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Mineralogical Characterization of the Shelburne Marble: A Vermont Marble Test Stone Used to Study the Effects of Acid Rain

by

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Abstract

The Shelburne Marble of Vermont has been used extensively in buildings and monuments and for this reason has been selected as a test stone for the National Acid Precipitation Assessment Program (NAPAP) stone exposure studies. Mineralogical characterization of fresh Shelburne Marble provides a basis for recognizing mineralogical changes that may occur in samples when they are weathered.

The Royal variety of Shelburne Marble is a white marble with gray streaks of inclusions. It is predominantly composed of calcite (97%) but contains inclusions of dolomite, layer silicates, framework silicates, and non-silicates. The inclusions are heterogeneously distributed in the rock and commonly form linear clusters that are dominated by dolomite + phlogopite ± rutile ± chlorite. Less abundant inclusions are: muscovite, talc, quartz, feldspar, pyrite and apatite. All of the minerals that comprise the Shelburne Marble have nearly end-member compositions. Mineral composition, grain size and associations of the inclusions may significantly contribute to the durability (or weakness) of marble used in buildings or monuments that are exposed to conditions of acid precipitation.

Introduction

Stone deteriorates (weathers) when it is exposed to rain, wind, freezing and thawing, etc., and although weathering is a natural process, increasing air pollution may be accelerating the normal weathering processes. Acid precipitation formed from the reaction of sulfur oxides, nitrogen oxides, ozone, and water in the atmosphere has been recognized as a widespread environmental problem (Babich et al., 1980, Franks, 1983, Armbruster et al., 1983, Likens et al., 1979) and marked deterioration of some stone buildings, monuments, and statues has been attributed to the effects of acid rain (Pearce, 1985, Peterson, 1985). Concern about the accelerated deterioration has prompted numerous studies that attempt to determine the extent and causes of damage (Butlin et al., 1985, Lal, 1985, Guidobaldi, 1981, Esbert et al., 1981) and that seek ways of preserving or protecting stone that is particularly susceptible (Gauri, 1978, Skoulikidis and Beloyannis, 1981, de Castro, 1981, Accardo et al., 1981).

The National Acid Precipitation Assessment Program (NAPAP) in the United States, is addressing the problem of materials damage due to acid precipitation by funding studies that examine the causes and processes of damage due to acid precipitation. One such study is the stone exposure program in which stone samples have been placed at five exposure sites in the eastern United States where atmospheric and environmental conditions are carefully monitored (Sherwood and Doe, 1984, NAPAP, 1984). The Salem Limestone from Indiana (Ross and Knab, 1984) and the Shelburne Marble from Vermont (Ross, 1985) were chosen for the exposure studies because both have been used in many buildings and because carbonate stone will show weathering effects more rapidly than stone composed primarily of silicate minerals (Winkler, 1973), probably even within the 10-year time frame of the studies. Samples of unexposed limestone and marble must be carefully characterized so that changes in the stone after exposure can be identified. Studies to be conducted on the exposed samples include observations and measurements of: changes in mineralogy, chemistry, surface roughness, and the runoff chemistry of the rainwater (Sherwood, 1984). This paper provides the initial mineralogical characterization of the marble used in the exposure program. The composition, arrangement, and kinds of minerals that compose the marble will influence how the stone responds to the environment; it is those features that are the focus of the present study.

Selection of the Study Stone

The Shelburne Marble of Vermont was selected as a test stone for the exposure studies because it has been used in many monuments and historic buildings, particularly in the eastern and northeastern United States, and where acid rain has long been recognized as a problem. Some of the major buildings that are made of Vermont marble are listed in Table 1. The quarry that supplied the stone for the exposure study also supplied stone for some of the buildings listed in Table 1.

Marble that is quarried in western Vermont is in layers that contain different kinds and amounts of inclusions. The inclusions give the marble distinctive colors and striking patterns, and may vary significantly from one layer to the next. Six broad groups of colors and patterns identified by Bain (1933) (white with gray dolomite mottling, white, white with greenish veining, gray and blue gray, fine textured black, and red) reflect some of the differences in the layers and illustrate the diverse appearance of the marble in the Shelburne Marble. The appearance of the stone and types of inclusions that it contains influence the uses to which a specific marble can be applied. Thus, the marble producing companies have given commercial or trade names (e.g. Royal, Imperial, Danby, and Dorset B) to marble layers within the Shelburne that relate to the color characteristics of the marble. Many names have been used for the various layers and although the names given to the marbles were used for many years, new names were sometimes used if a quarry changed hands. The Royal marble from the Danby quarry was selected for the exposure study because it was similar in appearance and physical characteristics to the marble in many of the buildings listed in Table 1 (Ross, 1985).

