Jadeite–K-feldspar rocks and jadeitites from northwest Turkey

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Abstract

Blueschist-facies rocks with jadeite–K-feldspar–lawsonite paragenesis occur as exotic blocks in Miocene debris flows in the blueschist belt of northwest Turkey. The jadeite–K-feldspar rocks have a very fine grain size and although recrystallized locally retain a relict porphyritic volcanic texture. The former nepheline microphenocrysts, recognized from their characteristic shapes, are pseudomorphed by jadeite and K-feldspar, while the relict magmatic aegirine has rims of jadeite. The matrix of the rock consists of very fine-grained aggregates of jadeite, K-feldspar and lawsonite. In some blocks, jadeite makes up >60% of the mode. Jadeite, K-feldspar and lawsonite in the blocks are essentially pure end-member in composition. $P-T$ estimates for these rocks are 8 ± 2 kbar and 300 ± 50°C. The preserved volcanic texture, relict aegirine and the bulk rock composition indicate that these rocks represent metamorphosed phonolites. The paragenesis in these rocks shows that jadeite–K-feldspar is a stable mineral pair in blueschist-facies $P-T$ conditions.

KEYWORDS: jadeite, K-feldspar, lawsonite, jadeitite, blueschist, Turkey.

Introduction

THE paragenesis jadeite + K-feldspar is not recorded from blueschist-facies rocks. In the eclogite-facies it is reported from metamorphosed acidic magmatic rocks from the Western Alps (Lefêvre and Michard, 1965; Saliot, 1979; Compagnoni and Maffeo, 1973; Biino and Compagnoni, 1992) and from New Caledonia (Black *et al.*, 1988). Compagnoni and Maffeo (1973) and Biino and Compagnoni (1992) regard K-feldspar in eclogite-facies metagranites as a metastable relic from the igneous parent and inherently unstable in the eclogite facies. Here, I describe jadeite–K-feldspar rocks from blueschist-facies metaphonolites from northwest Turkey. In some of these rocks, jadeite comprises >60 modal per cent, justifying the title jadeitite. Like jadeitites from Burma (Lacroix, 1930) and Guatemala (Harlow, 1994), the jadeite–K-feldspar rocks from northwest Turkey are commercially utilized and exported as jades. However, unlike these classical jadeitites, which occur as blocks in serpentinite and have a largely metasomatic origin, jadeite–K-feldspar rocks from northwest Turkey are found as blocks in the Miocene debris flows and represent metamorphosed phonolites.

The jadeite–K-feldspar rocks occur in the western part of the Tavşanlı Zone of northwest Turkey. The Tavşanlı Zone is a 50–60 km wide and 300 km long tectonic belt of blueschist, volcano-sedimentary complex and ophiolite (Okay, 1984). Blueschists represent a coherent continental margin to platform sequence of metapelites, metapsammites, marbles, metabasites and metacherts. The depositional age of the protoliths to the blueschists is probably Paleozoic to Mesozoic, while the age of metamorphism, based on Ar/Ar laser probe dating, is Late Cretaceous (Okay and Kelley, 1994; Harris *et al.*, 1994). The blueschists are tectonically overlain by a Cretaceous volcano-sedimentary complex and large peridotite slabs. The volcano-sedimentary complex consists of mafic volcanic and volcanoclastic rocks, radiolarian cherts, pelagic shales and serpentinites, and represents a Cretaceous oceanic accretionary complex. Blueschists, the accretionary complex and peridotite are unconformably overlain by Miocene terrigenous sedimentary and volcanic rocks.

Geological setting

Jadeite–K-feldspar rocks occur in the Bektaşlar region, west of the town of Harmancık and 60 km south of Bursa (Fig. 1). The area shows the typical tectonostratigraphy of the Tavşanlı Zone with coherent blueschists at the base, tectonically overlain

