LA-13694-MS

Evaluation of Ultramafic Deposits in the Eastern United States and Puerto Rico as Sources of Magnesium for Carbon Dioxide Sequestration

Los Alamos
NATIONAL LABORATORY
Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

Cover Photo: View looking northwest of a freshly excavated face in the Rockville Quarry, Maryland. Darker rocks consist of relatively pure, Mg-rich serpentinite in which the dominant mineral is antigorite. Lighter rocks contain Ca-bearing rodingite in which the dominant minerals are grossular and diopside. This quarry contains roughly 150 million tons of serpentinite that may be suitable as a source rock for CO_2 sequestration (photo by F. Goff).

An Affirmative Action/Equal Opportunity Employer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither The Regents of the University of California, the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by The Regents of the University of California, the United States Government, or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of The Regents of the University of California, the United States Government, or any agency thereof. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

LA-13694-MS

Issued: April 2000

Evaluation of Ultramafic Deposits in the Eastern United States and Puerto Rico as Sources of Magnesium for Carbon Dioxide Sequestration

Fraser Goff
George Guthrie
Bruce Lipin[*]
Melissa Fite[**]
Steve Chipera
Dale Counce
Emily Kluk
Hans Ziock

---

[*] *Collaborator at Los Alamos. U.S. Geological Survey, Reston, VA 20192*
[**] *Graduate Research Assistant at Los Alamos. University of California, Santa Barbara, CA 93106*

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

Table of Contents

List of Tables

List of Figures

EVALUATION OF ULTRAMAFIC DEPOSITS IN THE EASTERN UNITED STATES AND PUERTO RICO AS SOURCES OF MAGNESIUM FOR CARBON DIOXIDE SEQUESTRATION

by

Fraser Goff, George Guthrie, Bruce Lipin, Melissa Fite,
Steve Chipera, Dale Counce, Emily Kluk, and Hans Ziock

ABSTRACT

In this report, we evaluate the resource potential of extractable magnesium from ultramafic bodies located in Vermont, the Pennsylvania-Maryland-District-of-Columbia (PA-MD-DC) region, western North Carolina, and southwestern Puerto Rico. The first three regions occur in the Appalachian Mountains and contain the most attractive deposits in the eastern United States. They were formed during prograde metamorphism of serpentinized peridotite fragments originating from an ophiolite protolith. The ultramafic rocks consist of variably serpentinized dunite, harzburgite, and minor lherzolite generally containing antigorite and/or lizardite as the major serpentine minor phases. Chrysotile contents vary from minor to major, depending on occurrence. Most bodies contain an outer sheath of chlorite-talc-tremolite rock. Larger deposits in Vermont and most deposits in North Carolina contain a core of dunite. Magnesite and other carbonates are common accessories. In these deposits, MgO ranges from 36 to 48 wt % with relatively pure dunite having the highest MgO and lowest H_2O contents.

Ultramafic deposits in southwestern Puerto Rico consist of serpentinized dunite and harzburgite thought to be emplaced as large diapirs or as fragments in tectonic melanges. They consist of nearly pure, low-grade serpentinite in which lizardite and chrysotile are the primary serpentine minerals. Chlorite is ubiquitous in trace amounts. Magnesite is a common accessory. Contents of MgO and H_2O are rather uniform at roughly 36 and 13 wt %.

Dissolution experiments show that all serpentinites and dunite-rich rocks are soluble in 1:1 mixtures of 35% HCl and water by volume (i.e., a ~5 to 6*N* HCl solution). The experiments suggest that low-grade serpentinites from Puerto Rico are slightly more reactive than the higher grade, antigorite-bearing serpentinites of the Appalachian Mountains. The experiments also show that the low-grade serpentinites and relatively pure dunites contain the least amounts of undesirable insoluble silicates.

Individual ultramafic bodies in the Appalachian Mountains are as great as 7 km^3 although typically they are ≤1 km^3. The total volume of all deposits in the eastern United States is conservatively estimated at ≤50 km^3. In contrast, ultramafic deposits in southwestern Puerto Rico have an estimated volume of roughly 150 km^3. Based on the few detailed geophysical studies in North Carolina and Puerto Rico, it is evident that volume estimates of any ultramafic deposit would benefit greatly from gravity and magnetic investigations, and from corehole drilling. Nevertheless, the data show that the ultramafic deposits of the eastern United States and southwestern Puerto Rico could potentially sequester many years of annual CO_2 emissions if favorable geotechnical, engineering, and environmental conditions prevail.

INTRODUCTION

Steady increases in world CO_2 emissions have raised legitimate concerns about global warming and the terrestrial carbon cycle (Ramanathan 1988; Sabine et al. 1997; Weart 1997). These concerns have resulted in research on new technologies to capture and immobilize waste CO_2 to prevent environmental impacts to the atmosphere and climate (Lackner et al. 1998). Conversion of CO_2 into thermodynamically stable magnesite (see Table 1 for mineral identifications) is one of many technologies under current examination because the sequestered CO_2 is comparatively immobile in geologic environments (Lackner et al. 1995). Considerable resources of ultramafic rocks (Mg-rich peridotite and serpentinite) exist within the eastern United States and Puerto Rico (Goff and Lackner 1998; see the Appendix for a glossary of geologic terms). Most of the common minerals in peridotite and serpentinite (e.g., forsterite, lizardite, chrysotile, and brucite) are relatively soluble in ~5 to 6*N* HCl; thus, huge quantities of Mg can be easily dissolved for further chemical uses. Engineering and technology advances could lead to the construction of coal- or gas-fired power plants in which waste CO_2 is fed to a sequestering plant adjacent to an open-pit ultramafic mine. A synopsis of CO_2 sequestering in solid form, including probable mining costs, has been outlined previously (Lackner et al. 1995).

Retrofitting all existing fossil fuel plants for benign CO_2 disposal is surely an impractical task, but the global community must eventually deal with the CO_2 dilemma. We envision CO_2 sequestering in magnesite as one of many technologies that will eventually reduce or stabilize emissions. The environmental impact of large-scale ultramafic mining and CO_2 sequestering, with associated impacts on energy costs, would have to be weighed against the counter impact of continued CO_2 emissions to the atmosphere and the risk of accelerated climate change.

Table 1. Summary of Dominant Mineralogy in Serpentinite, Peridotite, and Associated Rocks

Mineral Group	Mineral Species	Ideal Formula	Rock Type(s) Typically Found In
serpentine	chrysotile	$Mg_3Si_2O_5(OH)_4$	serpentinite; altered peridotite
serpentine	lizardite	$Mg_3Si_2O_5(OH)_4$	serpentinite; altered peridotite
serpentine	antigorite	$Mg_3Si_2O_5(OH)_4$	high-grade serpentinite; altered peridotite
olivine	forsterite	Mg_2SiO_4	dunite; peridotite
orthopyroxene	enstatite	$MgSiO_3$	peridotite
clinopyroxene	diopside	$CaMgSi_2O_6$	peridotite
amphibole	anthophyllite	$Mg_2Mg_5Si_8O_{22}(OH)_2$	high-grade serpentinite
amphibole	tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$	high-grade serpentinite
spinel	magnetite	Fe_2FeO_4	serpentinite, peridotite, dunite
spinel	chromite	Cr_2FeO_4	serpentinite, peridotite
carbonate	magnesite	$MgCO_3$	altered serpentinite
carbonate	dolomite	$CaMg(CO_3)_2$	altered serpentinite
silica	quartz, chalcedony	SiO_2	altered serpentinite
silica	opal	$SiO_2 \cdot nH_2O$	altered serpentinite

The object of this report is to evaluate the ultramafic deposits of four regions in the eastern United States and Puerto Rico as sources of magnesium for industrial sequestration of carbon dioxide. In so doing, we describe the geology, distribution, volume, mineralogy, and magnesium content of ultramafic rocks in each region. Much of our evaluation originates from information available in the literature, but many of these published chemical and mineralogical data are not uniform. Hence, new chemical and mineral analyses were obtained on samples from many deposits described herein to provide systematic data on magnesium content and mineral characteristics. Large-scale ultramafic mining for CO_2 sequestration will produce abundant iron, chromium, and nickel as byproducts (Goff and Lackner 1998); thus, where possible, the content of these elements and the oxidation state of iron in the deposits are mentioned. Because ultramafic rocks vary widely in their mineralogy, we also describe results from additional acid dissolution experiments to compare the relative reactivity of various types of ultramafic samples from the four regions.

PREVIOUS RESOURCE EVALUATIONS

Goff and Lackner (1998) evaluated ultramafic bodies in the United States as sources of magnesium for CO_2 sequestration with an emphasis on two California sites: the Del Puerto ultramafic mass and the Wilbur Springs serpentinite. The reactivity of various ultramafic rocks, as conducted in simple acid dissolution experiments, was compared by Goff et al. (1997). Goff and Guthrie (1999) discussed the geology, tectonics, alteration history, present exploitation, and environmental situation of extensive ultramafic deposits in the Clear Lake region, California. These reports present examples of the geologic configurations, resource variations, and environmental impacts that must be considered during large-scale ultramafic mining for magnesium extraction.

The ultramafic bodies described herein all belong to ophiolite sequences, the most voluminous and widespread of all ultramafic deposits (Coleman 1977). Goff et al. (1997) and Goff and Lackner (1998) also evaluated magnesium resources in large, layered intrusions, the second most voluminous class of ultramafic rocks. Although volumetrically significant in a few locations in the United States, layered intrusions containing ultramafic rocks are not significant in the eastern United States or Puerto Rico. Exposed volumes of other ultramafic rock types are comparatively small worldwide (Coleman 1977) and are not discussed further because they generally contain too little magnesium for large-scale industrial processing.

Mineralogy and Chemistry of Ultramafic Rocks

The mineralogy of ultramafic rocks is highly variable, depending of their geologic history. A few key minerals (olivine and serpentine) are of most interest for purposes of CO_2 sequestration because they are regionally abundant, rich in magnesium, and readily soluble in HCl. Table 1 presents the common species and their formulae for minerals in typical ultramafic rocks (serpentinites, dunites, and peridotites, which includes harzburgites and lherzolites). Many of the mineral groups have mineral species that are Mg- or Ca/Mg-end members. Many minerals contain additional elements that substitute for elements in the idealized formulae. For example, chromite may contain considerable Mg and Al substituting for Cr and Fe. Also note the difference between magnesite (a carbonate) and magnetite (an iron oxide). Many accessory minerals of relatively insignificant volume are not included in Table 1. The Appendix contains a glossary of geologic terms frequently used in this report but unfamiliar to nongeologists.

Geologic Background

The magnesium-rich, ultramafic rocks (primarily peridotite and serpentinite) that we envision as candidate ores in the CO_2 sequestering process, are distributed throughout the world (Goff and Lackner 1998). As mentioned above, the most voluminous and widespread ultramafic rocks are the alpine (“metamorphic”) peridotites that form the basal sequence of ophiolites, slabs of oceanic crust uplifted and eroded along present and past subduction zones and plate boundaries (Coleman 1977). The basal peridotites represent detached slices of the Earth’s upper mantle exposed by these tectonic processes (Dickinson et al. 1996). Because they occur mostly along the upper plate of present and past subduction zones, ophiolites are found as belts throughout most of the world, having discontinuously exposed dimensions of as much as 1,000 km by 100 km. Within North America, ophiolite belts are found along the Appalachian mountain chain stretching from the southeast United States into Quebec and Newfoundland, and along the Cordilleran mountain chain stretching from Alaska through British Columbia to California (Figure 1). Smaller belts containing significant volumes of ultramafic deposits are found in Guatemala and in the Caribbean (Cuba, Dominican Republic, and Puerto Rico).

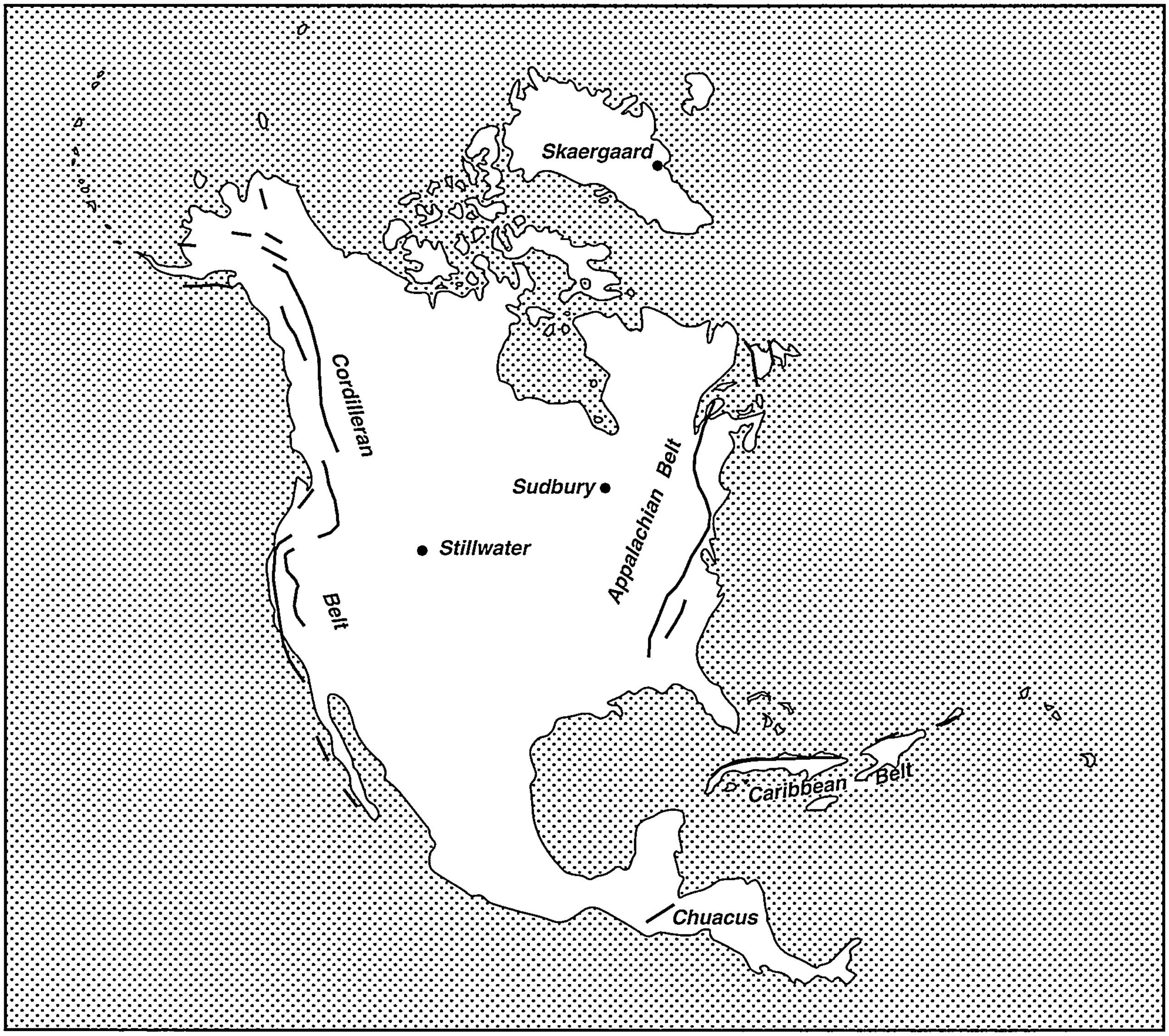

Figure 1: Map of North America showing generalized distribution of ophiolite belts and the three largest layered intrusive bodies (modified from Coleman 1977).

When examined more closely, the basal ultramafic rocks in ophiolite belts are found to be elongate ribbons and fragments that parallel regional geologic structures. The tectonic processes that create ophiolites and expose elongate fragments of upper mantle peridotite are complex and usually take several million years to complete (Coleman 1977; Harper 1984). Using plate tectonic theory, these processes are relatively easy to visualize in general terms but may be difficult to visualize when examining ultramafic bodies in the field. Exposures of ultramafic rock may occupy hundreds of square kilometers or may be as small as hand samples incorporated into fault zones.

The complex geologic history of ultramafic deposits produces serpentinites that are structurally and mineralogically complex, which may impact the exploitation of these deposits for sequestration purposes. For example, structural complexities often result in scattered surface outcrops for the deposits and a likely complex subsurface distribution. This makes estimation of the total volume of the deposits difficult in the absence of geophysical data. Magnetic and gravity surveys are probably excellent methods to make a first-cut determination of deposit dimensions because of the relatively high magnetic properties and high density of many ultramafic deposits. Mineralogical complexities may also lead to variations in the kinetics and conditions of the sequestration process, inasmuch as antigorite (the serpentine mineral that occurs in the rocks exposed to higher pressure and temperature during metamorphism) behaves somewhat differently than chrysotile and lizardite (the other two serpentine minerals). Rocks dominated by olivine (the major preserpentization mineral in dunite) may also behave uniquely in the sequestration process.

