Contrib Mineral Petrol (1982) 79:361–367

Contributions to
Mineralogy and
Petrology

Incipient Blueschist Metamorphism and Metasomatism in the Tavşanlı Region, Northwest Turkey

A.I. Okay*
Department of Earth Sciences, Downing Place, Cambridge CB2 3E, England

Abstract. Volcano-sedimentary rocks in an imbricate tectonic zone around a peridotite massif have been studied northeast of the town of Tavşanlı in Northwest Turkey. Basic volcanic rocks, which are the dominant rock type in this zone, show incipient blueschist metamorphism and associated metasomatism. While the igneous textures of the volcanic rocks are retained, augites are partially to completely replaced by sodic pyroxene, and plagioclase is albitised resulting in rocks with 6–8 wt.% Na_2O. The volcanic rocks are cross-cut by numerous veins of calcite, aragonite, quartz, pumpellyite, albite, lawsonite and sodic pyroxene. Pelagic limestones, which are interbedded with the basic volcanic rocks, consist of coarse aragonite grains showing partial replacement by calcite. The occurrence of aragonite, lawsonite and albite indicates conditions of metamorphism for the whole zone in the range of 5–8 kb and 150–200° C. Metasomatism, probably related to high pressure serpentinization, has occurred contemporaneously with the incipient high pressure metamorphism.

* *Present address:* Temel Araştirmalar, Mineral Research and Exploration Institute (MTA), Ankara, Turkey

Introduction

This is the third in a sequence of papers describing the blueschist facies rocks from Northwest Turkey. The two previous papers (Okay 1980a, b) have described the glaucophane-lawsonite and lawsonite zone blueschists in the Tavşanlı region. This paper deals with the volcano-sedimentary rocks, which are the protoliths of the blueschists and show incipient high pressure, low temperature metamorphism and associated metasomatism.

As shown in Fig. 1 several east-west oriented tectonic zones can be recognised in Northwest Turkey. In the south is a dome shaped HT/LP metamorphic complex (Menderes Massif) with a gneissic core and a cover of greenschist facies rocks. To the north the Menderes Massif is in tectonic contact with a 20 km wide peridotite zone consisting largely of harzburgites and dunites with very minor gabbro bodies (Lisenbee 1971; Okay 1980c). The peridotites are cut by a swarm of gabbroic dykes, now all boudinaged and saussuritised, and are thrust over a tectonised complex of spilites, cherts, isolated serpentinite bodies, greywackes and shales. Palaeontological (Özkoçak 1969, p. 76; Lisenbee 1971, p. 355) and radiometric (Çoğulu and Krummenacher

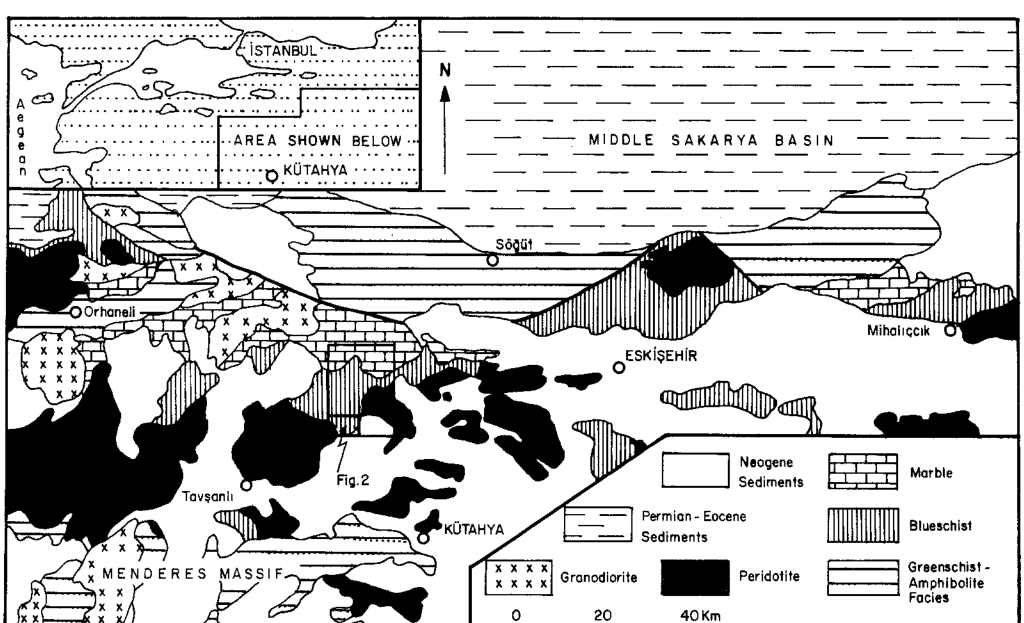

Fig. 1. Generalised geotectonic map of Northwest Turkey, compiled from the geological maps of Turkey (Maden Tetkik ve Arama Enst. 1963, 1964) and the author's own observations