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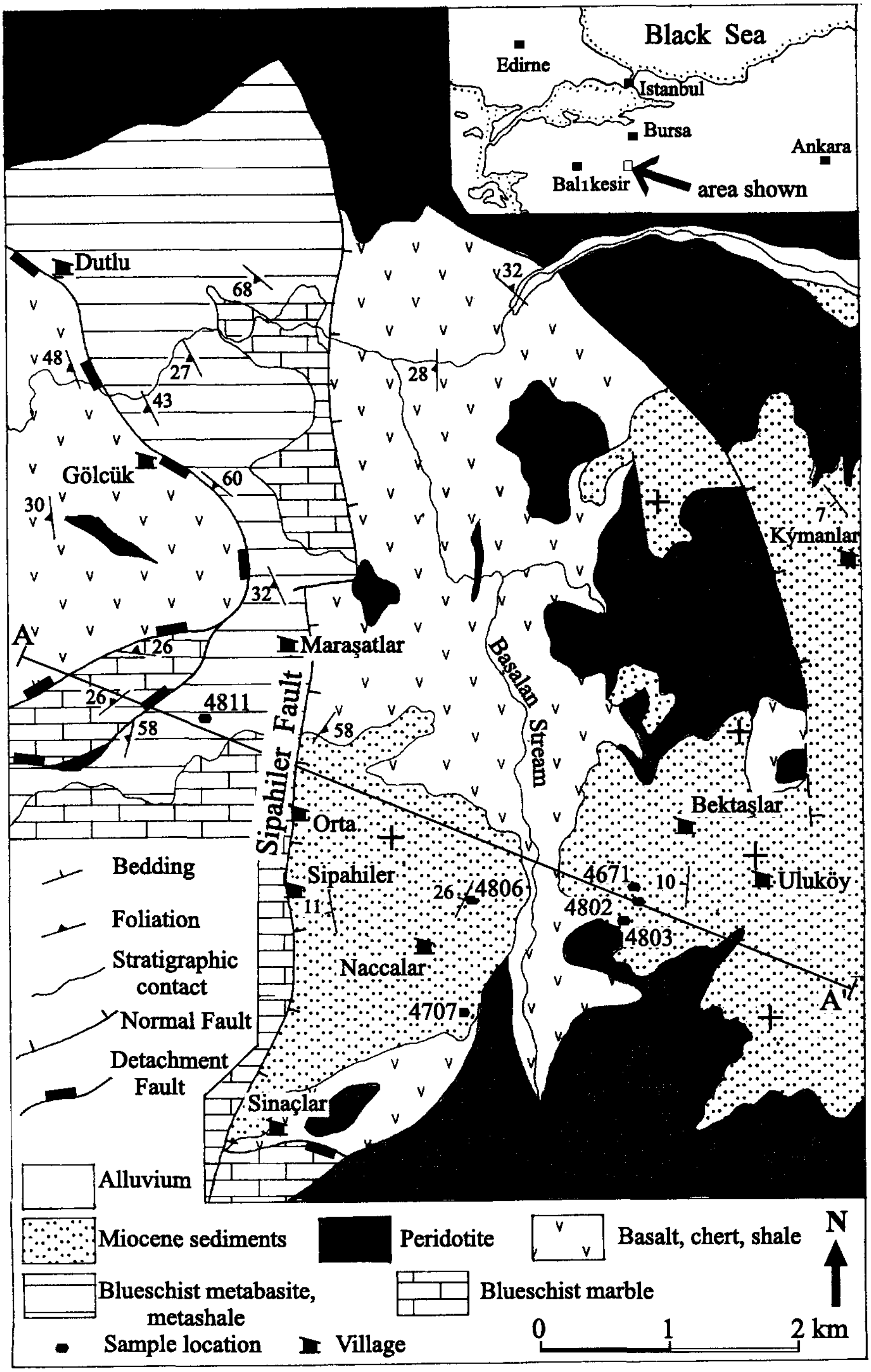

FIG. 1. Geological map of the Bektaşlar region, northwest Turkey. Locations of the analysed samples are shown. The inset shows the regional setting of the area studied.