The selection and procurement of the test sample block of Shelburne marble is described by Ross (1985). A block that measured 3.5 x 6.5 x 6.5 feet was obtained from the C-layer of the Danby Quarry in Danby Vermont. The block was cut into 252 12 x 24 x 2 inch slabs and into 18 12 x 24 x 4 inch slabs. One large face of each slab was given an 80-grit finish to resemble the finish commonly given stone in buildings. Some of the slabs were later cut into briquettes that measure 3 x 3 5/8 x 2 inches. Briquettes are used in the studies that will look for mineralogical changes in the stone after exposure at yearly intervals.

Geologic Description

The Shelburne Marble is of Early Ordovician age and is a low grade, regionally metamorphosed marble that forms part of the marble belt in western Vermont.

The Shelburne is interbedded with and overlain by schist. The complexly folded marble beds lie along the Middlebury synclinorium. They are bounded on the east by the Green Mountains, where low angle thrust faults dip to the east, and are bounded on the west by the Adirondack Mountains where thrust faults dip to the west along the northern portion of the marble belt and normal faults dip to the east along the southern portion. The Shelburne varies from sedimentary limestones near the Canadian border to the coarse grained marble that is quarried in Danby. The Danby quarry lies in the southernmost of three main stuctural units that form the marble belt (Bain 1934). The southernmost structural unit extends from Manchester to Middlebury and is characterized by medium to coarse grained marbles in complex flowage and fold structures. The two structural units to the north have experienced less tectonic and metamorphic activity than the southernmost unit: the central structural region of the marble belt lies between Middlebury and Milton and it is characterized by fine textured stone in simple, open folds between thrust faults; the northern structural unit, in the vicinity of Plattsburg, New York and Isle la Motte, Canada, is a faulted area of unmetamorphosed sediments.

The Danby quarry in Vermont is the source of the test stone used for this study and it is also the only producing quarry in the Shelburne Marble. The gently plunging (8°) synclinal structure at the Danby quarry location has favored the making of improvements in quarrying techniques and thus allowed the quarry to be a contender in the world market (Meade, 1980). The nature of the folding in the marble beds is a significant factor for the commercial value of a particular layer of marble. As the marble beds were folded, the calcite became plastic with resultant elongation and thinning of the beds along the limbs of the folds and thickening of the beds at the ends of the folds (Dale, 1912, Dale, 1914). Locally, a marble layer may be thinned to inches and at other places it may be thickened to more than 300 feet (Bain 1959). It is from the thickened beds that large, useable blocks of marble can be removed and they are thus more likely to be of commercial value.

Method of Study

The ultimate goal of the mineralogical studies in the exposure program is to look for changes in the mineralogy of the stone and to determine whether those changes are due to the environmental conditions at the exposure sites. Thus two questions have guided this study of the mineralogy of the unexposed stone: what are the 'reactants' and what characteristics or features of the minerals in the marble may be significant to the weathering of the stone.

For the initial characterization, five polished sections were made from the H1-3 slab (Fig. 1) of the marble. The sections were made to represent the diversity of the random inclusions in the stone. In each section the minerals were identified and their composition, distribution, association, and relative abundances were determined. Four main techniques were used in the characterization: optical microscopy, modal analysis, scanning electron microscopy, and electron microprobe analysis.

Modal analysis was used to determine the abundances of the individual minerals and to give an idea of the abundance of inclusions relative to calcite. Point counts were made on each of the five polished thin sections to determine the relative abundances of the 11 different minerals identified in the marble.

Many phases were never or rarely encountered, so the results were combined into groups of mineral types (carbonates, layer silicates, framework silicates, and non silicates) because of the small numbers and the difficulty in clearly distinguishing some phases that occur as very small grains.

Quantitative chemical analyses of the mineral phases were obtained with an ARL-SEMQ electron microprobe. Standards similar to the unknowns were measured to check on analysis quality, and unknown analyses were judged to be acceptable if the oxide total was 98 - 102 and if the the cation stoichiometry was correct for the mineral analyzed. Several points were analyzed on each grain, and representative occurrences of a mineral were sought.

Silicates and oxides were analyzed at 15 KV with a beam current of 0.1 μa, 20 second counts and a minimum (1 - 2 μm) spot size. Bence and Albee (1968) correction procedures with modifications by Albee and Ray (1970) were used and data were reduced on-line (McGee 1983). The elements analyzed varied for each mineral group (Table 2). Water in layer silicates was calculated (Flohr, 1983) after the on-line data reduction. Sulfides were analyzed with procedures similar to those used for silicates and oxides but an accelerating voltage of 25 KV was used to enable measurement of Zn, Cu, Ni, and Co.