0010-7999/82/0079/0361/$01.40

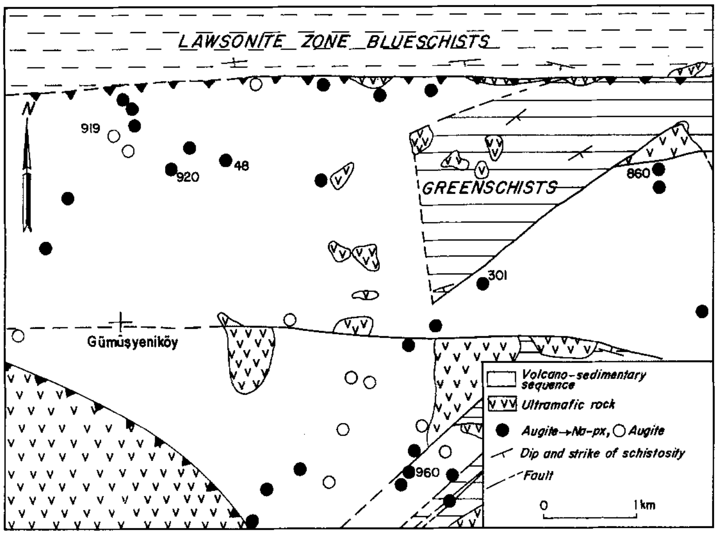

Fig. 2. Simplified geological map of the Gümüşyeniköy area, Tavşanlı, Northwest Turkey. Only the major shear zones and large serpentinite outcrops are shown. Blank areas consist of closely intercalated pelagic sediments, basic volcanic rocks and serpentinite, all of which are incipiently metamorphosed and metasomatised. *Circles* indicate specimen localities; *filled circles:* augite partially or completely replaced by sodic pyroxene; *open circles:* no such replacement. *Numbers* of the analysed specimens are also indicated

1967) data indicate an Upper Cretaceous depositional age for some of these rocks. Blueschist metamorphism is not evident in this volcano-sedimentary sequence and HP/LT minerals, such as lawsonite and aragonite, occur in the amygdales and veins in the volcanic rocks. The incipient nature of this blueschist metamorphism in the Tavşanlı region is the subject of this paper.

Lawsonite and glaucophane-lawsonite zone blueschists are produced by the progressive metamorphism of these volcano-sedimentary rocks. They form an extensive metamorphic belt of varying thickness and lie on a very thick marble series. The interfolded blueschist-marble contacts, the parallel lineation directions in marbles and blueschists, and small inliers of blueschists in the marble (Okay 1980b, 1981) all show that the marbles have undergone the same HP/LT metamorphism as the blueschists. Massive, white marble is in steep tectonic contact, marked by extensive brecciation, linear serpentinites and Tertiary dacite intrusions, with a high temperature/moderate pressure metamorphic belt. The major rock types in this belt are basic volcanic rocks, pelites and limestones. Progressive metamorphic zones from zeolite to amphibolite facies have been mapped in this belt near Sögüt (Yilmaz 1979). As the metamorphic age of the HT/MP metamorphic belt is not well established, it is not yet clear whether it forms a paired metamorphic belt together with the Upper Cretaceous blueschists. The HT/MP metamorphic belt is in thrust contact to the north with the granitic basement of the Middle Sakarya Zone. The Middle Sakarya Zone consists of an autochthonous epicontinental sedimentary sequence ranging in age from Permian to Eocene (Altinli 1975; Saner 1980).

There are Tertiary granodiorite intrusions superimposed on this east-west oriented tectonic pattern (Ataman 1974) and an extensive cover of Neogene lacustrine sediments and volcanics.

Geology and Rock Types

Volcano-sedimentary sequences with small serpentinite bodies characterised by a chaotic internal structure are common along the margins of the peridotite massifs in Northwest Turkey. Although such sequences are called ophiolite or ophiolitic melange by some workers (Lisenbee 1971; Kaya 1972), the repeated intercalation of sedimentary and volcanic rocks, lack of sheeted dyke complexes and gabbros does not merit the current usage of the term ophiolite for these rocks. Two major areas of such rocks have been recognised in the Tavşanlı area: the one north of the village of Ketenlik occurs as a tectonic klippe among the lawsonite zone blueschists (Okay 1980b, Yeniköy Group of Fig. 5). A larger area lies to the south around the village of Gümüşyeniköy. This paper deals mainly with the volcano-sedimentary rocks in the Gümüşyeniköy area, although both areas are lithologically and structurally very similar.

The volcano-sedimentary rocks of the Gümüşyeniköy area occur directly below a large peridotite massif in an imbricate tectonic zone of 2–3 km width (Fig. 2). The dominant lithologies in this zone are rocks of the Steinmann trinity: basic volcanic rocks, radiolarian cherts and serpentinites in conjunction with red and green shales, greywackes, manganese deposits, pink thinly-bedded limestones, keratophyres and exotic blocks of white limestone. This group of rocks is characterised by a rich lithological variety; several different rock types can often be seen interbedded over a distance of ten meters, any single lithology is rarely more than ten meters thick (cf. Okay 1981, Fig. 4). The whole zone is strongly tectonised with large numbers of shear zones marked by serpentinite and talc outcrops; slivers of greenschists occur as fault-bounded blocks. Only the major shear zones and the larger serpentinite bodies are shown in Fig. 2. The strong tectonism and lithological heterogeneity makes the mapping of individual rock types impossible on a 1:25000 scale (cf. Kaya 1972, Fig. 10).