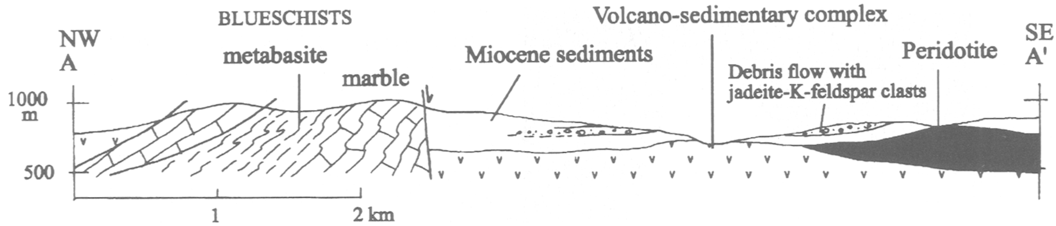

FIG. 2. Geological cross-section of the Bektaşlar region. For location of the cross-section see Fig. 1. The thickness of the Miocene debris flow is greatly exaggerated for clarity.

by the volcano-sedimentary complex and peridotite slabs (Figs. 1, 2). Miocene terrigeneous deposits lie unconformably over the older units. Blueschists in the region are made up of white massive marbles overlain by metabasites with some metashales (Fig. 1). The volcano-sedimentary complex consists predominantly of mafic volcanic and volcaniclastic rocks (>70%) with minor radiolarian chert, pelagic shale and serpentinite. It is cut by large number of shear zones and forms an imbricate thrust stack. The peridotite lies with a sharp, low-angle fault contact over both the blueschists and the accretionary complex (Figs 1, 2). It is made up of harzburgite with dunite bands and chromite lenses.

Jadeite–K-feldspar rocks are found as exotic blocks in the Miocene sedimentary sequence. The Miocene rocks in the region consist of mainly lacustrine marl, sandstone and shale. They have been dated palaeontologically as Middle Miocene (Kavuşan, 1984). Below subhorizontally bedded, undisturbed Miocene lacustrine marls, there is a ~6 m thick, poorly cemented, chaotic breccia horizon well exposed along a road section (Fig. 3). The breccia layer consists of very poorly sorted, matrix supported blocks of blueschist, peridotite, marble and jadeite–K-feldspar rock in a mudstone/sandstone matrix. The size of the clasts ranges from 3 m down to a few mm with jadeite–K-feldspar rocks forming the largest blocks (Fig. 3). The very poor sorting and chaotic mixing of the blocks, and lack of internal layering, suggest that the breccias represent debris flows. Jadeite–K-feldspar, blueschist, marble and peridotite clasts, from the same or an overlying debris flow, occur as loose or half-buried boulders in the fields covering several hundred square meters on either side of the Başalan stream (Fig. 1). The farmers have carried most of these blocks to the margins of their fields and have used them to make stone walls. All the exported jadeite–K-feldspar rocks come from these stone walls or from the boulders in the fields.

Two lines of evidence indicate that the debris flow, and hence the jadeite–K-feldspar blocks, came from west of the Sipahiler fault, a major north-trending normal fault, which forms the contact between the Miocene rocks and the blueschists (Figs 1, 2). First, all the different block rock types, with the exception of jadeite–K-feldspar rocks, can be identified in the region west of the Sipahiler fault, whereas the blueschists are not exposed to the east of the fault (Figs 1 & 2). Second, the breccias are restricted to within 3 km of the Sipahiler fault and are not reported from the extensive Miocene deposits from farther east. The debris flows may have been triggered by Miocene earthquake activity along the Sipahiler fault. Similar earthquake-generated debris flows have been described from active faults (e.g., Keller, 1986). However, a careful search for *in situ* jadeite–K-feldspar rocks to the west of the Sipahiler fault was fruitless, suggesting that such rocks are completely eroded.

FIG. 3. Field photograph of the Miocene debris flow. The white blocks in the centre are the jadeite–K-feldspar rocks. Note the hammer below centre for scale.