Ultramafic rocks containing large amounts of silicate minerals that are not easily reacted with industrial reagents (i.e., amphiboles, pyroxenes, talc, etc.) must be avoided. Ultramafic rocks containing significant secondary carbonate minerals are also to be avoided because the sequestration potential of these rocks has already been tapped by natural processes.

ULTRAMAFIC DEPOSITS OF VERMONT

Ultramafic bodies of Vermont (Figure 2) vary widely in size and mineralogical character. They occur in a belt extending from Massachusetts to Quebec and Newfoundland (Chidester 1962: Chidester et al. 1978) and are part of a continuum of ultramafic bodies that outcrop along the entire length of the Appalachian mountain ranges (Misra and Keller 1978). The ultramafic rocks are generally mapped as north-striking lenticular to tabular masses enclosed by folded, metamorphosed sedimentary and volcanic rocks (primarily gneiss and schist) on the eastern limb of the Green Mountain anticlinorium. The ultramafic rocks originated as mantle peridotite and were presumably the basal part of an ophiolite sequence. Subduction during early Paleozoic time thrust fragments of ophiolite into and over a variety of continental rocks (Stanley and Ratcliffe 1985). Initial serpentinization of the peridotite is not constrained but probably occurred previous to and during subduction. Adjacent amphibolite bodies that may be equivalent to former mafic rocks in the ophiolite sequence are dated at roughly 500 Ma (Laird et al. 1984). Structural deformation and metamorphism of the accumulated rock package (Taconian orogeny) along the ancient continental margin were more or less complete by late Devonian time (350 Ma). Unmetamorphosed mafic dikes of Permian to Triassic age cut the metasedimentary and metavolcanic sequence.

Mining of asbestos, talc, and ornamental serpentine from the various ultramafic bodies has occurred during the last 150 years. Several reports debate whether silica and/or magnesia is added or subtracted during serpentinization (Labotka and Albee 1979; Sanford 1982; O'Hanley 1992). It is not entirely clear from the literature if the rare, dunite-rich cores of larger bodies represent relict, unmetamorphosed rock from the mantle protolith (Chidester et al. 1978) or represent dunite formed during higher grade metamorphism (e.g., Lipin 1984). Hoffman and Walker (1978) point out that some olivine grains in the East Dover dunite body show obvious recrystallization textures and an especially high Mg content (i.e., with a forsterite component (or fo) as high as fo ≤97%) and that the chromites have been metamorphosed (i.e., Lipin 1984). If so, this implies that the high forsterite component of Belvidere Mountain olivines (fo = 97) reported by Chidester et al. (1978) may also result from recrystalization during prograde metamorphism.

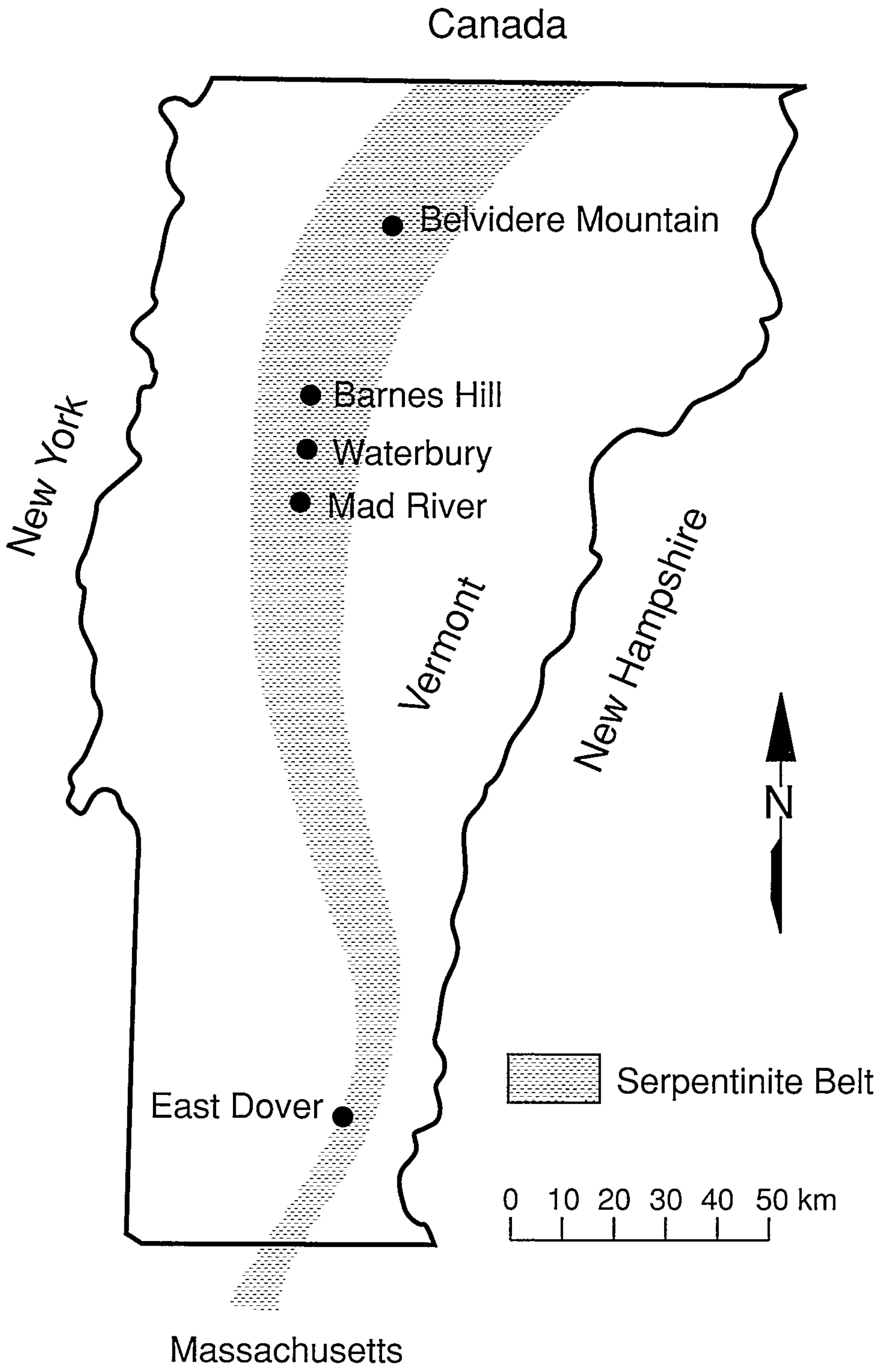

Figure 2: Map of Vermont showing the location of the ultramafic belt and five bodies described in the text.

Dunite-Free (Verde Antique) Deposits

This ultramafic type is the most common in Vermont. The ultramafic masses are generally lenticular, ranging in size from a few meters in length to more than 1.5-km long and 600-m wide (Chidester 1962). They consist of a core of serpentinite or irregularly distributed masses of serpentinite within an alteration sheath grading outward from talc-carbonate rock to talc-rich rock ("steatite") to chlorite-rich rock ("blackwall"). Generally the gradations between the different mineralogical zones in the alteration sheath are sharp. The entire alteration sheath may be only a few meters wide. Serpentinite from these deposits is often sold as ornamental stone and is sometimes referred to as "verde antique."

Chidester (1962) has described the geology of three such serpentinite bodies (Barnes Hill, Mad River, and Waterbury). The serpentinite consists primarily of antigorite with minor chrysotile, lizardite, talc, carbonate, chlorite, tremolite, and magnetite (Table 2). The carbonate mostly consists of dolomite and/or magnesite. The only primary mineral is relict chromite, which occurs in small quantities (usually less than 1 wt %). The serpentinites are massive to schistose. Slip cleavage, jointing, fracturing, and faulting are locally pervasive. Some of the larger bodies have been cored to assess three-dimensional tonnage of talc-bearing rocks. However, the depth of individual bodies may vary substantially along strike (Figure 3). Thus, it is difficult to estimate the total mass of larger bodies without drill-core or geophysical surveys. The estimated masses of serpentinite in the three bodies described above vary from about 10×10^6 to 150×10^6 tons, but average about 37 ±1 wt % MgO.

Table 2. Resource Information on Example Ultramafic Bodies in Vermont

Body Name	Mineralogy[1]	Surface Area (m^2)	Thickness (m)	Max. Volume (km^3)	Density (g/cm^3)	Ore Mass (metric tons)	MgO (wt %)	Comments	References
Barnes Hill	Primary: Chr (trace) Secondary: Srp-Mgs-Dol-Tlc-Mag-Chl	53,000	150	0.008	2.70	10×10^6	38	50% of deposit is composed of talc schist and talc-carbonate rock.	Chidester (1962)
Belvidere	Primary: Ol (fo=0.97)-En-Chr-Di Secondary: Srp-Tlc-Carb-Chl-Mag-Ath	6.1×10^6	450	2.75	2.9	$8{,}000 \times 10^6$	43	Density ranges from 3.25 to 2.66 in main body; estimated area as high as 12×10^6 m^2	Chidester et al. (1978); Labotka and Albee (1979)
East Dover	Primary: Ol (fo=0.93)-Chr-En Secondary: Srp-Chl-Tlc-Tr-Carb-Mag	6.8×10^6	400?	2.70?	2.9?	$7{,}800 \times 10^6$	43	No information on thickness or density	Hoffman and Walker (1978)
Mad River	Primary: Chr (trace) Secondary: Srp-Tlc-Dol-Mag-Tr-Chl	305,000	200	0.061	2.68	$\geq 147 \times 10^6$	37	≥90% of deposit is serpentinite; small serpentinite-rich bodies occur nearby.	Chidester (1962)
Waterbury	Primary: Chr (trace) Secondary: Srp-Dol-Tlc-Mag-Tr-Chl	145,000	120	0.018	2.66	41×10^6	37	90%(?) of body is serpentinite; small serpentinite-rich bodies occur nearby.	Chidester (1962)

[1] Mineral symbols according to Kretz (1983). Ol=olivine (forsterite component, or fo, given if known); En=enstatite; Di=diopside; Chr=chromite; Srp=serpentine (undifferentiated); Chl=chlorite; Ath=anthophyllite; Tr=tremolite; Carb=carbonate (undifferentiated); Mag=magnetite; Dol=dolomite; Mgs=magnesite; Tlc=talc

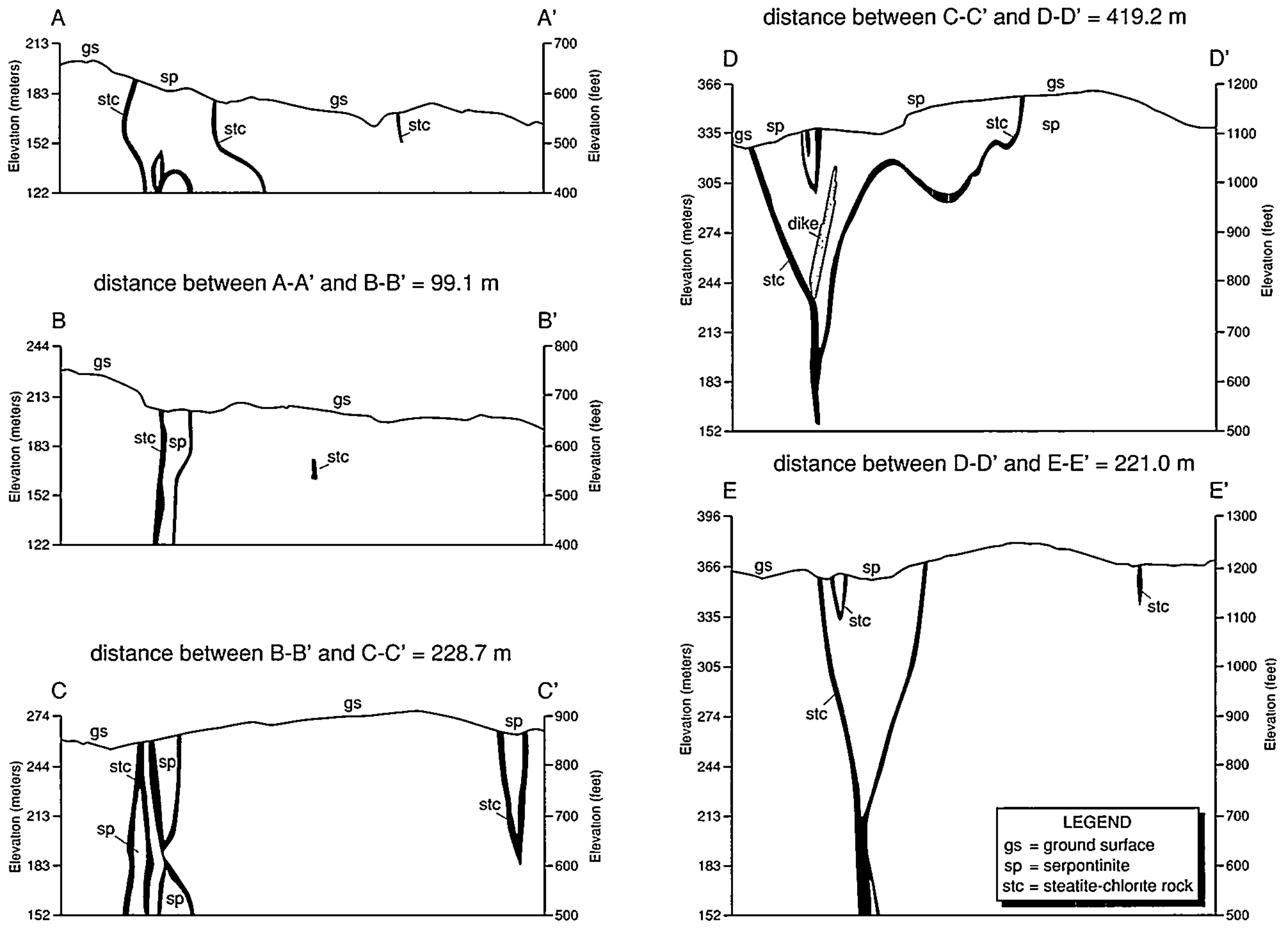

Figure 3: East-west cross sections of the Waterbury ultramafic body, Vermont from drill holes, underground intercepts, and geologic relations. Section A-A' is north and section E-E' is south. Horizontal and vertical scales are equal (modified from Chidester 1962).

Table 3 shows that relatively pure serpentinite in the "verde antique" deposits has reasonably constant MgO but variable SiO_2 and Fe_T (total Fe). The FeO/Fe_2O_3 ratio is also quite variable. Contents of Cr and Ni are relatively normal for serpentinized mantle peridotite in ophiolite sequences. Metamorphism is so extensive that the original texture and mineralogy of the rocks cannot be ascertained (i.e., dunites or harzburgites). The progressive addition of talc, chlorite, and other silicates to the serpentinite during metamorphism decreases the MgO content substantially (compare the various Mad River and Waterbury analyses in Table 3).

Table 3. Chemical composition of example ultramafic and related rocks in Vermont; values in wt % unless otherwise noted; LOI includes H_2O (+) and CO_2.

	Dunite-Free Bodies						Dunite-Rich Bodies						
	Bames Hill[1]	Mad River[2]	Mad River[3]	Water-bury[4]	Water-bury[5]	Water-bury[6]	Belvi-dere[7]	Belvi-dere[8]	Belvi-dere[9]	Belvi-dere[10]	E. Dover[11]	E. Dover[12]	E. Dover[13]
No. of Analyses	1	1	1	1	1	1	3	2	2	9	Zone 1	Zone 2	Zone 3
SiO_2	38.30	41.60	38.80	43.10	60.50	25.60	39.7±1.1	39.7±0.6	34.4±1.6	40.8±2.2	41.70	40.00	41.00
TiO_2	0.01	0.01	0.08	0.01	0.01	3.47	0.0	0.01	0.0	0.02±0.03	<0.01	<0.01	<0.01
Al_2O_3	1.14	0.36	1.60	1.06	0.82	18.90	0.4±0.5	0.6±0.5	0.7±0.4	1.1±0.5	0.49	0.34	0.90
Fe_2O_3	5.93	3.85	8.20	1.07	0.10	1.64	n.a.	2.3±0.6	n.a.	2.7±2.1	n.a.	n.a.	n.a.
FeO	2.25	4.46	n.a.	5.22	4.59	20.10	8.9±2.7	3.5±0.5	14.3±1.4	2.5±2.2	5.47	8.05	5.95
MnO	0.09	0.07	0.09	0.11	0.09	0.90	0.2±0.2	0.19	0.2±0.0	0.10±0.04	0.08	0.16	0.10
MgO	38.30	37.10	32.80	37.10	28.50	18.50	48.3±1.4	48.5±1.0	36.9±0.8	39.4±2.1	46.20	48.40	43.70
CaO	0.23	0.36	3.60	0.00	0.02	0.01	n.a.	0.02	n.a.	0.14±0.26	n.a.	n.a.	n.a.
Na_2O	0.00	0.00	0.17	0.00	0.00	0.01	n.a.	0.00	n.a.	0.03±0.09	n.a.	n.a.	n.a.
K_2O	0.03	0.05	0.09	0.03	0.03	0.02	n.a.	0	n.a.	0.02±0.03	n.a.	n.a.	n.a.
P_2O_5	0.01	0.01	0.06	0.01	0.02	0.01	n.a.	0.01	n.a.	0.02±0.04	n.a.	n.a.	n.a.
Cr_2O_3	0.30	0.12	n.a.	0.31	0.26	n.a.	1.6±0.7	0.25	0.6±0.2	0.26±0.13	0.56	0.64	0.73
NiO	0.22	0.28	n.a.	0.22	0.20	0.02	n.a.	0.29	n.a.	0.26±0.08	0.04?	0.36	0.05?
H_2O (+)	10.73	11.32	n.a.	11.77	4.94	10.80	1.2±0.8	5.4±1.9	11.8±0.9	12.1±0.9	5.58	2.03	8.26
H_2O (-)	0.07	0.07	n.a.	0.11	0.00	0.09	n.a.	n.a.	n.a.	0.30±0.39	n.a.	n.a.	n.a.
CO_2	2.46	0.64	n.a.	0.08	0.00	0.05	n.a.	0.11±0.04	n.a.	0.25±0.29	n.a.	n.a.	n.a.
LOI	13.19	11.96	14.40	11.85	4.94	10.85	1.2	5.55	11.8	12.35	5.58	2.03	8.26
Total	100.07	100.30	99.89	100.20	100.08	100.12	100.3	100.9	98.9	100.0	100.12	99.98	100.69
MgO/SiO_2	1.00	0.89	0.85	0.86	0.47	0.72	1.22	1.22	1.07	0.96	1.11	1.21	1.07
FeO/Fe_2O_3	0.38	1.16		4.88	4.59	12.30		1.52		0.93			

[1] Massive serpentinite (Chidester 1962).

