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CONTACT-METAMORPHIC LAPIS LAZULI: THE ITALIAN MOUNTAIN DEPOSITS, COLORADO

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ABSTRACT

In the Italian Mountain area (Colorado), lazurite formed early, apparently in equilibrium with diopside, forsterite and perhaps barian phlogopite, whereas grossular formed later. Thomsonite represents a late-stage hydrothermal alteration of lazurite. Thomsonite, chlorite and hisingerite, just beyond the lapis-lazuli zones, are also late minerals. The deposits resulted from contact metamorphism of subgreywacke and dolostone of the Pennsylvanian Belden Formation by quartz monzonite and quartz diorite of the Tertiary Italian Mountain stocks. Na, S, Ba, Sr, Cl and F were introduced in aqueous magmatic fluids. Early barite may have localized later barian phlogopite and lazurite. Late introduction of Fe produced the Fe-rich silicates, unusual in lapis lazuli. Peak metamorphic conditions were P ~ 250 bars, T ~ 600°C.

Keywords: lapis lazuli, Italian Mountain, Colorado, Belden Formation, contact metamorphism, lazurite, metasomatism.

SOMMAIRE

Dans la région dite Italian Mountain (Colorado), la lazurite s'est formée tôt, vraisemblablement en équilibre avec le diopside, la forstérite et peut-être le phlogopite barifère; le grossulaire a cristallisé plus tard. La thomsonite représente un stade tardif d'altération hydrothermale de la lazurite. Thomsonite, chlorite et hisingérite, minéraux que l'on trouve au-delà des zones à lapis lazuli, sont aussi de formation tardive. Ces gisements résultent du métamorphisme de subgrauwackes et de dolomies du Belden (Pennsylvanien) au contact de monzonite et diorite quartzifères de plutons tertiaires. Na, S, Ba, Sr, Cl et F proviennent de fluides magmatiques aqueux. Une première génération de barytine aurait amorcé la cristallisation ultérieure de phlogopite barifère et de lazurite. L'introduction tardive du fer a produit des silicates de Fe, rares dans le lapis lazuli. Les conditions métamorphiques ont atteint environ 250 bars et 600°C.

(Traduit par la Rédaction)

Mots-clés: lapis lazuli, Italian Mountain, Colorado, formation Belden, métamorphisme de contact, lazurite, métasomatisme.

INTRODUCTION

Lapis lazuli comprises a group of rare metamorphic rocks having lazurite as an essential constituent. The most common type, composed of coarse-grained lazurite and diopside and interbedded with marble, is remote from any igneous rock that can be related to its formation. Recently, Kulke (1976a, b) and Hogarth & Griffin (1978) proposed that rocks of this type in Afghanistan and on Baffin Island constitute meta-evaporites recrystallized during high-grade regional metamorphism. The deposits in Gunnison County, central Colorado, differ in many respects from these. They are comparatively fine grained, other minerals are significant, and the deposits lie within the contact-metamorphic aureole around an intrusive rock.

Several occurrences are known, clustered in two localities known as North Italian and Italian Mountains. The lapis is restricted to impure marble layers of the Belden Formation (Pennsylvanian) near their contact with quartz monzonite and quartz diorite of the Italian Mountain stocks (Tertiary). Locations are given in Figure 1.

Both localities are within the contact-metamorphic aureole of the Northern Intrusive Centre, the youngest of the three stocks comprising the Italian Mountain Complex (Cunningham 1976). This northern stock is a composite intrusive body with an outer zone of melanogranodiorite and quartz monzonite. The inner part, made up of porphyritic quartz monzonite, is pierced by a plug of finer grained quartz monzonite, interpreted as a vent facies by Cunningham. The Italian Mountain occurrences (Fig. 1) probably were also affected by contact metamorphism during the intrusion of the quartz diorite

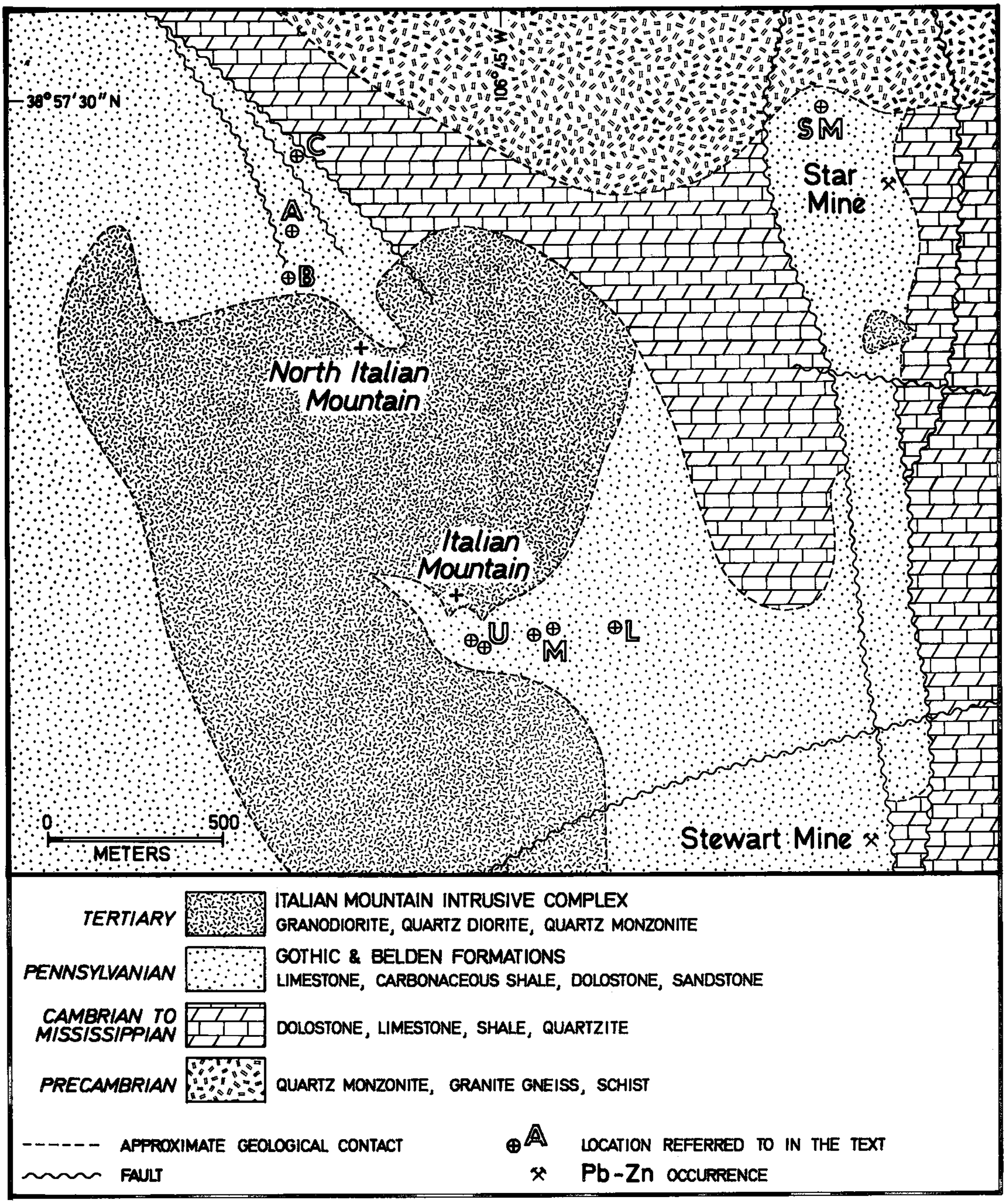

FIG. 1. Geology and lapis lazuli occurrences in the Italian Mountain area. The north-trending faults are part of the Castle Creek Fault system. Geology after Cunningham (1973, 1976), with minor alterations after Truebe (1977) and personal observations by D.D. Hogarth. Drawing by E.W. Hearn (University of Ottawa).

from the Central Intrusive Centre, the oldest of the three.

