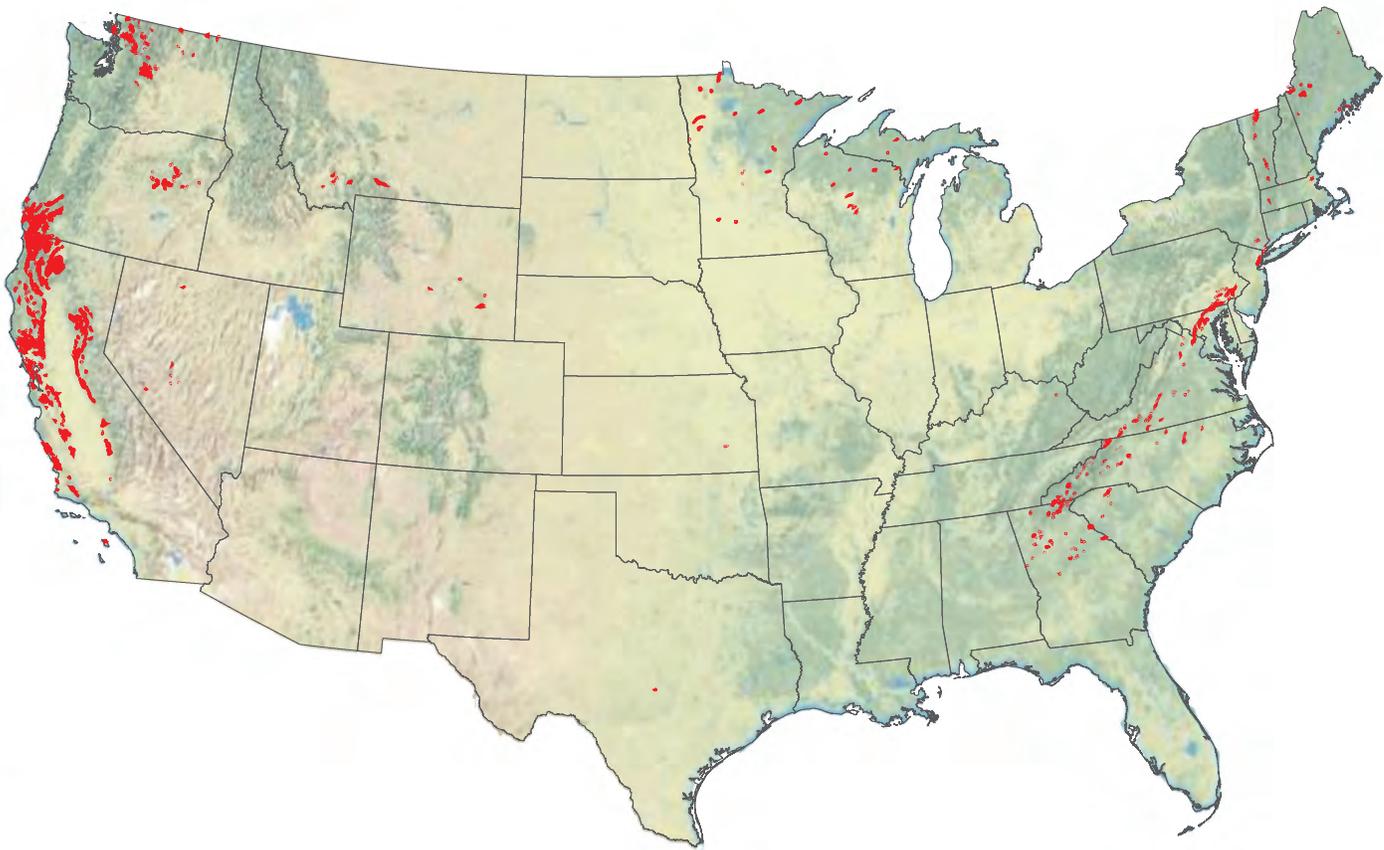


Prepared in cooperation with the Earth Institute at Columbia University

# Mapping the Mineral Resource Base for Mineral Carbon-Dioxide Sequestration in the Conterminous United States



Data Series 414

# **Mapping the Mineral Resource Base for Mineral Carbon-Dioxide Sequestration in the Conterminous United States**

By S.C. Krevor, C.R. Graves, B.S. Van Gosen, and A.E. McCafferty

Prepared in cooperation with the Earth Institute at Columbia University

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## Plate

1. Map of ultramafic rock bodies suitable for carbon-dioxide sequestration [see separate Plate]
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# Mapping the Mineral Resource Base for Mineral Carbon-Dioxide Sequestration in the Conterminous United States

By S.C. Krevor<sup>1</sup>, C.R. Graves<sup>1</sup>, B.S. Van Gosen<sup>2</sup>, and A.E. McCafferty<sup>2</sup>

## Abstract

This database provides information on the occurrence of ultramafic rocks in the conterminous United States that are suitable for sequestering captured carbon dioxide in mineral form, also known as mineral carbon-dioxide sequestration.

Mineral carbon-dioxide sequestration is a proposed greenhouse gas mitigation technology whereby carbon dioxide (CO<sub>2</sub>) is disposed of by reacting it with calcium or magnesium silicate minerals to form a solid magnesium or calcium carbonate product. The technology offers a large capacity to permanently store CO<sub>2</sub> in an environmentally benign form via a process that takes little effort to verify or monitor after disposal. These characteristics of the technology are unique among its peers in greenhouse gas disposal technologies.

The 2005 Intergovernmental Panel on Climate Change Special Report on Carbon Dioxide Capture and Storage suggested that a major gap in mineral CO<sub>2</sub> sequestration is locating the magnesium-silicate bedrock available to sequester the carbon dioxide. It is generally known that silicate minerals with high concentrations of magnesium are suitable for mineral carbonation. However, no assessment has been made in the United States that details their geographical distribution and extent, nor has anyone evaluated their potential for use in mineral carbonation.

Researchers at Columbia University and the U.S. Geological Survey have developed a digital geologic database of ultramafic rocks in the conterminous United States. Data were compiled from varied-scale geologic maps of magnesium-silicate ultramafic rocks. The focus of our national-scale map is entirely on ultramafic rock types, which typically consist primarily of olivine- and serpentine-rich rocks. These rock types are potentially suitable as source material for mineral CO<sub>2</sub> sequestration.