Analyis of carbonates required special analytical conditions because carbonates tend to be unstable under the operating conditions used for silicates and oxides. Thus, carbonates were analyzed using: 12 KV accelerating voltage, .05 μa beam current, 20 second counts, and a spot size of ~ 0.2 mm. Data were reduced on-line using the MAGIC method of Colby (1968). CO_2 amounts were calculated off-line for each of the carbonate analyses using three assumptions: 1- the analysis total with CO_2 equals 100, 2- CO_2 was the only oxide in the mineral that was present and not measured by the electron microprobe, and 3- there is enough CO_2 present to make the analysis total 100. Since the oxide totals and mineral stoichiometry of the CO_2-free analyses could not be used directly to check the analysis quality, modified checks were needed. By comparing standard calcite and dolomite analyses with the CO_2-free microprobe analyses, good CO_2-free totals for calcite (55 - 56 wt. %) and dolomite (52 - 53 wt. %) were determined. A check on mineral stoichiometry was obtained after CO_2 was calculated and cation values were redetermined. A good carbonate analysis should have a sum for cations (Ca + Mg + Fe + Mn + Sr) of 1.0 ± 0.2.

Mineralogical Characterization

The Shelburne Marble is predominantly composed of white calcite. Ten other minerals form heterogeneously distributed inclusions in the marble and, as they are commonly intergrown and some are dark in color, they give the marble a characteristic streaked appearance (Fig. 2). The minerals that comprise the Shelburne Marble are divided into four groups: carbonates (calcite, dolomite), layer silicates (phlogopite, muscovite, chlorite, talc), framework silicates (quartz, feldspar), and nonsilicates (rutile, pyrite, apatite). A common association is phlogopite + dolomite ± rutile ± chlorite (Fig. 3). Modal abundances are as follows: carbonates = 97.3 %, layer silicates = 1.8 %, framework silicates = 0.1 %, non-silicates close to 0 %, and pits or holes = 0.7 %. The modal abundances for each mineral and sample are shown in Table 3. Most of the inclusions are relatively small grains (Table 4). Compositions of the minerals do not vary much, either within a thin section or overall (Table 5) and the compositions are mostly similar to the end-member or ideal composition for the mineral. A description of each mineral in the Shelburne Marble is given below and representative analyses of each phase are shown in Table 2.

Carbonates

Although the Shelburne Marble is predominantly (~ 97 %) calcite, it also contains dolomite (~ 0.6%). The calcite is white in hand specimen and optically it is unzoned and inclusion-free. The calcite grains are equidimensional but vary in size from 290 to 860 µm; grain widths vary over relatively short distances, and within the scale of a thin section they commonly vary 300 µm. Grains are irregularly shaped with subangular to slightly curved edges and they are tightly interlocked. Twinning of calcite is common but much of the twinning probably was caused by sample preparation. Compositionally, the calcite is fairly pure $CaCO_3$ with an MgO content that averages 0.8 wt. % (Table 2,5).

Dolomite is light to dark gray in hand specimen but optically it has a speckled appearance from numerous tiny black inclusions. The inclusions are probably graphite (Dale, 1912 identifies one type of marble as graphitic calcite marble), but the inclusions have not been positively identified in this study as they are of submicron size and are not at the surfaces of the grains. Dolomite grains are irregularly rounded in shape and range in diameter from 10 to 290 µm. They are commonly found in clusters with or without phlogopite, but solitary grains of dolomite in the calcite are also present. The association of dolomite + phlogopite grains gives the marble its characteristic streaked appearance (Fig. 2,3). Dolomite composition is very close to the ideal $(Ca,Mg)CO_3$ although it contains very small amounts of FeO (~ 0.3 wt. %) (Table 2,5).

Layer Silicates

Layer silicates (phlogopite, muscovite, chlorite, and talc) are the second most abundant mineral group in the Shelburne Marble (0.3 - 4 %). None of the layer silicates has a large compositional range (Fig. 4). The layer silicates give the marble its distinctive wavy streak pattern as they form linear clusters of thin blades.

Phlogopite is by far the predominant layer silicate phase; in hand specimen it has a pale brown color and with dolomite it is readily visible in the colored streaks of the marble. Optically, the phlogopite is only weakly pleochroic (very pale brown to white) and thin blades of phlogopite grains are intergrown together. Phlogopite + dolomite ± chlorite is a common association but phlogopite also occurs as small isolated grains. Phlogopite blades range from 20 to nearly 600 µm in length, but are commonly 150 to 300 µm long. Phlogopite is Mg-rich (MgO = 25.8 - 28.0 wt. %) (Table 2,5) and it contains minor amounts of FeO (~ 0.6), TiO_2 (~ 0.3), and F (~ 2.4 wt. %).

Muscovite is relatively rare. It is small (10 - 100 µm in length) and occurs as sparsely scattered colorless grains. Muscovite contains a small amount of MgO (2 - 5 wt. %), very minor amounts of CaO (~ 0.4 wt. %) and TiO_2 (0.4 - 0.9 wt. %), and is close to the ideal muscovite composition (Table 2,5).

Chlorite is nearly as rare as muscovite but the grains are larger (~ 50-200 µm long) and it is usually intergrown with phlogopite (or with phlogopite and dolomite). The grains are colorless in thin section. Compositionally, the chlorite is nearly end-member Mg-chlorite (Table 2,5) with 32 - 33 wt. % MgO and only ~ 1 wt. % FeO.