In the field the rocks of the volcano-sedimentary sequence appear unmetamorposed and do not show penetrative deformation. Volcanic rocks are the most common rock type. They form massive green flows interbedded with radiolarian cherts and redgreen shales, and include dolerites, spilites, pyroclastics and minor amounts of keratophyres, trachybasalts and more acidic differentiates. Pillow lavas are very rare. Clinopyroxene compositions from the volcanic rocks indicate that most of them were subalkaline, although some kaersutite-bearing spilites and pyroclastics have marked alkaline affinities (Okay 1980c).

Serpentinite occurs as bodies of various sizes ranging

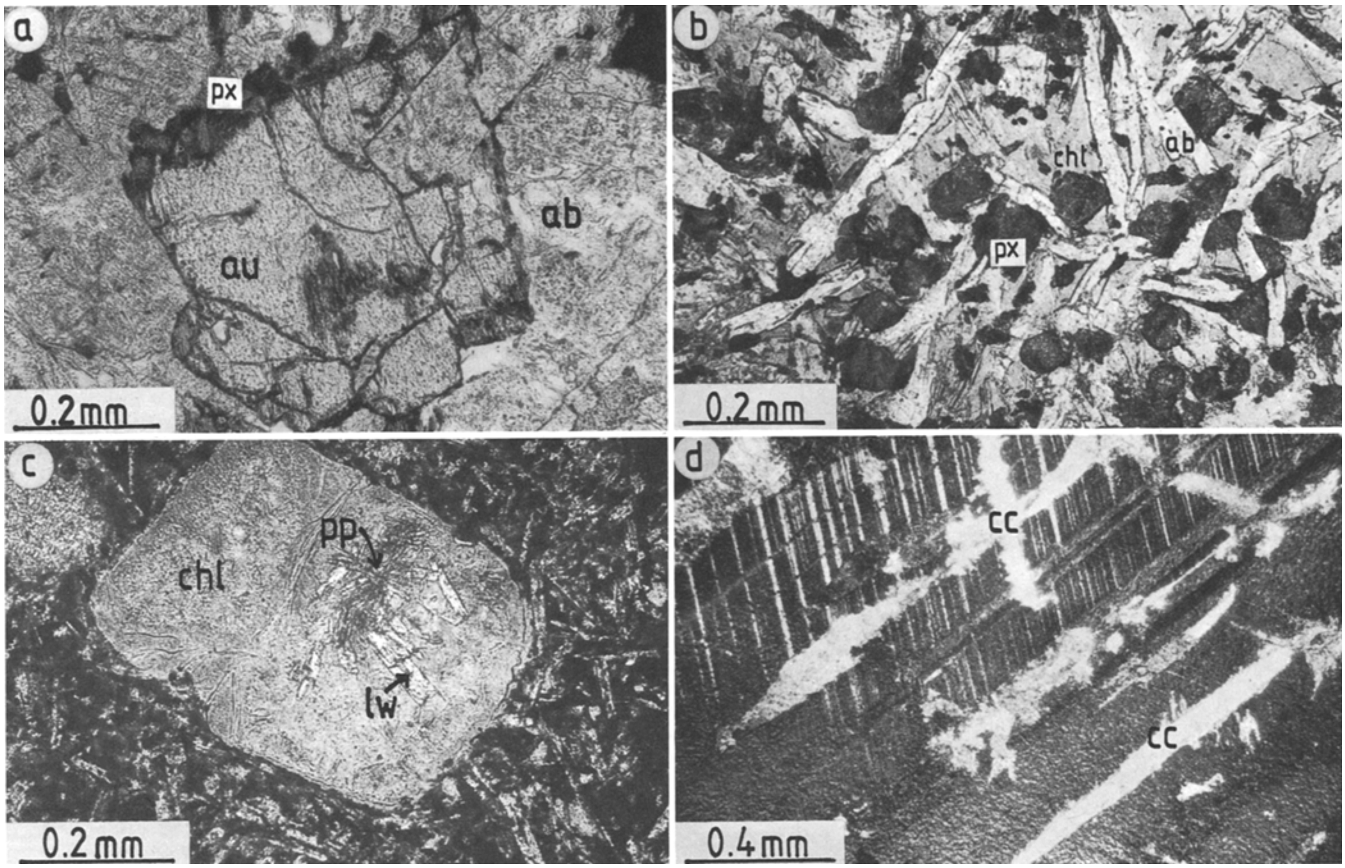

Fig. 3a–d. Photomicrographs from the incipiently metamorphosed zone: **a** Augite partially replaced by sodic pyroxene (*px*, dark areas) with leucoxene and albite (*ab*) in a dolerite (K48). **b** Completely metasomatised dolerite (K920) with sodic pyroxene pseudomorphs (*px*) after augite, albite (*ab*) and interstitial chlorite (*chl*). **c** Lawsonite laths (*lw*), fibrous pumpellyite (*pp*) and chlorite (*chl*) in an amygdale of a fine-grained spilite (K864). The groundmass shows no signs of any metamorpism. **d** Aragonite marble; a large aragonite grain (in extinction position) is expitaxically and partially replaced by elongate lamellae of calcite (cc). Aragonite shows the characteristic (110) multiple twinning parallel to the replacing calcite lamellae