[2] Schistose serpentinite (Chidester 1962).

[3] Massive serpentinite (Chidester 1962); contains talc, chlorite, and carbonate.

[4] Massive serpentinite (Chidester 1962).

[5] Talc schist (steatite; Chidester 1962).

[6] Ilmenite-chlorite schist (blackwall, Chidester 1962).

[7] Average of three bulk dunite samples from microprobe analyses (Labotka and Albee 1979).

[8] Average of two dunite samples (Chidester et al. 1978).

[9] Average of two bulk serpentinite samples from microprobe analyses (Labotka and Albee 1979).

[10] Average of nine serpentinite samples (Chidester et al. 1978).

[11] Weighted average of microprobe analyses assuming 55% olivine, 44% antigorite, and 1% chromite (Hoffman and Walker 1978).

[12] Weighted average of microprobe analyses assuming 80% olivine, 16% antigorite, 1% chromite, and 3% magnetite (Hoffman and Walker 1978).

[13] Weighted average of microprobe analyses assuming 30% olivine, 65% antigorite, 1% chromite, and 4% magnetite (Hoffman and Walker 1978).

Dunite-Rich Deposits of Belvidere Mountain and East Dover

Ultramafic deposits of this type are generally much larger than the former type. The interiors of the bodies consist of partially serpentinized dunite and subordinate harzburgite (as pure as 80% by volume of unserpentinized rock). This grades outward into more highly serpentinized rock that in turn is surrounded by a relatively thin alteration sheath of talc-carbonate-chlorite rocks. The primary minerals are olivine, enstatite, chromite, and sparse diopside. The serpentine is predominately antigorite with highly variable chrysotile contents and minor lizardite. Some of the chrysotile-rich zones occur as cross-fiber and slip-fiber veins. The Belvidere Mountain deposit is noteworthy for once being a primary domestic source of chrysotile asbestos (Chidester et al. 1978; Labotka and Albee 1979). The rocks are locally faulted, fractured, and sheared with serpentinite concentrated in these structures. Thus, it is common to observe relatively unserpentinized blocks surrounded by highly serpentinized fractures and shears.

Belvidere Mountain also contains abundant rodingite (Ca-rich, metamorphosed mafic rock in contact with serpentinite; Bell et al. 1911; Coleman 1977). Typical rodingite minerals are grossular (Ca-rich garnet) and diopside but more than 20 other minerals have been identified in the rodingites exposed in the Belvidere quarries (Van Baalen et al. 1999).

The semiconcentric nature of serpentinization has been mapped out at the East Dover body (Figure 4; Hoffman and Walker 1978). This ultramafic mass is roughly 1.5 km by 4.5 km in dimension. The depth of the body is not known, although it is a lenticular mass enclosed by folded metasedimentary and metavolcanic rocks. Presumably, the thickness could be estimated from both gravity and magnetic surveys. The Belvidere Mountain mass is better exposed and has been drilled to exploit asbestos. It is a folded slab of ultramafic rocks having a maximum average thickness of about 450 m, also enclosed in various metamorphic rocks (Figure 5). The areal extent of the Belvidere Mountain deposit is variably estimated at 6×10^6 to 12×10^6 m^2. We conservatively estimate that both the Belvidere and East Dover deposits contain roughly $8{,}000 \times 10^6$ tons of rock averaging about 43 wt % MgO (Table 3).

Chemical analyses of the dunites and serpentinites from Belvidere Mountain are compared in Table 3. Analyses were performed both by conventional methods (Chidester et al. 1978) and by electron microprobe methods (Labotka and Albee 1979). The two methods yield comparable results on dunites for both SiO_2 and MgO but microprobe results for Fe_T and Cr are suspiciously high, and the loss-on-ignition (LOI) is too low. These samples, which lie adjacent to chrysotile veins, probably contain abnormal amounts of magnetite. Using conventional analyses as the best overall guides of bulk composition, MgO/SiO_2 and FeO/Fe_2O_3 average about 0.96 and 0.93, respectively.

No conventional analyses were found for rocks from the East Dover ultramafic mass (Table 3). The approximate composition of the rocks was created from bulk mineral analyses by electron microprobe of individual zones described by Hoffman and Walker (1978). The MgO/SiO_2 ratio exceeds 1.07 and LOI is low (commonly <10 wt %) because of the low content of serpentine minerals. As pointed out by these authors, bulk rock Cr and Ni values determined by microprobe are suspect due to imperfect analytical characterization.

BALTIMORE AND LIBERTY COMPLEXES (PA-MD-DC REGION)

The Baltimore Mafic Complex (Drake et al. 1989) and the Liberty Complex (Linder et al. 1992) consist of a broad north-northeast-trending belt of mafic and ultramafic rocks about 150-km long, extending from southeast Pennsylvania through Maryland into central Virginia (Morgan 1977). These complexes are interpreted to be a fragmented ophiolite sequence—one of the largest such sequences in the Appalachian mountain ranges—that was emplaced during early Paleozoic subduction. As in Vermont, the ophiolite has been severely metamorphosed during later events associated with development of the Appalachians. Geologic relations suggest that the minimum age of emplacement and metamorphism is no younger than late Ordovician (≥320 Ma). Because they host extensive chromite deposits, serpentinized ultramafic rocks of the Baltimore Mafic Complex and the Liberty Complex have been studied since the 1820s. At one time, these chromite deposits were among the most productive in the United States and the world (Pearre and Heyl 1960).

We collected samples from a series of quarries in these complexes stretching from the Pennsylvania-Maryland Border district (along the state line) into south-central Maryland (Figure 6). These quarries are primarily mined for road fill, rip-rap, and building stone. The Rockville quarry (a.k.a. Hunting Hill quarry), which lies a few kilometers northwest of Washington D.C., is also famous as a collecting site for rodingite minerals (Larrabee 1969). We also sampled the Soldier's Delight body (Maryland) that hosts a famous, old chromite mine (Choate Mine; Pearre and Heyl 1974; Johnsson 1996).

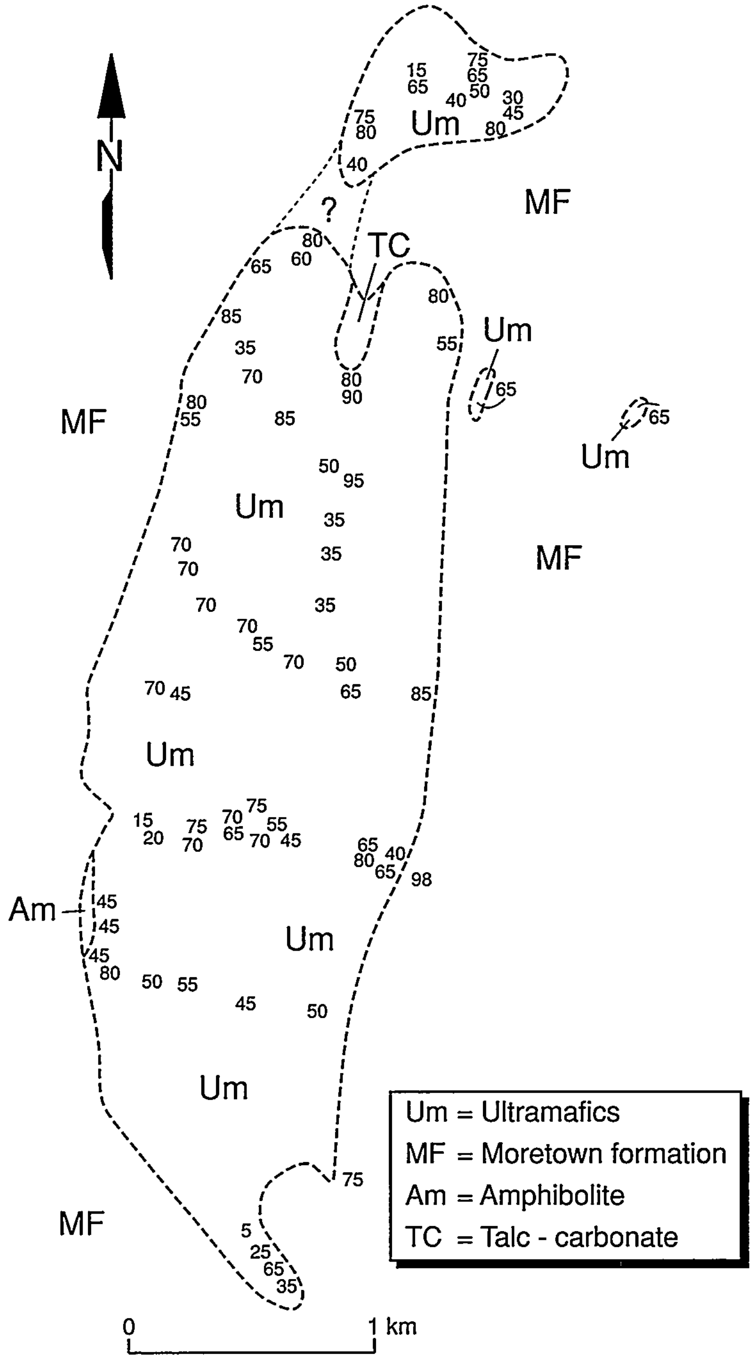

Figure 4: Simplified geologic map of the East Dover ultramafic body, Vermont (from Hoffman and Walker 1978). Numbers indicate the degree of serpentinization in terms of total serpentine + chlorite expressed in volume percent (±5%).

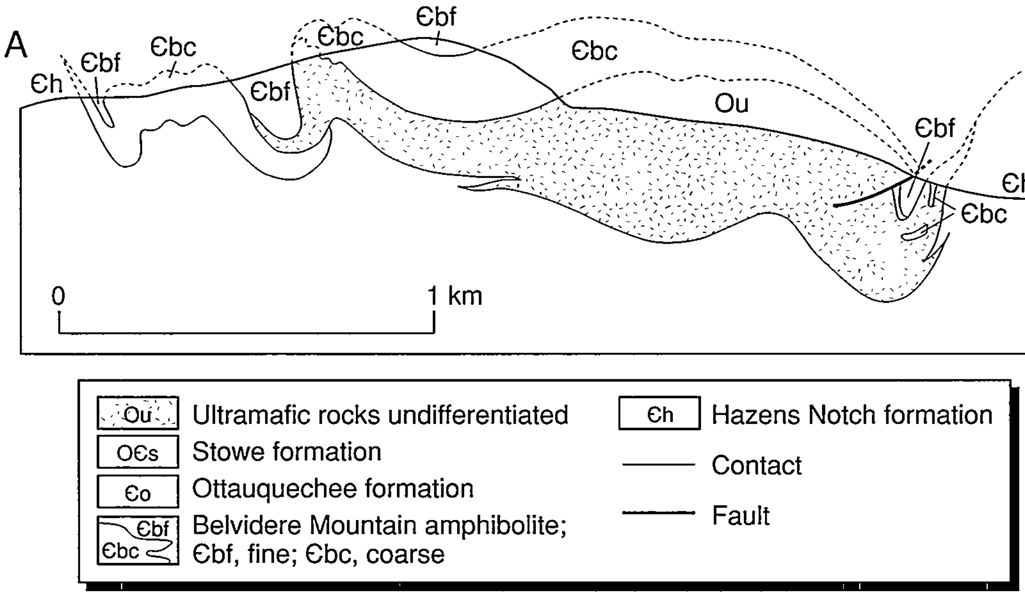

Figure 5: Cross section of the Belvidere Mountain ultramafic body, Vermont (from Chidester 1961).

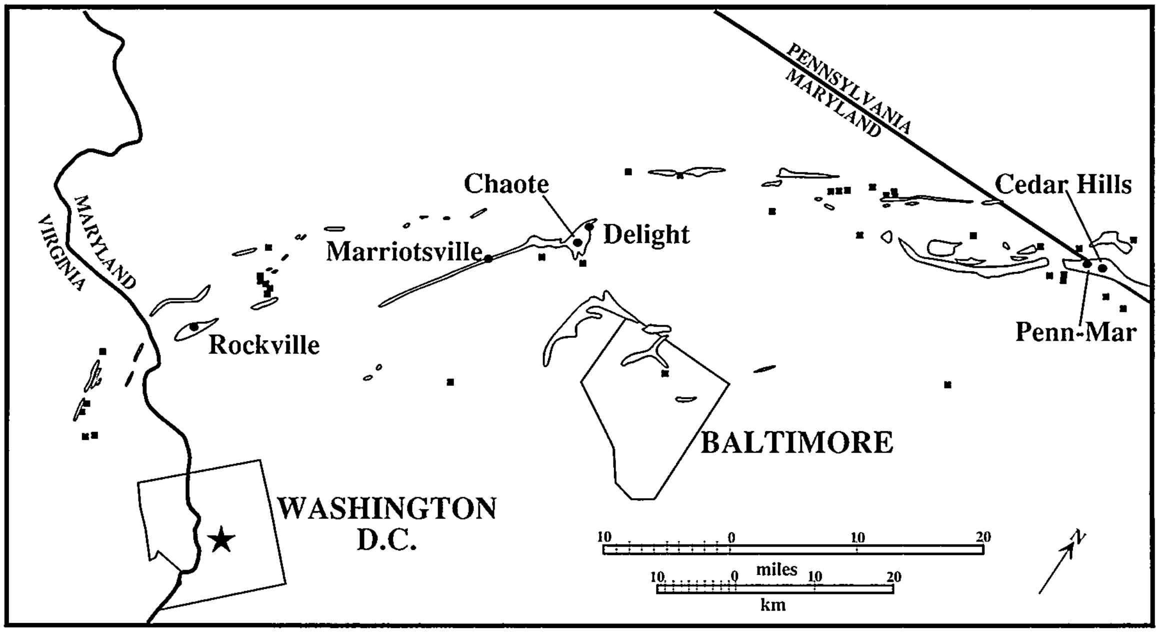

Figure 6: Map of the PA-MD-DC region showing the distribution of ultramafic bodies and the quarries visited during this investigation (from Larrabee 1966).

Because extensive regional metamorphism has affected the ultramafic rocks of the Baltimore Mafic Complex and the Liberty Complex, the rocks are generally of moderate metamorphic grade and look surprisingly different from site to site. As a result, the nature of the original peridotite (harzburgite, dunite, etc.) is difficult to ascertain. Residual olivine is observed in some specimens, but bastite pseudomorphs after pyroxene are absent, suggesting that most of the original peridotite was dunite. Most specimens we collected contain some chlorite, tremolite, and talc as well as the usual serpentine minerals (antigorite with minor chrysotile and lizardite), and secondary magnetite (Table 4). Thin layers and small pods of chromite can be seen in many quarry exposures. In addition, veins and veinlets filled with magnesite, silica, and other minerals cut the serpentinites.

Although individual serpentinite bodies hosting the quarries may be substantial, mineable reserves in each quarry may be relatively small because of various land restrictions. For example, the Hunting Hill serpentinite is roughly 10.2 km^2, and the serpentine averages at least 100-m thick (about 1 km^3). However, mineable reserves at the Rockville Quarry are only 170×10^6 tons, about 0.1 km^3. Environmental restrictions in heavily populated areas of the Maryland-Pennsylvania region may impede exploitation of some serpentinite deposits. Descriptions of individual quarry sites follow.