The north-northwest-trending Castle Creek fault zone (Fig. 1) predates the intrusive rocks, and probably provided channels for movement of fluids during and after the metamorphism.

The faults were reactivated in late Cenozoic time (Cunningham 1976).

North Italian Mountain

Locality A, the Anderson occurrence, has produced a small amount of gem-quality lapis lazuli over a number of years (Rosencrans 1941, Truebe 1977). The productive horizon has been stripped in an east-northeast direction for 30 m. A pit, said to expose some lapis lazuli but now filled with debris, lies on strike 17 m to the west. The rock dips 30 to 40° to the north and into the slope. Lapis lazuli of varying color is restricted to a layer of dark tactite one m thick. This layer is itself divided into centimetric to millimetric lazurite-rich sublayers alternating with lazurite-free horizons.

Lapis lazuli also occurs at two nearby localities. To the south, blocks of lapis are found in a talus slope within an area of 0.4 hectares. At one point (locality B) an exposure of pale lapis several metres across appears to be in place. The closest outcrop of the Italian Mountain stock is 40 m away.

The other locality, the Christopher occurrence, is on a spur of the steep northeast-facing slope of the mountain (locality C). The rock here is intensely brecciated and composed of contorted fragments of limestone and mudstone cemented by coarse carbonate. It was mapped as part of the Castle Creek fault zone by Cunningham (1976). Somewhat separated blocks of white, lazurite-bearing silicated limestone up to 25 cm long are found in the breccia over an area of 8 m^2. Some of the pieces contain sky-blue patches, but normally the color is very pale. Yellow and grey blocks are lazurite-free.

Italian Mountain

The Truebe occurrences are on Italian Mountain about 1½ km south of the Anderson occurrence. Lapis lazuli is found in place at the upper occurrence (U in Fig. 1), and in float probably derived from nearby bedrock at the middle (M) and lower (L) occurrences; adjacent blue marble, *in situ*, contains scattered lazurite grains.

The upper occurrence is the largest and best exposed. Here lazurite occurs in marble over a width of 1.5 m but lapis lazuli of good color does not appear to exceed 2.5 cm in width. The lazurite-bearing layer can be followed about 30 m down the slope of the mountain. It is cut off by a fault to the east, but lazurite reappears in blue marble (specimen U20, Table 1) 15 m still further to the east.

MINERALOGY

The Italian Mountain peaks have long been known as prolific mineral localities. Cross & Shannon (1927) described 28 minerals from tactite developed in the Belden limestone. Although lazurite was not noted, the general assemblage is closely similar to that described below. Grossular, diopside, scapolite, thomsonite, sphene, calcite, pyrite and barite, described by Cross & Shannon, were also noted in our studies.

The lapis lazuli occurrences comprise an interesting mineral suite, but the size of grains and their morphological development are no rival for the minerals described by Cross & Shannon. Rather, the grains are roundish to irregular and microcrystalline, with individuals down to and beyond the resolution of the microscope. Specimens from the Christopher occurrence are extremely fine grained and quite unsuitable for point counting. The size of grains was a prime consideration in selecting specimens for microprobe analysis.

From 54 thin-sectioned specimens of the lapis

TABLE 1. MODAL ANALYSES OF MARBLE, LAPIS LAZULI AND TACTITE FROM ITALIAN MOUNTAIN AREA

	North Italian Mountain							Italian Mountain		
	A2	A4	A10	A25	B26	C2	C3	U20	U23	U24
Calcite	0.7	70.3	52.9	85.0	69.2	+	+	89.5	40.2	47.4
Diopside	59.5	18.3	22.8	12.0	13.5	+	+	5.6	3.7	24.7
Forsterite	0.0					+	+			
Lazurite	0.0	8.3	19.4	2.8	10.9		+	3.1	21.5	19.2
Thomsonite	12.3						+			
Phlogopite	11.3	0.0	1.2	0.0	0.4			0.0	0.0	0.9
Grossularite	0.0	0.0	0.9	0.0	0.0		+	0.0	4.0	0.0
Saponite	0.0	0.1	0.1	Tr	Tr			0.0	26.7	0.0
Chlorite	0.9	0.0	0.0	0.0	0.0			0.0	0.0	0.0
Hisingerite	4.1	0.0	0.0	0.0	0.0			0.0	0.0	0.0
Pyrite & Pyrrhotite	11.2	2.8	2.7	0.1	6.0	+	+	1.8	3.9	7.6
Sphalerite	0.0	0.2	Tr	0.1	0.1			Tr	Tr	0.1

Specimen prefixes A, B, C and U correspond to locations in Figure 1.

A2	Nodule in light yellow tactite, 0.3 m above lapis lazuli layer. Collected.
A4	Pale blue lapis lazuli. West end trench. Collected.
A10	Bright blue lapis lazuli. Loose material on side of trench. Collected.
A25	Pale blue-green lapis lazuli. J. Adams, donor.
B26	Pale blue lapis lazuli. Centre of small outcrop. Collected.
C2	Gray tactite. Immediately east of lapis-lazuli deposit. Collected.
C3	Pale blue lapis lazuli from part of outcrop richest in lazurite. Collected.
U20	Blue marble. 10 m east of lapis lazuli. H. Truebe, donor.
U23	Pale blue lapis lazuli. Pit 25. Collected.
U24	Bright blue lapis lazuli. Pit 24. H. Truebe, donor.