Talc is rare but notable because the grains are large (400 - 530 µm long). It is colorless in hand specimen and in thin section. The talc is in inclusion-rich areas and it is most closely associated with quartz and dolomite. It is nearly ideal in composition (Table 2,5) containing very minor amounts of Al_2O_3 (0.2-0.4 wt. %), FeO (~ 0.3 wt. %), and F (0.4 - 0.7 wt. %).

Framework Silicates

Framework silicates in the Shelburne Marble include feldspar and quartz; which constitute up to 0.3 % of the marble. Both feldspar and quartz are rounded, colorless 40 - 150 µm grains. They are usually isolated, although they may also be present in inclusion-rich areas. Quartz is nearly pure SiO_2 (Table 2). Sodium feldspar is the primary feldspar in the Shelburne Marble and it is commonly 50 - 100 µm in diameter. A very minor amount of small (30 - 40 µm) potassium feldspar is present too. Both feldspars are very close to their respective ideal compositions (Table 2,5).

Non-Silicates

Rutile, pyrite, and apatite comprise the non-silicates in the Shelburne Marble. All are rounded, small grains; rutile and pyrite are similar in size (10 - 60 µm and 10 - 40 µm in diameter, respectively) and apatite is a little larger (30-100 µm). Rutile and apatite are colorless and best seen in thin section. Large grains of pyrite are visible in hand specimen but they are rare. Pyrite is not framboidal in the unexposed marble; the surface texture of the pyrite is nearly indistinguishable from that of the surrounding calcite (Fig. 5). Rutile, pyrite, and apatite may occur as isolated grains or may be associated with phlogopite in inclusion-rich areas (Fig. 6). In one sample, very rare sphene (~ 20 µm) is associated with rutile ± quartz in an inclusion-rich area. The distribution of the non-silicates is very heterogeneous; pyrite grains are commonly localized in small areas. Rutile is the most widely distributed of the three phases and apatite is a very minor inclusion. Rutile is nearly pure TiO_2 (Table 2,5) although it does contain some CaO (~ 1.2 wt. %), which may be due to the small grain size and overlap effects during analysis. Pyrite is homogenous in composition (Table 2,5); it contains ~ 45.5 wt. % Fe, ~ 52.7 wt. % S, and very minor Co (~ 0.12 wt. %).

Implications for Marble Durability

Mineralogical changes are likely to occur because of chemical weathering processes that include: hydration, hydrolysis, oxidation, reduction, and exchange reactions (Reiche, 1950, Ollier, 1975). Chemical weathering processes are a particular concern for this study because the objective of the stone exposure studies is to determine the contribution to the weathering of marble that is due to acid precipitation. Thus, it is expected that solution, hydrolysis, and cation exchange will be important processes in the deterioration of the marble. The interaction between physical and chemical weathering processes is significant however and cannot be ignored in a study of stone deterioration.

The varied susceptibility of minerals in the weathering environment will influence how the marble responds to the environment. Since the Shelburne Marble is so dominantly composed of calcite, dissolution of calcite under acidic conditions will be a significant component of the weathering processes that act on the marble. However, the degree to which calcite dissolution is important in the overall durability of the marble will be influenced by a number of other factors. Dolomite, the layer silicates, and possibly pyrite are also likely to play a significant role in the weathering of the marble as they react with water, pollutants, and each other in the marble. Crystal size, crystal shape, crystal perfection, and access of the weathering agent and removal of weathered products are important factors to consider in addition to composition and structure, when determining the rates of weathering in minerals (Ollier, 1975). The Shelburne Marble is medium to coarse grained and contains a variety of mineral inclusions that are heterogeneously distributed throughout the rock and are clustered together in linear streaks. Dale (1912) recognized the significance of grain size and shape when he noted that although fine textured marbles present more surface area to rain water, water can travel rapidly in a coarse textured loosely compacted marble, and thus readily weather coarse marble. Bain (1941) also identified the width of intergranular openings in marble as a significant factor in the rate of marble weathering due to the accessibility of water provided by the cracks. A similar accessibility to water is present around the grain boundaries of large flakes or crystals of silicate inclusions in marble (Dale, 1912). Pore space and cracks are rare in the marble; calcite grain boundaries are difficult to distinguish with scanning electron microscopy. Where calcite grains meet inclusions, the boundaries are more visible because of slight differences in texture and grain shapes. Although the Shelburne Marble is tightly compacted and not very porous, the movement of water along grain boundaries especially where large silicate inclusions are present could be significant. Lewin and Charola (1981) studied a dolomitic marble with large platy or fibrous inclusions and concluded that it is particularly susceptible to the effects of freezing and thawing when the inclusions are present, resulting in a blistered and pitted appearance on the stone surface. It is likely that the inclusions will weather preferentially in the Shelburne Marble or that their presence contributes to increased intergranular water in local areas. Preliminary observations of Shelburne Marble columns on the Jefferson Memorial in Washington, DC have found pock marks and grooves that mimic the silicate inclusion pattern, some of which still contain small flakes of mica. Thus, the inclusions may be more significant to the deterioration of the stone in buildings than the dissolution of the calcite.

