584	2.86384	3.76348	6.85272	9.4136	3.52072	4.1538	2.78292	2.42116
Mg#	0.6480021	0.6394918	0.7180262	0.6887218	0.177077	0.1191806	0.6209218	0.6054232	0.6812658	0.7072061
Fe3/Fe3+Fe2	0.3602484	0.3641457	0.3839384	0.3459716	0.3118661	0.2750958	0.3449664	0.2916288	0.4041647	0.4394597
Fet/Fet+Mg	0.4591926	0.469943	0.3892934	0.4086507	0.8710247	0.9106769	0.4824088	0.4791803	0.4398418	0.4256674
Xab	0.678	0.707	0.673	0.658	0.822	0.76	0.574	0.665	0.703	0.699
T (±40°C)	740.78689	719.53591	738.31762	798.84865	720.36138	745.76474	738.56393	775.83662	773.36048	742.7682
Pas	3.6801263	4.185	2.1313196	1.7092756	6.1385168	7.9500783	2.7296616	2.57838	1.4339577	1.6529916

would slow and eventually cease and hence hornblende composition would potentially reflect the pressure (depth) at which the magma solidified.

Pressure of amphibole crystallization were calculated on the basis of 4 above relations and the results of representative analyses are presented in Table 3 as P1 to P4 for relation of (1) to (4), respectively. Granitoid rocks show pressures 2-4.6 kbar and monzodiorite sample has 1.7-2.8 kbar (the only exception is the sample of N24 which gives unusually high pressures and will be discussed in below).

Anderson and Smith (1995) suggest a revised Eq. 4 and incorporate the effect of temperature:

$$P\ (\pm 0.6\text{kbar}) = \{4.76\text{AI}-3.01-([T°(C)-675]/85\} \times \{0.530\text{AI} + 0.005294[T°(C)-675]\} \quad (5)$$

To obtain a revised estimate of pressure, the calculated temperature of Holland and Blundy thermometer (1994, next section) are used in (5). Representative results presented by Pas in Table 3. Mean of revised pressures show 3.8, 1.9 and 1.6 kb for the granitoid samples of N1, N18 and N41 respectively and 1.6 kb for the sample of N56 (it should be noted that in Table 3 only representative analyses are inserted).

Anderson and Smith (1995) and Schmidt (1992) established limits in terms of Mg and Fe content of

Table 4: Representative analyses of pyroxenes

Sample ID	N18	N18	N18	N18	N56	N56	N56	N56	N56
Minerals	CPX	CPX	CPX	CPX	CPX	CPX	CPX	OPX	OPX
SiO_2	50.45	52	53.01	52.33	52.7	51.9	51.18	52.02	53.14
TiO_2	0.81	0.61	0.26	0.46	0.58	0.67	1.1	0.45	0.35
Al_2O_3	3.99	3.84	1.69	2.67	1.99	2.94	2.52	1.01	0.67
Cr_2O_3	0.03	0.09	0.08	0.06	0.1	0.26	0.06	0.02	0
NiO	0.03	0.03	0	0	0.08	0	0.02	0.06	0.02
FeO	6.7	5.65	7.17	8.47	6.33	10.35	8.78	23	21.63
MnO	0.2	0.08	0.41	0.34	0.22	0.26	0.29	0.54	0.47
MgO	15.11	17.02	14.62	15.18	16.06	17.99	14.11	21.27	23.12
CaO	21.68	21.18	22.79	19.01	22.18	16.48	21.68	2.3	1.44
Na_2O	0.34	0.25	0.44	0.54	0.32	0.31	0.41	0.05	0.01
K_2O	0.01	0.02	0.05	0.18	0.01	0.02	0.02	0.02	0.02
F	0.05	0.09	0.12	0.23	0.12	0.12	0.11	0.1	0.13
Cl	0.04	0	0	0.02	0	0.02	0	0.02	0.01
Total	99.45	100.87	100.63	99.5	100.7	101.32	100.28	100.87	101.01
4 cationes/6 O	2.225068	2.175898	2.21022	2.235254	2.195867	2.183719	2.231172	2.233485	2.209859
Si	1.86842	1.883267	1.950129	1.946918	1.926135	1.886402	1.900656	1.933853	1.954592
Ti	0.022563	0.016616	0.007194	0.012872	0.015944	0.018316	0.030725	0.012582	0.009683
Al	0.174147	0.163897	0.073269	0.117068	0.085715	0.125934	0.110289	0.044249	0.029043
Cr	0.000878	0.002577	0.002327	0.001765	0.002889	0.007471	0.001762	0.000588	0
Ni	0.000894	0.000874	0	0	0.002352	0	0.000597	0.001794	0.000592
Fet	0.207487	0.171104	0.220561	0.263502	0.193456	0.314565	0.272647	0.714964	0.665264
Mn	0.006273	0.002454	0.012774	0.010713	0.00681	0.008003	0.009121	0.017001	0.014641
Mg	0.834263	0.918952	0.801822	0.841964	0.875078	0.974816	0.781187	1.178815	1.26779
Ca	0.86019	0.821782	0.898197	0.757706	0.86848	0.641721	0.86255	0.091602	0.056744
Na	0.024412	0.017553	0.031381	0.038949	0.022674	0.021844	0.029519	0.003604	0.000713
K	0.000472	0.000924	0.002346	0.008542	0.000466	0.000927	0.000947	0.000948	0.000938
F	0.005855	0.010307	0.013959	0.027058	0.013869	0.013792	0.012917	0.011755	0.01512
Cl	0.00251	0	0	0.001261	0	0.001232	0	0.00126	0.000623
En	0.438638	0.480664	0.417489	0.451898	0.451766	0.504798	0.407636	0.593748	0.637145
Wo	0.45227	0.429839	0.46767	0.406675	0.44836	0.332308	0.450092	0.046138	0.028517
Fs	0.109092	0.089497	0.114841	0.141426	0.099874	0.162894	0.142272	0.360114	0.334338