Petrology and mineral chemistry

The jadeite–K-feldspar rocks form very tough, white, pale green to purple rocks with a very fine-grained, homogeneous texture. Samples from 34 individual blocks were petrographically examined. They consist of jadeite, K-feldspar, lawsonite and aegirine, which comprise >80 % of the mode (Table 1) with very minor quartz, monazite, phengite and secondary sericite. The non-foliated, fine-grained texture of these rocks is largely inherited from the volcanic protolith. This is beautifully illustrated in Fig. 4*a*, where former nepheline microphenocrysts, recognized from their square and hexagonal shapes, are set in a groundmass of jadeite and very-fine grained aggregates (<0.02 mm) of K-feldspar. Nepheline is also pseudomorphed by jadeite and cryptocrytalline aggregates of K-feldspar. Reddish brown to green aegirine is the sole surviving magmatic mineral. Another common, granular variety of the jadeite–K-feldspar rock consists of 1 mm large aegirine crystals partially and topotactically replaced by jadeite set in a matrix of jadeite and cryptocrystalline aggregates of K-feldspar (Fig. 4*b*). A similar texture involving overgrowth of aluminous sodic pyroxene on aegirine has recently been described from metamorphosed nepheline-syenites from Malawi (Woolley *et al.*, 1996). Albite occurs in one sample as small interstitial crystals with jadeite and bundle-shaped, curved aegirine crystals (Fig. 4*c*). Albite and jadeite are closely associated with no apparent reaction textures (Fig. 4*c*), suggesting that they form a stable mineral pair. Lawsonite is generally a minor phase and occurs together with K-feldspar aggregates (Fig. 4*d*). In some samples it is pseudomorphous after the rare plagioclase microphenocrysts. Quartz forms rare and isolated patches of relatively coarse-grained crystal aggregates (0.3–0.4 mm) and is also found in veins along with lawsonite. It does not occur in the matrix with jadeite, K-feldspar or albite. Brownish phengite is a rare interstitial mineral and has probably formed at the expense of the volcanic glass. Late stage alteration is minor and is represented by the partial sericitization of K-feldspar.

The *in situ* blueschists from the Bektaşlar region consist largely of metabasites with sodic amphibole + lawsonite + sodic pyroxene + chlorite + phengite mineral paragenesis, similar to those described from farther east in the Tavşanlı region (Okay, 1980). Jadeitites were found only in one locality as ~50 cm boulders; they may represent rare, metamorphosed rhyolite flows. The jadeitite consists of interlocking aggregates of jadeite with interstitial quartz (Fig. 5, sample 4811A, Table 1), and is texturally and mineralogically different from the jadeite–K-feldspar rocks from the Miocene debris flows.

The volcanosedimentary sequence in the region shows an incipient blueschist metamorphism. The mafic volcanic and volcanoclastic rocks retain their magmatic textures. However, augite is commonly rimmed and veined by sodic pyroxene, and plagioclase is replaced by albite ± lawsonite (Okay, 1982).

Eight jadeite–K-feldspar and jadeitite samples were analysed using an SX-50 Cameca electron microprobe in the Université Paris 6. One jadeitite sample (4811A) comes from the west of the Sipahiler fault, the other samples are collected from the Miocene debris flows; one of them (4806C) is from the lower debris flow horizon, while the rest are from boulders belonging to the upper horizon (Fig. 1). The

TABLE 1. Estimated modal amounts of the analysed samples

Sample	4671A	4707I	4802E	4802F	4802I	4803A	4803D	4806C	4811A
Jadeite	34	35	39	62	65	74	38	48	85
Aegirine	–	17	9	–	2	4	–	22	–
K-feldspar	42	21	43	26	7	6	39	–	–
Lawsonite	21	–	2	3	5	1	18	6	2
Albite	–	–	–	–	–	–	–	21	–
Phengite	–	–	–	tr.	–	–	–	3	–
Sericite	–	27	4	5	19	8	–	–	–
Quartz	$3_{v,m}$	–	3_m	3_m	2_v	7_m	$5_{v,m}$	–	13_m
Monazite	tr.	tr.	tr.	–	–	tr.	tr.	–	–
Piemontite	–	–	tr.	–	–	–	–	–	–
Magnetite	–	–	–	tr.	–	–	–	–	tr.
	100	100	100	100	100	100	100	100	100