from a few meters to a few kilometers concentrated along the shear zones. In the few samples examined, antigorite is the main serpentinite mineral. Veins of andradite garnet occur frequently in these serpentinites.

Greenschists associated with serpentinites occur in two wedge shaped areas. Well-marked thrust planes separate them from the volcano-sedimentary rocks. The dominant rock type is a strongly foliated metabasite with a mineral assemblage of actinolite + epidote + chlorite + albite + quartz. Some greenschist metabasites contain relict lawsonite or pumpellyite.

Method

Mineral compositions were determined for twelve elements (Na, Ca, K, Fe, Mg, Mn, V, Ni, Cr, Ti, Al, Si) using an energy dispersive electronprobe with a Harwell Si (Li) detector and pulse processor. The correction procedures are given by Sweatmann and Long (1969). The method for estimating ferric iron in sodic pyroxene is given in an earlier paper (Okay 1978). Whole rock analysis were made on an X-ray spectrometer using fused discs with a lithium tetraborate flux. Na and K were determined by flame photometry and FeO by titration.

Petrography and Mineralogy

Fifty-five specimens of basic volcanic rocks, including pyroclastic flows, dolerites and spilites, from the vicinity of the village of Gümüşyeniköy were investigated petrographically (Fig. 2). All retain their igneous textures and their essential mineralogy consists of augite altering to sodic pyroxene, albite (An_0), chlorite and leucoxene. In many specimens pumpellyite occurs as irregular stringers in large albitised plagioclase grains. Epidote and actinolite characteristic of many spilites, are absent.

Topotactic Replacement of Augite by Sodic Pyroxene

The replacement of augite by greenish-yellow sodic pyroxene in the volcanic rocks is variable in extent, ranging from thin rims and veins (Fig. 3a) to complete pseudomorphs (Fig. 3b). On a regional scale 44 out of 55 spilites contain such replacement textures (Fig. 2). The replacement of augite by sodic pyroxene has occurred topotactically, on an ion by ion basis, leaving the igneous texture intact (Carpenter and Okay 1978). This replacement process seems to be controlled by the available mineral structure; in an alkali basalt kaersutite has rims of blue sodic amphibole, whereas titanaugite in the same rock has been replaced by sodic

Table 1. Representative mineral analyses

	Sodic Pyroxene				Pumpellyite		Albite	Lawsonite		Chlorite			Garnet	
	K48	K860	vein	K919/2	K160	K733/1	K733/1 vein	K301	K960	K36	K48	K485/2	K301 core	rim
SiO_2	52.75	53.46	57.00	52.54	37.04	37.93	68.17	38.30	37.17	30.31	30.81	30.67	38.00	35.76
TiO_2	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	0.61	2.39	8.01	2.11	21.97	24.17	19.41	27.92	29.72	14.39	13.53	14.37	9.91	1.54
FeO*	26.18	24.24	18.61	22.19	8.59	6.01	0.00	5.25	2.23	24.57	24.29	23.59	16.12	27.29
MgO	1.84	1.14	0.77	2.91	2.26	2.40	0.00	0.00	0.00	16.93	14.56	16.06	0.00	0.00
MnO	0.36	0.24	0.00	0.22	0.17	0.25	0.00	0.00	0.00	0.23	0.25	0.32	0.44	0.23
CaO	6.90	3.53	2.26	7.36	22.31	23.07	0.11	17.32	16.99	0.24	0.80	0.83	34.95	33.69
Na_2O	10.13	12.73	13.81	9.92	0.00	0.00	12.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.00
Total	98.77	98.01	100.46	97.25	92.34	93.83	99.92	88.79	86.11	86.67	84.48	85.84	99.42	98.51
Number of cations per														
	4 cations				16 cations		8 O	5 cations		28 oxygens			12 cations	
Si	2.00	1.99	2.03	2.00	6.07	6.07	2.99	2.03	2.01	6.41	6.70	6.51	3.01	2.97
Al^4	*0.00*	*0.01*	*0.00*	*0.00*	*0.00*	*0.00*	*0.01*	*0.00*	*0.00*	*1.59*	*1.30*	*1.49*	*0.00*	*0.03*
Al^6	0.03	0.10	0.34	0.10	4.25	4.56	0.99	1.75	1.90	1.99	2.17	2.11	0.92	0.08
Ti	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.71	0.76	0.55	0.63	0.75	0.44	0.00	0.23	0.10	4.34	4.42	4.19	*1.08*	*1.89*
Fe^{2+}	0.12	0.00	0.00	0.07	0.43	0.37	0.00	0.00	0.00				0.00	0.00
Mg	0.10	0.06	0.04	0.16	0.56	0.57	0.00	0.00	0.00	5.33	4.72	5.08	0.00	0.00
Mn	*0.01*	*0.01*	*0.00*	*0.01*	*0.02*	*0.03*	0.00	*0.00*	*0.00*	0.04	0.05	0.06	0.03	0.03
	0.97	*0.94*	*0.93*	*0.97*	*6.01*	*5.97*		*1.98*	*2.00*					
Ca	0.28	0.14	0.08	0.30	3.92	3.96	0.005	0.99	0.99	0.06	0.19	0.19	2.96	3.00
Na	0.74	0.92	0.99	0.73	0.00	0.00	1.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
	1.02	*1.06*	*1.07*	*1.03*	*3.92*	*3.96*	*5.04*	*0.99*	*0.99*	*19.76*	*19.62*	*19.63*	*2.99*	*3.03*
Jd	3	10	34	10	* Total iron							Andr.	54	96
Ac	71	76	55	63	as FeO							Gross.	46	4
Au	26	14	11	27										

