The Canadian Mineralogist
Vol. 45, pp. 1501-1509 (2007)
DOI: 10.3749/canmin.45.6.1501

THE FIELD OF STABILITY OF BLUE JADEITE: A NEW OCCURRENCE OF JADEITITE AT SORKHAN, IRAN, AS A CASE STUDY

Roland OBERHÄNSLI[§] and Romain BOUSQUET

Institute of Geosciences, Potsdam University, Karl Liebknecht Str. 27, D–14476 Potsdam, Germany

Hesam MOINZADEH

Department of Geology, College of Arts and Sciences, Shahid Bahonar University, Kerman, 76176, Iran

Mohssen MOAZZEN

Department of Geology, University of Tabriz, Tabriz, 51664, Iran

Mohsen ARVIN

Department of Geology, College of Arts and Sciences, Shahid Bahonar University, Kerman, 76176, Iran

Abstract

A new occurrence of "blue jade" is described. The jadeitite occurs as metasomatic veins in magnesite bodies within meta-ultramafic rocks in the Sorkhan area of southeastern Iran. The veins are composed of almost pure jadeite, 90 to 99.5 mol.% Jd, contain minor amounts of Ba-bearing K-feldspar, lawsonite and katophoritic amphibole, but unlike other occurrences of "blue" or "lavender jade", do not contain high amounts of Ti. The jadeitite veins formed at low-temperature – high-pressure conditions, around 1.6 GPa and 420°C. Such P–T conditions are characteristic of zones of cold subduction in which lawsonite blueschists to lawsonite eclogites typically form. Thermodynamic studies show that the mineral assemblage within the blue jade is strongly pressure- and temperature-dependent. Jadeitites containing two clinopyroxenes (jadeite and omphacite) are stable at high pressure ($\geq$0.8 GPa) and low temperature ($\leq$430°C) conditions, whereas blue jade with only one clinopyroxene (jadeite) forms at higher temperature or lower pressure. On the basis of these new calculations, P–T conditions of formation are re-examined for all occurrences of blue jade.

Keywords: blue jade, jadeitite, lawsonite, two-clinopyroxene stability, high-pressure petrology, Sorkhan, Iran.

[§] *E-mail address*: roob@geo.uni-potsdam.de

INTRODUCTION

The beauty and wide-ranging expression of jade have held a special attraction for mankind for thousands of years. Jade is, strictly speaking, a generic term for two different types of rocks, nephrite and jadeitite, dominated either by amphibole or jadeite, respectively. Nephrites range mainly from medium to dark green or grey-green, but can also be white, yellowish or reddish. Rarer, somewhat harder, and therefore regarded as more precious, jadeitites display hues that include green, but also white or pink, and red, black, brown, violet, lavender and blue. In both rock types, the way the color is distributed varies considerably. Jadeitites, and especially blue jadeitites, are rather uncommon rocks. Generally, they are associated with subduction-related serpentinites along fault zones (Harlow 2001) and generally interpreted as crystallizing from hydrous fluids derived from dehydration of subducted slabs at high P and T (Manning 1998, Harlow 1994, Johnson & Harlow 1999). In an extensive review on the color of jadeitite, Howard (2002) reported that most samples of so-called blue jadeitite are in fact blue-green. Truly blue and lavender jadeitites are reported from only a few localities around the world. The most renowned occurrences are the Olmec blue jade (Quebrada Seca, Guatemala, Harlow *et al.* 2004) and blue jade from Ohmi–Kotaki in Japan (Chihara 1971). Lavender jadeitite is known from Tavsanli in Western Anatolia, Turkey (Okay 1984), and green and bluish jadeites are well known in Burma (Chhibber 1934). Up to now, the blue color has been assigned to titanium-rich omphacite (Harlow *et al.* 2004), which occurs in clots and veins in jadeitite. The Guatemalan "blue jade" contains assemblages of omphacite, phengite, titanite, zircon, allanite and rutile, whereas the Japanese "blue jade" comprises assemblages of omphacite, titanite, albite, and analcime. The Tavsanli "lavender jade" is rather homogeneous, but a patchy pattern allows the identification of an alkaline magmatic precursor that was metasomatized to jadeitite (Okay 1997). This jadeitite contains quartz, jadeite, K-feldspar, lawsonite, and aegirine.

We report here a new locality of clear, sky-blue jadeitite occurring near Sorkhan, in a blueschist belt of southeastern Iran. The jadeitite occurs in a vein system along a serpentinite – magnesite contact. From this study, we discuss the composition and the stability of one- and two-pyroxene-bearing jadeitites.