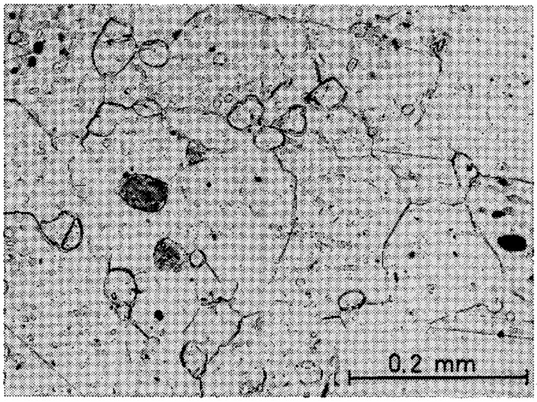

FIG. 2. Anhedral grains of diopside and forsterite lying mainly along the grain boundaries of calcite, plus random grains of lazurite (dark grey to black). Specimen A25. Plane-polarized light. Photograph by Georges Ben-Tchavtchavadze (University of Ottawa).

lazuli occurrences, 10 were selected for modal analyses (Table 1). Of these, 8 were suitable for microprobe work. Seven microprobe analyses were made at Carleton University (P. Morton, analyst) with a Cambridge MK 5 probe using a defocused beam. Wherever possible several grains (up to 8) *per* section were analyzed; analytical data are an average of these values. Standards were a combination of synthetic and natural minerals. Data were reduced using a modified EMPADR VII program (Rucklidge & Gasparrini 1969). One sample (A25) was analyzed in Oslo with an ARL-EMX microprobe using the methods outlined by Hogarth & Griffin (1976, 1978).

All 10 specimens, as well as 2 specimens of relatively unaltered Belden Formation, were analyzed for 19 constituents by wet or instrumental methods under the direction of E.J. Brooker, X-ray Assay Laboratories, Toronto.

Lazurite crystals are optically isotropic and normally anhedral or ovoid, although tiny dodecahedra were noted in thin section U24 (Italian Mountain) and in a thin section from locality B (North Italian Mountain). Grains greater than 0.1 mm in diameter are rare.

Lazurite is distributed as inclusions in calcite (Fig. 2) and as many larger and paler crystals located on grain boundaries. It shows a slight tendency to be associated with other silicates, and some lazurite grains are rimmed by diopside. Pyroxene and olivine, where coarse grained, are in contact with lazurite.

In Table 2, lazurite has been assigned the formula $(Na,Ca,K,Fe,Mg)_{8-x}(Si,Al)_{12}O_{24}(SO_4,Cl,F)_2$. Sulfur valencies were not resolved, and the surplus of S+Cl+F possibly is due to a replacement of O^{2-} by S^{2-} as proposed by Hogarth & Griffin (1976). Compared to lazurite from most known occurrences, potassium in these samples (0.3% K_2O) is high. Similarly, chlorine is high at Italian Mountain (0.4% Cl) but normal at North Italian Mountain (0.1–0.2% Cl). Light- and dark-colored varieties (B26, Table 2) show little difference in chemical composition; the color variations must be ascribed to different species of sulfur ions within the lazurite structure, as previously proposed by Hogarth & Griffin (1976).

Both *diopside* and *forsterite* are present as somewhat rounded grains and in thin section

TABLE 2. MICROPROBE ANALYSES OF LAZURITE

	Italian Mountain				North Italian Mountain					
	U23		U24		A25		B26 (pale blue)		B26 (bright blue)	
SiO_2	33.00		32.29		31.7		33.36		33.94	
TiO_2	-		-		0.01		0.0		0.0	
Al_2O_3	27.68		27.95		26.4		27.05		27.59	
FeO*	0.05		0.03		0.0		0.04		0.02	
MnO	0.0		-		-		-		-	
MgO	0.0		0.05		0.06		0.06		0.09	
CaO	8.25		8.36		8.20		8.67		9.24	
Na_2O	16.99		16.36		16.2		13.45		13.08	
K_2O	0.28		0.27		0.32		0.24		0.31	
SO_3**	14.06		15.74		17.01		16.55		17.40	
Cl	0.42		0.38		0.14		0.19		0.19	
F	-		0.0		-		0.05		0.07	
	100.73		101.05		100.04		99.66		101.93	
Ions based on 12 Z cations										
Si	6.034	12.00	5.940	12.00	6.056	12.00	6.136	12.00	6.128	12.00
Al	5.966		6.060		5.944		5.864		5.872	
Fe	0.008	7.71	0.005	7.56	0.000	7.77	0.006	6.58	0.003	6.47
Mn	0.000		-		-		-		-	
Mg	0.000		0.014		0.017		0.016		0.024	
Ca	1.616		1.648		1.678		1.709		1.788	
Na	6.024		5.835		6.001		4.797		4.579	
K	0.065		0.063		0.078		0.056		0.071	
S total	1.929	2.06	2.173	2.29	2.437	2.48	2.284	2.37	2.358	2.46
Cl	0.130		0.118		0.045		0.059		0.058	
F	-		0.000		-		0.029		0.040	

*All iron reported as FeO. **All sulfur reported as SO_3.

TABLE 3. MICROPROBE ANALYSES OF DIOPSIDE AND FORSTERITE

	Diopside											
	Italian Mountain				North Italian Mountain							
	U23		U24		A2		A25-L		A25-N		B26	
SiO_2	54.44		53.29		53.84		54.5		55.4		54.69	
TiO_2	0.10		0.28		0.12		0.35		0.0		0.00	
Al_2O_3	0.35		1.58		0.88		1.20		0.42		0.48	
Fe_2O_3*	0.23		0.11		0.94		0.0		0.09		0.48	
MnO	0.54		0.06		0.08		-		-		0.61	
MgO	18.11		18.63		18.23		18.0		17.9		17.93	
CaO	25.72		25.92		26.15		26.2		26.1		26.17	
Na_2O	0.23		0.09		0.06		0.06		0.22		0.12	
K_2O	0.0		0.0		0.0		0.03		0.03		0.0	
	99.72		99.96		100.30		100.34		100.16		100.48	
	Ions based on 4 cations											
Si	1.970	1.99	1.917	1.98	1.939	1.98	1.960	2.00	1.995	2.00	1.969	1.99
Al^{IV}	0.015		0.067		0.037		0.040		0.005		0.020	
Al^{VI}	0.000	1.00	0.000	1.01	0.000	1.01	0.011	0.98	0.013	0.98	0.000	0.99
Ti	0.003		0.008		0.003		0.009		0.000		0.000	
Fe	0.006		0.003		0.026		0.000		0.002		0.013	
Mn	0.017		0.002		0.002		-		-		0.019	
Mg	0.977		0.999		0.979		0.965		0.961		0.962	
Ca	0.997	1.01	0.999	1.01	1.009	1.01	1.009	1.01	1.007	1.02	1.009	1.02
Na	0.016		0.006		0.004		0.004		0.015		0.008	
K	0.000		0.000		0.000		0.001		0.001		0.000	
	Molecular per cent											
CaTi-Ts	0.27		0.74		0.32		0.94		0.00		0.00	
Jd	0.94		0.61		0.41		0.56		1.67		0.83	
Ac	0.65		0.00		0.00		0.00		0.00		0.00	
Ca-Ts	0.00		2.23		1.31		1.31		0.05		0.60	
Joh	1.63		0.18		0.24		-		-		1.84	
CaFe-Ts	0.00		0.15		1.26		0.00		0.12		0.64	
Woll	48.28		47.22		48.19		49.14		50.19		48.45	
Fs	0.00		0.00		0.00		0.00		0.00		0.00	
En	48.23		48.87		48.26		48.05		47.97		47.64	
[Fe/Fe+Mn+Mg]·100												
	0.6		0.3		2.5		0.0		0.25		1.3	