Table 4. Resource information on example serpentinite quarries and bodies, PA-MD-DC region

Quarry Name(s) (Body Name)	Mineralogy[1]	Surface Area (km^2)	Thick-ness (m)	Max. Volume (km^3)	Density (g/cm^3)	Ore Mass (metric tons)	Reserves[2] (metric tons)	MgO (wt %)	Comments
Cedar Hill-Penn Mar	Primary: Ol (≤5%)-Chr						55×10^6	40	(See footnote 2)
(State Line)	Secondary: Srp-Chl-Mag-Mgs-Dol-Brc	≥30	≥200	≥6	2.5	15×10^9			
Chaote Mine area	Primary: Chr								Volume from H.B. Johnson (The Arundel Corp.)
(Soldier's Delight)	Secondary: Srp-Mag-Mgs-Chl	69	≥100	≥7	2.4	17×10^9		38	
Delight	Primary: Chr Secondary: Srp-Dol-Mgs-Mag-Tlc				2.4		0.91×10^6	38	Reserve value from H.B. Johnson (The Arundel Corp.)
Marriotsville	Primary: None observable Secondary: Tr-Ath-Tlc-Chl-Srp-Carb					very small		28	Schist on southeast margin of body
Rockville	Primary: Chr-Ol						155×10^6	38	Reserve value from J.S. Croney (Bardon, Inc.) Volume from Larabee (1969)
(Hunting Hill)	Secondary: Srp-Chl-Tr-Tlc-Mag-Carb	10	≥100	≥1	2.5	2.5×10^9			

[1] Mineral symbols according to Kretz (1983). Ol=olivine (forsterite component, or fo, given if known); En=enstatite; Di=diopside; Chr=chromite; Srp=serpentine (undifferentiated); Chl=chlorite; Ath=anthophyllite; Tr=tremolite; Carb=carbonate (undifferentiated); Mag=magnetite; Dol=dolomite; Mgs=magnesite; Tlc=talc; Brc=brucite

[2] Reserve value given is for Penn-Mar Quarry from from D. Chandler; value for Cedar Hill Quarry is proprietary information; current production = 0.55×10^6 tons/yr (E. Nordstrom; D.H. Stoltzfus & Son, Inc., personal communication).

Cedar Hill and Penn-Mar (Rock Springs) Quarries

These quarries are described together because they occur side by side in the same ultramafic body. Most rocks in these quarries consist of dark greenish-black to black, massive to slightly sheared serpentinite. There are also zones of more highly sheared brownish-green serpentinite. Small olivine relicts are observable in some hand samples. Rare veinlets of chrysotile cut the rock. Some larger shear zones are filled with chlorite and vermiculite-rich material. Veins and veinlets of opaline carbonate to nearly pure magnesite cut the serpentinite. Thin sections show that the serpentinite locally contains a small percentage of chlorite-tremolite-talc and up to 5 vol % forsteritic olivine. Iron oxides fill many of the shear planes. Brucite was identified in one sample using x-ray diffraction methods.

Chemically, three serpentinite samples from the adjacent quarries contain 38.7 to 42.0 wt % MgO (Table 5). The MgO/SiO_2 ratio is 1.0 to 1.2, and the FeO/Fe_2O_3 ratio is ≤0.25. Two of the samples are greenish-black and contain more MgO because they have slightly more relict olivine, but these samples also contain slightly more carbonate. The single brownish-green sample has elevated Cr. Otherwise, the three samples show very typical Cr and Ni values compared to most ophiolitic serpentinites. Samples from these quarries also contain exceptionally low Al and Ca suggesting that they were originally dunite and not harzburgite.

Table 5. Chemical composition of example ultramafic bodies in the PA-MD-DC region; values in wt % unless otherwise noted; LOI includes H_2O (+) and CO_2.

	Cedar Hill[1]	Cedar Hill[2]	Penn-Mar[2]	Chaote Mine[3]	Delight[4]	Delight[5]	Marriotsville[6]	Rockville[7]	Rockville[8]	Rockville[9]
No. of Analyses	1	1	1	1	1	1	1	104	2	41
SiO_2	39.20	35.10	36.00	39.30	38.40	33.10	52.40	39.40	38.20 ± 0.80	42.50
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.04	0.01 ± 0.01	0.13
Al_2O_3	0.00	0.00	0.24	0.00	0.00	0.27	2.66	1.20	0.71 ± 0.13	17.00
Fe_2O_3	6.77	5.68	4.94	7.64	6.00	2.53	0.98	5.10	5.53 ± 0.69	1.60
FeO	0.38	1.42	1.39	0.28	1.36	3.27	5.30	2.50	2.16 ± 0.42	2.30
MnO	0.05	0.10	0.10	0.08	0.08	0.11	0.13	0.12	0.12 ± 0.03	0.13
MgO	38.70	42.00	41.90	38.40	38.60	36.70	28.90	37.70	39.10 ± 0.20	13.10
CaO	0.00	0.00	0.00	0.00	0.94	3.51	1.49	0.35	0.00	19.00
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.16
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.03	0.00	0.02
Cr_2O_3	0.58	0.39	0.42	0.39	0.41	0.30	0.51	n.a.	0.35 ± 0.01	n.a.
NiO	0.33	0.33	0.33	0.36	0.32	0.25	0.11	n.a.	0.27 ± 0.01	n.a.
H_2O (+)	13.50	14.44	14.06	14.13	11.62	9.22	5.76	12.40	12.57 ± 0.06	3.70
H_2O (-)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.50	n.a.	0.16
CO_2	0.27	0.67	0.80	0.33	3.21	11.00	1.03	0.24	0.37 ± 0.03	0.26
LOI	13.77	15.11	14.86	14.46	14.83	20.22	6.79	12.64	12.94	3.96
Total	99.78	100.13	100.18	100.91	100.94	100.26	99.42	99.78	99.39	100.06
MgO/SiO_2	0.99	1.20	1.16	0.98	1.01	1.11	0.55	0.96	1.02	0.31
FeO/Fe_2O_3	0.06	0.25	0.20	0.04	0.23	1.29	5.41	0.49	0.39	1.44

[1] Brownish-green serpentinite; analysis by LANL.
[2] Greenish-black serpentinite; analysis by LANL.
[3] Greenish-gray serpentinite; analysis by LANL.
[4] Mottled gray serpentinite; analysis by LANL.
[5] Banded dolomite-bearing serpentinite; analysis by LANL.
[6] Antigorite-chlorite-talc-tremolite schist; analysis by LANL.
[7] Average serpentinite analysis from samples all around the quarry (Larrabee 1969).
[8] Average of two analyses on dense, black serpentinite determined by LANL.
[9] Average rodingite analysis from Larrabee (1969).

Delight Quarry

Serpentinite from the Delight Quarry (Figure 7) consists mostly of massive to slightly foliated, mottled brownish-gray serpentinite cut by several generations of carbonate and silica-rich veins and veinlets. Magnesite-bearing silica veins occur up to 1.5-m thick but most such veins are much thinner. The serpentinite also contains lenses and small pods of chromite-rich rock. Thin sections show that talc constitutes up to about 20% of some rocks. The talc often forms small pod-like masses 0.5 cm wide. A major episode of dolomite replacement parallels the foliation in many specimens. The dolomite was followed by a later stage of magnesite and opaline magnesite veining that cuts the foliation.

Chemically, two samples from this quarry contain 36.7 and 38.6 wt % MgO (Table 5). The samples also show chemical differences, which presumably reflect a difference in the content of a calcium-bearing carbonate, possibly dolomite [$(Ca,Mg)CO_3$]. The anomalous sample also has lower than "normal" Cr and Ni. As mentioned above, carbonate-rich zones such as those at Delight Quarry would have to be avoided during mining for CO_2 sequestration.

Soldier's Delight Body and Chaote Mine

Ultramafic rocks from this site vary in appearance from massive brownish-green to foliated gray-green serpentinite. Layers of chromite may locally comprise over 80% of the rock by volume. In some specimens, thin sections show that the serpentine is coarse grained and has a preferred orientation of foliation. Veins and veinlets of magnesite containing pieces of serpentine cut the rock. Thicker layers of chromite are embedded in a mixture of serpentine and minor carbonate and often occur with rose-colored, Cr-rich chlorite (kämmererite). As described below, x-ray diffraction shows that antigorite occurs with minor lizardite or chrysotile.

Chemically, a single sample of massive serpentinite from about 100-m north of the Chaote Mine entrance contains 39.3 wt % MgO (Table 5). The MgO/SiO_2 ratio is about 1 and FeO/Fe_2O_3 is very low (0.04). Low Al and Ca suggests that the original peridotite was dunite. Values of Cr and Ni are typical for serpentinized peridotite of mantle origin.

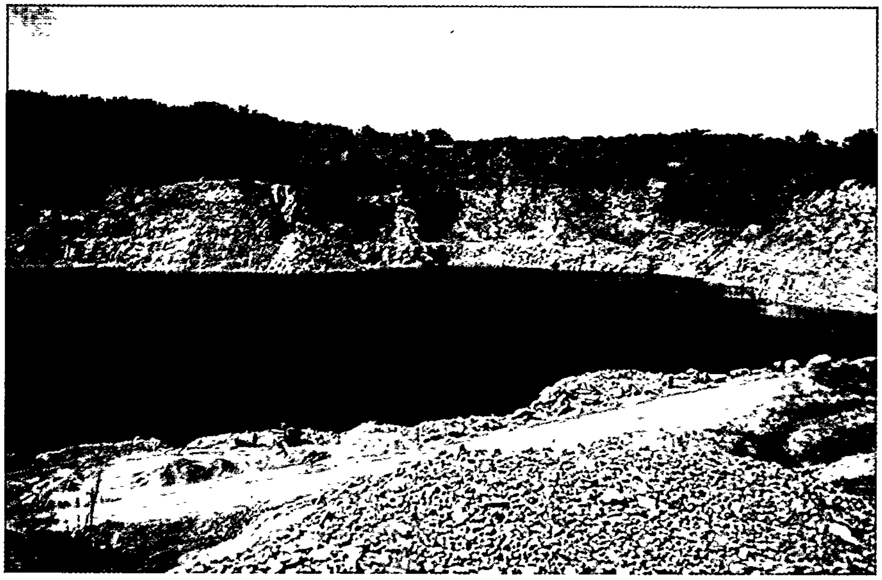

Figure 7: Photo of the Delight Quarry, Maryland, in late May 1999. Analysis of the pit water revealed it is a dilute Mg-Ca-HCO_3 water (total dissolved solids of 270 ppm) with pH = 7.7 and with low contents of minor and trace metals.

Marriotsville Quarry

Ultramafic rock from the east Marriotsville quarry consists of highly foliated, gray-blue, talc-tremolite-anthophyllite schist. Thin sections reveal that 70 vol % of the rock is an intimate mixture of talc and amphiboles. Pod-like areas of chlorite and serpentine are immersed in the schistose minerals. There are occasional patches of carbonate. X-ray diffraction shows that the serpentine is primarily antigorite and that the carbonate is probably a mixture of magnesite and dolomite.

Chemically, a single analysis of the schist is substantially lower in MgO (only 28.9 wt %) and LOI (<7 wt %) but higher in SiO_2, Al_2O_3, and CaO than typical serpentinites of this region (Table 5). It also has unusually high Cr but low Ni. Obviously, magnesia and water have been removed but silica, alumina, and lime have been added during prograde metamorphism of the serpentinite into schist. Rocks from this quarry are probably not satisfactory for CO_2 sequestration because of low amounts of easily reactable serpentine minerals (i.e., antigorite and lizardite) and high amounts of residual silicates as described above.

Rockville Quarry

Serpentinite from the Rockville Quarry (Figure 8) is predominately dense, massive, and black to dark brownish-black in color making up roughly 75 to 80 vol % of the quarry rock. Most samples are cut by small veinlets of a white fibrous amphibole (tremolite) and many samples have a greasy, talc-like touch. Rare veinlets of chrysotile cut the rock. The serpentinite is also cut by dike-like bodies of rodingite consisting mostly of diopside, grossular, and a variety of other Ca-bearing minerals (Larrabee 1969). Thin sections of the serpentinite show that it is predominately composed of serpentine minerals (chiefly antigorite) containing trace amounts of chlorite, tremolite, and talc. Veinlets of tremolite with minor talc and chlorite cut the serpentinite. There are also occasional veinlets of carbonates and silica minerals. Talc, tremolite, and carbonate are not detectable in massive serpentinite by X-ray diffraction.

Chemically, two samples we analyzed agree quite well with the average of 104 analyses previously obtained by Larrabee (1969) (Table 5). The serpentinite contains about 39 wt % MgO and has MgO/SiO_2 of about 1. The contents of Al_2O_3 and CaO indicate the original peridotite was probably borderline between dunite and harzburgite. Average FeO/Fe_2O_3 is about 0.5. Cr and Ni contents are relatively normal for serpentinized peridotite. Rodingite analyses in Larrabee (1969) contain considerably less MgO, Fe_T, and LOI and considerably more Al and Ca than serpentinite.

WESTERN NORTH CAROLINA

An excellent review of the geology and tectonics of alpine-type ultramafic rocks in the southern Appalachians is presented by Misra and Keller (1978). A distinctive group of small ultramafic bodies, consisting primarily of dunite and altered dunite, occurs in the Blue Ridge physiographic province of western North Carolina (Hunter 1941). The ultramafic rocks are enclosed in both middle Precambrian crystalline rocks and in overlying upper Precambrian metasedimentary and metavolcanic rocks (mostly gneiss with subordinate schist and amphibolite). Individual ultramafic bodies are generally massive, small and lenticular, usually aligned parallel to the regional foliation. In cross section, the bodies probably have configurations resembling those observed in Vermont (see Figure 3). Many of the dunites are cut by later pegmatites.

The association of these small ultramafic bodies with remnants of other ophiolite sequence rocks is difficult to establish. Lipin (1984) has shown that the Blue Ridge dunites are not primary mantle peridotite fragments. Rather, they are serpentinized mantle peridotites emplaced at cool temperatures (<500°C) in late Precambrian time that were later dehydrated during regional metamorphism occurring at least 450 Mya (Misra and Keller 1978). Conversion of serpentinite into dunite occurred at maximum temperatures of about 700°C (Lipin 1984).

More than 275 ultramafic bodies of all types have been identified in a belt nearly 50-km long and 50-km wide (Figure 9). Considerable information exists on the mineralogy, petrology, and size of the larger dunite bodies (Table 6) because of their economic potential for forsterite, chromite, vermiculite and asbestos (Hunter 1941; Hunter et al. 1942; Murdock and Hunter 1946; Conrad et al. 1963). The "primary" minerals in the dunites are forsteritic olivine with subordinate orthopyroxene (enstatite) and chromite. Clinopyroxene (diopside) is found in localized zones at some bodies. Olivine compositions are rather uniform in each body, ranging from fo_{89} to fo_{94} (Carpenter and Phyfer 1976; Lipin 1984). The margins of most bodies grade into schistose rocks composed of secondary talc-chlorite-serpentine±tremolite and/or anthophyllite±vermiculite. Minor alteration minerals include various carbonates, silica, brucite, and others.

Figure 8: Photo looking northwest of the Rockville Quarry, Maryland, in late May 1999.

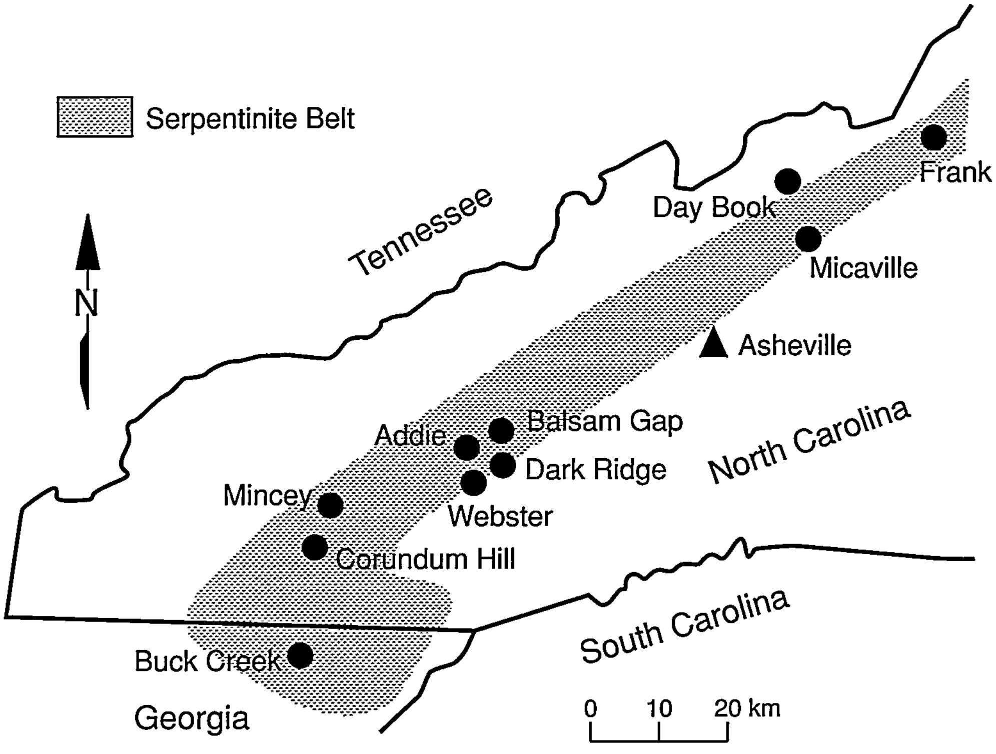

Figure 9: Map of western North Carolina showing the location of the ultramafic belt and several bodies described in the text (modified from Hunter 1941). Individual bodies within the belt are relatively small (Table 5).