GEOLOGY OF THE SORKHAN SECTOR

In southeastern Iran, Mesozoic ophiolitic mélanges occur between the Zagros fold-and-thrust belt (representing the Arabian plate) and the metamorphic rocks and volcanic arc sequences of the Sanandaj–Sirjan Zone (northern continental margin of Tethys) (Fig. 1A). The colored mélanges of the suture zone are complex and contain metamorphic as well as non-metamorphic sequences. Near Sorkhan, a belt containing high-pressure (HP) metamorphic rocks is juxtaposed against a sequence of non-metamorphic ultramafic to mafic rocks, considered to be of Precambrian age. Whole-rock ^{40}K–^{40}Ar ages on gabbros and diabases near Sorkhan (Fig. 1B) range from 130 to 140 Ma, and the amphibolites east of Sorkhan are 202 Ma old (Ghasemi *et al.* 2002).

North of this area, at Ashin-e-Bala (Fig. 1B), serpentinized harzburgites contain talc, anthophyllite and enstatite (Sabzehei 1974), indicating a post-serpentinization metamorphic overprint. These meta-ultramafic rocks correlate with the Abdasht ultramafic suite, where chromian spinel associated with reddish chromian clinochlore is mined; it occurs in a series of amphibolites, micaschists, marbles and greenschists that are mapped as glaucophane schists (Hadjabad quadrangle). In this rock series, blue amphibole can be recognized only locally, and lower amphibolite facies to upper greenschist facies successions are prevalent. In mafic rocks, green amphibole commonly shows a thin rim of glaucophane, indicating that all rocks underwent a HP–LT overprint. Micaschists near Ashin-e-Bala have been dated at around 80.7 ± 1.5 Ma (^{40}K–^{40}Ar, phengite; Ghasemi *et al.* 2002) and around 93 ± 5.9 Ma by ^{40}Ar/^{39}Ar (Agard *et al.* 2006). To the north of the meta-ultramafic suite, another rock association comprises a serpentinite mélange, composed of blueschists (in some cases, pure glaucophanites), marbles and garnet micaschists in a serpentinite-rich matrix. These rocks, mapped as serpentinite schists, underwent metamorphism to the lawsonite blueschist to lawsonite eclogite facies (Sabzehei 1974).

Along the northern contacts of these metamorphosed ultramafic bodies to the serpentinite mélange with blueschists, large lenses of magnesite occur. One of these lenses contains veins of white and blue jadeitite. The jadeitite veins, completely enclosed in the magnesite lenses, are 5 to 15 cm wide, and show symmetrical zoning. The outer portions are snow white, whereas the inner portions (*ca.* 10 cm for the widest veins) show a clear, sky-blue color.

PETROGRAPHY AND CHEMICAL COMPOSITION

In the blueschist mélange (serpentinite schists) north of the Sorkhan region, mafic rocks contain glaucophane, albite, phengite and, in some cases, lawsonite and rutile. In rare cases, omphacite was found. Within this metamorphic belt, large bodies of ultramafic rocks with lenses of chromite are widespread. These mainly metadunitic rocks contain talc, enstatite, forsterite and antigorite. The associated chromitite is rich in reddish chromian clinochlore. Along the contacts of the ultramafic rocks against the blueschist-bearing serpentinite mélange, lenses of magnesite (30 to 80 m by 5 to 20 m)