pyroxene. Sodic pyroxene also occurs as acicular crystalls in monomineralic veins.

Sodic pyroxene compositions from eight rocks are plotted in the acmite-jadeite-augite ternary diagram in Fig. 4 and four sodic pyroxene analyses are shown in Table 1. Sodic pyroxenes from the incipiently metamorphosed zone have high acmite components (generally over 50%) and are compositionally similar to the sodic pyroxenes from the lawsonite zone metabasites. Conversely sodic pyroxenes from the glaucophane-lawsonite zone metabasites show a wider range of compositions (Fig. 4). A lack of omphacitic compositions is characteristic of all three metamorphic zones in the Tavşanlı region.

The main chemical changes involved in the constant volume replacement of augite by sodic pyroxene are an increase in sodium and ferric iron, and a concomitant decrease in calcium and magnesium. For a specific case (sample K48):

$$100\text{ g augite} + 9.44\text{ g } Na_2O + 13.52\text{ g } Fe_2O_3 + 2.65\text{ g } SiO_2 + 0.08\text{ g } Al_2O_3 + 0.38\text{ g } O_2 = 103.85\text{ g sodic pyroxene } (Jd_8Ac_{59}Au_{33}) + 9.90\text{ g CaO} + 11.88\text{ g MgO} + 0.59\text{ g } TiO_2.$$

However, as the composition of the replacing sodic pyroxene changes (Fig. 4), the chemical balance in the isovolume replacement is variable.

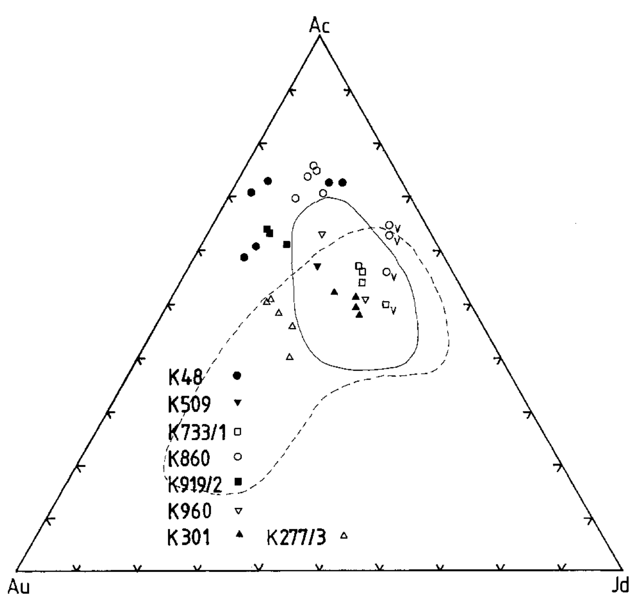

Fig. 4. Sodic pyroxene compositions from the incipiently metamorphosed basic volcanic rocks plotted on the acmite-jadeite-augite diagram. Subscript *v* indicates compositions of sodic pyroxenes from the veins. Compositional fields of sodic pyroxenes from the lawsonite zone (*continuous lines*) and glaucophane-lawsonite zone (*dashed lines*) metabasites are also indicated

Table 2. Analyses of three metasomatised basic volcanic rocks. Oxides are normalised to 100 wt.%

	K960	K775	K920
SiO_2	50.02	50.66	53.82
TiO_2	0.97	2.10	1.57
Al_2O_3	16.10	16.22	14.79
Fe_2O_3	5.63	5.52	5.03
FeO	3.74	3.81	6.05
MgO	5.92	4.89	4.69
MnO	0.15	0.19	0.21
CaO	7.05	5.04	2.90
Na_2O	6.09	6.19	7.79
K_2O	0.20	0.14	0.20
P_2O_5	0.11	0.75	0.10
H_2O	4.02	4.49	2.85