## Introduction

Mineral CO<sub>2</sub> sequestration is a proposed greenhouse gas mitigation technology whereby CO<sub>2</sub> is disposed of by binding it with calcium or magnesium to form a solid magnesium or calcium carbonate product. The reaction offers virtually unlimited capacity to permanently store CO<sub>2</sub> in an environmentally benign form via a process that takes little effort to either verify or monitor. The technology had its origins in the 1990s; the initial idea was credited to Seifritz (1990) and its initial development was by Lackner and others (1995) at Los Alamos National Laboratory.

The 2005 Intergovernmental Panel on Climate Change Special Report on Carbon Dioxide Capture and Storage (International Panel on Climate Change, 2005) suggested that a major gap in mineral CO<sub>2</sub> sequestration is locating the magnesium-silicate bedrock available to sequester CO<sub>2</sub>. Previous work performed by researchers at Los Alamos National Laboratory has provided resource base estimates and detailed mineralogical information for specific sites throughout the conterminous United States (Goff and others, 1997; Goff and others, 2000). With this work, a country-wide digital database has been compiled detailing locations throughout the conterminous United States where ultramafic minerals potentially suitable for mineral CO<sub>2</sub> sequestration are found. This work can be used to better characterize the country-wide mineral resource base for a mineral CO<sub>2</sub> sequestration process. In addition, the database will provide a publicly available reference for anyone wishing to identify suitable locations for the development of a pilot or industrial process.

## Minerals Suitable for Mineral Carbon-Dioxide Sequestration

Potential silicate minerals suitable for CO<sub>2</sub> sequestration should be abundant, concentrated in magnesium, and reactive with respect to the process being utilized. Silicate minerals are the most abundant mineral in the Earth's crust and make an

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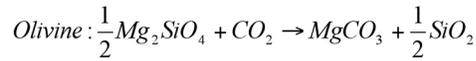
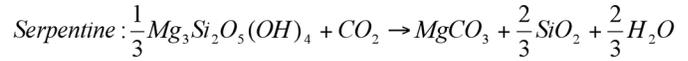
<sup>2</sup>U.S. Geological Survey.

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obvious choice for magnesium ores. Calcium silicates are also suitable but far less abundant than magnesian silicates.

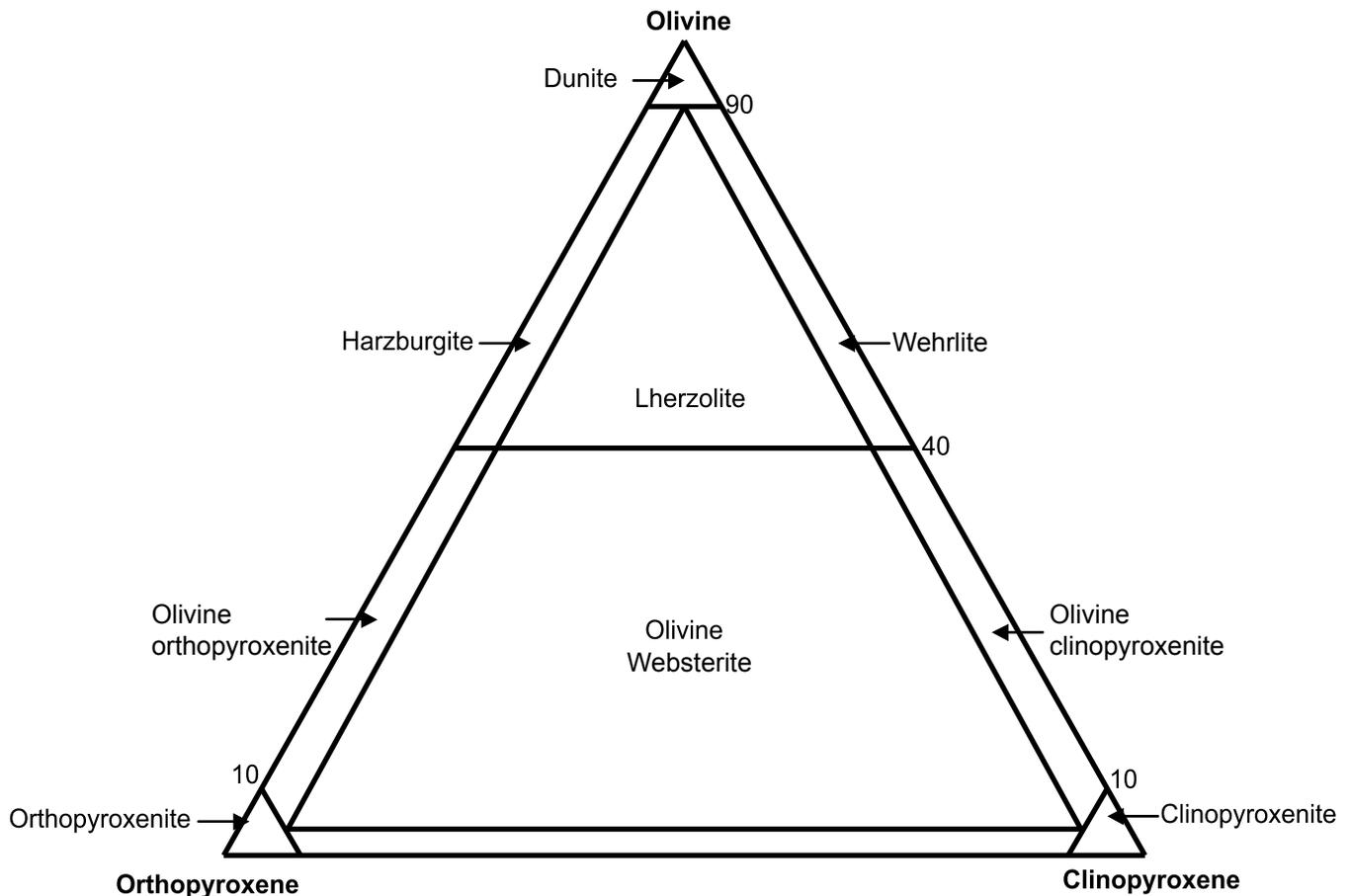
Silicate minerals with high concentrations of magnesium and iron are referred to as mafic minerals. The rock name (wehrlite, lherzolite, harzburgite, and so forth, see fig. 1) depends on the proportions of these minerals. Ultramafic rocks often undergo metamorphic hydration to produce rocks known as serpentinites, which are also potentially suitable for mineral carbonation. The ultramafic rock types deemed suitable for mineral sequestration—dunite, peridotite, harzburgite, wehrlite, lherzolite, picrite, and their altered form, serpentinite—are also ultrabasic rocks, meaning they have silica ( $\text{SiO}_2$ ) contents of less than 45 percent (Wyllie, 1967; Hess, 1989). Ultramafic rocks are often associated with mafic rocks, such as gabbro, which contain approximately equal amounts of mafic minerals and feldspar (Ca-, Na-, and K-bearing aluminosilicate minerals). Mafic rocks, however, would not contain the high concentration of magnesium necessary for mineral carbonation.