Table 6. Resource Information on Example Dunite Bodies in Western North Carolina

Name	Mineralogy[1]	Surface Area (m^2)	Thick-ness (m)	Maximum Volume (km^3)	Density[2] (g/cm^3)	Ore Mass[3] (metric tons)	MgO (wt %)	Comments	References
Addie	Primary: Ol (fo=91.4)-En-Chr	410,000	150	0.063	3.17	200×10^6	46	Part of Webster-Addie "ring dike"	Hunter (1941); Miller (1953); Condie and Madison (1969); Carpenter and Phyfer (1975)
	Secondary: Srp-Chl-Vrm-Tlc-Mag-Mgs					(120×10^6)			
Balsam Gap	Primary: Ol (fo=92.7)-En-Di-Chr	130,000	150	0.019	3.17	60×10^6	45	Magnetic survey contrains thickness; petrofabric study inconclusive	Hunter (1941); Honeycutt and Heimlich (1979); Carpenter and Phyfer (1975); Astwood et al. (1972)
	Secondary: Tlc-Srp-Mag					(45×10^6)			
Buck Creek	Primary: Ol (fo=89.2)-En-Chr	1,500,000	200	0.29	3.17	920×10^6	46	Largest dunite body in region	Hunter (1941); Carpenter and Phyfer (1975)
	Secondary: Srp-Chl-Tlc-Tr-Mag-Mgs					(270×10^6)			
Corundum Hill	Primary: Ol (fo=92.4)-En-Chr	60,000	130	0.008	3.17	25×10^6	47	Mined for corundum in early 1900s	Hunter (1941); Yurkovich (1977); Carpenter and Phyfer (1975)
	Secondary: Srp-Tlc-Vrm-Chl-Ath-Mag					(7×10^6)			
Dark Ridge	Primary: Ol (fo=92.5)-En-Chr	130,000	120	0.016	3.17	50×10^6	46	Petrofabric study shows no preferred orientation of olivine	Hunter (1941); Astwood et al. (1972)
	Secondary: Tlc-Srp-Mag					(37×10^6)			
Day Book	Primary: Ol (fo=93.0)-En-Chr	110,000	120	0.013	3.17	40×10^6	47	Presently mined for foundry olivine (Green Moutain peridotite)	Hunter (1941); Kulp and Brobst (1954); Carpenter and Phyfer (1975); Goff et al. (1997)
	Secondary: Srp-Chl-Tlc-Tr-Ath-Mag		(30)[4]			(9×10^6)			
Frank	Primary: Ol (fo=92.4)-En-Chr	52,000	130	0.007	3.17	20×10^6	43	Mined for vermiculite	Hunter (1941); Carpenter and Chen (1978); Carpenter and Phyfer (1975)
	Secondary: Ath-Tlc-Srp-Vrm-Mag					(11×10^6)			
Micaville	Primary: Ol-En-Di-Chr	44,000	100	0.004	3.17	14×10^6	45	Adjacent altered pegmatite mined for kaolin	Kingsbury and Heimlich (1978)
	Secondary: Srp-Chl-Tlc-Vrm-Ath-Mag								
Mincy	Primary: Ol (fo=89)-En-Chr	7,000	50	0.0003	3.17	1.1×10^6	48	Long axis of dunite body not parallel to foliation of enclosing gneiss	Hahn and Heimlich (1977)
	Secondary: Vrm-Tlc-Chl-Srp-Ath-Mag								
Webster	Primary: Ol (fo=90)-En-Di-Chr	1,300,000	150	0.2	3.17	640×10^6	44	Type locality of websterite; part of Webster-Addie "ring dike"	Hunter (1941); Miller (1953); Condie and Madison (1969); Carpenter and Phyfer (1975)
	Secondary: Srp-Chl-Tlc-Dol-Mag					(200×10^6)			

[1] Mineral symbols according to Kretz (1983). Ol=olivine (forsterite component, or fo, given if known); En=enstatite; Di=diopside; Chr=chromite; Srp=serpentine (undifferentiated); Chl=chlorite; Ath=anthophyllite; Tr=tremolite; Carb=carbonate (undifferentiated); Mag=magnetite; Dol=dolomite; Mgs=magnesite; Tlc=talc; Brc=brucite; Vrm=vermiculite

[2] The density used is the average of 70 measurments reported by Hunter (1941).

[3] Upper value is our estimate based on geologic relations and the magnetic survey conducted at the Balsam Gap deposit (see comments in table and text); lower value is minimum estimate from Hunter (1941).

[4] Depth of present open-pit mining (C. Karr, UNIMIN Corporation, personal communication).

Hunter (1941) previously calculated the mass of commercial dunite deposits in western North Carolina and adjacent Georgia. He determined a total mass of 208 × 10^6 metric tons of relatively unaltered olivine containing more than 45 wt % MgO and a mass of 908 x 10^6 metric tons of partly serpentinized dunite composed of 50% or more olivine averaging about 44 wt % MgO. These tonnages were figured using exposed rock outcrops at base levels determined from the deepest eroded cut (stream or river) in each ultramafic body. No attempt was made at that time to determine the absolute thickness of each body. We know of only one body that has been investigated since that time for which geophysical methods (magnetic survey) were employed to determine the thickness or depth of a deposit (Balsam Gap, about 150 to 170-m thick; Honeycutt and Heimlich 1979). This would indicate a lenticular configuration as mentioned above. Combining geophysical techniques with slim-hole core drilling would yield accurate dimensional estimates at other deposits. Using the Balsam Gap study as an example (Figure 10), we estimated thicknesses of example deposits from this region (Table 6). As a result, we figure that the actual mass of ultramafic deposits in western North Carolina is at least 2 to 3 times larger than the earlier estimates of Hunter (1941).

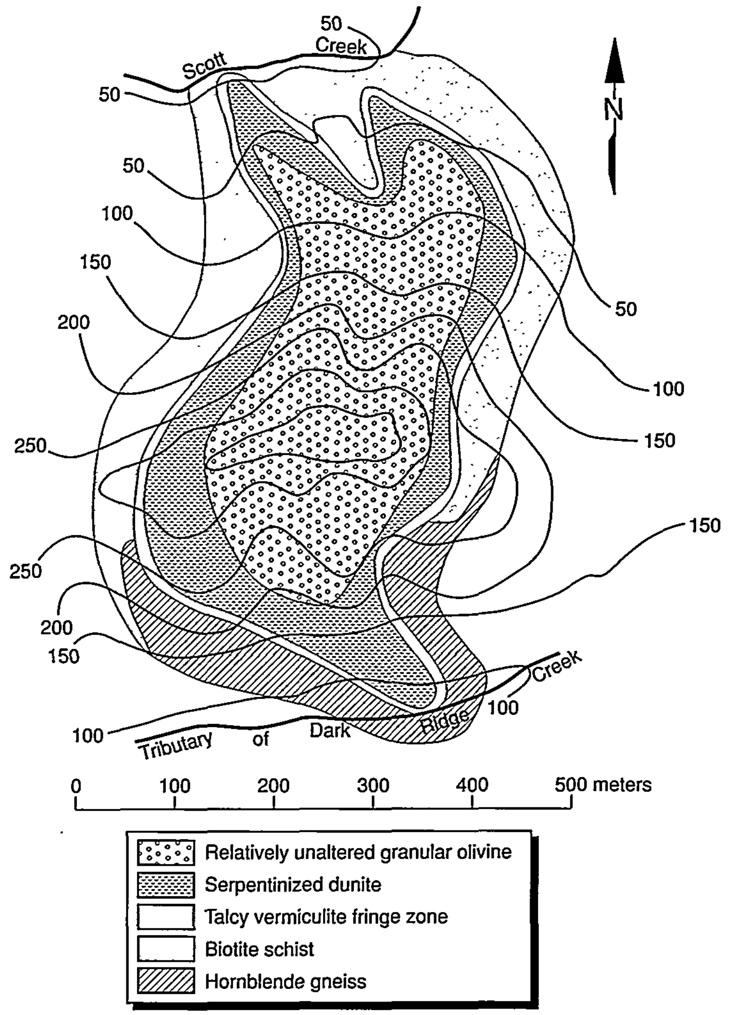

Figure 10: Geologic map of the Balsam Gap dunite deposit (from Hunter, 1941). Contours are in feet. Modeling of magnetic data indicates that the dunite body is pod-shaped, plunging steeply northward (Honeycutt and Heimlich 1979). This model needs confirmation from a detailed gravity survey or core drilling.

Chemically, the deposits vary somewhat in their MgO contents (Table 7), but all contain an average of more than 43 wt % MgO. The MgO/SiO_2 ratio is ≥1.0 in all cases and ≥1.1 in most cases. Surprisingly few of the bodies have had complete analyses run on their respective rocks. Where data are available, the FeO/Fe_2O_3 ratio varies from 5.7 at the relatively unserpentinized Day Book deposit (Green Mountain peridotite) to 1.4 at the relatively serpentinized Frank deposit. The Cr contents of some bodies exceed 0.5 wt %, higher than most mantle peridotites. The Ni contents are relatively normal.

Table 7. Chemical composition of example dunite bodies in the western North Carolina region; values in wt % and all Fe as Fe_2O_3 unless otherwise noted; LOI includes H_2O (+) and CO_2.

	Addie[1]	Balsam Gap[2]	Buck Creek[1]	Corundum Hill[1]	Dark Ridge[1]	Day Book[3]	Day Book[4]	Frank[5]	Micaville[6]	Mincey[7]	Webster[1]	DTS-1 STD[8]
No. of Analyses	9	6	1	6	2	5	1	7	9	20	3	
SiO_2	40.0±1.4	44.4±2.1	38.70	41.0±0.5	42.3±1.8	40.9	40.67	41.9±0.9	45.8±4.3	42.6±2.4	39.5±2.2	40.41
TiO_2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.01	0.03±0.02	n.a.	n.a.	n.a.	0.005
Al_2O_3	n.a.	0.47±0.37	n.a.	n.a.	n.a.	1.32	0.75	0.94±0.23	2.23±1.83	1.23±0.65	n.a.	0.19
Fe_2O_3	9.55±1.11	7.81±0.43	10.70	8.12±0.46	9.82±0.11	7.60	1.15	3.24±0.85	5.52±0.51	7.19±0.75	8.67±0.64	1.03
FeO	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6.56	4.71±0.77	n.a.	n.a.	n.a.	6.97
MnO	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.12	n.a.	n.a.	n.a.	n.a.	0.12
MgO	46.7±1.5	45.1±3.9	46.50	47.8±1.4	46.9±4.0	48.8	48.77	43.0±2.0	45.7±5.4	48.7±2.9	44.1±1.3	49.59
CaO	0.22±0.10	n.a.	0.56	trace	0.62±0.87	0.29	0.00	0.29±0.25	n.a.	n.a.	0.24±0.07	0.17
Na_2O	n.a.	n.a.	n.a.	n.a.	n.a.	0.13	0.00	n.a.	n.a.	n.a.	n.a.	0.015
K_2O	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.03	0.02±0.01	n.a.	n.a.	n.a.	0.001
P_2O_5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.02	n.a.	n.a.	n.a.	n.a.	0.002
Cr_2O_3	n.a.	0.60±0.29	n.a.	n.a.	n.a.	n.a.	0.32	n.a.	0.56±0.37	0.47±0.02	n.a.	0.58
NiO	n.a.	0.33±0.06	n.a.	n.a.	n.a.	n.a.	0.31	0.30±0.01	0.29±0.01	0.29±0.01	n.a.	0.30
Ti+Al+Cr Oxides	1.30±0.27	n.a.	2.52	1.05±0.63	1.07±0.98	n.a.		n.a.	n.a.	n.a.	1.59±0.67	
H_2O (+)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.38	5.30±2.34	n.a.	n.a.	n.a.	0.44
H_2O (-)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.08	0.35±0.16	n.a.	n.a.	n.a.	0.06
CO_2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.12	n.a.	n.a.	n.a.	n.a.	0.08
LOI	1.92±0.95	n.a.	1.77	1.96±0.79	1.06±0.64	1.09	1.5	5.30	n.a.	n.a.	5.18±3.66	0.52
Total	99.69	98.71	100.80	99.93	101.8	100.1	100.29	99.08	100.10	100.48	99.28	99.96
MgO/SiO_2	1.17	1.02	1.20	1.17	1.11	1.19	1.20	1.03	1.00	1.14	1.12	1.23
FeO/Fe_2O_3							5.70	1.45				6.77

[1] Analyses listed in Hunter (1941) for fresh and partly serpentinized dunite.
[2] Analyses listed in Honeycutt and Heimlich (1979); Hunter reports five relatively unaltered samples having average of 49.2±1.0 wt % MgO.
[3] Average of five analyses listed in Hunter (1941); individual analyses not given.
[4] Analysis from Kulp and Brobst (1954); analyses listed in Goff et al. (1997, Appendix B, "Green Mtn Peridotite") range from 46.7 to 47.7 wt % MgO.
[5] Analyses listed in Carpenter and Chen (1978).
[6] Analyses listed in Kingsbury and Heimlich (1978).
[7] Analyses listed in Hahn and Heimlich (1977).
[8] Analysis of rock standard from Twin Sisters Dunite, Washington (Govindaraju 1994).

SOUTHWESTERN PUERTO RICO

The island of Puerto Rico is located along the northern boundary of the Caribbean plate where it is juxtaposed against the North American plate. The highlands of the island consist of an uplifted core of subducted sedimentary and associated volcanic and plutonic rocks emplaced from ≥120 to 45 Ma (Jolly et al. 1998). Serpentinized mantle peridotite occurs in three belts restricted to the southwest part of the island (Mattson 1960; Figure 11). The serpentinized peridotite (referred to hereafter as serpentinite) is the basal part of one or more disrupted ophiolite sequences. Previous workers claim that most or all Puerto Rican serpentinites were emplaced diapirically through overlying rocks (Jolly et al. 1998). Much of the serpentinite occurs as melange, and some occurs as sedimentary deposits draping the edges of the major bodies (Griscom 1964). In 1961, a 305-m-deep core (AMSOC hole) was drilled into the Rio Guanajibo serpentinite 6-km south of Mayagüez to provide chemical and physical data for the newly initiated deep-sea drilling program (Burk 1964). A gravity survey associated with the drilling project indicates that the Rio Guanajibo serpentinite is at least 2.8-km thick (Figure 12; Bromery and Griscom 1964).