This characterization of mineral sizes, habits and compositions in the Shelburne Marble test block provides a basis for future studies of the weathering behavior of the marble, particularly as it is exposed in urban environments at the exposure sites and in existing buildings. Careful study of buildings made with Shelburne Marble could help to determine whether the dissolution of calcite in an acid environment or the preferential deterioration of inclusions is more significant in the deterioration of stone used in buildings and monuments. Examination, at one-year intervals, of briquettes and slabs exposed at monitored exposure sites, will provide information that may help in understanding the role of acid precipitation in the weathering and deterioration of building stone, as comparisons can be made between samples exposed to known environmental conditions.

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Table 1. Major Buildings Constructed of Vermont Marble

Building	Location	Date
New York City Library	New York City	1911
Federal Reserve Bank	Philadelphia	
Buildings of the Harvard Medical School	Boston	c. 1912
John Hay Memorial Library	Providence, R.I.	c. 1912
Memorial Continental Hall (Daughters of the American Revolution)	Washington, DC	1909
Red Cross Building	Washington, DC	1917
The Supreme Court	Washington, DC	1936
Jefferson Memorial	Washington, DC	1943
The Rayburn Buildings	Washington, DC	1965
The French Embassy	Washington, DC	1984
The Art Association Bldg.	Montreal, Canada	c. 1912

Table 2. Representative Mineral Compositions

2A. - Carbonates

	calcite	dolomite
CaO	54.87	30.66
MgO	0.78	21.05
MnO	0.00	0.00
FeO	0.05	0.31
SrO	0.10	0.03
CO_2	44.20*	47.95*
	100.00	100.00

2B. - Layer Silicates

	phlogopite	muscovite	chlorite	talc
SiO_2	42.60	49.07	30.54	62.52
Al_2O_3	14.64	30.20	20.82	0.20
K_2O	10.45	10.47	0.00	0.00
CaO	0.25	0.33	0.19	0.09
MgO	26.00	3.34	33.26	30.96
FeO	0.69	0.12	1.09	0.34
BaO	0.00	0.11	0.00	0.02
TiO_2	0.35	0.55	0.00	0.05
Na_2O	0.05	0.13	0.00	0.05
MnO	0.00	0.01	0.00	0.02
F	2.14	0.17	0.39	0.53
H_2O calc	3.29	4.41	12.73	4.44
	100.46	98.91	99.02	99.22

Table 2. Representative Mineral Compositions (continued)

2C. - Framework Silicates

	Na-rich feldspar	K-rich feldspar	Quartz
SiO_2	68.08	65.02	99.05
Al_2O_3	19.90	18.91	0.00
Na_2O	11.76	0.26	0.01
CaO	0.19	0.16	0.13
K_2O	0.09	16.55	0.00
BaO	0.00	0.16	0.04
FeO	0.00	0.00	0.00
MgO	0.00	0.00	0.00
	100.02	101.06	99.23
Ab:	98.62	2.30	
An:	.89	.80	
Or:	.49	96.89	

2D. - Non Silicates

	rutile
TiO_2	98.09
Cr_2O_3	0.02
Al_2O_3	0.04
FeO	0.07
MgO	0.07
MnO	0.00
NiO	0.02
CaO	0.59
SiO_2	0.00
	98.90

	pyrite
Fe	45.42
S	52.83
Cu	0.00
Zn	0.00
Co	0.13
Ni	0.00
	98.38

*CO_2 calculated by difference and stoichiomentry;
H_2O calculated based on site occupancies

Table 3. Modal Abundances (%), by sample

	H1-3N-6	H1-3N-7	H1-3N-8	H1-3N-9	H1-3N-10
Carbonates					
Calcite	98.3	95.4	96.5	98.8	94.2
Dolomite	0	0	1.6	0	1.5
Layer Silicates					
Phlogopite	.2	3.3	.6	.2	2.9
Muscovite	0	.1	.1	.4	0
Chlorite	.1	.7	.2	.1	.6
Talc	0	0	0	0	0
Framework Silicates					
Quartz	0	0	0	0	0
Na- Feldspar	.1	0	.3	0	0
K- Feldspar	0	0	0	0	0
Non-Silicates					
Rutile	0	0	0	0	0
Pyrite	0	0	0	0	0
Apatite	0	.1	0	0	0
Pits, spots, misc.	.4	.3	.2	.3	.7
Holes	.7	.2	.3	.3	.1