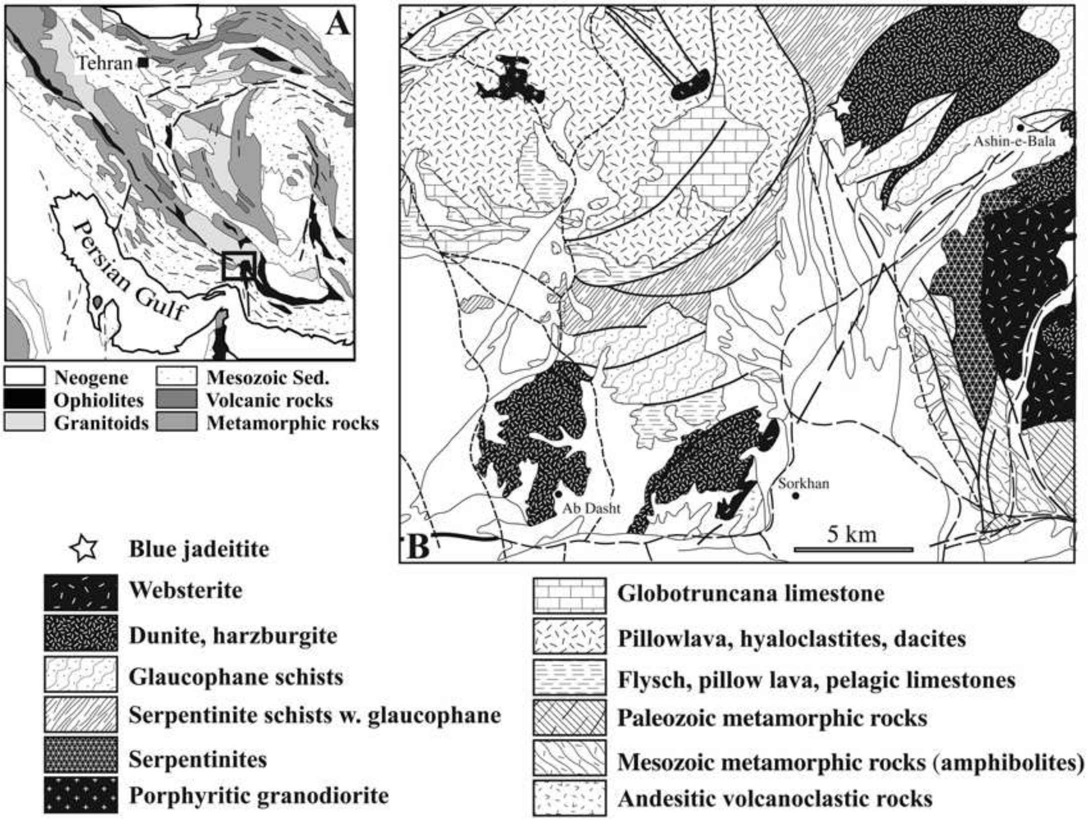

FIG. 1. A. Geological map of Iran showing the major ophiolite sutures, with the study area shown as an inset. B. Geological map of the Sorkhan area showing the ultramafic bodies containing magnesite lenses and the mélange formed by glaucophane-bearing serpentinite schists. The star indicates the sample locality.

which are mined, developed metasomatically. In one of these magnesite lenses, veins of jadeitite (Fig. 2) show white and sky-blue colors.

The minerals forming the bluish veins were analyzed (Table 1) with an electron microprobe (Camebax, SX100) at the GeoForschunsgZentrum (GFZ) in Potsdam (15 kV, 20 nA, ZAF correction procedure) using natural and synthetic mineral standards: wollastonite (Si, Ca), orthoclase (Al, K), albite (Na), periclase (Mg), rhodonite (Mn), hematite (Fe), rutile (Ti), chromite (Cr). Raman spectra were obtained on a LabRam HR800 with green laser light (Nd:YAG laser, 532 nm) at the Institute of Geosciences Potsdam. The major-element composition of blue parts of the jadeitite vein was determined by X-ray fluorescence at GFZ (Philips XRF–PW2400) using fused lithium tetraborate disks. The estimated precision is better than 1–3%. Concentrations of trace elements were determined by inductively coupled plasma – mass spectrometry (ICP–MS) using solution nebulization after mixed-acid digestion (HF–$HClO_4$) under pressure (Dulsky 2001).

The blue jadeitite contains the assemblage jadeite – lawsonite – amphibole plus minor Ba-bearing K-feldspar and white mica. The outer part of the jadeitite veins, generally white, is partly retrogressed and show flakes of white mica and secondary albite. The inner part of the veins, with a blue hue, is extremely fresh; the blue as well as white parts are composed of jadeite. The modal composition of the jadeitite attains up to 99 vol.% jadeite. Jadeite has a dusty aspect and contains many two-phase (liquid – gas) fluid inclusions. In the fine-grained (0.1–0.2 mm) jadeitite matrix, additional minerals such as lawsonite, katophorite and Ba-bearing K-feldspar occur. Minute crystals of Ba-bearing K-feldspar are dispersed randomly; no textural relations could be deciphered. Lawsonite is found along white veinlets (0.1–0.2 mm wide) cutting the blue jadeite matrix as well as in the matrix (Fig. 3)