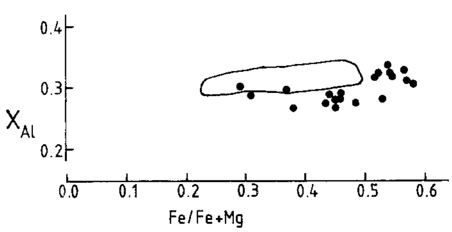

Fig. 5. Chlorite compositions from the incipiently metamorphosed basic volcanic rocks plotted in terms of their Fe/Fe + Mg and Al/Al + Fe + Mg ratios. Compositional fields of chlorites from the lawsonite zone metabasites are also indicated

Three analyses of strongly metasomatised basic volcanic rocks are shown in Table 2. Compared with basalts or spilites, the analyses show increases in Na_2O (from 1–4.5 wt.% in basalts and spilites to 6–8 wt.%), SiO_2 and Fe_2O_3, but do not indicate a marked change in the total iron content. Magnetite is absent in these rocks, and iron seems to have been redistributed to sodic pyroxene. There are corresponding decreases in CaO and MgO. Al_2O_3 and TiO_2 have apparently stayed fairly constant. TiO_2 and some of the released calcium is retained in leucoxene, which forms small inclusions in sodic pyroxene pseudomorphs.

Chlorite is the major secondary mineral found in the interstices of plagioclase and pyroxene crystals (Fig. 3b), and in amygdales (Fig. 3c). It forms fine-grained aggregates or bladed crystals. Some of the chlorites show relatively high interference colours apparently related to their relatively high potassium and calcium contents (Table 1). Compositionally, chlorites from the incipiently metamorphosed basic volcanic rocks are slightly less aluminous and more siliceous than lawsonite and glaucophane-lawsonite zone chlorites (Fig. 5, Table 1). Phengite is absent in these rocks and only appears in the lawsonite zone metabasites as slender crystals embedded in chlorite.

All plagioclase in the volcanic rocks is completely albitised. Albitised plagioclase is cloudy and quite distinctive from the fresh, invariably twinned albite in the veins. It has less than 1% anorthite component and minor amounts of FeO (0.1 to 0.5 wt.%).

Mineralogy of the Veins and Amygdales in the Basic Volcanic Rocks

The basic volcanic rocks are cross-cut by numerous veins of calcium carbonate (in 26 samples out of 55), quartz (in 18), pumpellyite (in 18), albite (in 13), lawsonite (in 6), sodic pyroxene (in 4) and garnet (in 2). Composite veins containing two to four minerals are fairly common with quartz-carbonate and carbonate-albite being the most frequent combinations. More complex veins of pumpellyite-lawsonite-quartz-calcite (K265), pumpellyite-garnet (K301) and albite-lawsonite are also present. Carbonate minerals, pumpellyite, chlorite and lawsonite also occur frequently in amygdales (Fig. 3c).

Aragonite was identified as the primary $CaCO_3$ polymorph in 12 specimens from its multiple (110) twin lamellae (Fig. 3d); it forms large (1-10 mm) crystals in the veins and amygdales, and is being replaced by small, irregular stringers of calcite. In some rocks extraordinary anastomosing veins composed of single crystals of aragonite up to 26 mm long and only 0.1 mm wide are present.

Pumpellyite is present in almost every sample either in amygdales (Fig. 3c), in veins or as pale yellow microgranular patches overgrowing the glassy matrix of the volcanic rocks; in some glassy volcanic rocks it makes up 70% of the mode. In veins and amygdales it forms aggregates of radiating acicular crystals showing anomalous interference colours. Pumpellyites have virtually constant Mg contents and show restricted Al for Fe^{3+} substitution (Table 1). Compositionally they are similar to analysed pumpellyites from other low-grade metamorphic terrains (cf. Coombs et al. 1976).

Albite in the veins occurs as fresh idioblastic crystals invariable showing simple or multiple twinning. It has less than 1% anorthite component (Table 1).

Lawsonite apart from its usual tabular shape, displays unusual acicular and bow-tie habits in the veins. It is found in the amygdales of a volcanic rock, that otherwise appears unmetamorposed, in association with chlorite and pumpellyite (Fig. 3c). Analysed lawsonites from the incipiently metamorphosed zone have consistently higher Fe_2O_3 contents (1.5–5.5 wt.%) than lawsonites from the glaucophane-lawsonite and lawsonite zones (Table 1).

Garnets of the andradite-grossular series occur in two strongly metasomatised volcanic rocks in association with pumpellyite and sodic pyroxene. They show discontinuous zoning profiles with intermediate andradite-grossular cores and pink andradite rims (Table 1). Garnets of similar composition are also found in talcs and serpentinites of the incipiently metamorphosed zone and of the lawsonite zone (Okay 1980b).