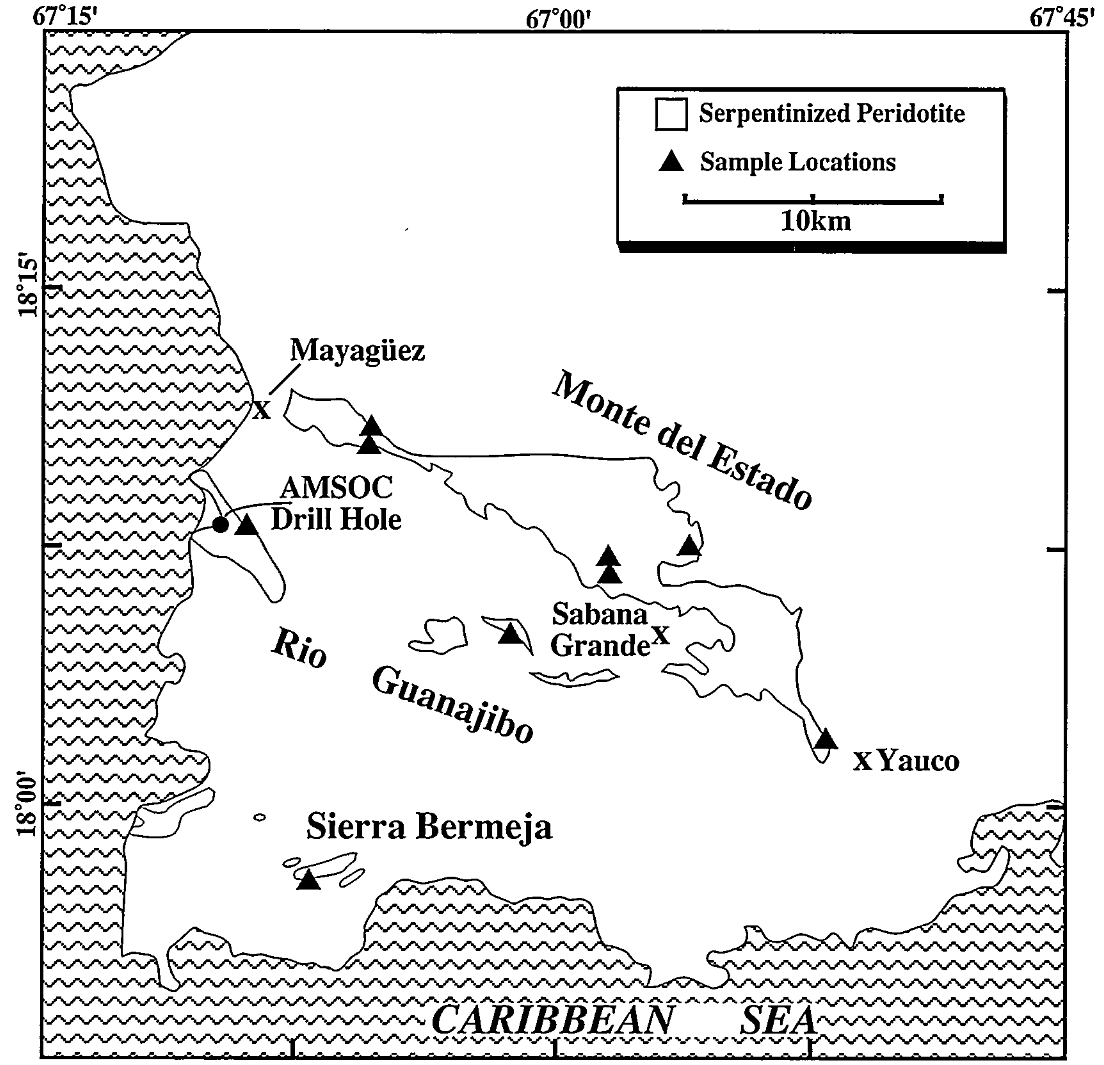

Figure 11: Map of the serpentinized peridotite belts of southwestern Puerto Rico (from Jolly et al. 1998).

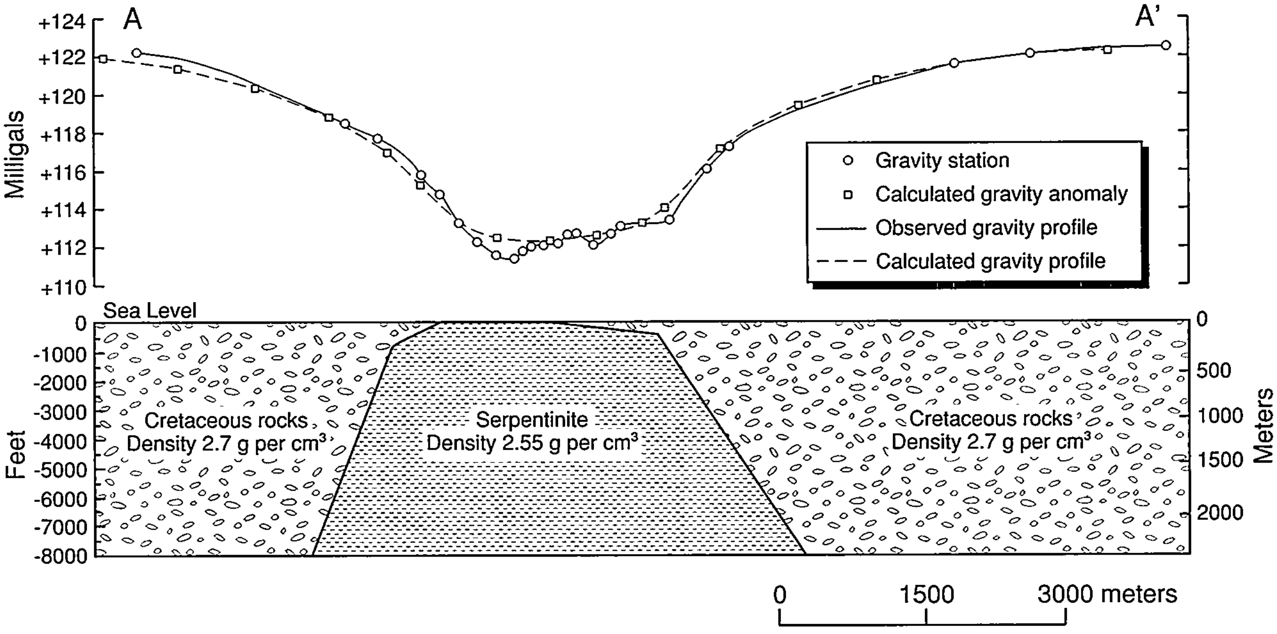

Figure 12: Idealized southwest-northeast cross section of Rio Guanajibo serpentinite belt based on the gravity model of Bromery and Griscom (1964). The profile was obtained a few kilometers southeast of the AMSOC corehole. According to these authors, the serpentinites of this body and the Monte del Estado body form the cores of anticlines that plunge to the west-northwest. Jolly et al. (1998) imply that these serpentinite bodies are diapirically emplaced through overlying Cretaceous sediments. Regardless of structure or mechanism, the gravity model implies that the serpentinite is over 2.8-km thick.

Although a large population exists near Mayagüez, much of the serpentinite occurs in areas with lower population density. On the other hand, the Monte del Estado serpentine belt crosses the boundaries of two parks (Bosque Estatal de Maricao northwest of Sabana Grande and Bosque Estatal de Susúa east of Sabana Grande) which may have environmental restrictions for development.

We collected samples of serpentinite melange, sedimentary serpentinite breccia, and massive serpentinite from various locations in the three serpentine belts. Superficially, Puerto Rican serpentinites resemble those from California in color, texture, and many geologic relations (Goff and Lackner 1998; Goff and Guthrie 1999). The margins of larger bodies contain fragments and blocks of other lithologies in serpentinite melange while some smaller bodies consist entirely of melange. Most hand samples are mottled gray-green to gray-blue, showing abundant fracturing and shearing. Small veinlets of white to gray carbonate and amorphous silica cut many of the outcrops we examined. In addition, nodular magnesite is locally common. Some of the serpentinites are deeply weathered and overlain by laterite deposits up to several meters thick (Figure 13; western Rio Guanajibo belt), whereas others have very little soil development because of rapid uplift and erosion (Figure 14; central Monte del Estado belt).

Thin sections of most samples show intense shearing. The original peridotite was predominately harzburgite because bastite pseudomorphs after pyroxene are ubiquitous (Table 8). A sample of sedimentary serpentine breccia east of Mayagüez displays rare small pieces of volcanic rock in a sheared matrix of coarse and fine serpentinite fragments. A sample from a quarry west of Yauco contains conspicuous veinlets and pods of magnesite. Samples from a site in the Sierra Bermeja region and from a site northeast of Sabana Grande consist of sheared serpentinized harzburgite. Sabana Grande samples may also contain relict orthopyroxene and olivine.

Figure 13: Photo looking west of laterite (dark reddish brown in photo) over serpentinite in the Rio Guanajibo body, Highway 100 south of Mayagüez.

Figure 14: Photo looking northwest of heavily vegetated, but unweathered serpentinite near the axis of the Monte del Estado body, Highway 306 north of Sabana Grande.

Table 8. Resource Information on Three Serpentinite Belts in Southwestern Puerto Rico

Belt Name	Mineralogy[1]	Surface Area (km^2)	Thick-ness (m)	Max. Volume (km^3)	Density (g/cm^3)	Ore Mass (metric tons)	MgO (wt %)	Comments
Monte del Estado	Primary: Ol-En-Chr-Di Secondary: Srp-Mag-Chl-Mgs	90	≥1500	≥135	2.55	$\geq 340 \times 10^9$	36	Thickness from Griscom (1964) and density from Bromery and Griscom (1964).
Rio Guanajibo	Primary: Ol-En-Chr-Di Secondary: Srp-Mag-Chl-Mgs	15	≥1500	≥22	2.55	$\geq 55 \times 10^9$	36	Thickness from Griscom (1964) and density from Bromery and Griscom (1964).
Sierra Bermeja	Primary: Ol-En-Chr-Di Secondary: Srp-Mag-Chl-Mgs	4	200	0.8	2.55	2×10^9	36	Thicknesses in this belt are poorly constrained; each serpentinite fragment is interpreted as melange (Jolly et al., 1998).

[1] Mineral symbols according to Kretz (1983). Ol=olivine (forsterite component, or fo, given if known); En=enstatite (orthopyroxene); Di=diopside (clinopyroxene); Chr=chromite; Srp=serpentine (undifferentiated mix of lizardite/chrysotile); Chl=chlorite; Ath=anthophyllite; Tr=tremolite; Carb=carbonate (undifferentiated); Mag=magnetite; Dol=dolomite; Mgs=magnesite; Tlc=talc; Brc=brucite; Vrm=vermiculite

Chemically, nine outcrop samples are rather inhomogeneous containing between 34.4 and 37.9 wt % MgO (Table 9). The rather high Al_2O_3 contents (1.0 to 2.3 wt %) indicate that most rocks were originally harzburgites. Average MgO/SiO_2 is about 0.90 and average FeO/Fe_2O_3 is about 0.25. Samples with higher MgO content and higher FeO/Fe_2O_3 contain relict olivine and orthopyroxene. The Cr and Ni contents of most samples are quite normal for serpentinized mantle peridotite. A single sample from near San Germán contains slightly lower than normal Cr and Ni.

Thin-section work on samples from the 305-m-deep corehole drilled in the western Rio Guanajibo belt indicates that harzburgite is about twice as abundant as dunite in the original peridotite (Burk 1964). X-ray diffraction studies indicate that the serpentinite is a mixture of lizardite-chrysotile with minor magnetite and chlorite. No antigorite is found (Hess and Otalora 1964). Relict olivine is usually present in amounts of less than 5 vol %. Brucite is present in many samples in amounts of up to 4 vol %. A few samples contain hydrogrossular. The average MgO content of 13 samples is 37.7 wt %. Three of these samples contain higher than average amounts of relict olivine.

Table 9. Chemical composition of serpentinites in southwestern Puerto Rico; values in wt % unless otherwise noted; LOI includes H_2O (+) and CO_2.

	Monte del Estado[1]	Monte del Estado[2]	Rio Guanajibo[3]	Sierra Bermeja[4]	AMSOC Hole[5]	Wilbur Spgs[6]	Sed. Serp[7]	Sed. Serp[8]	Detrital Serp[9]
No. of Analyses	1	6	2	1	13	15	1	1	10
SiO_2	40.40	39.60 ± 0.90	40.20 ± 1.20	39.60	36.05	40.60 ± 1.20	40.10	40.00	40.40
TiO_2	0.04	0.03 ± 0.02	0.03 ± 0.02	0.03	0.03	0.04 ± 0.02	0.03	0.10	0.08
Al_2O_3	1.98	1.62 ± 0.45	2.04 ± 0.40	1.44	1.62	1.99 ± 0.40	1.44	2.8	2.58
Fe_2O_3	5.05	6.12 ± 1.10	6.21 ± 1.94	6.69	4.81	5.06 ± 1.30	5.46	5.5	4.55
FeO	1.92	1.47 ± 0.51	1.39 ± 0.07	1.94	2.80	2.94 ± 1.00	1.40	2.9	3.16
MnO	0.15	0.13 ± 0.02	0.11 ± 0.06	0.11	0.10	0.14 ± 0.15	0.10	0.09	0.17
MgO	37.10	36.80 ± 0.70	36.10 ± 2.50	36.10	37.67	36.20 ± 1.10	37.80	35.60	33.80
CaO	1.00	0.43 ± 0.41	0.00	0.00	1.20	0.42 ± 0.10	0.30	0.13	1.87
Na_2O	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.17
K_2O	0.00	0.00	0.00	0.00	<0.005	0.00	0.00	0.00	0.18
P_2O_5	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.06	0.07
Cr_2O_3	0.38	0.39 ± 0.04	0.35 ± 0.15	0.38	0.37	0.42 ± 0.02	0.33	n.a.	n.a.
NiO	0.32	0.30 ± 0.03	0.29 ± 0.09	0.31	0.35	0.32 ± 0.01	0.26	n.a.	n.a.
H_2O (+)	11.70	13.20 ± 0.90	13.50 ± 0.80	13.28	12.74	12.60 ± 1.10	12.97	11.7	10.26
H_2O (-)	n.a.	n.a.	n.a.	n.a.	1.84	n.a.	n.a.	1.0	1.41
CO_2	0.24	0.21 ± 0.09	0.11 ± 0.01	0.11	n.a	n.a	0.16	0.05	2.31
LOI	11.94	13.41	13.61	13.39	12.74	12.60	13.13	11.75	12.57
Total	100.28	100.30	100.33	99.99	99.98	100.73	100.35	99.93	101.01
MgO/SiO_2	0.92	0.93	0.90	0.91	1.04	0.89	0.94	0.89	0.84
FeO/Fe_2O_3	0.38	0.24	0.22	0.29	0.58	0.58	0.26	0.53	0.69

[1] Serpentinized harzburgite north of Sabana Grande; contains about 5% relict orthopyroxene and olivine.
[2] Average of six serpentinites, including the sedimentary serpentinite in column seven; analyses by LANL.
[3] Average of two serpentinites; analyses by LANL.
[4] Single sample from south side of fault zone juxtaposing serpentinite against greenstone; analysis by LANL.
[5] Normalized average from Hess and Otalora (1964); Cl and F analyzed at 0.02 and <0.005 wt%, respectively (mean density = 2.58±0.08, n=15).
[6] Average of massive serpentinites throughout body (Goff and Lackner 1998).
[7] Sheared detrital serpentinite from south margin of Monte del Estado body, about 5-km east of Mayagüez; analysis by LANL.
[8] Detrital serpentinite shale from Colombia (Lockwood 1971).
[9] Average detrital serpentinite (Lockwood 1971).

DISSOLUTION OF ULTRAMAFIC SAMPLES IN HCL

Selected samples of ultramafic rocks from the eastern United States and Puerto Rico were dissolved in hydrochloric acid to evaluate their relative solubility and to determine the mineralogy of residues (described below). The dissolution experiments provide a comparison of how easily the magnesium is extracted and how much insoluble residue is contained in the various samples. Results of the dissolution experiments are given in Table 10 and are compared with results from California ultramafic rocks published previously (Goff et al. 1997).

Table 10. Extractable MgO and Residuals Resulting from Dissolution of Ultramafic Rock Powders in Hot ~5 to 6 *N* HCl

SAMPLE #	DESCRIPTION	MgO from HCl (wt %)	Error (%)	Residuals (wt %)	MgO from XRF (wt %)
PA-MD-DC region					
F99-79a	Rockville Quarry Serp., MD	28.50	0.78	55.4	38.94
F99-79d	Rockville Quarry Serp., MD	31.94	1.19	59.2	39.21
F99-80	Marriotsville Quarry Schist, MD	4.08	0.91	91.3	28.93
F99-81a	Delight Quarry Serp., MD	23.37	1.72	53.8	36.69
F99-81b	Delight Quarry Serp., MD	27.97	0.73	56.5	38.61
F99-82b	Choate Mine Serp., MD	36.19	0.86	49.8	38.41
F99-83a	Penn-Mar Quarry Serp., PA	29.86	1.28	57.8	41.92
F99-84a	Cedar Hill Quarry Serp., PA	39.19	1.67	46.6	38.65
F99-84b	Cedar Hill Quarry Serp., PA	33.30	0.55	51.9	44.51
North Carolina					
UNIMIN-2	Day Book Dunite, NC	46.89	1.63	53.0	47.93
Southwestern Puerto Rico					
F99-68	Rio Guanajibo Serp., PR	35.09	2.02	44.9	34.38
F99-70b	Monte del Estado Serp., PR	37.20	2.12	42.8	36.91
F99-71a	Rio Guanajibo Serp., PR	33.99	2.59	53.5	37.87
F99-72	Sedimentary Serp. Breccia., PR	38.03	0.63	48.1	37.82
F99-73	Monte del Estado Serp., PR	37.39	1.19	45.9	36.39
F99-74b	Sierra Bermeja Serp., PR	35.87	3.03	46.2	36.07
F99-75	Monte del Estado Serp., PR	38.79	1.38	44.9	37.07
F99-76	Monte del Estado Serp., PR	36.81	0.66	47.7	37.13
F99-78	Monte del Estado Serp., PR	37.32	0.51	45.2	35.66
California					
FG96-312	San Mateo Serp., CA	30.92	0.98	48.8	33.06
UM96-14	Wilbur Springs Serp., CA	34.04	1.12	42.2	35.41
UM96-17	Del Puerto Harzburgite, CA	34.64	0.89	46.7	41.63
UM96-21	Del Puerto Dunite, CA	41.82	1.13	43.4	44.31
F99-12	Yerba Buena Serp., San Jose CA	32.72	1.18	52.1	33.00
F99-13	Yerba Buena Serp., San Jose CA	36.40	1.03	46.4	35.72
F99-18	Silver Creek Serp., San Jose CA	27.65	0.22	59.8	26.74
F99-23	New Idria Serp., CA	37.86	3.15	49.1	36.99
F99-27	McLaughlin Mine Serp., CA	33.14	0.22	45.6	35.21
F99-30	Howard Springs Harzburgite, CA	2.93	2.74	95.3	32.37
F99-33	SE Geysers Serp., CA	33.45	0.63	46.8	34.43
F99-34	SE Geysers Serp., CA	38.17	0.88	45.0	37.44
F99-85	Josephine Ophiolite Serp., CA	37.78	1.28	51.9	40.40
F99-86	Josephine Ophiolite Serp., CA	40.16	2.11	49.5	41.59
F99-87	Josephine Ophiolite Serp., CA	41.09	1.99	47.5	43.41

Rock samples weighing at least 1 kg were cleaned and crushed into fragments. About 200 g of fragments were pulverized in a tungsten carbide shatter box to a size of <75 micrometers (<200 mesh). The resulting powders were used for the dissolution experiments and for x-ray fluorescence analyses as reported in the Tables. About 1 g of powdered sample was mixed with 20 ml of 1:1 solution of 35% HCl and water (i.e., ~5 to 6 *N*) and heated to 60°C for 2 hours. The mixtures cooled overnight on a shaker table. Masses were then adjusted to 25 g with deionized water, the solutions were allowed to settle, and 5 g of solution were removed for Mg analysis by inductively coupled plasma emission spectroscopy (ICP). Results are reported as wt % MgO for comparison with XRF results (Table 10). The residues were filtered, dried, and weighed, and the dried residues were then used for x-ray diffraction work.