tr., trace (<0.5 %); v, vein mineral; m, matrix mineral

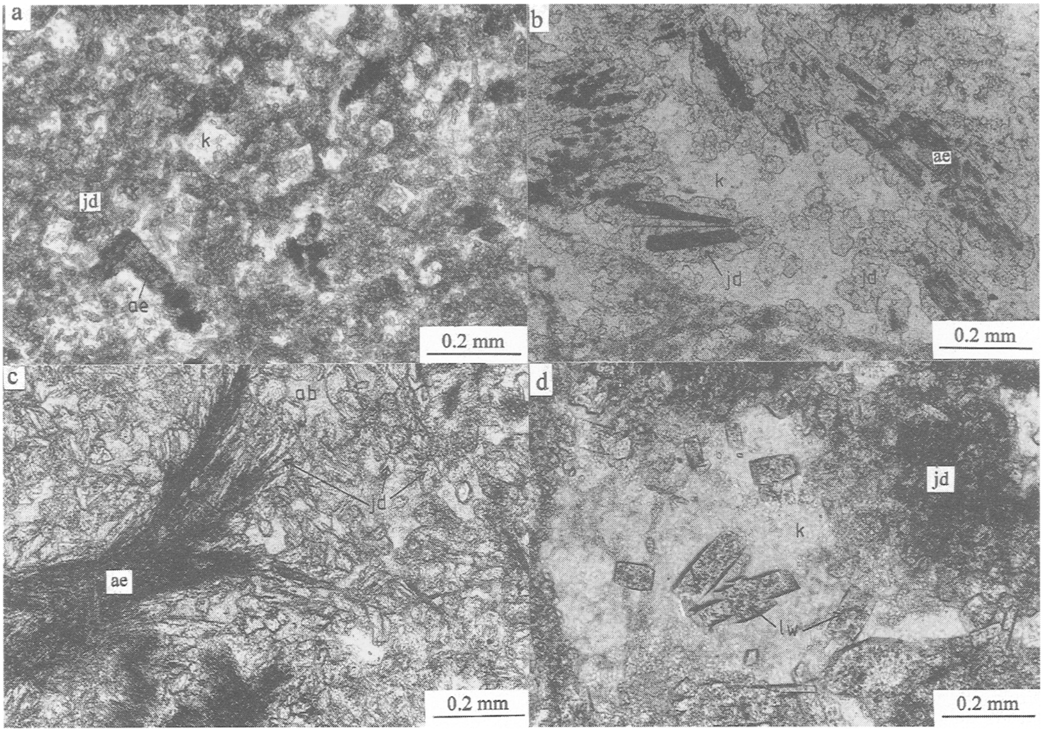

FIG. 4. Plane polarized photomicrographs of the jadeite–K-feldspar rocks. (*a*) Relict magmatic aegirine (ae) associated with K-feldspar (k) and jadeite (jd). Notice the square and hexagonal shape of the former nepheline microphenocrysts (sample 4802E). (*b*) Prismatic aegirine (ae) topotactically replaced by jadeite (jd) associated with K-feldspar (k) and jadeite (jd) (sample 4707I). (*c*) Bundles of curved aegirine crystals (ae) set on a fine-grained matrix of jadeite and albite. Notice the regular jadeite–albite grain boundaries suggesting that they form an equilibrium pair. Aegirine is topotactically replaced by jadeite (sample 4806C). (*d*) Fine-grained, brownish pink aggregates of jadeite (jd) associated with lawsonite (lw) and K-feldspar (k) (sample 4671A).

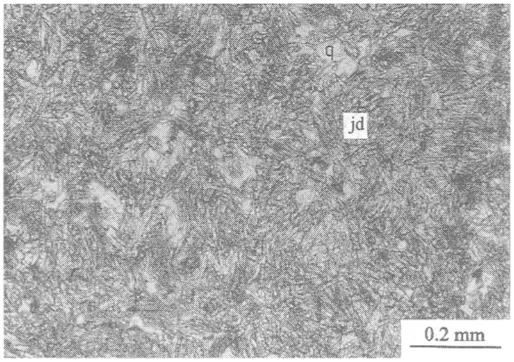

FIG. 5. Photomicrograph of jadeitite with interlocking prismatic grains of jadeite (jd) and interstitial quartz (q) (sample 4811A).

operating conditions for the microprobe were 15 kV accelerating voltage, 15 nA beam current and 10 μm beam size. Representative mineral compositions are given in Table 2. The structural formula of jadeite was calculated on the basis of six oxygens; the jadeite end-member was taken to be equal to Al^{vi}, aegirine to $Na\text{-}Al^{vi}$, and the rest was assigned to augite. The structural formula of aegirine was calculated on the basis of four cations, with the same end-member calculation as in jadeite.