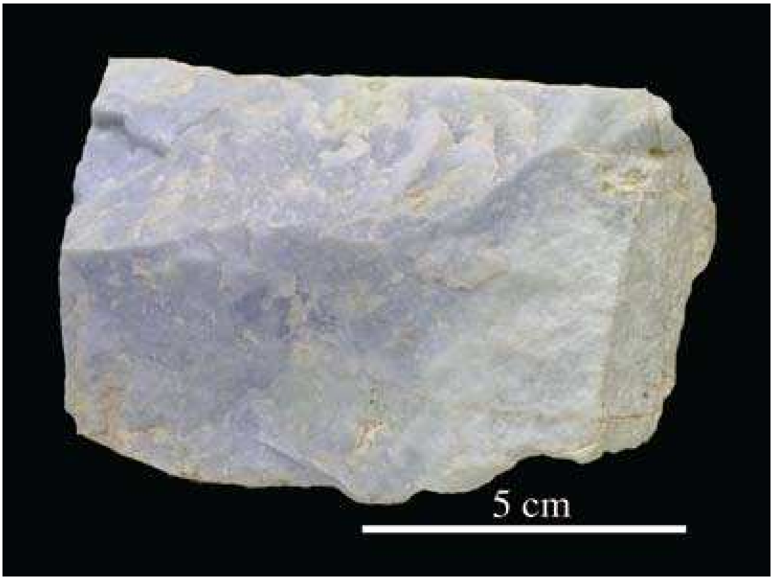

FIG. 2. Photograph of a sample composed of blue and white jadeite.

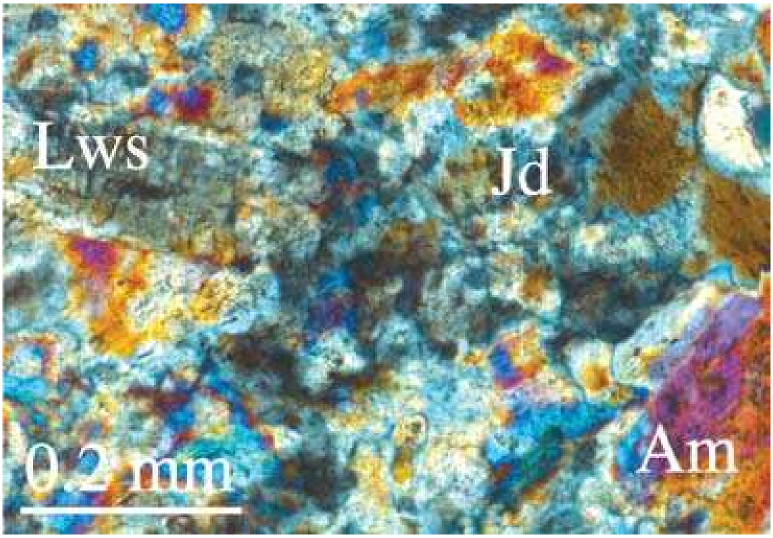

FIG. 3. Photomicrograph of lawsonite and katophorite (Am) in the jadeite-dominant matrix of the Sorkhan blue jadeitite.

and has been characterized both by Raman spectroscopy and electron-microprobe analysis. From the fact that these veinlets are filled with jadeite, we conclude that these are closely related to the processes forming the jadeitite matrix. Later, significantly larger cracks (0.5 –1.2 mm wide) cutting white and blue jadeitite as well as the veinlets contain albite (Fig. 2). A third conspicuous mineral forming small clots within the jadeitite matrix microscopically shows all the textural features of amphibole. The observed amphibole is colorless in thin section, shows moderate birefringence ($n_\gamma - n_\alpha \approx 0.02$), oblique extinction ($X, Y, Z \wedge c$ in plane // (010) ≈ 15°). Rutile has not been found.

In the Sorkhan jadeitites, clinopyroxene is close to the ideal jadeite composition (Table 1). All pyroxene analyses (>50) show jadeite contents close to the end-member composition, ranging from 90 to 99.5 mol.% Jd. Both, FeO_{tot} (0.04 to 0.5 wt%) and TiO_2 (0 to 0.1 wt%) are lower than those reported for blue jadeitites elsewhere. Electron-microprobe analyses of the amphibole reveal the composition $Na(Na_{1.1}Ca_{0.9})Mg_{4.1}Fe_{0.1}(Al_{0.7})(Si_{7.5}Al_{0.5})O_{22}(OH)_2$, with a very small amount of Fe and a slight excess of Mg. The composition fits on the join eckermannite $[NaNa_2(Mg_4Al)Si_8O_{22}(OH)_2]$ – magnesiokatophorite $[Na(NaCa)(Mg_4Al)Si_7AlO_{22}(OH)_2]$.