Aragonitised Limestone

If the ambient pressures in the volcano-sedimentary rocks were high enough to stabilize aragonite in the veins and amygdales of basic volcanic rocks, then one would similarly expect calcite in limestones, which are often interbedded with basic volcanic rocks, to have transformed to aragonite. Indeed, all the petrographically examined limestones consist of coarse crystals of aragonite showing various degrees of replacement by calcite.

Two types of aragonitised limestone have been recognised petrographically. In the first type the sedimentary fabric of the limestone with the radiolaria tests, fossil fragments and clay fraction is perfectly preserved. However, the whole biomicritic groundmass now consists of several centimeters large grains of aragonite. In the second type the limestone is recrystallised and consists of very large clear aragonite grains partially and epitaxially replaced by smaller grains of calcite (Fig. 3d).

Discussion

The presence of aragonite as well recrystallised large grains in the volcanic rocks and limestones of the Tavşanlı region and its association with lawsonite and sodic pyroxene indicate that the volcano-sedimentary sequence has undergone an incipient HP/LT metamorphism. The absence of jadeite and zeolites and the presence of aragonite, albite and lawsonite in some of the basic volcanic rocks indicates pressures of 5 to 8 kbars and temperatures 150–200° C during the incipient metamorphism (Newton and Smith 1967; Hlabse and Kleppa 1968; Johannes and Puhan 1971).

In the incipiently metamorphosed volcanic rocks metasomatism is evidenced by the sodic pyroxene pseudomorphs after augite coexisting with albite and chlorite. The presence of similar sodic pyroxene pseudomorphs after augite in lawsonite zone metabasites, which occur north of the main east-west trending thrust (Fig. 2), point out to the close relationship between HP/LT metamorphism and metasomatism. However, in the lawsonite zone metabasites, where lawsonite is abundant and albite absent, there is no evidence of sodium metasomatism.

The presence of greenschist tectonic slices within the volcano-sedimentary sequence (Fig. 2) indicate that the incipient HP/LT metamorphism and metasomatism has occurred prior to the strong tectonism. The imbrication of the whole sequence can be related to the emplacement of the large ultramafic slab (Fig. 1) on the volcano-sedimentary rocks. There is an important difference between the main body of peridotite, which is only partially serpentinised and has chrysotile as the main serpentine mineral, and the smaller completely serpentinised bodies within the volcano-sedimentary sequence, which contain antigorite. Several meters thick reaction zones of pumpellyite, albite, sodic pyroxene, chlorite etc. have been found at the contact zones of serpentinites in Northwest Turkey (Okay 1980c) and in California (Chesterman 1960; Leonardes and Fyfe 1967). If the small ultrabasic bodies in the Tavşanlı region were part of the volcano-sedimentary sequence and were serpentinised during the HP/LT metamorphism, then they would be expected to produce similar metasomatic zones during their serpentinization. This might explain the presence of extremely metasomatised pumpellyite-andradite rock types or "unmetasomatised" spilites, which by analogy must have formed respectively near or far away from the serpentinite contacts. However, the strong late tectonism has mostly obliterated the field evidence linking these rocks to serpentinite contacts.

Metasomatism has often been cited as an active agent in the formation of the blueschists (e.g. Gresens 1969). Thus Taliaferro (1943) ascribed the formation of blueschists to the "local introduction of soda, iron and magnesium into sandstones, shales, cherts and basalts near contacts with ultrabasic intrusions". However, experimental studies have demonstrated convincingly the high pressure stabilities of blueschist minerals, and in general it is true that blueschist metamorphism is isochemical. Nevertheless, as documented here, very low-grade incipiently high pressure metamorphosed rocks show extensive metasomatic effects. It seems that although blueschists are not produced by metasomatism, metasomatism is widespread in low-grade blueschist facies conditions.

Summary of the Blueschist Metamorphic Zones in the Tavşanlı Region

In Northwest Turkey a thick sequence of intercalated basic volcanic rocks, cherts and shales has undergone blueschist metamorphism. Based on the metabasic mineral assemblage and textures, observed both in the field and under the microscope, three blueschist metamorphic zones have been differentiated in the Tavşanlı region.

The lowest grade zone, decribed in this paper, consists of a closely intercalated volcano-sedimentary sequence. The high pressure metamorphism was incipient and is chiefly evidenced in the vein and amygdale mineralogy, which includes pumpellyite, aragonite, lawsonite, albite and sodic pyroxene. Associated with this incipient metamorphism, there has been extensive sodium metasomatism involving topotactic replacement of augite by sodic pyroxene.

The incipiently metamorphosed volcano-sedimentary rocks tectonically overlie the lawsonite zone blueschists. Rock types in the lawsonite zone are similar to those of the incipiently metamorphosed zone and appear similarly unmetamorphosed in the field. However, under the microscope the metabasic rocks consist of sodic pyroxene pseudomorphs after augite, lawsonite and chlorite. The original texture has been largely retained and there is little penetrative deformation (Okay 1980b).