	Forsterite					
	Italian Mountain		North Italian Mountain			
	U24		A25		B26	
SiO_2	42.11		43.0		43.24	
TiO_2	0.0		0.01		0.0	
Al_2O_3	0.0		0.13		0.0	
Fe_2O_3*	0.12		0.03		0.12	
MnO	0.15		-		0.04	
MgO	57.00		56.5		56.06	
CaO	0.17		0.55		0.16	
Na_2O	0.0		0.0		0.0	
K_2O	0.0		0.0		0.0	
	99.55		100.22		99.62	
	Ions based on 4 oxygens					
Si	0.993	0.99	1.005	1.01	1.015	1.02
Al	0.000		0.004		0.000	
Mg	2.004	2.01	1.968	1.98	1.962	1.97
Fe	0.002		0.001		0.002	
Mn	0.003		-		0.001	
Ca	0.004		0.014		0.004	
Na	0.000		0.000		0.000	
K	0.000		0.000		0.000	
Fo	99.32		98.58		99.45	
Fa	0.11		0.03		0.11	
Mont	0.43		1.39		0.40	
Teph	0.15		-		0.04	
[Fe/Fe+Mn+Mg]·100						
	0.1		0.03		0.1	

*All iron reported as Fe_2O_3

TABLE 4. MICROPROBE ANALYSES OF PHLOGOPITE, SAPONITE, HISINGERITE AND CHLORITE

	Phlogopite						Saponite			
	Italian Mountain		North Italian Mountain				Italian Mountain		North Italian Mountain	
	U24		A2		B26		U23		B26	
SiO_2	37.94		43.48		30.86		56.86		55.98	
TiO_2	1.86		0.44		3.95		0.0		0.0	
Al_2O_3	17.24		14.12		18.57		1.79		0.09	
FeO*	0.18		1.56		0.13		3.04		0.13	
MnO	0.0		0.0		0.03		0.32		-	
MgO	25.93		26.60		24.10		28.32		28.61	
CaO	0.10		0.14		0.0		1.12		0.45	
BaO	3.89		0.0		13.54		0.0		-	
Na_2O	1.32		0.08		0.42		0.05		0.0	
K_2O	7.18		10.18		4.69		0.17		0.12	
SO_3**	-		-		-		0.15		-	
Cl	-		-		-		-		0.0	
F	0.55		-		0.59		0.15		0.0	
	96.19		96.60		96.88		91.97		85.43	
O F,Cl	0.23		-		0.25		0.06		0.00	
	95.96		96.60		96.63		91.91		85.43	
	Ions based on 44 positive charges									
Si	5.370	8.00	5.969	8.00	4.674	7.99	7.662	7.95	7.926	7.94
Al^{IV}	2.630		2.031		3.315		0.284		0.015	
Al^{VI}	0.245	5.78	0.254	5.92	0.000	5.91	0.000	6.07	0.000	6.05
Ti	0.198		0.045		0.450		0.000		0.000	
Fe	0.021		0.179		0.016		0.343		0.015	
Mn	0.000		0.000		0.004		0.037		-	
Mg	5.470		5.443		5.441		5.688		6.038	
Ca	0.015	1.89	0.021	1.83	0.000	1.83	0.162	0.20	0.068	0.08
Ba	0.216		0.000		0.804		0.000		-	
Na	0.362		0.021		0.123		0.013		0.000	
K	1.296		1.783		0.906		0.029		0.009	
F	0.246	4.06	-		0.283	3.69	0.064	7.32	0.000	13.77
Cl	-		-		-		-		0.000	
S_{Total}	-		-		-		0.038		0.013	
OH†	3.814		3.11		3.405		7.218		13.760	
[Fe/Fe+Mn+Mg]·100										
	0.4		3.2		0.3		5.6		0.25	

	Hisingerite		Chlorite			
	North Italian Mountain		North Italian Mountain			
	A2		A2 (core)		A2 (rim)	
SiO_2	42.62		25.97		27.66	
TiO_2	-		0.02		0.0	
Al_2O_3	17.00		24.06		23.08	
FeO*	20.29		23.40		17.24	
MnO	0.06		0.48		0.26	
MgO	2.96		14.00		20.13	
CaO	2.88		0.05		0.06	
BaO	-		-		-	
Na_2O	0.04		0.0		0.0	
K_2O	0.22		0.0		0.0	
SO_3**	-		-		-	
Cl	-		-		-	
F	-		-		-	
	86.07		87.98		88.43	
O F,Cl	-					
	86.07		87.98		88.43	
	Ions based on 4 cations		Ions based on 20 cations			
Si	1.948	2.00	5.454	8.00	5.556	8.00
Al^{IV}	0.052		2.546		2.444	
Al^{VI}	0.864	2.00	3.409	12.00	3.020	12.00
Ti	-		0.003		0.000	
Fe	0.775		4.110		2.986	
Mn	0.002		0.085		0.044	
Mg	0.202		4.382		6.027	
Ca	0.141		0.011		0.013	
Na	0.004		0.000		0.000	
K	0.013		0.000		0.000	
OH†	4.24		16.84		15.50	
	79.2		47.9		32.3	

*All iron as FeO. **All sulfur as SO_3. †OH calculated from deficit in total.

are difficult to distinguish one from the other. In contrast to lazurite, crystals commonly grow along the grain boundaries of calcite.

Pyroxene is close to end-member diopside composition (Table 3). At the Anderson occurrence, some crystals are zoned with a core of normal diopside ($Z\wedge c$ 42°) and a rim of diopside with higher extinction angle ($Z\wedge c$ 48°). These grains were not analyzed. However, the analyzed thin section did show neighboring pyroxene grains of different chemical composition. Cathodoluminescent diopside (specimen A25–L, Table 3) is characterized by appreciable Ti and Al but negligible Fe and Na; nonluminescent diopside (specimen A25–N) is characterized by low Ti and Al but appreciable Fe and Na.

Olivine is nearly pure forsterite (Table 3). Al_2O_3 in A25 varies from grain to grain, perhaps owing to an impurity.

Phlogopite tends to form the largest crystals of the silicate assemblage, some as isolated metacrysts up to 0.5 mm diameter. They are subhedral and relatively pure but contain some round inclusions of calcite.

The composition of this mineral (Table 4) is remarkable. Barium concentrations are high; for example, in specimen B26, Na:Ba:K = 0.14:0.89:1 (atomic). The other barium-rich phlogopite analyzed (specimen U24) is also remarkable. Individual grains show little compositional zoning but the barium content varies greatly from one grain to the next. One small crystal contains about 8% BaO. The analysis is an average of two parts of a single large phlogopite crystal.