TABLE 1. SELECTED ANALYTICAL DATA PERTAINING TO THE SORKHAN BLUE JADEITITE

	Pyroxene						Amphibole
	04-6	04-12	04-15	04-27			1-19
SiO_2 wt%	59.26	59.07	59.08	59.18			54.94
TiO_2	0.00	0.11	0.04	0.06			0.30
Al_2O_3	25.13	23.54	24.74	24.87			7.46
FeO	0.04	0.47	0.22	0.11			1.19
MnO	0.00	0.01	0.00	0.00			0.01
MgO	0.47	1.32	0.70	0.41			20.08
CaO	0.01	2.02	0.92	0.32			6.00
Na_2O	14.88	13.65	14.13	14.66			7.98
K_2O	0.00	0.00	0.03	0.00			0.20
Cr_2O_3	0.00	0.00	0.00	0.00			0.01
Total	99.60	100.19	99.85	99.60			98.15
Si *apfu*	2.001	2.004	2.004	2.006	*T*	Si	7.527
^{IV}Al	0.000	0.000	0.000	0.000		^{IV}Al	0.473
Σ*T*	2.001	2.004	2.004	2.006		Fe^{3+}	0.000
^{VI}Al	1.000	0.941	0.989	0.994		Ti	0.000
Fe^{2+}	0.001	0.013	0.006	0.003		Σ*T*	8.000
Fe^{3+}	0.000	0.000	0.000	0.000	*C*	$Al^{(VI)}$	0.731
Mg	0.000	0.043	0.003	0.002		Ti	0.031
Ti	0.000	0.003	0.001	0.001		Fe^{3+}	0.000
Cr	0.000	0.000	0.000	0.000		Cr	0.001
Σ*M*1	1.000	1.000	1.000	1.000		Mg	4.100
Na	0.974	0.898	0.929	0.963		Fe^{2+}	0.136
Ca	0.000	0.074	0.033	0.012		Mn	0.001
Mg	0.025	0.024	0.032	0.019		Ca	0.000
Σ*M*2	0.999	0.996	0.994	0.994		Σ*C*	5.000
					B	Ca	0.881
Jd %	98.73	92.13	96.13	98.21		Na	1.119
Di %	1.21	6.57	3.28	1.56		Σ*B*	2.000
Hd %	0.06	1.30	0.59	0.23	*A*	Ca	0.000
Ae %	0.00	0.00	0.00	0.00		Na	0.999
						K	0.035
						Σ*A*	1.034

Blue jadeitite ZAG 04X Mw (N = 4)

SiO_2 wt%	56.50	Li ppm	57.7	Cd ppm	0.03
TiO_2	0.15	Sc	9	Sn	0.06
Al_2O_3	23.00	Co	3	Sb	0.04
Fe_2O_3*	0.27	Ni	62	Cs	3.0
MnO	0.00	Cu	2	Ta	2.0
MgO	1.52	Ga	5.5	Tl	0.05
CaO	2.90	Rb	1.4	Pb	0.13
Na_2O	12.82	Sr	49	Th	9.6
K_2O	0.01	Nb	15	U	0.50
		Mo	0.41		
Total	97.17				

* All Fe is calculated as Fe_2O_3. Analyses of jadeite and amphibole were done with an electron microprobe. The bulk-rock analysis of blue jadeitite (1 cm^3) was done by X-ray fluorescence spectrometry, whereas the concentrations of the trace elements were established by inductively coupled plasma – mass spectrometry (ICP–MS).

The Sorkhan jadeitite is very pure. A bulk chemical analysis (Table 1) on a 1 cm^3 sample of blue jadeitite yielded very low Ti (0.15 wt% TiO_2), whereas Mg (1.52 wt% MgO), Fe (0.27 wt% Fe_2O_3) and Ca (2.90 wt% CaO) are relatively high. Except for Ti, these minor amounts of major elements can be attributed to the accessory phases such as amphibole, feldspar and lawsonite, although Ca is incorporated to some extent into jadeite also X_{Ca}^{jd} in the range 0.05–0.1). A Ti-phase was not observed in the high-pressure assemblage. There are very low concentrations of the trace elements (Table 1) except for Ni, Sr and Li (62, 49, 57 and 7 ppm, respectively), which may relate to the same accessory phases mentioned above.