This study focuses on the location of ultramafic rocks as a potential resource base for a mineral  $\text{CO}_2$  sequestration process. Example carbonation reactions for serpentine and olivine are:



### Ultramafic Complexes

The most abundant occurrences of ultramafic rocks are in orogenic (deformational) zones that are most often the result of collisions between continental and oceanic tectonic plates. Two general types of ultramafic rocks are found in orogenic zones: alpine-type ultramafics and ultramafic volcanic-arc plutons. Ultramafic bodies also are formed in the interior of continental plates in extensional zones (rifts) and include



**Figure 1.** International Union of Geological Sciences classification diagram for ultramafic rocks based on modal percentages of three mafic minerals (olivine, orthopyroxene, and clinopyroxene). The ultramafic rock types deemed suitable for mineral  $\text{CO}_2$  sequestration (dunite, harzburgite, lherzolite, wehrlite) are those in the upper part of the diagram. From Hess (1989).

layered intrusions and smaller sills and dikes (Wyllie, 1967). In addition, metamorphosed ultramafic lava flows (komatiites) and related subvolcanic intrusions are found locally in some of the oldest parts of continental plates (cratons). All of these rocks have separate petrologic and tectonic histories and as such exhibit differences in location, mineralogy, and mineralogical distribution (table 1).

## Orogenic Occurrences

*Alpine ultramafic rocks (ophiolitic).*—Alpine-type ultramafic rocks are remnants of lower oceanic crust and related mantle that have been obducted (thrust up) onto adjacent crust as plates collided. The suite of oceanic crust and upper mantle rocks resulting from this process is known as an ophiolite (Coleman, 1977). Ophiolites are typically located along active or previous convergent plate boundaries. In the United States these rocks constitute the majority of ultramafic rock exposures and are located primarily in north-south-trending belts in the East and West Coast States (fig. 2).

The ultramafic part of the ophiolitic suite is divided into two categories based on the texture of the material. Tectonite forms the bottom section and consists of dunite pods and lenses in harzburgite or lherzolite all formed as the residue of melting, melt extraction, and melt transport beneath an oceanic spreading ridge; the complementary lavas rose to form oceanic crust. The tectonite layer grades upward into what is known as the cumulate section, in which olivine crystals that settled

from basalt magmas form the dominant phase; these are interpreted to have formed via crystallization of rising lava beneath an oceanic spreading ridge. Both tectonite and cumulate sections will show varying ranges of serpentinization, which involves conversion of the olivine and pyroxenes to serpentine (Coleman, 1977).

*Volcanic arc plutons.*—Ultramafic volcanic arc plutons are concentrically zoned ultramafic rocks that were formed as the feeder zones of subvolcanic magma chambers in volcanic arc complexes. Volcanic arcs are volcanic chains that form along convergent margins, above zones where oceanic crust is subducted (thrust down) into the mantle. Obduction of ophiolites occurs when a fragment of oceanic crust and upper mantle is thrust up rather than down along a subduction zone. Because both arcs and ophiolites accumulate on the overthrust plate above subduction zones, ancient arc rocks are found in linear belts in relatively close proximity to ophiolites. The plutons generally contain a core of dunite surrounded by successive zones of ultramafic and mafic rocks (Wyllie, 1967).

## Intracratonic Occurrences

*Mafic to ultramafic layered intrusions.*—These formations are the fossil magma chambers in continental crust in which magma slowly crystallized and differentiated, perhaps via gravity settling of solids. The tectonic setting of these intrusions is not fully understood, but there is evidence that they are associated with zones of crustal rifting, often in areas where

**Table 1.** Ultramafic complex types in the United States. Modified from Voormeij and Simandl (2004).

Geologic setting	Complex type	Description	Distribution of ultramafic minerals	Examples
Orogenic	Alpine-type	The basal section of ocean-floor crust that has been tectonically emplaced onto continental crust (ophiolite).	Tectonite section contains harzburgite and lherzolite hosting pods of dunite, whereas cumulate section contains layers of dunite. Rock types are often highly serpentinized, but some are fresh and probably constitute the largest individual sources of olivine in North America.	East and West Coasts United States. Large unaltered dunites are found at Balsam Gap, N.C., and Twin Sisters, Wash.
	Volcanic arc plutons.	Intrusion formed in an island arc complex accreted onto continental crust.	Concentrically zoned mineral distribution with a dunite core surrounded by successive zones of clinopyroxenite and orthopyroxenite. Variable serpentinization.	East and West Coasts United States. Duke Island, Alaska.
Intracratonic	Layered intrusions.	Large intrusions formed under or in continental crust.	Layers of peridotite and pyroxenite extending laterally over the length of the intrusion. Variable serpentinization, with the most alteration along faults and shear zones. Though ultramafic layers occur, mafic layers predominate.	Stillwater, Mont.
	Komatiitic metavolcanic rocks.	Differentiated flows and subvolcanic sills in Archean and Early Proterozoic submarine mafic volcanic sequences.	Basal parts of thin to thick flows and sills, generally peridotitic. Highly variable degree of serpentinization.	Central and southern Wyoming, northern Minnesota.

the continental crust is relatively thin, thereby allowing for the transport and emplacement of magma closer to the surface.