Jadeite occurs as individual crystals in the matrix, and as rims on aegirine. In both modes of occurrence it contains >90% jadeite end-member and many crystals are essentially pure end-member jadeite (Table 2). The striking pink colour of many jadeite–K-feldspar rocks comes from jadeite, which is commonly pale brownish pink in thin-section. The origin of the colour of jadeite is unclear but may be related to the trace elements in the mineral (cf.

TABLE 2. Representative mineral compositions from the jadeite–K-feldspar rocks

	Jadeite				Aegirine	K-feldspar			Lawsonite			K-mica		Albite
Sample	4671A	4707I	4803D	4806C	4707I	4671A	4707I	4803D	4671A	4803D	4806C	4803A	4806C	4806C
	147	166	123	175	198	141	168	121	153	135	77	31	168	176
SiO_2	58.72	59.66	58.97	59.28	52.50	64.57	64.87	64.36	38.40	38.05	38.03	47.81	50.12	68.41
TiO_2	0.01	0.05	0.00	0.00	0.12	0.00	0.01	0.00	0.00	0.00	0.10	0.00	0.11	0.00
Al_2O_3	22.94	25.66	23.84	25.52	0.91	18.49	18.31	18.37	31.96	31.75	32.26	31.65	24.61	19.80
Cr_2O_3	0.06	0.08	0.08	0.03	0.00	0.03	0.00	0.02	0.04	0.00	0.00	0.00	0.00	0.03
FeO	2.60	0.25	2.00	0.18	29.04	0.00	0.06	0.13	0.15	0.29	0.54	1.36	4.43	0.08
MgO	0.05	0.01	0.03	0.00	0.08	0.00	0.03	0.00	0.00	0.00	0.01	1.67	2.37	0.06
MnO	0.09	0.08	0.07	0.08	0.43	0.16	0.01	0.04	0.04	0.37	0.06	0.88	0.80	0.09
CaO	0.66	0.32	0.50	0.23	2.03	0.00	0.00	0.00	17.58	17.34	17.32	0.03	0.24	0.01
Na_2O	14.67	14.81	14.78	15.08	12.43	0.05	0.09	0.07	0.03	0.00	0.01	0.00	0.00	11.51
K_2O	0.09	0.05	0.00	0.05	0.09	16.77	16.71	17.09	0.03	0.01	0.00	11.41	10.70	0.59
Total	99.86	100.96	100.28	100.45	97.63	100.07	100.08	100.08	88.22	87.80	88.32	94.81	93.37	100.58
Formula recalculations based on: oxy. = oxygens, cat. = cations														
	6 oxy.	6 oxy.	6 oxy.	6 oxy.	4 cat.	8 oxy.	8 oxy.	8 oxy.	8 oxy.	8 oxy.	8 oxy.	11 oxy.	11 oxy.	8 oxy.
Si	2.002	2.000	2.002	1.999	2.002	2.990	3.000	2.987	2.016	2.011	1.997	3.223	3.469	2.980
Al^i	0.000	0.000	0.000	0.001		1.010	0.998	1.005				0.777	0.531	1.017
Ai^{vi}	0.917	0.994	0.938	0.992	0.041				1.978	1.978	1.997	1.737	1.478	
Ti	0.000	0.001	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.006	0.000
Cr	0.002	0.002	0.002	0.001	0.003	0.001	0.000	0.001	0.002	0.000	0.000	0.000	0.000	0.001
Fe^{3+}	0.054		0.042		0.878	0.000	0.002	0.005	0.007	0.013	0.024			0.003
Fe^{2+}	0.020	0.007	0.015	0.005	0.048							0.077	0.256	
Mg	0.002	0.000	0.001	0.000	0.005	0.000	0.002	0.000	0.000	0.000	0.001	0.167	0.244	0.004
Mn	0.003	0.002	0.002	0.002	0.014	0.006	0.000	0.002	0.002	0.017	0.003	0.050	0.047	0.003
Ca	0.024	0.011	0.018	0.008	0.083	0.000	0.000	0.000	0.989	0.982	0.974	0.002	0.018	0.001
Na	0.971	0.963	0.972	0.986	0.919	0.005	0.008	0.006	0.003	0.000	0.001	0.000	0.000	0.972
K	0.004	0.002	0.000	0.002	0.004	0.991	0.986	1.012	0.002	0.001	0.000	0.981	0.944	0.033
Total	3.999	3.984	3.993	3.997	4.001	5.002	4.997	5.018	4.997	5.000	5.001	7.014	6.993	5.013
jadeite	0.917	0.994	0.938	0.992	0.041									
aegirine	0.054	0.000	0.034	0.000	0.878									
augite	0.029	0.006	0.028	0.008	0.081									