STABILITY FIELD OF THE BLUE JADEITE

Using thermodynamic calculations [DOMINO–THERIAK, Gibbs free energy minimization; De Capitani & Brown (1987), database of Berman (1988)] and the measured bulk-rock composition of the sample, we can estimate the field of stability of blue jadeite. Our results (Fig. 4) show some remarkable features. The P–T space is divided into two areas. The low-temperature side of the diagram (Figs. 4a–c, white) comprises assemblages with two clinopyroxenes, omphacite and jadeite, in assemblages with lawsonite – chlorite – glaucophane, lawsonite–amphibole, lawsonite – glaucophane – paragonite, quartz – lawsonite – paragonite, lawsonite–paragonite or garnet – feldspar – paragonite, depending on pressure. The high-temperature assemblages (Figs. 4a–c, grey) contain only a single clinopyroxene phase, namely jadeite in similar assemblages containing garnet, feldspar, clinozoisite, paragonite, lawsonite, glaucophane or amphibole.

Our calculation produces a relatively small, well-constrained field for the stability of the assemblage jadeite – lawsonite – magnesiokatophorite (Fig. 4a, dark grey; Jd–Lws–Am) at about 1.6 GPa and 420°C. The diagram shows the existence of a stability field for the assemblage two clinopyroxenes (Jd–Omph) – lawsonite – amphibole on the low-temperature side of the peak assemblage (Fig. 4a). By comparing the observed modal (Fig. 4b) and chemical (Fig. 4c) compositions of the samples of blue jadeitite [Jd–Lws–Mkt] with our grid, an excellent fit is obvious. This assemblage contains very high modal amounts of pyroxene [94% of the rock] (Fig. 4b) and the calculated composition of the pyroxene [X^{Jd}_{Jd} 90 mol.%] (Fig. 4c) fits the electron-microprobe measurements [$X^{Jd}_{Jd} > 90$ mol. %].

Interestingly, the modal amount and composition of jadeite in the natural sample coincide very well with the petrogenetic grid (Table 2), whereas for amphibole, a slight but significant misfit is obvious. We attribute it to the fact that thermodynamic properties are not determined for all amphibole end-members and solid