Minerals are concentrated into layers in these intrusions as the result of the settling of different minerals as cooling and chemical differentiation processes take place in the magma chamber. Layers often occur in cycles, with many stacked layer cycles forming a series in the intrusion. An ultramafic series, for example, may contain alternating layers of dunite, harzburgite, and orthopyroxenite. The layers themselves are often laterally continuous across the length of the intrusion and thus can present a relatively simple opportunity for resource exploitation (Hess, 1989).

*Komatiitic metavolcanic rocks.*—The last major ultramafic rock type is related to Archean (rocks older than 2.5 billion years) komatiitic metavolcanic rocks and accompanying subvolcanic intrusions (Arndt, 1994). Peridotite and minor amounts of dunite cumulates form by crystal settling from thick basaltic, pyroxenitic, and peridotitic lava flows and subvolcanic sills. Serpentine minerals, talc, chlorite, magnesite, anthophyllite, and tremolite often form in the basal parts during metamorphism. These lava flows and sills are commonly a few meters to 0.5 km thick and may be exposed over 1–5 km. They are typically associated spatially with thick submarine tholeiitic basalt sequences. Their tectonic environment of formation remains controversial, ranging from ocean floor volcanism related to mantle plumes to compressional and tensional arc environments.

## Ultramafic Rocks in the United States

Exposed ultramafic rocks are most concentrated on the East and West Coasts of the United States, where past convergent plate boundaries resulted in the emplacement of ophiolites and volcanic arc terranes with a relatively small number of volcanic arc plutons. Ultramafic rocks in the interior United States are generally sparse, but include one major layered intrusive type body in Montana (the Stillwater complex), a suite of komatiitic metavolcanic rocks in Wyoming and Minnesota, and a number of small serpentinite and ultramafic bodies located in central Texas, Arkansas, Kentucky, and Kansas (fig. 2).

### Western United States

The ultramafic rocks of the Western United States, particularly in California, Oregon, and Washington, likely host the largest bodies of both olivine and serpentine in the conterminous United States (Irwin, 1977). They consist of multiple ophiolite and arc pluton assemblages emplaced during multiple orogenic events of the late Paleozoic and Mesozoic Eras (Bailey and others, 1964). The ultramafic bodies of the West Coast have been extensively studied for their geologic importance, as well as their economic importance as a resource base for mineral resources, including aggregate



**Figure 2.** Map of ultramafic rock bodies (black) suitable for carbon-dioxide sequestration, drawn from the dataset discussed in this work. Ultramafic rocks are enlarged for visibility.

(crushed stone), asbestos, chromite, nickel, talc (soapstone), and olivine foundry sand (Dellinger, 1988).

The ultramafic rocks of the Western United States can be separated into five distinct geologic zones. From north to south, they are: (1) the ophiolitic terranes of western Washington, (2) the Canyon Mountain complex of eastern Oregon, (3) the Klamath-Trinity region of the western California–Oregon border, (4) the western foothills of the Sierra Nevada of California, and (5) the Coast Ranges of California (Bailey and others, 1964; Irwin, 1977).

In Washington, several ophiolitic terranes containing dunite and harzburgite dominate, with the Ingalls complex representing the largest single ultramafic body. Of special note is the Twin Sisters dunite of northwestern Washington, containing large volumes of unaltered olivine.

The Canyon Mountain complex of eastern Oregon contains an east-west-striking formation of partially serpentinized ultramafic rocks that are part of an ophiolite (Thayer, 1977).

The Klamath Mountains of northwestern California and southwestern Oregon contain the largest concentration of ultramafic rocks in the country. The bulk of the ultramafic rock here exists in two formations—the Trinity ultramafic sheet of the eastern Klamath Mountains and the Josephine peridotite of the western Klamath Mountains. The Trinity sheet is the larger of the two and is more serpentinized (Irwin, 1977). The Josephine peridotite contains 30–50 percent serpentinized harzburgite across five large exposures (Harper, 1984). Various volcanic arc formations are also present in the region (Himmelberg and Loney, 1973; Kelemen and Ghiorso, 1986).

The Sierra Nevada of California contains ultramafic rocks in a 375-km-long ophiolite belt on the western edge of the mountain chain. Long continuous serpentinized belts in the north give way to isolated bodies and *mélange* (a jumbled mix of rock units) in the middle to southern end (Saleeby, 1982).

The Coast Ranges of California contain ultramafic rocks in a band starting at the southern end of the Klamath Mountains and running 1,130 km southwest to the Transverse Ranges of Monterey County. The largest outcrops are located in the north, are tabular, and are mainly composed of serpentine. Farther south, isolated plugs exist, such as the highly sheared New Idria asbestos deposit of San Benito County (Bailey and others, 1964; Irwin, 1977).

## Eastern United States

Ultramafic rocks exist in exposures along the entire Appalachian belt of eastern North America, from Newfoundland in Canada to Alabama in the southeastern United States (Williams and Talkington, 1977). They are generally taken to be ophiolitic in origin, formed during the closing of the Iapetus Ocean (a precursor to the Atlantic) during much of the Paleozoic era. A previous resource assessment for ultramafic rocks suitable for mineral sequestration on the East Coast was performed in 2000 (Goff and others, 2000). In this study, the

ultramafic rocks of the Eastern United States were divided into three main sections: (1) ultramafic rocks of Vermont, (2) the Baltimore and Liberty complexes of the Pennsylvania–Maryland–District of Columbia region, and (3) dunites of western North Carolina (Goff and others, 2000; Misra and Keller, 1978; Williams and Talkington, 1977).

Ultramafic rocks lie along a north-south-striking band through central Vermont, with the largest outcrops located in the north. Belvidere Mountain was notably one of the largest sources for asbestos production in the United States (Chidester and others, 1978; Hadden, 1996; Van Baalen and others, 1999). Rock units are classified as one of two types: those with dunitic cores, such as at Belvidere Mountain, and those with a serpentinite core with steatized (altered to talc-carbonate rocks) borders (Goff and others, 2000).