Table 4. Largest dimensions of grain (μm), by sample

	H1-3N-6	H1-3N-7	H1-3N-8	H1-3N-9	H1-3N-10
Carbonates					
Calcite	700-860	350-570	450-570	290-570	360-500
Dolomite		20	10 -90	60-290	20-180
Layer Silicates					
Phlogopite		40-500	25-580	80-375	20-480
Muscovite	10 -40	20-100	20- 30		
Chlorite		50- 70	100-200		60-100
Talc				530	400
Framework Silicates					
Quartz	40-100			150	50- 70
Na- Feldspar	40 -75	50-150	15 -75		130
K- Feldspar	30 -40				
Non-Silicates					
Rutile		10- 50	10 -35	60	40
Pyrite		10- 40			
Apatite		30			40-100

Table 5. Compositional Ranges

Carbonates:

	Calcite (42)		Dolomite (11)	
	Min	Max	Min	Max
CaO	53.59-	55.94	29.84-	34.09
MgO	.21-	1.28	18.37-	21.72
MnO	0.00-	.01	0.00-	0.00
FeO	0.00-	.37	.18-	.65
SrO	0.00-	.32	0.00-	.25
CO_2	43.29-	44.97	47.15-	48.21

Framework Silicates:

	Feldspar (28)		Quartz (10)	
	Min	Max	Min	Max
SiO_2	67.25-	69.63	98.07-	101.50
Al_2O_3	19.28-	20.35	0.00-	.05
Na_2O	11.31-	12.13	0.00-	.04
CaO	.03-	.60	0.00-	.05
K_2O	.03-	.11	0.00-	.03
BaO	0.00-	.04	.06-	.38
FeO	0.00-	.03	0.00-	.13
MgO	0.00-	.01	0.00-	.10

Layer Silicates:

	Phlogopite (34)		Muscovite (4)		Chlorite (5)		Talc (3)	
	Min	Max	Min	Max	Min	Max	Min	Max
SiO_2	41.67-	44.57	48.96-	49.84	30.41-	31.37	62.05-	63.44
Al_2O_3	12.15-	15.12	30.20-	33.56	20.23-	21.50	.16-	.36
K_2O	9.69-	10.90	10.28-	10.47	0.00-	.71	0.00-	0.00
CaO	.03-	.53	.33-	.49	.03-	.19	.09-	.16
MgO	25.76-	27.97	2.32-	3.34	32.34-	33.26	30.70-	31.54
FeO	.52-	.76	.10-	.12	.86-	1.13	.29-	.35
BaO	0.00-	.11	.11-	.18	0.00-	.04	0.00-	.04
TiO_2	.22-	.42	.52-	.88	0.00-	.07	.05-	.07
Na_2O	.04-	.22	.11-	.14	0.00-	.02	.05-	.06
MnO	0.00-	.02	0.00-	.02	0.00-	.02	0.00-	.04
F	2.06-	2.83	.13-	.17	0.36-	0.49	.45-	.66
H_2O ca	2.98-	3.41	4.41-	4.57	12.66-	12.74	4.44-	4.45

Table 5. Compositional Ranges (continued)

Non Silicates:

	Rutile (8)			Pyrite (5)	
	Min	Max		Min	Max
TiO_2	96.55	98.35	Fe	45.30	45.76
Cr_2O_3	0.00	.14	S	52.43	52.99
Al_2O_3	0.00	.04	Cu	0.00	0.00
FeO	0.00	.18	Zn	0.00	0.00
MgO	0.00	.08	Co	.06	.20
MnO	0.00	0.00	Ni	0.00	0.00
NiO	0.00	.02			
CaO	.21	2.01			
SiO_2	0.00	.08			

( ) = number of grains analyzed

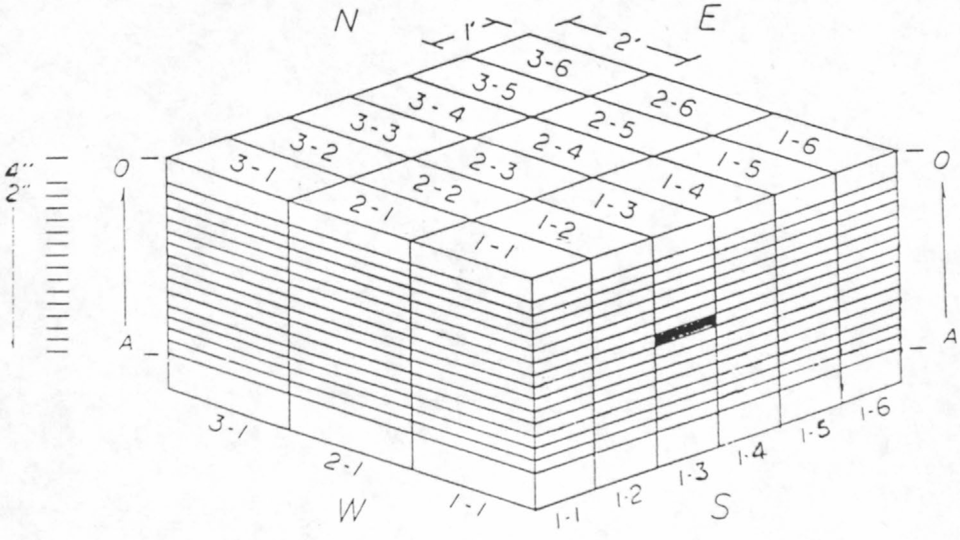

Figure 1. Marble block, shading indicates the location of the H1-3 slab used in the mineralogical characterization.