Garnet, occurring as subhedral dodecahedra up to 1 mm across, is associated with saponite and lazurite in specimen U23. The dodecahedra are anisotropic, zoned and complexly twinned. Analyses (Table 5) show considerable compositional variation and indicate that the most Fe-rich portions, which correspond to regions of lowest birefringence, tend to be on the rims of the crystals. In general, they are grossular with some andradite and minor spessartine. Garnet was also observed in thin sections from the Anderson and Christopher occurrences as anhedral grains rimming diopside.

TABLE 5. MICROPROBE ANALYSIS OF GARNET*

	Grain 5 (core)	Grain 5A (core)	Grain 6 (core)	Grain 8 (rim)	Grain 8 (core)
SiO_2	38.39	37.68	39.04	37.91	38.86
TiO_2	-	-	-	0.0	-
Al_2O_3	16.14	13.92	19.09	15.92	18.42
Fe_2O_3	7.81	11.08	4.27	9.45	6.53
MnO	1.60	1.06	1.85	0.41	0.79
CaO	32.26	35.58	35.96	36.19	36.37
MgO	0.0	0.0	0.0	0.29	0.0
	100.20	99.32	100.21	100.17	100.97
Ions based on 16 cations					
Si	5.898	5.889	5.958	5.870	5.915
Al	2.922 } 3.93	2.564 } 4.01	3.434 } 3.92	2.905 } 4.01	3.304 } 4.05
Fe^{3+}	1.003	1.448	0.490	1.101	0.748
Mn	0.208	0.140	0.239	0.054	0.102
Ca	5.968 } 6.18	5.958 } 6.10	5.880 } 6.12	6.004 } 6.12	5.931 } 6.03
Mg	0.000	0.000	0.000	0.067	0.000
Molecular per cent					
And	24.37	35.62	12.02	27.25	18.61
Gross	72.26	62.08	84.08	71.86	79.70
Spess	3.37	2.30	3.91	0.89	1.69

*Specimen U23, Italian Mountain

Soft, fibrus *saponite* $(Mg,Fe)_6Si_8O_{20}(OH)_4$ is a major mineral in specimen U23 (see Tables 1 and 4) and a minor mineral in several other specimens from the area. It is nonpleochroic and pale brown (perhaps stained by decomposed pyrite) to colorless. The mineral gave an X-ray-diffraction pattern of smectite, and saponite was established by microprobe analysis.

Chemically, saponite is of two types: iron-rich (specimen U23) and iron-poor (specimen B26, Table 4). In order to avoid possible contamination with oxidized pyrite, only colorless grains were analyzed in specimen U23. Small amounts of Ca^{2+}, Na^+ and K^+ balance the negative layer-charge. Octahedral Al is very low, a feature apparently common to saponites from other regions (Deer *et al.* 1962, pp. 233-234, analyses 12–15).

Thin section U23 is composed of carbonate and silicate bands. The bulk of the carbonate band is made up of coarse calcite. Accessory minerals are diopside, lazurite and sulfides in minute, roundish grains. No saponite was observed in this part of the section. In contrast, the silicate portion contains major amounts of fine-grained saponite and, rarely, coarse vein-like aggregates of saponite with packets of fibres in random orientation. Grossular grains are glomeroblastic and occur within or close to the saponite, which is veined by late calcite. Tiny diopside grains are scattered through calcite and lazurite.

Rather different is the saponite from North Italian Mountain (specimen B26) with only 0.13% FeO. This mineral occurs as isolated cryptocrystalline aggregates or as fibrous growths forming a rim around olivine, apparently derived directly from it.

Thomsonite, in parallel fibrous packets, is the common alteration product of lazurite in the area. An analysis of thomsonite from Italian Mountain (specimen U24) is presented in Table 6. Thomsonite from North Italian Mountain (specimen B26) has a similar composition.

Fined-grained thomsonite in lapis lazuli seems to have formed by alteration of lazurite. In contrast, coarse-grained thomsonite from lazurite-free A2 shows no evidence whatsoever of being an alteration product of lazurite or any

TABLE 6. MICROPROBE ANALYSES OF PYRRHOTITE, CALCITE AND THOMSONITE

	Pyrrhotite			
	Italian Mountain			North Italian Mountain
	U23	U24a	U24b	B26
Fe	60.18	60.78	60.63	60.26
Co	0.19	0.0	0.0	0.20
Ni	0.04	0.0	0.0	0.0
Mn	0.0	0.04	0.07	0.05
Zn	0.0	0.0	0.0	0.0
S	38.85	38.83	38.94	39.13
	99.26	99.65	99.64	99.64
	Ions based on 1 atom S			
Fe	0.889	0.899	0.894	0.884
Co	0.003	0.000	0.000	0.003
Ni	0.001	0.000	0.000	0.000
Mn	0.000	0.001	0.001	0.001
Zn	0.000	0.000	0.000	0.000
S	1.000	1.000	1.000	1.000
x	0.107	0.101	0.105	0.112
N FeS	0.9398	0.9463	0.9435	0.9368
Log fS_2‡	-6.9	-10.2	-8.9	-6.0
T(°C)‡	400	325	355	440

	Calcite		
	Italian Mountain		North Italian Mountain
	U23	U24	B26
FeO*	0.12	0.0	0.0
MnO	0.0	0.0	0.0
MgO	0.06	0.52	0.42
CaO	54.90	55.17	54.90
SrO	-	-	1.29
CO_2**	43.22	43.86	44.09
	98.30	99.55	100.70
	Ions based on 1 cation		
Fe	0.002	0.000	0.000
Mn	0.000	0.000	0.000
Mg	0.002	0.013	0.010
Ca	0.997	0.987	0.977
Sr	-	-	0.012

	Thomsonite			
	Italian Mountain		North Italian Mountain	
	U24		A2	
SiO_2	36.38		39.76	
Al_2O_3	30.31		29.55	
FeO*	0.08		0.0	
MnO	-		0.0	
MgO	0.21		0.0	
CaO	13.56		12.55	
BaO	0.03		0.0	
Na_2O	3.04		4.77	
K_2O	0 0		0.0	
	83.61		86.63	
	Ions based on 40 Z-ions			
Si	20.182	40.00	21.323	40.00
Al	19.818		18.677	
Fe	0.037	11.55	0.000	12.17
Mn	-		0.000	
Mg	0.174		0.000	
Ca	8.060		7.211	
Ba	0.007		0.000	
Na	3.270		4.960	
K	0.000		0.000	
H_2O†	30.32		23.91	

*All iron assumed FeO. **Calculated assuming CO_3 as 1 anion. † Calculated from deficit in total.
‡ Equilibration conditions from Toulmin & Barton (1964).

other mineral. Rather, this thomsonite fills cavities in the rock. Both varieties are probably products of late hydrothermal activity.