The Baltimore and Liberty complexes extending from southwest Pennsylvania to northern Virginia contain the largest exposures of ultramafic rocks in the Eastern United States. Completely serpentinized dunite occurs in belts starting at 10–30 km in length at the northern end decreasing in size to isolated lenses in Virginia (Morgan, 1977).

In the Southern Appalachian States of Virginia, North Carolina, and Georgia, the Blue Ridge Belt contains more than 275 individual lenses of ultramafic material. Notably, the bodies of western North Carolina have high concentrations of pure olivine, which appears to have recrystallized from a host serpentinite (Goff and others, 2000; Misra and Keller, 1978; Williams and Talkington, 1977).

## United States Interior

The largest known layered ultramafic intrusion in the United States is the Stillwater complex of southwestern Montana. A peridotite unit near its base spans the 48-km length of the intrusion and contains olivine and pyroxene minerals that are 20–100 percent serpentinized (Page, 1976; Raedeke and McCallum, 1984). This peridotite unit is the only unit of the Stillwater complex included in this compilation (fig. 3).

In Texas, a few small serpentine bodies are located in Gillespie, Blanco, and Llano Counties (Barnes and others, 1950).

Our study also includes ultramafic rocks in the upper midcontinent States of Minnesota, Michigan, and Wisconsin. Bedrock in these States is often concealed by a thin veneer of glacial deposits. Consequently, the ultramafic rocks were, at times, mapped from interpretation of aeromagnetic anomalies in combination with sparse outcrop and drill-hole data (Day and others, 1994). The magnetite produces distinct magnetic anomalies and allows for intrusions exposed at the surface to be mapped into the shallow subsurface in areas of poor bedrock exposure due to the vegetative and (or) glacial cover.

Data on ultramafic rocks in Minnesota are from a recent data release compiled by the Minnesota Geological Survey for the purpose of mapping rocks with potential for platinum group elements (Jirsa and others, 2006). Ultramafic rocks that have been mapped in outcrop and locations of drill holes that

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intersected ultramafic rocks in the subsurface are included in our database.

Many small serpentinite deposits are associated with Archean komatiitic metavolcanic rocks and related subvolcanic intrusive rocks in northern Minnesota and Wyoming (Day and others, 1994; Hausel, 1991; Klein, 1981; Snyder and others, 1989).

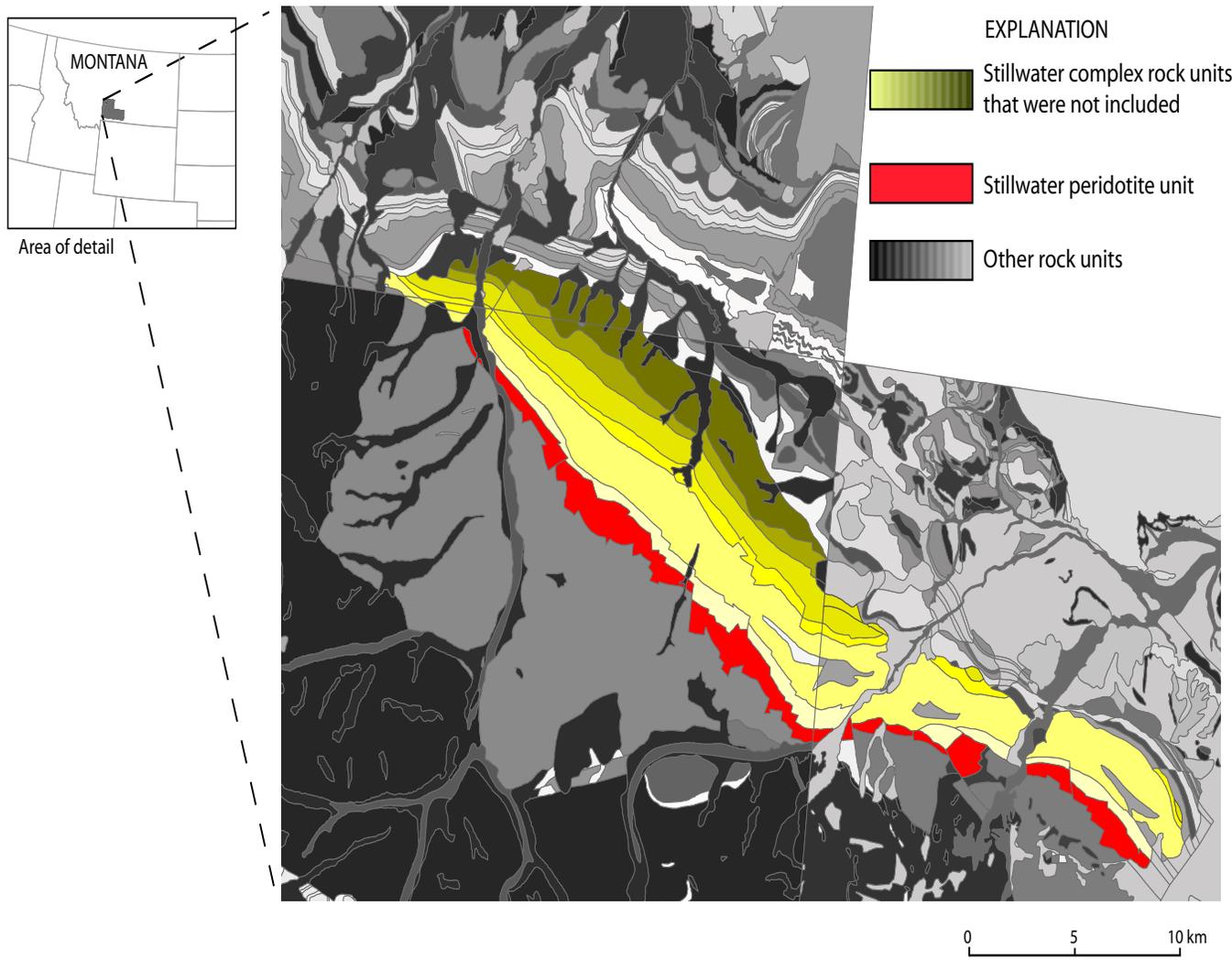
### Notable Mine Localities

*Belvidere Mountain, Vt.*—Belvidere Mountain in northern Vermont is the site of one of the oldest and one of the largest asbestos producing mines in the United States. The asbestos at Belvidere, which is chrysotile, was first discovered in 1896, and the site saw intermittent production until the 1920s. In 1929, the Vermont Asbestos Company (VAC) was formed and 64 years of constant production was begun, initially at the

Eden quarry on the mountain. The VAC was purchased by the Ruberoid Company in 1936, and the ownership was later taken over by an employee-owned cooperative in 1975, known as the Vermont Asbestos Group (VAG). The Eden quarry shut down in 1949, but by 1953 two more mines on the mountain had opened, the Lowell and C-Area quarries (Hadden, 1996; Van Baalen and others, 1999).