amphiboles that are suitable for Al-in-hornblende barometry unless they have $0.4<Fe^{tot}/(Fe^{tot}+Mg)<0.65$ and $0.2<Fe^{3+}/(Fe^{3+}+Fe^{2+})$, where Mg and Fe are calculated by the 13eCNK method. As it is clear in Table 3, amphiboles in the sample of N24 have $Fe^{tot}/(Fe^{tot}+Mg)>0.65$ and high pressure values are not reliable.

Brown (1977) applied NaM4 versus AlIV diagram for amphibole geobarometry in metamorphic rocks. If this diagram is applicable to the products of igneous crystallization, then the pressure of amphibole crystallization in our studied plutons is 2.5-4.3 kbar (Fig. 4d).

THERMOMETRY

If minerals in granitic magmas all equilibrated on a water-saturated solidus, there would be little reason to determine the temperature as solidus temperatures for most igneous systems are well known. For pressure >3 kbar, for example, the water-saturated granite solidus is nearly isothermal at 650-675°C (Wyllie, 1984). Yet thermobarometric data for many granitic plutons yield temperatures above 700°C (Anderson and Smith, 1995) either due to the preservation of compositions required above the solidus or vapour undersaturation. In this section different thermometer methods will be viewed for mineral assemblage in aqadeh, Pasveh and Delkeh plutons to obtain reasonable conclusion of crystallization temperatures.

Hornblende-Plagioclase thermometer: The Al content of hornblende is not only a function of pressure but also temperature, mainly through an edenitic exchange involving the substitution of Al for Si in the T site coupled with Na and K substitution for vacancies in the A site (Blundy and Holland, 1990). Holland and Blunby (1994) calibrate this thermometer and defined following conditions for using it: temperature in the range 400-900°C, amphiboles which have $Na^{A}>0.02$ pfu, $Al^{VI}<1.8$ pfu and Si in the range 6.0-7.7 pfu and plagioclases with Xan < 0.90.

These conditions are true in the amphiboles of our area, so temperatures were calculated based on Holland and Blundy (1994) equation. This thermometer needs pressure and first, we used of Schmidt (1992) barometer (P4 in Table 3) to estimate temperature. After revised pressure with Anderson and Smith (1995) correctness, ew resulted pressure (P5 in Table 3) used in thermometer and it is found that new temperature yields <30°C difference with former temperature that lies in error

Table 5: Ternary feldspar thermometry calculated by application of SOLVCALC software

Sample name	TN and B	TE and G	TL and N	TG	TF and L	TG and U
N1	497	423	418	562	456	371
N1	530	465	439	513	447	476
N1	513	433	479	error	495	360
N18	558	488	467	552	510	540
N18	576	536	448	564	497	564
N24	654	684	664	673	691	647
N24	763	789	754	773	772	746
N41	528	393	353	432	386	502
N41	417	337	281	329	352	440
N54	719	738	700	723	732	701
N54	908	880	827	895	821	1086
N56	684	790	759	764	767	error
N56	661	719	657	704	697	666

N and B= Nekvasil and Burnham (1987), E and G= Elkins and Grove (1990), L and N= Lindsley and Nekvasil (1989), G= Ghiorso (1984), F and L= Fuhrman and Lindsley (1988), G and L= Green and Usdansky (1986)

interval (±40°C) of thermometer. Core and rim of amphiboles give different temperatures: 670-750°C and 730-843°C for the rim and core of amphiboles in granitoids and 710-745 and 733-869°C for the rim and core of monzodiorite, respectively. Representative results of hornblende-plagioclase thermometer of amphiboles are presented in Table 3.

Feldspar thermometry: There are many thermometric models which use feldspar compositions involve two-feldspar and ternary feldspar methods. More recent calibrations, including Ghiorso (1984), Green and Usdansky (1986), Nekvasil and Burnham (1987), Fuhrman and Lindsley (1988), Lindsley and Nekvasil (1989) and Elkins and Grove (1990) offer three calibrations for each feldspar pair based on exchange of albite, anorthite and orthoclase components, respectively. Temperatures of studied samples were calculated using different ternary solution models (aforementioned methods) by means of SOLVCALC software (Wen and Nekvasil, 1994). Because the plagioclases are zoned, only out rims of them, which are believed to have been in equilibrium with alkali feldspars, used for thermometric calculations. Summary of the results of this thermometer represents in Table 5. Results are misleading, so that temperatures vary from 281 to 1086°C.