Serpentinites from the PA-MD-DC region generally contain minerals such as chlorite, talc, and tremolite that are not soluble in hot ~5 to 6 *N* HCl. Thus, the amount of acid soluble MgO in many samples from this region is 10 to 15 wt % less than the total MgO in the parent rock. Exceptions are the serpentinite sample from the Choate Mine and one sample from Cedar Hill quarry that release Mg into solution easily. Rapid dissolution is also true for serpentinites from southwestern Puerto Rico and those from California that contain mostly lizardite ± chrysotile and very little insoluble Mg-rich silicates (such as talc, tremolite, etc.). Apparently, antigorite is less rapidly dissolved under the conditions of our experiments than the other serpentine minerals. Hence, it is likely that the antigorite-rich serpentinites from Vermont will behave similarly to those of the PA-MD-DC region, but the chrysotile-rich serpentinites will behave similarly to those from Puerto Rico and California.

In contrast, relatively pure dunite from the Day Book deposit (North Carolina) and serpentinized dunite from the Del Puerto deposit (California) dissolve easily in hot ~5 to 6 *N* HCl. Vermont dunites will likely behave similarly to North Carolina and California dunites.

Ultramafic samples of more unusual mineral composition do not easily release MgO into a solution of hot ~5 to 6 *N* HCl. These include the Marriotsville schist near Baltimore (containing substantial tremolite-anthophyllite-talc), and two harzburgites from California (with significant but variable orthopyroxene contents).

X-RAY DIFFRACTION ANALYSES OF SERPENTINITES AND RESIDUES

Selected samples of serpentinite were analyzed by x-ray diffraction (XRD) to determine the composition of bulk minerals and acid dissolution residues (Tables 11 and 12). Powdered samples were prepared as front-packed mounts and analyzed in a Siemens D500 equipped with incident- and diffracted-beam Soller slits and a Si(Li) solid-state detector. Data were collected in steps of 0.02° 2θ Cu$K\alpha$ counting for times ranging from 8 s/step to 65 s/step. Under these conditions, crystalline phases present at the >1-wt % level can be readily detected, and for some phases the detection limits are much lower. Quantitative analysis of mineral phases using the XRD data was performed using a modification of the external-standard, matrix-flushing method of Chung (1974a, 1974b, 1975). Combinations of reference patterns from a 20:80 (by weight) mixture of corundum and a standard for each individual phase were used to fit the entire pattern. The relative amounts of each phase in the mixture can then be determined (i.e., actual wt % is based on the assumption that the crystalline phases analyzed account for 100 wt % of the sample).

Table 11. Semiquantitative x-ray diffraction analyses of ultramafic rocks samples; values are in wt %. Sample numbers are keyed to descriptions on Table 10. [The relative proportions of the serpentine minerals were determined using measured standard patterns for antigorite (sample from Conklin Quarry, Rhode Island), lizardite (sample from J.J. Gordon Quarry, New Jersey) and chrysotile (Canadian chrysotile sample from Ward's Scientific)].

			PA-MD-DC Region			
Minerals	F99-79a	F99-80	F99-81a	F99-82b	F99-83a	F99-84b
Antigorite[1]	95 ± 10	major	60 ± 10	10 ± 5	50 ± 10	15.5 ± 10
Lizardite				90 ± 10	35 ± 10	82 ± 10
Chlorite	0.2 ± 0.1	major				
Talc		major				
Tremolite		minor				
Anthophyllite		minor				
Orthopyroxene				0.1 ± 0.1?		
Forsterite						1 ± 0.5
Magnetite[2]	5 ± 2		1.5 ± 1.0	0.5 ± 0.3	3 ± 2	1.5 ± 1.0
Magnesite		trace?	25 ± 5			
Dolomite		trace?	13.5 ± 5			
Brucite+Sjögrenite[3]					12 ± 6	

	Southwestern Puerto Rico				California				
Minerals	F99-68	F99-72	F99-74b	F99-78	F99-12	F99-23	F99-27	F99-34	F99-85
Lizardite	84 ± 10	72 ± 10	98 ± 10	95 ± 10	85 ± 10	37 ± 10	89 ± 10	68 ± 10	64 ± 10
Chrysotile	10 ± 10	20 ± 10			10 ± 10	60 ± 10	10 ± 10	30 ± 10	
Chlorite		0.1 ± 0.1	0.5 ± 0.3	0.1 ± 0.1		0.5 ± 0.3	0.2 ± 0.1	0.4 ± 0.2	
Orthopyroxene	0.1 ± 0.1?	0.1 ± 0.1							7 ± 5
Forsterite									25 ± 10
Magnetite[2]	1 ± 0.5	3 ± 2	1 ± 0.5	5 ± 2	5 ± 2	3 ± 2	1 ± 0.5	2 ± 1	3 ± 2
"Expanded Clay"[4]	5 ± 3								
Unident. Phase[5]		5 ± 3							
Amphibole[6]									1 ± 1

[1] Not pure antigorite; a second serpentine mineral is apparently mixed with it (best match is the 6(3)T lizardite pattern).

[2] Magnetite and/or chromite.

[3] Both brucite and sjögrenite were present, at an estimated abundance of 12 wt % based on difference (i.e., assuming all crystalline phases summed to 100 wt %).

[4] "Expanded clay" refers to the phase that gave rise to diffuse diffracted intensity in the region of ~4–8° 2θ, which is typical for expandable clays such as smectite. However, no attempt was made to expand the material using ethylene glycol; hence, the identification of this material as an expanded clay was not confirmed.

[5] Three peaks at 0.2454 nm, 0.2335 nm, and 0.1963 nm (with relative integrated intensities of 100, 10, and 15, respectively) could not be matched with any mineral in the JCPDS database; the estimated abundance was based on assuming all crystalline phases summed to 100 wt %. The unknown lines may relate to material associated with volcanic rock fragments as observed in thin section.

[6] Amphibole based on the identification of a primary amphibole peak that could not be assigned to major or minor phases.

Table 12. X-ray Diffraction Identification of Mineral Phases in HCl Dissolution Residues[1]

			Residues[2]	
Sample No.	Description	Major	Minor	Trace
PA-MD-DC Region				
F99-79a	Rockville Quarry Serpentinite, MD	Atg[3]	Am SiO_2; Chl	Chr/Mag
F99-81b	Delight Quarry Serpentinite, MD	Atg[3]	Am SiO_2	Chr/Mag
F99-83a	Penn-Mar Quarry Serpentinite., PA	Atg[3]	Am SiO_2	Chr/Mag
F99-84b	Cedar Hill Quarry Serpentinite, PA	Am SiO_2; Atg[3]	Chr/Mag	Ol?
Southwestern Puerto Rico				
F99-72	Sedimentary Serpentinite Breccia., PR	Am SiO_2	Srp	Chl
F99-74b	Sierra Bermeja Serpentinite, PR	Am SiO_2	Srp; Chl	Chr/Mag
California				
F99-13	Yerba Buena Serpentinite, San Jose CA	Am SiO_2	nd	Chr/Mag; Srp?
F99-23	New Idria Serpentinite, CA	Am SiO_2; Srp	Chl	Chr/Mag
F99-27	McLaughlin Mine Serpentinite, CA	Am SiO_2	nd	Chr/Mag
F99-34	SE Geysers Serpentinite, CA	Am SiO_2	Chl	Chr/Mag; Srp?
F99-87	Josephine Serpentinite, CA	Am SiO_2; Srp	Chr/Mag; Chl	Ol

[1] Mineral symbols according to Kretz (1983). Atg=antigorite; Chl = chlorite; Chr/Mag=chromite or magnetite; Ol=olivine; Srp = serpentine (undifferentiated); Am SiO_2 = amorphous silica.

[2] Major ≥ 10 wt %; Minor = between 1 and 10 wt %; trace ≤ 1 wt %. Mineral assigned to category based on qualitative estimates.

[3] Not pure antigorite; apparently contains a second serpentine mineral (best match is the 6(3)T lizardite pattern).

Bulk samples from the PA-MD-DC region generally contain antigorite as the primary serpentine phase but may contain substantial lizardite. Chlorite and other magnesian silicates may also be present, particularly those that have been substantially metamorphosed (Mariottsville schist). Magnesite, dolomite and brucite are abundant in some specimens. A spinel-group mineral (probably magnetite and/or chromite) is ubiquitous in minor amounts. Relict orthopyroxene and forsterite are rare.

Samples from Puerto Rico and California are comparable in general appearance to each other but look quite different from the serpentinites of the PA-MD-DC region. The serpentine phases are lizardite with subordinate chrysotile. Trace amounts of chlorite are common. A spinel-group mineral (i.e., chromite or magnetite) is ubiquitous. Relict orthopyroxene and forsterite are rare to abundant. A serpentinite south of Mayagüez (F99-68) contains minor expandable clay. The sedimentary serpentinite breccia east of Mayagüez contains minor amounts of an unidentified phase, which, from thin section, consists of small volcanic rock fragments. A sample from the Josephine ophiolite in northwest California contains trace amphibole.

X-ray diffraction results from the HCl-dissolution residues show that antigorite remains as a significant identifiable phase after acid treatment in samples from the PA-MD-DC region. In contrast, residual serpentine minerals are less abundant in the acid-treated samples from Puerto Rico and California. Amorphous silica, which does not produce distinct peaks in x-ray diffraction patterns, is the most abundant phase in all residues. Chlorite, which is not soluble in hot ~5 to 6 *N* HCl, remains as a minor-to-trace component. Chromite/magnetite is unaffected. Surprisingly, trace amounts of olivine remain in some samples, although it is soluble in hot ~5 to 6 *N* HCl. These results suggest that lizardite and chrysotile are more rapidly dissolved in hot ~5 to 6 *N* HCl than olivine and antigorite.

SEQUESTERING POTENTIAL OF TYPICAL ULTRAMAFIC BODIES

The CO_2-sequestering potential of example ultramafic bodies from the eastern United States and Puerto Rico is compared in Table 13. Volume, bulk density, and Mg content for each body were estimated using geologic maps, data in published reports, and various chemical analyses listed in previous tables. As mentioned above, fresh peridotite, especially dunite such as from the Day Book deposit (NC) contains the most Mg per unit mass of rock. More Mg per unit mass of rock means it takes less dunite than serpentinite to consume a given quantity of CO_2. This is compared in Table 13 as the value R(CO_2), which is the idealized ratio of rock processed to CO_2 consumed. All other parameters being equal, rocks with low R-values such as Day Book are probably more desirable than those with high values such as the Puerto Rican deposits.

Table 13. Physical-Chemical and CO_2-Sequestering Properties of Example Ultramafic Bodies from the Eastern United States and Puerto Rico

	Vermont			PA–MD–DC–Region					Western North Carolina			Southwestern Puerto Rico		
	Belvidere Mtn	East Dover	Mad River	State Line	Penn-Mar Quarry	Soldier's Del.	Hunting Hill	Rockville Quarry	Buck Creek	Day Book	All[1]	M. del Estado	R. Guan-ajibo	S. Ber-meja
Volume-Density														
Volume (km^3)	2.75	2.70?	0.061	6	0.003	7	1	0.01	0.29	0.013	7.5	135	22	0.8
Density (g/cm^3)	2.9	2.9?	2.7	2.5	2.5	2.4	2.5	2.5	3.17	3.17	3.17	2.55	2.55	2.55
Ore mass (tons)	8.0×10^9	7.8×10^9	0.15×10^9	15×10^9	0.055×10^9	17×10^9	2.5×10^9	0.16×10^9	0.92×10^9	0.040×10^9	22×10^9	340×10^9	55×10^9	2×10^9
Rock-Mg Content														
Rock type	Serp. Dunite	Serp. Dunite	Serp.	Serp.	Serp.	Serp.	Serp.	Serp.	Serp. Dunite	Dunite	Serp. Dunite	Serp.	Serp.	Serp.
Wt % Mg	26	26	22	24	24	23	23	23	28	28	26	22	22	22
Sequestering Properties														
R(CO_2)[2]	2.13	2.13	2.51	2.30	2.30	2.40	2.40	2.40	1.97	1.97	2.13	2.51	2.51	2.51
Mg (10^9 tons)	2.08	2.03	0.033	3.60	0.013	3.91	0.58	0.037	0.26	0.011	5.72	74.8	12.1	0.44
CO_2 (10^9 tons)	3.76	3.67	0.060	6.52	0.024	7.08	1.04	0.067	0.47	0.020	10.4	135	21.9	0.80
Q-value[3]	1	1	2	2	2	2	2	2	2	1	1 to 2	1	1	1
Yr/million people, US[4]	200	190	3.2	350	1.3	380	57	3.5	25	1.1	570	7300	1200	43

[1] Calculated using a tonnage double that estimated by Hunter (1941) for all serpentinized dunites in the region.

[2] R(CO_2) is the calculated mass ratio of rock processed to CO_2 disposed.

[3] Q-value is a semiquantitative evaluation of dissolution properties that considers ease of magnesium extraction and residual insoluble silicates. A Q-value of 1 is best and 3 is worst (see text).

[4] Years per population center of one million people; assumes annual US CO_2 emission rate of about 5×10^9 tons/year and present population of 270 million people.

A semiquantitative rating (Q-rating) of 1 to 3 (Table 13) evaluates the approximate ease of magnesium extraction in hot ~5 to 6 *N* HCl and the quantity of insoluble silicate residues in rocks from the various deposits (1 is best and 3 is worst). Serpentinites from Puerto Rico and high-purity dunites such as Day Book have low Q-ratings because they dissolve easily and contain virtually no insoluble silicates. Metamorphosed serpentinites from the Appalachians tend to have intermediate R- and Q-values. Highly metamorphosed ultramafic rocks such as the anthophyllite schist from the Marriotsville Quarry (not listed in Table 13 because of low tonnage) have both high R- and Q-values. Thus, bodies of this type are the least attractive of the deposits we evaluated as magnesium sources for CO_2 sequestration.

All economic tradeoffs for exploiting the ultramafic rocks considered in this report have not been evaluated. Additional considerations would include land access and logistics, proximity to power plants and pipelines, environmental restrictions and rehabilitation costs, various mining, backfilling, and plant construction costs, and economic realization of waste silica, iron oxide, chromium and nickel (Goff and Lackner 1998).

CONCLUSIONS

The CO_2 sequestering potential of small ultramafic bodies is considerable when calculated in terms of large population groups. For example, the Belvidere Mountain ultramafic body in Vermont, having an estimated volume of roughly 2.75 km^3, is capable of handling the equivalent of 200 y of CO_2 emissions for a United States population center of 1 million people (these values include auto emissions). The volumes of serpentinite in the PA-MD-DC region (roughly 30 km^3) could sequester the CO_2 emissions of an equivalent population center for 1,600 years. The Monte del Estado serpentinite could dispose of the CO_2 emissions produced by a million people consuming energy at current U.S. rates for 7,300 years, if such a thick body could be totally exploited. Because the population of Puerto Rico is about 4 million, this body could sequester the waste CO_2 of the island for more than 1,900 years.

The ease of magnesium extraction by chemical means is greatest for relatively pure dunite and unmetamorphosed serpentinite bodies. From this perspective, high-purity dunite from bodies in Vermont and western North Carolina and the low-grade serpentinites of Puerto Rico are more desirable than the metamorphosed serpentinites that occur throughout most of the Appalachians.