By the 1960s, 3,500 tons of ore were being mined per day, amounting to over 30,000 tons of asbestos product per year. Until large-scale asbestos production began in California in the 1960s, Belvidere was the source of over 80 percent of the country's asbestos production (but constituted less than 10 percent of the U.S.A. supply).

Tailings at the mine consist of three main tailings piles, corresponding to the Eden, Lowell, and C-Area quarries (fig. 4). The piles have been estimated to have a collective weight of greater than 29–30 million tonnes (L. Elliott, Vermont



**Figure 3.** Generalized geologic map of the Stillwater intrusive complex (Berg and others, 1999; Lopez, 2001). The map distinguishes between various rock units that form the Stillwater complex. The peridotite unit (in red) was included in this digital database, whereas other units (in yellow) were not because they are not rich in magnesium. Rock units that are not a part of the Stillwater complex are shown in shades of gray.

Department of Environmental Conservation, written commun., 2008. Available at URL <http://www.anr.state.vt.us/dec/wastediv/SMS/VAG.htm>). An analysis of 25 samples taken from the three tailings piles showed a relatively consistent mineralogical makeup of greater than 95 percent serpentine minerals (Doria, 2005).

*New Idria, Calif.*—The New Idria serpentinite formation, which is host to the Coalinga asbestos deposits, covers an area of 130 km<sup>2</sup> in Fresno and San Benito Counties, Calif. The asbestos ores in this formation are some of the largest known chrysotile deposits in the United States and contain greater than 50 percent chrysotile in the form of very short fiber, highly sheared fibrous masses.

The area was exploited beginning in 1963 at three sites owned by Union Carbide, Johns-Manville Corporation, and Atlas Minerals Corporation. At its peak, these three operations produced nearly 75,000 tons of powdered asbestos each year, tripling total U.S.A. production of asbestos during the 1960s (Mumpton and Thompson, 1975).

Asbestos mining at the Atlas site occurred from 1967 to 1979, and it is estimated that around 3 million cubic yards of asbestos ore and tailings remain at the site. The Johns-Manville (Coalinga) site operated from 1962 to 1974, and it is estimated that around 450,000 cubic yards of ore and tailings remain at the site (CH2M HILL, 2006). The Union Carbide Site (now Kings County Asbestos Company) operated from 1962 to 1992.

*Copperopolis, Calif.*—The Pacific Asbestos Corporation (PAC) mine located near Copperopolis, Calif., in Calaveras County, began producing asbestos in 1962, with capacity for 70,000 tons of fiber annually. During much of its operation, it was the single highest volume asbestos producer in the country, at times trading places with VAG at Belvidere, Vt. It closed for 2 years starting in 1973, but then resumed operation until its final closure in 1987. It was converted into and still remains a disposal site for asbestos-containing materials, currently under the ownership of the California Asbestos Monofill



**Figure 4.** C-Area tailings pile at Belvidere Mountain, Vt. Photograph taken by authors in June 2005. It is estimated that more than 29–30 million tonnes of serpentine tailings are located at the site.

Company. No estimates are currently available for tailings piles left at this site.

*Non-asbestos mines.*—The Twin Sisters dunite, Washington, is one of the largest olivine deposits in the world, and is the site of the largest olivine production operations in the United States. Estimates have put remaining reserves of unaltered olivine at 200 gigatons (Harben and Smith, 2006). Unimin and the Olivine Corporation are the main producers of olivine from the Twin Sisters ultramafic body, with a combined production of around 100,000 short tons per year (Harben and Smith, 2006). Olivine has also been produced from several locations stretching from Watauga County, N.C., to White County, Ga. Recent production has been limited to about 100,000 tons per year (Harben and Smith, 2006).

The Stillwater intrusive complex in southern Montana contains several active mining sites. Most of the mining focuses on the production of palladium and platinum, but chrome, nickel, and copper are produced as well. The mining is focused in mafic sections of the complex, and the quantity, if any, of ultramafic mine tailings is not known.

## Description of the Data

### Source Material and Methodology for Compilation

A digital geologic database of ultramafic rocks in the conterminous United States was compiled from varied-scale geologic maps containing magnesium-silicate ultramafic rock units (table 2). Most of the sources consist of statewide geologic maps at the 1:250,000 or 1:500,000 scales in both digital and nondigital form. Secondary sources were used to confirm the accuracy of the statewide maps, clarify the mineralogical makeup of rock units, and provide higher resolution data for some areas. The focus of our national-scale map is on suitable ultramafic rock types, which typically consist primarily of olivine- and serpentine-rich rocks.

Digital datasets of the bedrock geology of the United States exist for the entire country and most States at varying scales. The datasets were used as source material, and ultramafic rock types were derived by filtering, using rock identifiers in the source attribute tables. These identifiers are listed under the ORIG\_LABEL field of the final dataset attribute table so that users may return to the source if further clarification is needed (see the following section).

The source maps used various labeling systems to describe the lithology of the geologic units included in the maps. Rock types that were described in the source material as having ultramafic rocks or minerals as a major component were included, whereas those that included the mafic minerals only as secondary or tertiary mineral types were not included as a suitable ore for mineral sequestration. Specifically, rock units labelled in the source material as ultramafic, serpentinite,

peridotite, dunite, and picrite were included. Amphibolites, pyroxenites, and hornblendites were excluded, among other rock types.