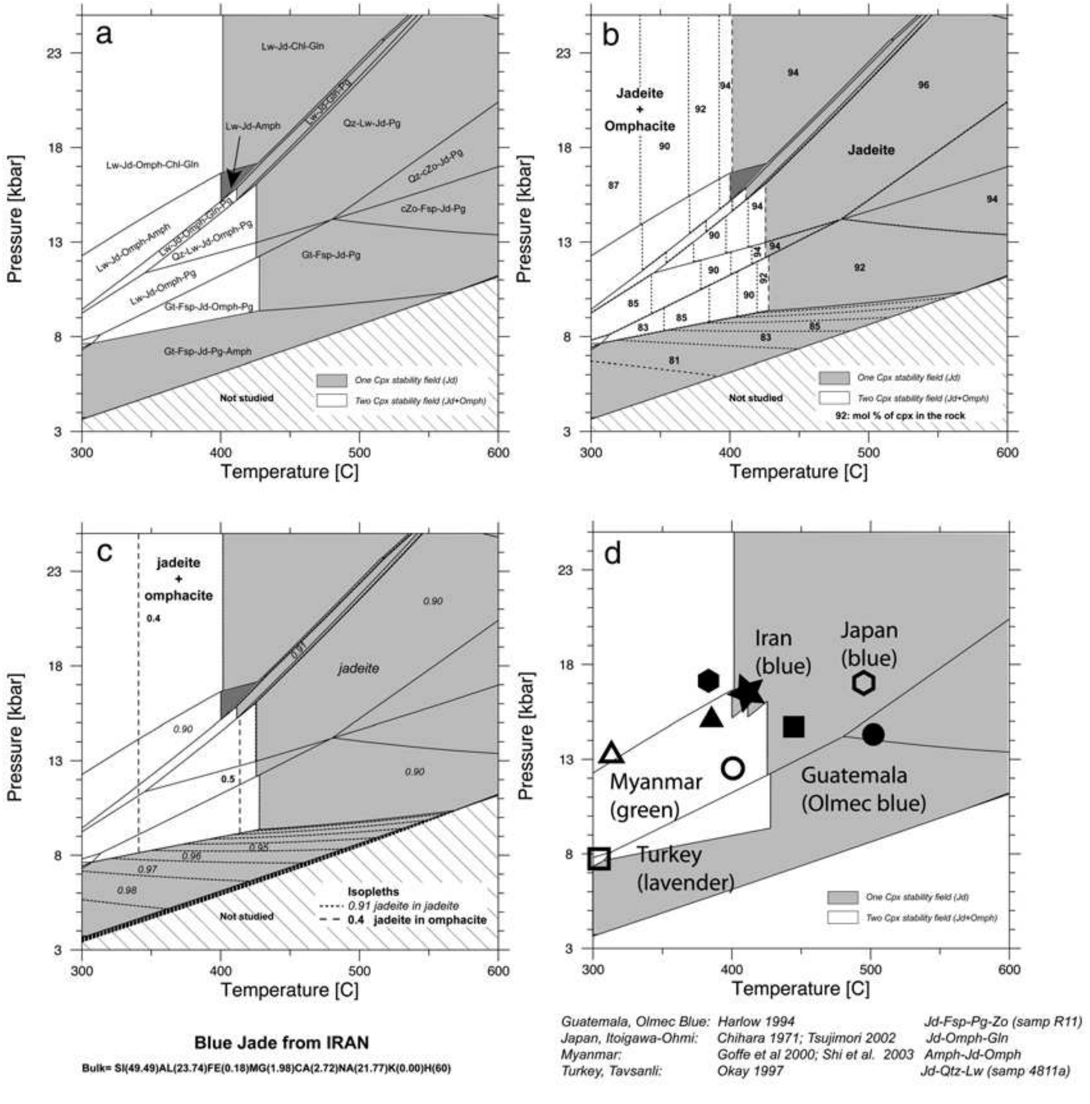

FIG. 4. Pressure – temperature diagrams calculated with the DOMINO software (de Capitani 1994) using the bulk-rock composition of the blue jadeitite. a) Phase relations showing stability domains with one or two clinopyroxenes. b) Molar abundance of clinopyroxene in the rock. Note the increase of the modal abundance of clinopyroxene with temperature under high-pressure conditions. c) Content of the jadeite end-member in clinopyroxene, given for jadeite and omphacite. d) Comparison of P–T conditions from the literature (open symbols) with new P–T estimates (filled symbols) according to our calculations based on published data on mineral assemblages.

solutions (*e.g.*, Ghiorso & Evans 2002, Dale *et al.* 2005). Bearing in mind the problem of thermodynamic properties of amphiboles, the fit produced in our calculation is astonishingly good. We believe that these calculations illustrate the excellent quality of the database used (Berman 1988), including its mixing and activity models. In addition, the P–T conditions deduced from the Sorkhan jadeitite fit well with the values deduced for the adjacent lawsonite blueschists (Agard *et al.* 2006). We thus are quite confident about the significance of our P–T grid, although pressures and temperatures deduced for the Sorkhan area differ significantly from published values for similar metasomatic rocks with blue jadeitite, e.g.: Itoigawa-Ohmi in Japan (Morishita 2005), Guatemala (Harlow 1994) or Myanmar (Goffé *et al.* 2000, Shi *et al.* 2003). We showed that observations similar

TABLE 2. COMPARISON OF MINERAL COMPOSITIONS CALCULATED WITH THE DOMINO–THERIAK SOFTWARE FROM THERMODYNAMIC DATA WITH MEASURED (EMPA) VALUES IN THE BLUE JADEITITE

	Amphibole		Pyroxene	
	calc.	meas.	calc.	meas.*
Si *apfu*	7.80	7.53	2.00	2.03
Al	2.10	1.21	0.93	0.94
Fe		0.16	0.01	0.03
Mg	3.10	4.10	0.07	0.03
Ca	0.20	0.88	0.07	0.03
Na	1.90	2.12	0.93	0.94

* Measured values are taken from Table 1 (the average of four compositions in the case of the pyroxene.

to the ones recently published for lawsonite eclogites from Olmec, Guatemala (Tsujimori *et al.* 2005) can be reproduced accurately, and therefore used the new thermodynamic calculations to re-estimate P–T conditions of the other occurrences of blue jadeitite based on their mineralogy (Fig. 4d).