The opaque minerals *pyrite, pyrrhotite* and very minor *sphalerite* are present in all lazurite-bearing specimens. Pyrrhotite surrounds pyrite and *vice versa.* Both have irregular outlines, but separate grains of each were also noted. Assuming that pyrite and pyrrhotite represent an equilibrium assemblage, pyrrhotite has equilibrated with pyrite at a moderate temperature and sulfur fugacity (Table 6).

An isotropic, grey, metallic mineral of low reflectivity with dark green internal reflections was noted in pyrite in polished thin sections from Italian Mountain (specimen U24) and North Italian Mountain (specimen B26). Analysis of specimen U24 gave Mn 54.64, Fe 6.87, Zn 0.02, S 34.78; total 96.31%. This reduces to *alabandite* $(Mn_{0.89}Fe_{0.11}Zn_{0.0003})S$.

Other minerals include the following: A very small grain of a mineral with the optical properties of scapolite was observed in grossular at Italian Mountain (specimen U23). Microprobe data suggest it is *mizzonite,* which is common in other metamorphic rocks at Italian Mountain (Cross & Shannon 1927). A small amount of coarsely crystalline *barite* was collected from the east end of the Anderson trench, and small grains of barite were tentatively identified in a thin section of white limestone from the Christopher occurrence (locality C, Fig. 1). *Calcite* is notably low in magnesium (Table 6). Tiny *sphene* anhedra were identified optically in specimen B26 and in a thin section from the Anderson occurrence.

Hanging wall of the Anderson deposit

The Anderson deposit it bounded by rock containing nodules of calcium and magnesium silicates. The mineralogy of this horizon differs markedly from that of lapis lazuli; although it contains no lazurite, the assemblage provides data pertinent to the origin of lapis lazuli. Its mineralogy was therefore studied in detail.

The dark layer, containing *lazurite,* is overlain by a thin, barren, yellow, nodular layer. This, in turn, is overlain by a cream-colored nodular layer 1.2 m thick from which our sample (A2) was taken. A dark brown nodule, 7 x 3 cm, is set in a mottled cream and grey microcrystalline groundmass. Individual diopside crystals in the nodules are themselves centimetric.

Prismatic *diopside* makes up the bulk of the nodule. Compared with diopside from lapis lazuli, it is notably high in iron (Table 3). *Phlogopite* forms fine-grained patches. It is also high in iron but notably low in barium compared with phlogopite from lapis lazuli of the area (Table 4). The iron-rich minerals chlorite and hisingerite grow around pyrite. Colorless *chlorite* forms radiating groups of crystals, richer in iron in the cores than on the

TABLE 7. CHEMICAL ANALYSES OF SPECIMENS MENTIONED IN THE TEXT

Lapis lazuli and associated marble

	Italian Mountain			North Italian Mountain							Unmet. Belden Fm		Tertiary stock
	U20	U23	U24	A2	A4	A10	A25	B26	C2	C3	SM1	SM2	IM1
SiO_2	2.41	33.58	20.15	47.71	10.47	10.24	15.51	12.72	18.94	16.66	4.30	75.98	66.7
TiO_2	0.01	0.49	0.08	0.22	0.07	0.06	0.05	0.16	0.07	0.06	0.03	0.93	0.46
Al_2O_3	0.57	10.47	3.07	8.04	2.13	1.73	0.93	3.70	2.03	2.42	0.48	13.70	15.9
FeO*	0.11	3.66	1.15	4.58	2.32	2.79	0.15	3.08	0.92	0.65	0.90	1.10	3.5
MnO	0.02	0.11	0.04	0.06	0.06	0.06	0.02	0.06	0.03	0.04	0.09	0.00	0.09
MgO	1.28	8.36	11.15	12.37	4.66	7.59	6.12	7.19	10.30	15.99	20.52	0.54	1.2
SrO	0.095	0.404	0.184	0.06	1.06	0.79	0.284	0.59	0.079	0.267	0.009	0.002	0.21
BaO	0.04	1.57	0.13	0.03	0.27	0.20	0.13	0.20	0.01	0.05	<0.006	<0.006	0.12
CaO	53.94	16.90	33.60	17.75	41.43	39.15	44.90	38.30	38.93	32.50	29.44	0.14	3.3
Na_2O	0.03	3.45	0.25	0.58	0.47	0.15	0.40	0.45	0.07	0.25	0.045	0.08	3.6
K_2O	0.03	0.22	0.52	0.52	0.08	0.07	0.07	0.12	0.11	0.09	0.05	3.40	3.1
Cl	0.015	0.16	0.015	0.09	0.015	0.005	<0.005	<0.005	0.020	0.025	0.045	<0.005	-
Br	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	-
F	0.04	0.09	0.20	0.25	0.05	0.18	0.08	0.04	0.13	0.17	0.031	0.07	-
SO_3**	0.60	7.37	2.50	5.89	6.89	7.74	0.60	6.04	1.50	1.50	0.27	0.10	-
CO_2	38.7	6.6	22.3	0.66	28.9	27.3	29.5	25.6	27.0	25.6	44.1	0.05	0.21
P_2O_5	0.09	0.23	0.15	0.14	0.04	0.05	0.17	0.06	0.15	0.15	0.07	0.02	0.29
H_2O^+	0.68	6.92	3.35	3.62	1.86	2.86	1.19	3.49	1.89	3.06	0.40	2.26	1.4
H_2O^-	0.16	1.27	0.48	0.48	0.35	0.40	0.20	0.35	0.14	0.29	0.19	0.75	0.6
	98.82	101.85	99.32	103.05	101.12	101.37	100.30	102.15	102.32	99.77	100.97	99.12	100.1
$\frac{S}{Fe}$ (atomic)	4.9	1.81	1.95	1.15	2.67	2.49	3.6	1.76	1.46	2.07			

*All iron reported as FeO. **All sulfur reported as SO_3.
Specimen prefixes A, B, C. U and SM correspond to locations in Figure 1; X-ray Assay Laboratories, Toronto, analysts.
IM1 is an average of 17 analysed specimens from Cunningham (1973).

rims (Table 4). Yellow *hisingerite* surrounds pyrite, sometimes as concentric growths (Table 4). *Thomsonite*, forming long crystals in restricted areas, has normal composition (Table 6). *Calcite*, occurring as isolated grains, is low in magnesium (0.25% MgO) but rather rich in iron (0.75% FeO). *Pyrite* is seen as local, coarsely crystallized clusters but pyrrhotite is apparently absent. A small amount of *chalcopyrite* is found with the pyrite. The assemblage is therefore comparatively rich in iron, with low-barium phlogopite, very different from the assemblage of lapis lazuli.

The fine-grained matrix was not examined by microprobe, but X-ray-diffraction studies by N.M. Miles showed that it was composed mainly of diopside, lesser amounts of epidote, small amounts of calcic plagioclase and minor potassium feldspar.

GEOCHEMISTRY

Elemental abundances

The relationship of most elements to specific minerals at Italian Mountain is obvious and only a few elements will be considered here. Bulk analyses are given in Table 7.