The ultramafic rock-bearing complexes described previously only contain ultramafic rocks as one part of the complex—for example, the peridotite section of an ophiolite or an ultramafic layer in a mafic layered intrusion. The precision of the source maps used in this compilation allowed for us to distinguish ultramafic sections of complexes from those that are not ultramafic. For example, for the Stillwater complex, only the basal ultramafic section has been included (fig. 3). Similarly, with the Josephine ophiolite, only the peridotite section of the ophiolite has been included.

### Attributes

The attribute table for the dataset was chosen to provide consistency in information among rock units while at the same time preserving important lithologic information available from the source material. Thus, in addition to geographical attributes such as State and area of the unit, the age of the unit is approximated under the UNIT\_AGE attribute, and the rock class (igneous or metamorphic) and rock types (for example, serpentinite, dunite) are given in as many as four lithologic attribute fields, LITH1 through LITH4. If the unit has been given its own name (for example, Twin Sisters dunite), that is provided in the UNIT\_DESCRIPTION attribute.

The reference to the source of the data is provided in the SOURCE field, with reference information provided in the State reference databases included with the dataset. The name of the unit as it appears in the source data is also provided in the field ORIG\_LABEL so the entire dataset can be reconstructed or checked as needed. See table 3 for a description of the data fields included in the dataset.

### Potential Uses and Limitations

The goal of this project was to make available a reference dataset that could be used to locate favorable geologic terrain host to magnesium-silicate minerals that may be suitable for a mineral CO<sub>2</sub> sequestration process. Potential uses of the database may include studies to:

- Map attractive locations for pilot or industrial-scale projects;
- Locate specific areas for more thorough site evaluation and assessment.

Many limitations arise from the compilation of a map from disparate sources. Table 2 includes information on the scale of the various maps used as source material for the dataset. Table 4 shows the horizontal precision for various map scales under United States National Map Accuracy Standards (U.S. Bureau of the Budget, 1947). Because there was not an attempt to use the highest resolution data that could be found, some of the large ultramafic units are not as uniform as they appear and many small outcrops have not been included.

**Table 2.** Primary data references for ultramafic rocks included in this compilation by State. References for original statewide geologic maps are given as well as digital data that were used to compile data in this report. More detailed references are given in the digital database where necessary.

State	Data source identifier	Reference <sup>1</sup>	Source (available as web link, paper, or CD-ROM)	Scale
AR	AR001	U.S. Geological Survey (2000)	<a href="http://pubs.usgs.gov/sm/arkansas/download/">http://pubs.usgs.gov/sm/arkansas/download/</a>	1:500,000
CA	CA	Jennings (1977)	Paper—State map publication	1:750,000
	CA001	Saucedo and others (2000)	Available on CD-ROM from the California Geological Survey	1:750,000
	CA002	Graymer and others (2002)	<a href="http://pubs.usgs.gov/mf/2002/2403/">http://pubs.usgs.gov/mf/2002/2403/</a>	1:62,500
	CA003	Blake and others (2002)	<a href="http://pubs.usgs.gov/mf/2002/2402/">http://pubs.usgs.gov/mf/2002/2402/</a>	1:62,500
	CA004	Blake and others (2000)	<a href="http://pubs.usgs.gov/mf/2000/2337/">http://pubs.usgs.gov/mf/2000/2337/</a>	1:62,500
CT	CT	Rodgers (1985)	Paper—State map publication	1:125,000
	CT001	Nicholson and others (2006)	<a href="http://pubs.usgs.gov/of/2006/1272/">http://pubs.usgs.gov/of/2006/1272/</a>	1:125,000
DE	DE	Spoljaric and Jordan (1966)	Paper—State map publication	1:300,000
	DE001	Dicken and others (2005b)	<a href="http://pubs.usgs.gov/of/2005/1325/">http://pubs.usgs.gov/of/2005/1325/</a>	1:300,000
GA	GA	Lawton (1976)	Paper—State map publication	1:500,000
	GA001	Dicken and others (2005a)	<a href="http://pubs.usgs.gov/of/2005/1323/">http://pubs.usgs.gov/of/2005/1323/</a>	1:500,000
	GA002	Larabee and others (1966)	Paper; ultramafic rocks digitized for this publication	1:500,000
ID	ID001	Godchaux and Bonnichsen (2007)	Paper; ultramafic rocks digitized for this publication	>1:62,500
IL	IL001	Kolata (2005)	<a href="http://www.isgs.uiuc.edu/nsd/home/webdocs/st-geolb.html">http://www.isgs.uiuc.edu/nsd/home/webdocs/st-geolb.html</a>	1:500,000
KS	KS001	Kansas Geological Survey (1991)	Paper; ultramafic rocks digitized for this publication	1:500,000
		Merriam (1999)	Paper; ultramafic rocks digitized for this publication	1:50,000
KY	KY	Noger (1988)	Paper—State map publication	1:500,000
	KY001	Nicholson and others (2005)	<a href="http://pubs.usgs.gov/of/2005/1324/">http://pubs.usgs.gov/of/2005/1324/</a>	1:500,000
MA	MA	Zen and others (1981)	Paper—State map publication	1:250,000
	MA001	Nicholson and others (2006)	<a href="http://pubs.usgs.gov/of/2006/1272/">http://pubs.usgs.gov/of/2006/1272/</a>	1:250,000
MD	MD	Cleaves and others (1968)	Paper—State map publication	1:250,000
	MD001	Dicken and others (2005b)	<a href="http://pubs.usgs.gov/of/2005/1325/">http://pubs.usgs.gov/of/2005/1325/</a>	1:250,000
MN	MN001	Jirsa and others (2006)	<a href="ftp://mgssun6.mngs.umn.edu/pub5/ofr06_03/">ftp://mgssun6.mngs.umn.edu/pub5/ofr06_03/</a>	Various
ME	ME	Osberg and others (1985)	Paper—State map publication	1:500,000
	ME001	Nicholson and others (2006)	<a href="http://pubs.usgs.gov/of/2006/1272/">http://pubs.usgs.gov/of/2006/1272/</a>	1:500,000
MI	MI001	Cannon (1986)	Paper	1:250,000
MT	MT001	Ruppel and others (1993)	<a href="http://pubs.usgs.gov/imap/i-1803-h/">http://pubs.usgs.gov/imap/i-1803-h/</a>	1:250,000
	MT002	Kellogg and Williams (2005)	<a href="http://www.mbm.mtech.edu/gmr/gmr-statemap.asp">http://www.mbm.mtech.edu/gmr/gmr-statemap.asp</a>	1:100,000
	MT003	Berg and others (1999)	<a href="http://www.mbm.mtech.edu/gmr/gmr-statemap.asp">http://www.mbm.mtech.edu/gmr/gmr-statemap.asp</a>	1:100,000
	MT004	Lopez (2001)	<a href="http://www.mbm.mtech.edu/gmr/gmr-statemap.asp">http://www.mbm.mtech.edu/gmr/gmr-statemap.asp</a>	1:100,000
NC	NC	Rhodes and Conrad (1985)	Paper—State map publication	1:500,000
	NC001	Dicken and others (2005a)	<a href="http://pubs.usgs.gov/of/2005/1323/">http://pubs.usgs.gov/of/2005/1323/</a>	1:500,000
NJ	NJ	Drake and others (1998)	Paper—Northern part of the State	1:100,000
	NJ	Owens and others (1998)	Paper—Southern part of the State	1:100,000
	NJ001	Nicholson and others (2006)	<a href="http://pubs.usgs.gov/of/2006/1272/">http://pubs.usgs.gov/of/2006/1272/</a>	1:100,000
NY	NY	Fisher and others (1970)	Paper—State map publication	1:250,000
	NY001	Dicken and others (2005b)	<a href="http://pubs.usgs.gov/of/2005/1325/">http://pubs.usgs.gov/of/2005/1325/</a>	1:250,000
NV	NV	Stewart and Carlson (1978)	Paper—State map publication	1:500,000
	NV001	Craford (2007)	<a href="http://pubs.usgs.gov/ds/2007/249/">http://pubs.usgs.gov/ds/2007/249/</a>	1:250,000
OR	OR001	Walker and MacLeod (1991)	<a href="http://geology.wr.usgs.gov/docs/geologic/or/oregon.html">http://geology.wr.usgs.gov/docs/geologic/or/oregon.html</a>	1:500,000
PA	PA	Berg and others (1980)	Paper—State map publication	1:250,000
	PA001	Dicken and others (2005b)	<a href="http://pubs.usgs.gov/of/2005/1325/">http://pubs.usgs.gov/of/2005/1325/</a>	1:250,000
SC	SC001	Dicken and others (2005a)	<a href="http://pubs.usgs.gov/of/2005/1323/">http://pubs.usgs.gov/of/2005/1323/</a>	1:500,000
TN	TN	Hardeman and others (1966)	Paper—State map publication	1:250,000
	TN001	Nicholson and others (2005)	<a href="http://pubs.usgs.gov/of/2005/1324/">http://pubs.usgs.gov/of/2005/1324/</a>	1:250,000
TX	TX001	Barnes (1992)	Paper; ultramafic rocks digitized for this publication	1:500,000
VT	VT	Doll and others (1961)	Paper—State map publication	1:250,000
	VT001	Nicholson and others (2006)	<a href="http://pubs.usgs.gov/of/2006/1272/">http://pubs.usgs.gov/of/2006/1272/</a>	1:250,000
VA	VA	Virginia Division of Mineral Resources (1993).	Paper—State map publication	1:500,000
	VA001	Dicken and others (2005b)	<a href="http://pubs.usgs.gov/of/2005/1325/">http://pubs.usgs.gov/of/2005/1325/</a>	1:500,000
WA	WA001	Washington Division of Geology and Earth Resources (2005).	<a href="http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pub_ofr05-3.aspx">http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pub_ofr05-3.aspx</a>	1:100,000
WI	WI001	Sims (1989)	Paper; ultramafic rocks digitized for this publication	1:250,000
	WI002	Sims (1990a)	Paper; ultramafic rocks digitized for this publication	1:250,000
	WI003	Sims (1990b)	Paper; ultramafic rocks digitized for this publication	1:100,000
	WI004	Cannon and others (1996)	Paper; ultramafic rocks digitized for this publication	1:100,000
	WI005	Sims (1992)	Paper; ultramafic rocks digitized for this publication	1:500,000
WY	WY001	Green and Drouillard (1994)	Data available on CD-ROM	1:500,000