All new P–T estimates for other localities of blue jadeitite based on the published mineralogy (Japan: Morishita 2005, Myanmar: Goffé *et al.* 2000, Shi *et al.* 2003, Turkey: Okay 1997) range from 0.8 GPa, 300°C to 1.8 GPa, 500°C (Fig. 4d). For example, the occurrence of zoisite in the blue jadeitite from Olmec, Guatemala (circle; Harlow 1994) implies higher-temperature conditions than originally estimated. Such results show that the Ca-phase (Zo, in the case of the blue jadeitite from Olmec) is stable during high-pressure conditions instead of being a breakdown product of jadeite (with albite) during retrogression. The Ca-phase (omphacite, zoisite or lawsonite) seems to be the determining criterion regarding the temperature conditions: occurrence of two clinopyroxenes (omphacite in equilibrium with jadeite) implies a stability field at low-temperature conditions (≤400–425°C) independently of pressure, whereas assemblages of jadeite in equilibrium with lawsonite or zoisite are stable under higher-temperature conditions (≥400–425°C).

DISCUSSION AND CONCLUSIONS

The Ti content of the Sorkhan clinopyroxene (jadeite) measured by electron microprobe (0–0.1 wt%) is significantly lower than that reported for clinopyroxene in "blue jade" elsewhere. For the Olmec samples, Guatemala, the Ti content of clinopyroxene (omphacite) ranges from 1.0 to 1.8 wt% TiO_2, and the Fe content is close to 3.5 wt% FeO, whereas in the Japanese "blue jade", the Ti content of omphacite reaches up to 7.5 wt% TiO_2. Omphacite without Ti or with very low Ti content is green (Harlow *et al.* 2003). The Shorkan jadeitite is blue, contains jadeite and no rutile. The question about the color remains open. The occurrence of a katophoritic amphibole confirms earlier observations. Both eckermannite (Bauer 1895, Lacroix 1930, Chhibber 1934, Mével & Kienast 1986, Harlow & Olds 1987, Htein & Naing 1994, Colombo *et al.* 2000) and magnesiokatophorite (Reynard & Ballèvre 1988, Dong *et al.* 1996) have been reported from jadeitites. The composition of the Shoran amphibole fits on the join eckermannite – magnesiokatophorite reported for jadeitite from Myanmar (Shi *et al.* 2003). The fact that it actually contains about 50 mol.% of each end member supports their conclusion that no miscibility gap is evident.

The occurrence of one (Iran, Guatemala, Japan) or two clinopyroxenes (Myanmar) in jadeitites is linked to temperature conditions. At temperatures below 400°C, two clinopyroxenes, jadeite and omphacite, are formed, whereas above 400°C, only one clinopyroxene together with a Ca-rich phase, lawsonite or zoisite, forms (Fig. 4).

The stability of one or two clinopyroxenes in a high-pressure paragenesis was discussed as function either of crystallographic ordering during retrogression (Tsujimori *et al.* 2005) or a compositional gap (*e.g.*, Mével & Kienast 1986, Myanmar; Matsumoto & Hirajima 2005, Sesia). We demonstrate that for blue jadeitite, the P–T conditions control this feature.

Despite the fact that only one clinopyroxene formed in the blue jadeitite from Sorkhan, temperature conditions were low, as indicated by the stability of lawsonite. In the case of the Olmec jadeitite, zoisite is stable as an additional Ca-phase, demonstrating that there, the jadeitite formed at higher temperatures. On the basis of our new grid and the descriptions of their respective mineralogy, we suggest revised P–T estimates for other occurrences of metasomatic blue jadeitite, all clustering close to 400°C and 1.6 GPa, except for the Olmec jadeitite, which experienced higher temperatures.

It is interesting to note that the Sorkhan locality is situated close to the famous prehistoric cultural site Arrata, near Jiroft in Iran. Although blue stones have always been considered as precious and Afghan lapis lazuli has been traded westward since the Iron Age, so far no blue jade has been found at Arrata.

ACKNOWLEDGEMENTS

We thank Bruno Goffé for stimulating discussions and a lively introduction on Myanmar and two-clinopyroxene jadeitites. Antje Müller and Onna Appel helped in the labs. We thank Dr. Rhede and the GFZ-Potsdam for the use of their EMPA facilities. The Iranian authorities and DAAD are thanked for making field work possible. The paper benefitted from the reviews of D. Schwarz and R. Guistetto and comments by R.F. Martin. Paddy O'Brien's scientific comments and his help as a native English speaker are appreciated. Last but not least, we thank Hakime, who ran our field camp in Abdasht.

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Received November 27, 2006, revised manuscript accepted July 30, 2007.