Clinopyroxene-hornblende thermometry: Clinopyroxene -hornblende thermometer is applicable in many intermediate rocks. Based on the partitioning of Mg/Fe, the thermometer is presented in graphical form by Perchuck *et al.* (1985) with no information about the nature or quality of calibration. Figure 4e shows the graphical form of the clinopyroxene-hornblende thermometer applied to monzodiorite (N56 sample) and quartz monzonite (N18 sample) of Delkeh and Pasveh plutons, respectively. Only the analyses were plotted on this diagram that relate to juxtaposition of amphibole and clinopyroxene (rims of minerals next to each other). According to this diagram the temperature of amphibole and clinopyroxene crystallization is between 820 to 970°C.

Two-pyroxene thermometer: Two-pyroxene thermometry has been applied to granulite, other high-temperature metamorphic rocks and gabbros. The thermometer is also applicable to many intermediate to felsic igneous rocks. Early forms of thermometer (Wood and Banno, 1973; Wells, 1977) were based on a binary model of Ca-Mg exchange. Kertz (1982) offered two calibrations, one based on a ternary model and the other for Fe-Mg exchange. The most complete formulations are those of Lindsley (1983) and Davidson and Lindsely (1985), who offer correction for non-quadrilateral components.

We calculated two-pyroxene thermometer temperature for the sample of N56 (monzodiorite of Delkeh pluton) by using of QUILF computer program (Andersen *et al.*, 1993). This program apply Lindsley (1983) and Davidson and Lindsely (1985) instructions for two-pyroxene thermometry. Resulted temperatures show 1020-1130°C. The sample of N54 (Delkeh granite) preserve relicts of pyroxene crystals that show exsolution texture (Fig. 3d). A few analyses were done on these pyroxenes which two-pyroxene thermometry indicates 885-980°C as exsolution temperatures.

DISCUSSION

It is impossible to define the exact pressure of crystallization and emplacement of our studied plutonic rocks because of the absence of appropriate mineral assemblage that is necessary to geobarometric calculations. Nevertheless, by the use of amphibole composition approximate assessment is possible. The application of Al in hornblende and crosstie content of amphibole suggest <4.5 kbar for the crystallization depth of Delkeh, Pasveh and Naqadeh plutons. Different textural relation of amphibole in various rocks of these plutons may cause un-equilibrated conditions that resulted in error pressure estimation by amphiboles. For example amphiboles in the sample of N56 are anhedral crystals which enclose pyroxenes as haloes, but their composition is completely magmatic hornblende and there is probability of equilibrium between amphibole and other necessary mineral for barometric method. The application of thermal effect on Al-in-hornblende barometry (Anderson and Smith, 1995) results in pressures between 1.6-3.8 kbar for crystallization of these plutons.

Different thermometric methods give disparate information on the crystallisation history of plutons. Hornblende –plagioclase thermometry suggest reliable temperatures for near solidus conditions of Naqadeh, Pasveh and Delkeh plutons, although, with regards to textural evidence in more felsic rocks (the samples of N54, N41, N24 and N1) quartz and k-feldspar may continue to crystallize after amphibole crystallisation was completed. Such case can be seen in thin sections which euhedral amphibole embedded by interstitial k-feldspar and quartz. In more mafic samples (N18 and N56), hornblende-plagioclase thermometer can be indicative of solidus temperature because of textural reasons that mentioned in above paragraph.

Two-pyroxene and hornblende-clinopyroxene thermometers represent hyper-solidus temperatures for more mafic samples. The highest temperatures in this study resulted by two-pyroxene thermometry (1020-1130°C) in the sample of N56. These data are assumed to reflect the actual temperature of initial pyroxene crystallisation from the Delkeh dioritic magma. Temperatures of two-pyroxene thermometer in the quartz monzonite sample of Pasveh pluton (the sample of N18) show temperatures (885-980°C) higher than solidus temperatures resulted by hornblende-plagioclase thermometer (695-760°C). In other words, two-pyroxene thermometer reflects hyper-solidus exsolution temperature.

Feldspar thermometry methods give temperatures that are very broad range even at one sample (Table 5). The low temperatures obtained by applying feldspar thermometry to plagioclase rims and coexisting K-feldspars (especially in the samples of N1, N18 and N41) confirm that sub-solidus re-equilibration affected feldspars in all the analysed rocks. This is a well-known problem in the application of feldspar thermometry to high-grade metamorphic rocks (Evangelakakis *et al*., 1993). Therefore, it should be noted that the use of feldspar thermometry in plutonic rocks may yield erratic results and sub-solidus re-equilibration is possible.

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