<sup>1</sup>References include both original geologic map publication, most often in paper form, and its updated digital equivalent for most of the States unless otherwise noted.

**Table 3.** Attributes of the digital ultramafic database (US\_ultra).

Attribute field label	Description
AREA	The surface area of the ultramafic map unit, in m <sup>2</sup> .
ORIG_LABEL	The unit label of the ultramafic map unit in the original reference.
SOURCE	Key to the source reference (table 2).
UNIT_AGE	Geologic age of the ultramafic map unit.
LITH_1	Primary ultramafic
LITH_2	lithologies present
LITH_3	in the rock unit
LITH_4	from the reference source.
STATE	State in which the ultramafic rock unit exists.
UNITDESC	Lithologic description of the map unit (for example, serpentinized dunite) or the unit name where applicable; for example, Twin Sisters dunite.
ROCK_CLASS	The rock type (igneous or metamorphic).
TOTAL_LITH	Aggregation of all lithologies listed in LITH1 to LITH4.

In addition to source map scale, limitations may also arise from the use of disparate source material in the mismatch among map units across State boundaries, differences in rock unit exposure in areas in which units were mapped, as well as differences in philosophy among sources as to which units should be included and how they should be classified (Nicholson and others, 2006).

Finally, with any mining operation, numerous social, economic, and political considerations will need to be taken into account to assess the possibility of development in any particular location. It would not be possible to include in this dataset the numerous laws, land jurisdictions, and permitting processes governing the areas where suitable minerals are available. Many publicly available datasets on land use and jurisdictions exist and may be used in conjunction with this dataset for initial analyses. Ultimately, the appropriate local, State, and Federal government offices will have to be consulted to understand the feasibility of development in any given location.

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**Table 4.** Horizontal precision of maps at different scales that meet United States National Map Accuracy Standards. Precision indicates that 90 percent or more of locations as represented on the map are within the stated horizontal distance of their actual location (U.S. Bureau of the Budget, 1947).

Map scale	Precision [m]
1:100,000	12.2
1:250,000	127
1:500,000	254

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