Table 3). Aegirine has >90% aegirine end-member; pyroxenes with intermediate jadeite contents appear not to have formed during the *HP*/*LT* metamorphism. K-feldspar always forms cryptocrytalline aggregates. Compositionally it is also very pure with very minor (1%) albite and anorthite components (Table 2). Albite and lawsonite are also close to their ideal end-member compositions (Table 2). The composition of the sericitic white micas with low Si pfu (per formula unit) (Table 2) indicates that, in contrast to the phengite with 3.45 Si pfu, they have formed during the low-pressure alteration of K-feldspar.

Pressure-temperature conditions of metamorphism

The critical blueschist-facies mineral assemblage in the jadeite–K-feldspar rocks is jadeite + K-feldspar ± lawsonite ± albite. The jadeite + albite paragenesis constrains the metamorphic pressure between 5 and 9 kbar at 300°C on the basis of the reactions (Fig. 6):

albite = jadeite + quartz
jadeite = nepheline + albite

In the presence of H_2O the estimate for the minimum pressure increases to 6 kbar based on the reaction (Manghnani, 1970):

jadeite + H_2O = analcite

The Si content of the phengite, ~3.45 pfu (Table 2), gives a minimum pressure estimate of 9 kbar at 300°C, based on the experimentally calibrated phengite barometer of Massone and Schreyer (1987). Estimates of metamorphic temperature are more uncertain and depend on the H_2O activity. The very fine-grained texture of the jadeite–K-feldspar rocks may be indicative of dry recrystallization. However, the quartz + lawsonite veins and the presence of lawsonite in the matrix indicates that at least some H_2O was available during the *HP*/*LT* metamorphism. For unit H_2O activity, the jadeite + lawsonite assemblage indicates temperatures <400°C, based on the reaction (Fig. 6):

jadeite + lawsonite = albite + paragonite
+ clinozoisite + H_2O

The very fine grain-size, and lack of retrograde reactions such as the albitization of jadeite suggests lower temperatures, probably ~300°C. A reasonable estimate for the *P*–*T* conditions of the jadeite–K-feldspar rocks is 8 ± 2 kbar and 300 ± 50°C.

TABLE 3. Major and trace element analyses of a jadeite–K-feldspar rock (4802F)

	wt.%		ppm
SiO_2	59.44	V	2
TiO_2	0.02	Cr	0
Al_2O_3	21.78	Co	87
Fe_2O_3	1.95	Ni	16
FeO	0.03	Cu	5
MgO	0.20	Zn	221
MnO	0.27	Ga	64
CaO	0.91	Rb	67
Na_2O	7.62	Sr	63
K_2O	5.19	Y	60
P_2O_5	0.08	Zr	1592
H_2O^+	1.21	Nb	578
H_2O^-	0.14	Sn	7
CO_2	0.22	Ba	120
Total	99.06	Pb	11