The quantity of insoluble silicate residues is yet a third consideration when evaluating the relative merits of various ultramafic bodies. Again, high-purity dunite and low-grade serpentinite contain the least insoluble residues; thus, they are relatively better than metamorphosed serpentinites. Altered ultramafic rocks containing secondary carbonates and silica are to be avoided because these minerals reduce the usable magnesium content of the deposits.

The results of this investigation show that valuable, magnesium-rich ultramafic deposits exceeding 1 km^3 are scattered throughout the Appalachian Mountains of the eastern United States. The best ultramafic rocks for CO_2 sequestration are the relatively pure dunite deposits such as Belvidere and Day Book. However, of the four regions considered, southwestern Puerto Rico has by far the largest volume of ultramafic deposits containing easily extractable magnesium and low contents of unwanted residual minerals.

ACKNOWLEDGMENTS

We thank L. Rodríguez-Iglesias, J. Joyce, and H. Schellekens (University of Mayagüez) for help with field work and for providing information on the serpentinites of Puerto Rico. The following people provided access and information to ultramafic rocks in the PA-MD-DC region: J. S. Croney (Bardon, Inc.), H. B. Johnsson (The Arundel Corp.), D. Chandler (Penn-Mar Quarry), and E. Nordstrom (D. H. Stoltzfus & Son, Inc.). M. Gale, Vermont Geological Survey provided considerable information on ultramafic rocks in that state. R. G. Coleman (Stanford University) provided valuable information used to collect samples in north-central California. J. Grossman and B. Morgan (both from the United States Geological Survey, Reston, Virginia) provided reviews of the draft manuscript. Figures were prepared by A. Garcia and D. Bergfeld (LANL). Editorial assistance was provided by Mable Amador (LANL). This research was funded by the United States Department of Energy through the Laboratory Directed Research and Development (LDRD) program at Los Alamos National Laboratory, by the Federal Energy and Technology Center (FETC), and by the United States Geological Survey.

REFERENCES

Astwood, P., Carpenter, J., and Sharp, W., 1972. A petrofabric study of the Dark Ridge and Balsam Gap dunites, Jackson County, North Carolina: Southeast. Geol., **14:**183–194.

Bell, J.M., Clarke, E. de C., and Marshall, P., 1911. The geology of the Dun Mountain subdivision, Nelson: N. Zeal. Geol. Surv., Bulletin 12, new series, 71 pp.

Bromery, R.W., and Griscom, A., 1964. A gravity survey in the Mayagüez area of southwest Puerto Rico, *in* (Burk, C.A., ed.) A study of serpentinite: The AMSOC core hole near Mayagüez, Puerto Rico: Nat. Res. Counc., Washington, D.C., Publication No. 1188, 61–74.

Burk, C.A. (ed.), 1964. A study of serpentinite: the AMSOC core hole near Mayagüez, Puerto Rico: Nat. Res. Counc., Washington, D.C., Publication No. 1188, 175 pp.

Carpenter, J.R., and Phyfer, D.W., 1975. Olivine compositions from southern Appalachian ultramafics: Southeast. Geol., **16:**169–172.

Carpenter, J.R., and Chen, H.S., 1978. Petrology and bulk rock chemistry of the Frank ultramafic body, Avery County, N.C., and associated other ultramafic rock bodies of the southern Appalachians: Southeast. Geol., **19:**21–25.

Chidester, A.H., 1961. Economic geology of the Belvidere Mountain asbestos area: New Eng. Intercoll. Geol. Congr., 1961 Field Trip Guide, Trip B-1, 3 pp. with map.

Chidester, A.H., 1962. Petrology and geochemistry of selected talc-bearing ultramafic rocks and adjacent country rocks in north-central Vermont: U.S. Geol. Surv. Prof. Pap. 345, 207 pp. with maps.

Chidester, A.H., Albee, A.L., and Cady, W.M., 1978. Petrology, structure, and genesis of the asbestos-bearing ultramafic rocks of the Belvidere Mountain area in Vermont: U.S. Geol. Surv. Prof. Pap. 1016, 95 pp. with maps.

Chung, F. H., 1974a. Quantitative interpretation of X-ray diffraction patterns. I. Matrix-flushing method of quantitative multicomponent analysis. J. Appl. Cryst., **7:**519–525.

Chung, F. H., 1974b. Quantitative interpretation of X-ray diffraction patterns. II. Adiabatic principle of X-ray diffraction analysis of mixtures. J. Appl. Cryst., **7:**526–531.

Chung, F. H., 1975. Quantitative interpretation of X-ray diffraction patterns. III. Simultaneous determination of a set of reference intensities. J. Appl. Cryst., **8:**17–19.

Coleman, R.G., 1977. Ophiolites: Springer-Verlag, Berlin, 229 pp.

Condie, K.C., and Madison, J.A., 1969. Compositional and volume changes accompanying progressive serpentinization of dunites from the Webster-Addie ultramafic body, North Carolina: Amer. Mineral., **54:**1173–1179.

Conrad, S., Wilson, W., Allen, E., and Wright, T., 1963. Anthophyllite asbestos in North Carolina: N. C. Div. Miner. Resour. Bull. 77, 61 pp.

Dickinson, W.R., Hopson, C.A., and Saleeby, J.B., 1996. Alternate origins of the Coast Range Ophiolite (California): Introduction and implications: GSA Today, **6:**1–10.

Drake, A.A., Sinha, A.K., Laird, J., Guy, R.E., 1989. The Taconic Orogen, *in* (Hatcher, R.D., Thomas, W.A., and Viele, G.W., eds.) The Appalachian-Ouachita Orogen in the United States. The Geology of North America, Vol. F-2, Geol. Soc. Amer., Boulder, Colorado, 101–177.

Goff, F., and Guthrie, G., 1999. Field Trip Guide to Serpentinite, Silica-Carbonate Alteration, and Related Hydrothermal Activity in the Clear Lake Region, California: Los Alamos National Laboratory report LA-13607-MS, 29 pp.

Goff, F., and Lackner, K. S., 1998. Carbon dioxide sequestering using ultramafic rocks: Environ. Geosci. **5**:89–101.

Goff, F., Guthrie, G., Counce, D., Kluk, E., Bergfeld, D., and Snow, M., 1997. Preliminary Investigations on the CO_2 Sequestering Potential of Ultramafic Rocks: Los Alamos National Laboratory report LA-13328-MS, 22 pp.

Govindaraju, K., 1994. Special issue: Geostandards Newsletter, **18**:1–15.

Griscom, A., 1964. Magnetic properties and aeromagnetic interpretation of serpentinite from southwest Puerto Rico, *in* (Burk, C.A., ed.) A study of serpentinite: The AMSOC core hole near Mayagüez, Puerto Rico: Nat. Res. Counc., Washington, D.C., Publication No. 1188, 39–48.

Hahn, K.R., and Heimlich, R.A., 1977. Petrology of the dunite exposed at the Mincy Mine, Macon County, North Carolina: Southeast. Geol., **19**:39–53.

Harper, G.D., 1984. The Josephine Ophiolite, northwestern California: Geol. Soc. Am. Bull., **95**:1009–1026.

Hess, H.H., and Otalora, G., 1964. Mineralogical and chemical composition of the Mayagüez serpentinite cores, in (Burk, C.A., ed.) A study of serpentinite: The AMSOC core hole near Mayagüez, Puerto Rico: Nat. Res. Counc., Washington, D.C., Publication No. 1188, 152–168.

Hoffman, M.A., and Walker, D., 1978. Textural and chemical variations of olivine and chrome spinel in the East Dover ultramafic bodies, south-central Vermont: Geol. Soc. Am. Bull., **89**:699–710.

Honeycutt, F.M., and Heimlich, R.A., 1979. Petrology of the Balsam Gap dunite, Jackson County, North Carolina: Southeast. Geol., **21**:251–260.

Hunter, C.E., 1941. Forsterite olivine deposits of North Carolina and Georgia: N. C. Div. Miner. Resour. Bull. 41, 117 pp.

Hunter, C.E., Murdock, T.G., and McCarthy, G.R., 1942. Chromite deposits of North Carolina: N. C. Div. Miner. Resour. Bull. 42, 39 pp.

Johnsson, H.B., 1996. Two historic metal mines in Maryland, *in* (Brezinski, D.K., and Reger, J.P., eds.) Studies in Maryland Geology: M. Geol. Surv., Special Publication 3, 71–86.

Jolly, W.T., Lidiak, E.G., Schellekens, J., and Santos, H., 1998. Volcanism, tectonics, and stratigraphic correlations in Puerto Rico, *in* (Lidiak, E., and Larue, D., eds.) Tectonics and Geochemistry of the Northeastern Caribbean: Geol. Soc. Amer., Special Paper 322, 1–34.

Karr, C., 1997, UNIMIV/Corporation, personal communication.

Kingsbury, R.H., and Heimlich, R.A., 1978. Petrology of an ultramafic body near Micaville, Yancey County, North Carolina: Southeast. Geol., **20**:33–46.

Kretz, R., 1983. Symbols for rock-forming minerals: Am. Mineral., **68**:277–279.

Kulp, J.L., and Brobst, D.A., 1954. Notes on the dunite and the geochemistry of vermiculite at the Day Book dunite deposit, Yancey County, North Carolina: Econ. Geol., **49**:211–220.

Labotka, T.C., and Albee, A.L., 1979. Serpentinization of the Belvidere Mountain ultramafic body, Vermont: Mass balance and reaction at the metasomatic front: Can. Mineral., **17**:831–845.

Lackner, K.S., Butt, D.P., and Wendt, C.H., 1998. The need for carbon dioxide disposal: A threat and an opportunity: Proceedings of the 23rd International Technical Conference on Coal Utilization and Fuel Systems, Coal Slurry Technology Association, Washington, D.C., 569–582.

Lackner, K.S., Wendt, C. H., Butt, D.P., Joyce, E.L., and Sharp, D.H., 1995. Carbon dioxide disposal in carbonate minerals: Energy **20:**1153–1170.

Laird, J., Lanphere, M.A., and Albee, A.L., 1984. Distribution of Ordovician and Devonian metamorphism in mafic and pelitic schists from northern Vermont. Am. J. Sci., **284**:376–413.

Larrabee, D.M., 1966. Map showing distribution of ultramafic and intrusive mafic rocks from northern New Jersey to eastern Alabama: U.S. Geol. Surv. Miscellaneous Investigations Map MI-476, scale 1:500,000 (color).

Larrabee, D.M., 1969. Serpentinite and rodingite in the Hunting Hill quarry, Montgomery County, Maryland. U.S. Geol. Surv. Bull. 1283, 1–34.

Linder, D.E., Wylie, A.G., and Candela, P.A., 1992. Mineralogy and origin of the State Line talc deposit, Pennsylvania: Econ. Geol. **87:**1607–1615.

Lipin, B.R., 1984. Chromite from the Blue Ridge province of North Carolina: Am. J. Sci., **284:**507–529.

Lockwood, J.P., 1971. Sedimentary and gravity-slide emplacement of serpentinite: Geol. Soc. Am. Bull., **82:**919–936.

Mattson, P.H., 1960. Geology of the Mayagüez area, Puerto Rico: Geol. Soc. Am. Bull., **71:**319–362.

Miller, R., 1953. The Webster-Addie ultramafic ring, Jackson County, North Carolina: Am. Mineralogist, **38:**947–958.

Misra, K.C., and Keller, F.B., 1978. Ultramafic bodies in the southern Appalachians: A review: Am. J. Sci., **278**:389–418.

Morgan, B.A., 1977. The Baltimore Complex, Maryland, Pennsylvania, and Virginia, *in* (Coleman, R.G., and Irwin, W.P., eds.), North American Ophiolites: Oreg. Dep. Geol. Miner. Ind. Bull. **95:**41–49.

Murdock, T.G., and Hunter, C.E., 1946. The vermiculite deposits of North Carolina: N. C. Div. Miner. Resour. Bull. 50, 44 pp.

Nordstrom, E. 1999. D. H. Stoltzfus and Son, Inc., personal communication.

O'Hanley, D.S., 1992. A solution to the volume problem in serpentinization: Geology, **20:**705–708.

O'Hanley, D.S., 1996. Serpentinites: Records of tectonic and petrological history: Oxford Monograph on Geology and Geophysics No. 34, 277 pp.

Pearre, N.C., and Heyl, A.V., 1960. Chromite and other mineral deposits in serpentine rocks of the Piedmont Upland, Maryland, Pennsylvania, and Delaware: U.S. Geol. Surv. Bull. 1082-K, 707–833.

Pearre, N.C., and Heyl, A.V., 1974. The history of chromite mining in Pennsylvania and Maryland: P. Dep. Environ. Resour. Information Circular **14:**1–27.

Ramanathan, V., 1988. The greenhouse theory of climate change: A test by an inadvertent global experiment: Science, **240:**293–295.

Sabine, C.L., Wallace, D.W.R., and Millero, F.J., 1997. Survey of CO_2 in the oceans reveals clues about global carbon cycle: EOS, **78:** 51,54–55.

Sanford, R.F., 1982. Growth of ultramafic reaction zones in greenschist to amphibolite facies metamorphism: Am. J. Sci., **282:**543–616.

Stanley, R.S., and Ratcliffe, N.M., 1985. Tectonic synthesis of the Taconian orogeny in western New England: Geol. Soc. Am. Bull., **96:**1227–1250.

Van Baalen, M.R., Francis, C.A., and Mossman, B.T., 1999. Mineralogy, petrology and health issues at the ultramafic complex, Belvidere Mt., Vermont, USA, *in* (Wright, S.F., ed.), Guidebook to Field Trips in Vermont and Adjacent Regions of New Hampshire and New York: New England Intercollegiate Geological Conference, 91st Annual Meeting, Burlington, Vermont, A4-1–A4-17.

Weart, S.R., 1977. The discovery of the risk of global warming: Phys. Today (Jan.), 34–40.

Yurkovich, S.P., 1977. The Corundum Hill dunite, Macon County, North Carolina: Southeast. Geol., **19:**55–68.

APPENDIX

Glossary of Geologic Terms Used in this Report

Alteration:	Changes or modifications in a rock, usually by fluid-rock reactions.
Bastite:	A pseudomorphous texture consisting of secondary serpentine replacing primary pyroxene.
Diapir:	A domal rock structure formed by a density instability that forms when low-density plastic material intrudes overlying high-density rock; common structure in serpentinized peridotites.
Dunite:	A rock consisting of ≥90 vol % olivine.
Harzburgite:	A rock consisting of ≥10 vol % orthopyroxene with the remainder mostly olivine.
Lherzolite:	A rock consisting of ≥10 vol % clinopyroxene and ≥10 vol % orthopyoxene with the remainder mostly olivine.
LOI:	Loss on ignition; the volatile component (mostly water but also CO_2) lost during initial heating of a rock sample before chemical analysis; heating is conducted at 900°C to 1100°C.
Mafic:	Said of rocks relatively high in magnesium, iron, and calcium but relatively low in silica, sodium, and potassium. Basalt is a common mafic rock.
Melange:	A broken or chaotic rock formation. Melange commonly forms at the boundary of thrust faults between incompetent rocks such as wet sediments and serpentinites; commonly found along subduction zones and ancient continental margins. Melange units generally contain hard rocks ranging in size from small fragments to house-sized blocks immersed in an incompetent matrix.
Ophiolite:	A rock association consisting of ancient oceanic crust; usually exposed along subduction zones and ancient continental margins. A complete ophiolite sequence consists of a basal slab of mantle peridotite overlain by gabbroic intrusive bodies, basaltic dikes and lavas, pillow basalt, chert, argillaceous siltstone, and fine-grained oceanic sediment.
Peridotite:	A rock usually consisting of the minerals olivine, orthopyroxene, minor clinopyroxene, and minor chromium spinel. Dunite, harzburgite, and lherzolite are types of peridotite.
Primary:	Said of the original minerals in a rock, particularly in magmatic rocks.
Prograde:	Metamorphism caused by an increase in temperature and/or pressure.
Protolith:	Original source rock before metamorphism or modification by other geologic processes.
Pseudomorph:	Describes a secondary mineral that replaces the form or shape of a primary mineral in a host rock.
Secondary:	Said of the new minerals formed during metamorphism or hydrothermal alteration.
Serpentine:	Generic name for the three Mg-rich, silicate minerals antigorite, chrysotile, and lizardite (see Table 1). Lizardite and chrysotile share the same ideal chemical formula, which differs slightly from that for antigorite.
Serpentinite:	A rock consisting dominantly of any combination of the three serpentine minerals and minor spinel; often formed by metamorphism of peridotite accompanied by extensive hydration.
Ultramafic:	Said of rocks rich in magnesium, iron, and, sometimes calcium but poor in silica, aluminum, sodium, and potassium. Ultramafic rocks generically include peridotites, serpentinites, their relatives, and mixtures.