Barium is known to concentrate in lazuritic horizons. Ivanov (1976) has shown that at Lake Baikal, Ba is contained in phlogopite (up to 0.9%) and to a lesser extent in lazurite and calcite (each to 0.1%). Ba-rich lazuritic horizons are also notable at Italian Mountain (*cf.*, Tables 1, 7). The lazurite-free specimens A2 and C2 contain a low amount of Ba, whereas the corresponding lazuritic specimens (A4 and C3) are enriched in Ba. The lowest values were encountered in specimens of the Belden Formation (SM1, SM2).

Considering the analyzed minerals, barium is a major constituent of phlogopite only, but Ba abundances show poor correlation with the modal concentrations of mica. U23, for example, contains 1.57% BaO but no phlogopite. Some Ba is concentrated in another phase, possibly barite or celsian (not observed in thin section). Barite has been observed locally in lapis lazuli, as noted above, and in lazurite-free tactites (Cross & Shannon 1927).

Strontium is contained predominantly in calcite, as in lapis lazuli from the Lake Baikal region (Ivanov 1976). Calcite from occurrences A and B generally contains about 1.3% SrO, judging from mineral and rock compositions. Calcite from occurrences C and U is notably lower in SrO (0.4% or less).

As at Baffin Island (Hogarth & Griffin 1978), *iron* is contained largely in sulfides, with very little entering the silicates. Thus about 90 (Italian Mountain) or 95% (North Italian Mountain) of the iron in the system is in sulfides. Some 80 (North Italian Mountain) or 85% (Italian Mountain) of the *sulfur* is in sulfides. The remainder is found in lazurite.

The occurrence of lazurite is dependent on a high S:Fe ratio (Table 7). If this ratio exceeds a specific value, sulfur must enter silicate structures. If S:Fe (atomic) is less than about 1.5:1 (as in specimens A2 and C2), pyrite and pyrrhotite, but not lazurite, appear; if above 1.5:1 (as in specimens U23, U24, B26, A4, A10 and C3) pyrite and pyrrhotite coexist with lazurite. Pyrite and lazurite, but not pyrrhotite, were observed in specimens A25 and U20 (S:Fe = 3.6 and 4.9:1). This relationship is responsible for the absence of lazurite in the mineralogically similar but more iron-rich rocks of the hanging wall of the Anderson deposit.

Chlorine is present in variable amounts. In general, chlorine is contained partly in lazurite, but in certain specimens Cl occurs in some other manner not understood at present. Chlorine is not necessarily enriched in lazuritic layers, as shown by a comparison of A2 (900 ppm Cl, lazurite-free) with the neighboring A4 (150 ppm Cl, 8.3 modal % lazurite + zeolites) and A10 (50 ppm Cl, 19.4 modal % lazurite + zeolites).

The amount of phlogopite, the only fluorine-bearing mineral encountered in the study, is poorly correlated with *fluorine* content; some other F-bearing mineral must be present in the specimens.

Source of elements

The major minerals of the lapis occurrences probably formed by contact metamorphism of the impure carbonates of the Belden Formation. However, several facts suggest that this metamorphism was not isochemical but involved considerable metasomatic activity. Cross & Shannon (1927) described the extensive development of massive garnet–diopside–vesuvianite in the marbles, as well as fissure filling of these minerals in the stocks. Cunningham (1976) noted the zonal development of hydrothermal base-metal deposits related to the Northern Intrusive. It is thus of interest to determine to what extent the occurrence of lapis lazuli was controlled by the metasomatic introduction of individual components.

Those lapis lazuli deposits that have been recognized as meta-evaporites (Kulke 1976a, b, Hogarth & Griffin 1978) are characterized by high contents of Na and K, high Na/K and Cl/S ratios and very low Fe contents. In comparison with these, the analyses of Table 7 are notable for their low K and Na, low Na/K and Cl/S ratios and relatively high Fe contents. These data alone suggest that the evaporite model cannot be applied to the Italian Mountain deposits. This agrees with the apparent absence of evaporite members elsewhere in the Belden Formation.

Two examples of "typical" unmetamorphosed carbonate and silicate members of the Belden Formation were analyzed in an attempt to define the probable compositional range of possible protoliths for the lapis lazuli. The samples, donated by C.G. Cunningham, came from approximately the same horizon as the Anderson lapis lazuli occurrence, but on the east side of the mountain (locality SM, Fig. 1).

The carbonate specimen SM1 consists of fine-grained dolomite (subordinate calcite). It is grey in hand specimen, lacks noticeable bedding but is brecciated and recemented with coarse, white dolomite. Tiny anhedral rhombs, now composed of polygranular dolomite and quartz, are sprinkled sparingly throughout the fine-grained portion. Very minor late calcite coats joint surfaces. Rare pyrite and hematite, a result of pyrite oxidation, are the only other minerals noted, and the rock shows no evidence whatsoever of metamorphism. Mineralogically and chemically (Table 7) the rock is dolostone.

The silicate specimen SM2 is a finely bedded, blackish rock containing small grains of pyrite that have locally decomposed to limonite and coated certain bedding planes with a yellow ochre. In thin section it is seen to consist of about 60% round quartz grains (average diameter about 0.1 mm). The remainder is made of finer grained illite, phlogopite, pyrite, limonite, various fine-grained unidentified minerals and rare detrital zircon, tourmaline and plagioclase. This mineralogy illustrates very low-grade metamorphism. The mineralogical and chemical composition (Table 7) suggests subgreywacke as defined by Pettijohn (1954).

Also in Table 7 is an average of 17 analyses (IM1) of the Italian Mountain stock representing quartz diorite, granodiorite, quartz monzonite and dacite porphyry. The data in Table 7 show that mixtures of the silicate and carbonate components of the Belden Formation could explain the range in composition of the lapis lazuli samples for most of the analyzed elements. However, the contents of Na, S, Fe, Sr, Ba, Cl and F are all too high to be explained in this fashion, and other possibilities must be considered.

The Italian Mountain stocks and lapis-lazuli horizons are rich in Ba and Sr, whereas the Belden dolostone and subgreywacke contain negligible amounts of these elements (Table 7). A similar trend was found in igneous rocks (syenites, subalkalic granites), lapis lazuli and unmetasomatized marble at Baikal by Ivanov (1976). In both regions Ba and Sr may have been introduced into the carbonate rocks by fluids that accompanied igneous intrusion.

In the Italian Mountain area, barite may have been a primary (authigenic) phase in some horizons of the Belden limestones, or it may have formed metasomatically during early stages of the metamorphic cycle. In either case, its stability implies oxidizing, high-pH conditions. Cross & Shannon (1927) noted that redbeds (the Pennsylvanian Maroon Conglomerate) change color from purple to green owing to reduction of Fe^{3+} in the contact aureole, and that graphite was formed in the marbles. These observations suggest that reducing conditions prevailed during at least the latter part of the metamorphic cycle. Under such conditions, barite would have become unstable (Bjørlykke & Griffin 1973), leading to the liberation of S and Ba for incorporation into sulfides and silicates. This model explains the presence of rare (relict) barite in the tactite. It also explains the absence of barium in the phlogopite of A2 and the bulk rock of C2 (both lazurite-free) compared with the appreciable barium in phlogopite and bulk-rock analyses of lazurite-bearing specimens. A somewhat similar breakdown of barite, leading to the formation of barium silicates and pyrite, was postulated by Bjørlykke & Griffin (1973).