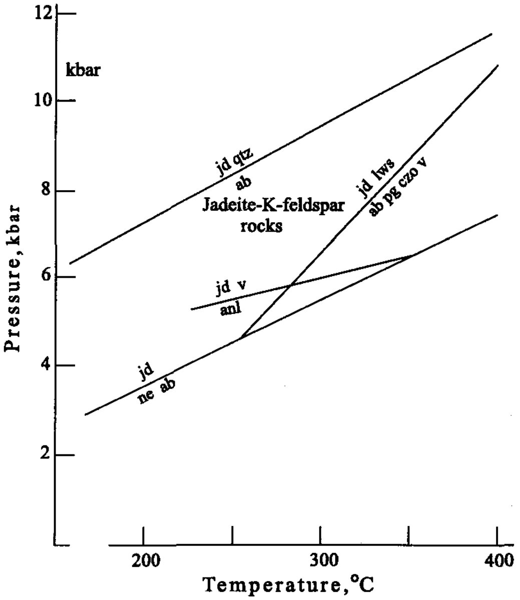

FIG. 6. Pressure–temperature diagram showing equilibria relevant to the estimation of the *P*–*T* conditions of the jadeite–K-feldspar rocks from northwest Turkey. The equlibria were calculated using the THERMOCALC of Holland and Powell (1990) except the analcite equilibrium, which is after Manghnani (1970). Mineral abbreviations are: ab, albite; anl, analcite; czo, clinozoisite; jd, jadeite; lws, lawsonite; ne, nepheline; pg, paragonite; qtz, quartz; v, H_2O.

In contrast to the jadeite–K-feldspar rocks, the stable jadeite + quartz assemblage from the jadeitite from the west of the Sipahiler fault indicates that the pressure of metamorphism for this jadeitite and associated metabasites was above the stability of albite, which is >12 kbar at 400°C (Fig. 6). Blueschist metapelites with metre-thick layers of jadeitite of quartz, jadeite and phengite, interpreted as metamorphosed acidic flows, occur 30 km to the northwest of the Bektaşlar region (Okay and Kelley, 1994). Equilibrium between glaucophane, chloritoid and jadeite in these sodic metapelites indicates blueschist-facies $P-T$ conditions of 20 $\pm$ 2 kbar and 430 $\pm$ 30°C (Okay and Kelley, 1994). The *in situ* blueschists in the Bektaşlar region form the eastward continuation of the same metamorphic belt and similar $P-T$ conditions may be assumed for the jadeitites and metabasites in the Bektaşlar area.

In terms of metamorphic grade the jadeite–K-feldspar rocks are intermediate between the regional blueschists and the volcanosedimentary sequence. It is possible that they have have formed a discrete tectonic slice between these two units (cf. Figs 1, 2), which was completely eroded during the Miocene.

Discussion and conclusions

The protoliths to the jadeitites must have been very fine-grained, silica-undersaturated, alkaline volcanic rocks. A whole rock XRF-analysis of a jadeite–K-feldspar rock is given in Table 3. SiO_2, Al_2O_3, Na_2O and K_2O comprise >94 wt.% of the rock. In terms of major and trace element chemistry the rock is a phonolite (e.g. Le Maitre, 1976; Cox *et al.*, 1979). The geochemistry and petrography of the rock suggests that it must have initially consisted mainly of aegirine, nepheline and sanidine/anorthoclase. The following metamorphic reactions are inferred:

$$\text{sanidine/anorthoclase} + H_2O = \text{K-feldspar} + \text{jadeite} + \text{lawsonite} + \text{quartz}$$

$$\text{nepheline} + \text{quartz} = \text{jadeite} + \text{K-feldspar}$$

The initial K-feldspar must have been sanidine or anorthoclase. The recrystallization of K-feldspar to cryptocrytalline aggregates may have been due to conversion of sanidine to microcline. The close association of K-feldspar, jadeite and lawsonite (cf. Fig. 4) indicates that this mineral paragenesis is stable in blueschist-facies conditions. The rarity of K-feldspar in blueschist-facies rocks is due to the unusual rock compositions required to form this mineral. Unlike albite, K-feldspar is stable at crustal temperatures up to 25 kbar (Seki and Kennedy, 1964; Huang and Wyllie, 1974), when it reacts with H_2O to form K-feldspar-hydrate.

In situ blueschist-facies metaphonolites are not known from the Tavşanlı Zone and are apparently unrecorded from blueschist-facies rocks worldwide. Phonolites with their high alkali and Al contents are volcanic rocks restricted to the continental crust. That they are metamorphosed in blueschist facies, is one more example that blueschist metamorphism is not restricted to oceanic subduction zones but occurs commonly during the continental subduction.

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