Metabasites of the lawsonite zone pass along a mapped isograd into the rocks of the glaucophane-lawsonite zone with the development of sodic amphibole from a reaction involving chlorite, sodic pyroxene and quartz. Metabasites of the glaucophane-lawsonite zone have lost all their primary igneous features and are often schistose. They are characterised by the dominance of sodic amphibole + lawsonite in the mineral assemblage (Okay 1980a). The common occurrence of relict sodic pyroxene, often in reaction relation to sodic amphibole, indicates that the glaucophane-lawsonite zone rocks have passed through the lawsonite zone stage.

Although there is ample evidence that lawsonite and glaucophane-lawsonite zones represent a progressive increase in metamorphic grade, the ubiquitous metasomatism in the incipiently metamorphosed rocks indicates that these rocks underwent a different set of physical conditions.

Acknowledgements. I thank R. Colston and J. Spray for reviewing the manuscript. This work was carried out while in receipt of a grant from the Mineral Research and Exploration Institute of Turkey (MTA), which is gratefully acknowledged.

References

Altınlı E (1975) Geology of the Middle Sakarya River (Turkey). In: Congress of Earth Sciences. MTA Publications, Ankara, pp 161–197

Ataman G (1974) Revue géochronologique des massifs plutoniques et métamorphiques de l'Anatolie. Hacettepe Bull Natl Sci Eng 3:75–88

Carpenter MA, Okay AI (1978) Topotactic replacement of augite by omphacite in a blueschist rock from NW Turkey. Mineral Mag 42:435–438

Chesterman CW (1960) Intrusive ultrabasic rocks and their metamorphic relationships at Leach Lake Mountain, Mendocino County, California. Rept Intern Geol Congr 21st Session Norden 13:208–215

Coombs DS, Nakamura Y, Vuagnat M (1976) Pumpellyite-actinolite facies schists of the Taveyanne formation near Loeche, Valais, Switzerland. J Petrol 17:440–471
Çogulu E, Krummenacher D (1967) Problèmes géochronométriques dans la partie NW de l'Anatolie Centrale (Turquie). Schweiz Mineral Petrogr Mitt 47:825–833
Gresens RL (1969) Blueschist alteration during serpentinization. Contrib Mineral Petrol 24:93–113
Hlapse T, Kleppa OJ (1968) The thermochemistry of jadeite. Am Mineral 53:123–133
Johannes W, Puhan D (1971) The calcite-aragonite transition, reinvestigated. Contrib Mineral Petrol 31:28–38
Kaya O (1972) Outlines of the ophiolite question in the Tavşanlı region (in Turkish). Bull Geol Soc Turk 15:26–108
Leonardos OH, Fyfe WS (1967) Serpentinites and associated albitites Moccosin Quadrangle, California. Am J Sci 265:609–618
Lisenbee A (1971) The Orhaneli ultramafic-gabbro thrust sheet and its surroundings. In: Campbell AS (ed), Geology and history of Turkey. Petr Expl Soc Libya, Tripoli, pp 349–368
Maden Tetkik ve Arama Enst (1963) Geological maps of Turkey; Ankara sheet. MTA Publications, Ankara
Maden Tetkik ve Arama Enst (1964) Geological maps of Turkey; İstanbul, Zonguldak, İzmir sheets. MTA Publications, Ankara
Newton RC, Smith JV (1967) Investigations concerning the breakdown of albite at depth in the earth. J Geol 75:268–286
Okay AI (1978) Sodic pyroxenes from metabasites in the eastern Mediterranean. Contrib Mineral Petrol 68:7–11
Okay AI (1980a) Mineralogy, petrology and phase relations of glaucophane-lawsonite zone blueschists from the Tavşanlı region, Nortwest Turkey. Contrib Mineral Petrol 72:243–255
Okay AI (1980b) Lawsonite zone blueschists and a sodic amphibole producing reaction in the Tavşanlı region, Northwest Turkey. Contrib Mineral Petrol 75:179–186
Okay AI (1980c) The petrology of blueschists in Northwest Turkey, Northeast of Tavşanlı. Ph D Thesis (unpubl). University of Cambridge
Okay AI (1981) The geology and blueschist metamorphism of the ophiolites in Northwest Turkey (Tavşanlı-Kütahya) (in Turkish). Bull Geol Soc Turk 24:85–95
Özkoçak O (1969) Etude géologique du massif ultrabasic d'Orhaneli et de sa proche bordure. These (unpubl). University of Paris
Saner S (1980) The paleogeographical interpretation of the Mudurnu-Göynücek basin based on the depositional features of the Jurassic and later sediments (in Turkish). Bull Geol Soc Turk 23:39–52
Sweatman RR, Long JVP (1969) Quantitative electronprobe microanalysis of rock forming minerals. J Petrol 10:332–379
Taliaferra WL (1943) Franciscan-Knoxville problem. Am Assoc Petroleum Geol Bull 27:109–219
Yılmaz Y (1979) Polyphase metamorphism of the Söğüt-Bilecik region and its tectonic implications. Bull Geol Soc Turk 22:85–100

Accepted May 13, 1982