The abundance of Na and S in lapis lazuli may also be related to magmatic fluids derived from the Tertiary stocks. Cunningham (1976) has demonstrated that the late-magmatic fluids were rich in Na, K, Ca, Cl and S.

The presence of scapolite in zones and veins near the contact (Cross & Shannon 1927) suggests extensive metasomatic addition of Cl (2.8% Cl in scapolite) by late-magmatic fluids. On the other hand, Cl in lapis lazuli could well have been supplied by a dolostone protolith (*cf.*, Table 7). The source of Cl must therefore remain ambiguous.

Fluorine is a significant component of late-formed vesuvianite (0.6%) and epidote (0.4%) in the contact rocks (Cross & Shannon 1927). It is thus reasonable to assume that the F of the lapis horizons has, at least in part, been introduced metasomatically.

Cunningham (1976) noted that late-magmatic hydrothermal activity has led to the breakdown of ferromagnesian minerals in the granitic rocks of the stocks. He also identified hematite as a daughter mineral in the fluid inclusions of quartz veins. These observations, and the late formation of vesuvianite, ferrian grossular and epidote in the tactites, imply that Fe and probably Al were mobile components during contact metasomatism.

Textural and compositional relations between the iron-poor and iron-rich phases in lapis lazuli also point to the introduction of iron at a late stage. Some veinlets of ferroan saponite transect grains of lazurite, diopside and calcite; others are interstitial, as in a specimen from occurrence U. Ferrian grossular is either in, or close to, the saponite. Zoned garnets suggest that iron in the system increased with time. In specimens from occurrences A and C, overgrowths indicate that garnet postdates diopside.

Some late iron may have contributed to the breakdown of lazurite. Deep blue lazurite becomes paler near pyrite and pyrrhotite, which implies that iron sulfides were generated at the expense of lazurite, causing a bleaching effect. The relevant reactions may be of the type:

$$\underset{\text{blue lazurite}}{Ca_2Na_6Al_6Si_6O_{24}SO_4S} + Fe^{2+} \rightarrow \underset{\text{colorless hauyne}}{CaNa_6Al_6Si_6O_{24}SO_4} + Ca^{2+} + FeS$$

PETROLOGY

The textures described above suggest that the major minerals formed early in the metamorphic history of the lapis lazuli, perhaps near the peak of metamorphism. Lazurite, which is included in the other silicates, may have formed first, but the larger grain-size of forsterite and diopside may reflect only kinetic factors. The minor Fe-rich silicates seem to have formed later, as a result of metasomatism, and are obviously not in equilibrium with the earlier phases.

Hogarth & Griffin (1978, Fig. 18) presented a petrogenetic grid for lapis-lazuli assemblages in the condensed system $CaO–MgO–SiO_2–AlO_3$, as functions of $\mu(Na_2O)$ and $\mu(K_2O)$ at unspecified P and T. In terms of this system, the observed assemblage lazurite + diopside + forsterite + phlogopite + calcite represents the reaction (PA): phlogopite + diopside + $Na_2O \rightleftarrows$ forsterite + K_2O + CaO + H_2O. This 5-phase assemblage is thus at least divariant; if the Ba content of the phlogopite is considered, another degree of freedom is added. All other observed assemblages contain fewer phases. Thus, equilibrium among the major phases of the Italian Mountain lapis lazuli is permissible on phaserule grounds. However, the grain-to-grain compositional variability of each phase implies that chemical equilibrium was attained only on a very local scale at best.

In contrast, the metamorphic assemblages of Baffin Island lapis lazuli are typically low in variance (5- and 6-phase assemblages, including calcite), and the minerals are very similar in composition within each specimen and from sample to sample. These features have been interpreted as reflecting closed-system equilibria at high grades of regional metamorphism. We therefore regard the relatively simple assemblages of the Italian Mountain deposits as reflecting the mobility of one or several components during the metamorphism.

The occurrence of the assemblages Di + Fo + Laz and Di + Phlog + Laz at Italian Mountain implies that $\mu(Na_2O)$, $\mu(K_2O)$ and $\mu(Na_2O)/\mu(K_2O)$ were higher than the corresponding values in the Baffin Island deposits (Hogarth & Griffin 1978, Fig. 18).

Conditions of metamorphism

Cunningham (1976) has used fluid-inclusion microthermometry to deduce a pressure of *ca.* 250 bars and a temperature *ca.* 450°C during a the late venting of the Northern Intrusion. This pressure corresponds to a depth of 2800 m (hydrostatic) or 950 m (lithostatic). Similar pressures may also be assumed for the lapis-lazuli horizons during their contact metamorphism.

The limited data available on unmetamorphosed rocks of the Belden Formation show that a probable critical premetamorphic assemblage in these rocks was dolomite + quartz. Subsequent metamorphism took the rocks through the reactions:

$$\text{dolomite} + \text{quartz} \rightarrow \text{diopside} + CO_2$$
$$\text{diopside} + \text{dolomite} \rightarrow \text{forsterite} + \text{calcite} + CO_2$$

At pressures of 250 bars, the second reaction indicates a minimum temperature of about 600°C (Eggler *et al.* 1976). The lower temperatures obtained from pyrrhotite–pyrite geothermometry (Table 6; Toulmin & Barton 1964) may represent re-equilibration during cooling from peak temperatures. We therefore suggest conditions of P ~ 250 bars, T ~ 600°C for the formation of the lapis-lazuli assemblages in the Italian Mountain area. The secondary Fe-rich phases may have formed closer to the 400–450°C range of temperatures suggested by Cunningham's fluid-inclusion data, whereas zeolites probably crystallized at even lower temperatures.

SUMMARY

The data presented here show that the lapis lazuli at Italian Mountain has formed by contact metamorphism at very shallow levels. The rapid heating, extensive metasomatic activity and presumably rapid cooling have resulted in relatively simple mineral-assemblages and a general failure to attain chemical or textural equilibrium except perhaps on a very local scale. The availability of hot, aqueous fluids with high contents of Na, S, Cl, F and other components probably was instrumental in producing lapis lazuli from protoliths that did not have high primary contents of these elements. The reduction of primary barite may, on the other hand, have been critical to the formation of sulfide and lazurite.

The Italian Mountain deposits thus differ dramatically in their mode of formation from the Baffin Island deposits. The latter are characterized by higher Na/K and Cl/S ratios, reflecting their origin as meta-evaporites. They have been subjected to high-grade (granulite-facies) regional metamorphism, apparently isochemical at the peak of metamorphism, and they show complex, but apparently equilibrium, mineral assemblages.

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