Figure 2. Photograph of a 12x24x2 inch slab of the Shelburne Marble, note the streaked appearence of the dark, dolomite + phlogopite inclusion areas.

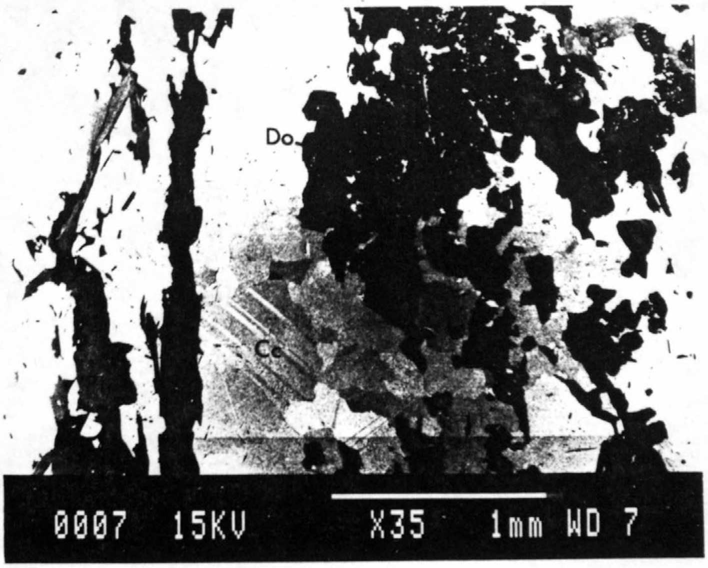

Figure 3. Typical association of phlogopite + dolomite ± rutile. Photograph is a back scattered electron image, Cc = calcite, Do = dolomite, Ph = phlogopite. Scale in lower right.

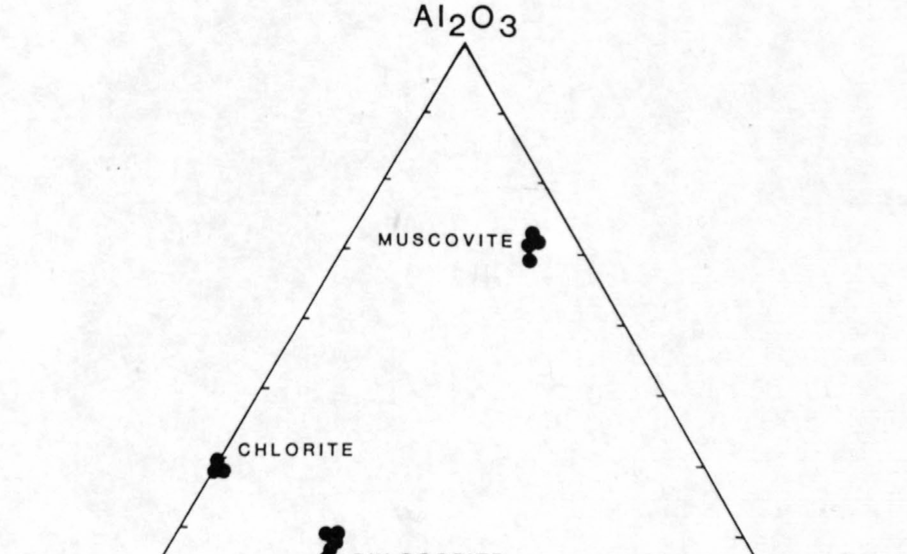

Figure 4. Al_2O_3 - K_2O - MgO ternary diagram for chemical compositions of the layer silicate minerals.

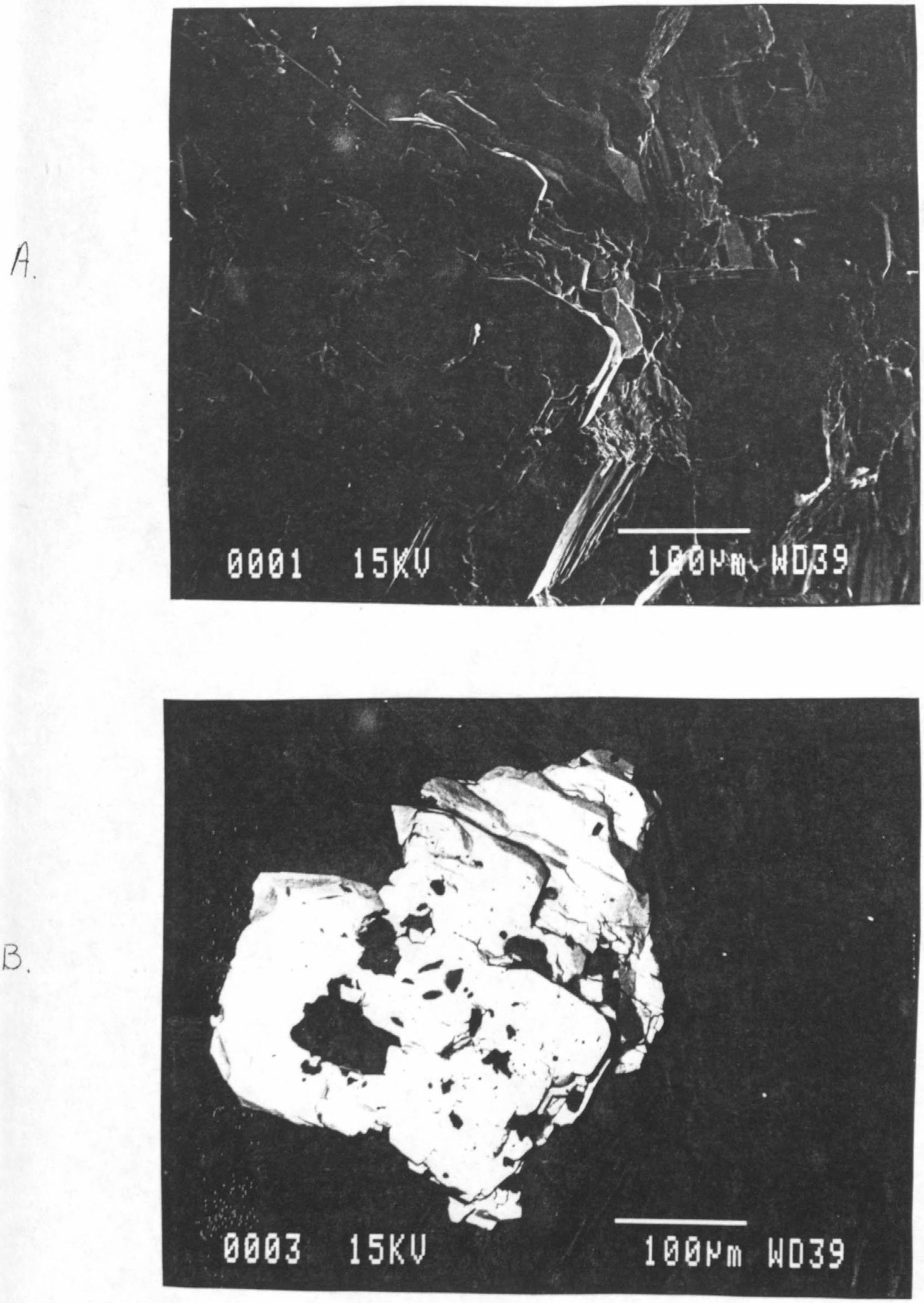

Figure 5. Scanning electron images of pyrite and calcite in a fractured surface of unexposed Shelburne Marble. A) Secondary electron image. B) Back-scattered electron image; pyrite is white and calcite is gray.

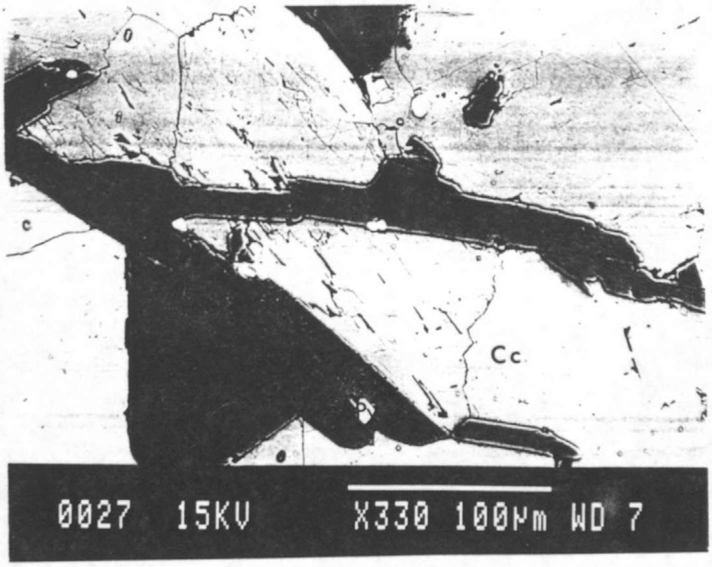

Figure 6. Typical association of pyrite with phlogopite. Photograph is a back scattered electron image, Cc = calcite, Ph = phlogopite, Py = pyrite. Scale in lower right.