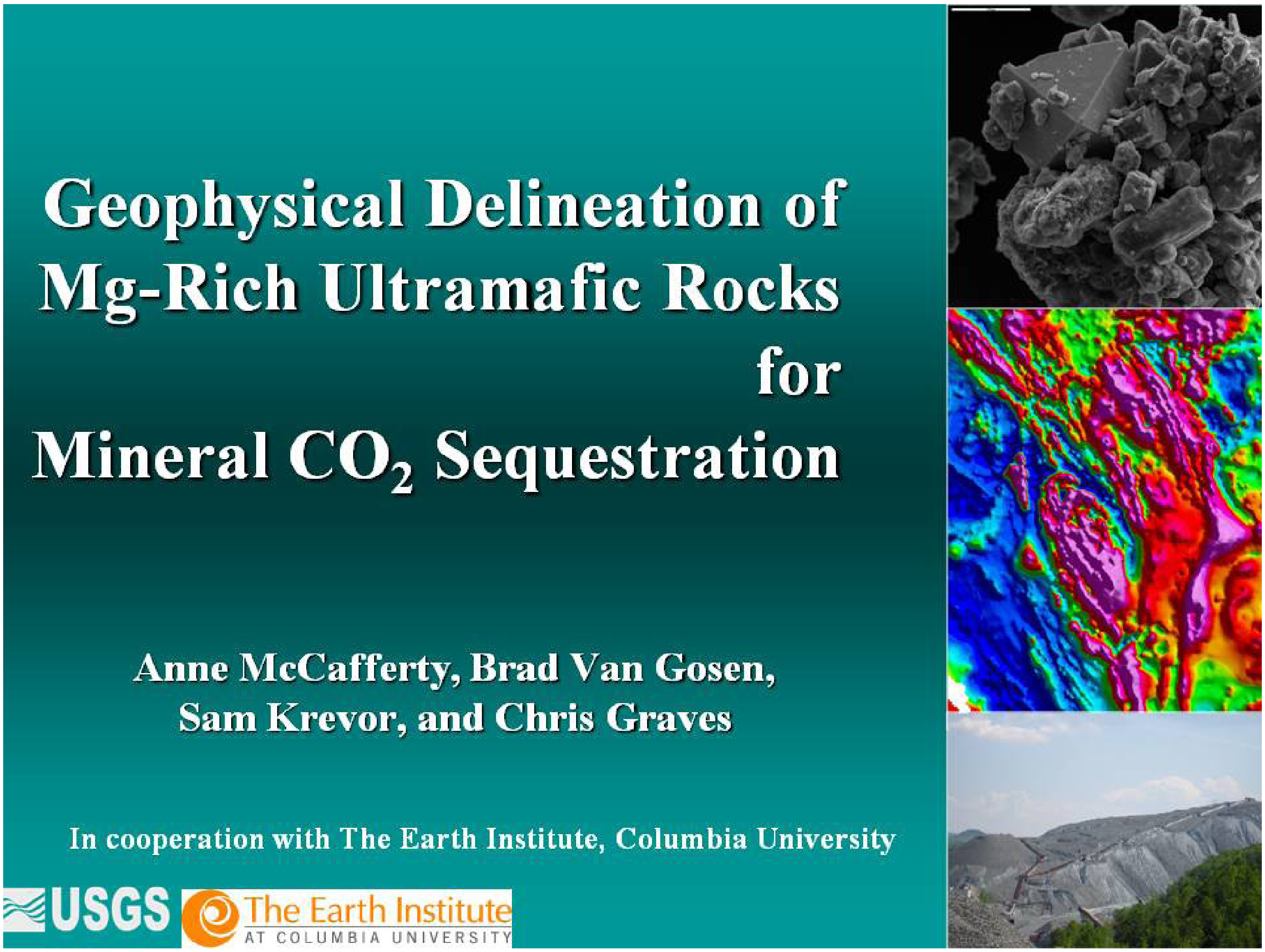
Prepared in cooperation with the Earth Institute of Columbia University, New York City

Geophysical Delineation of Mg-Rich Ultramafic Rocks for Mineral Carbon Sequestration



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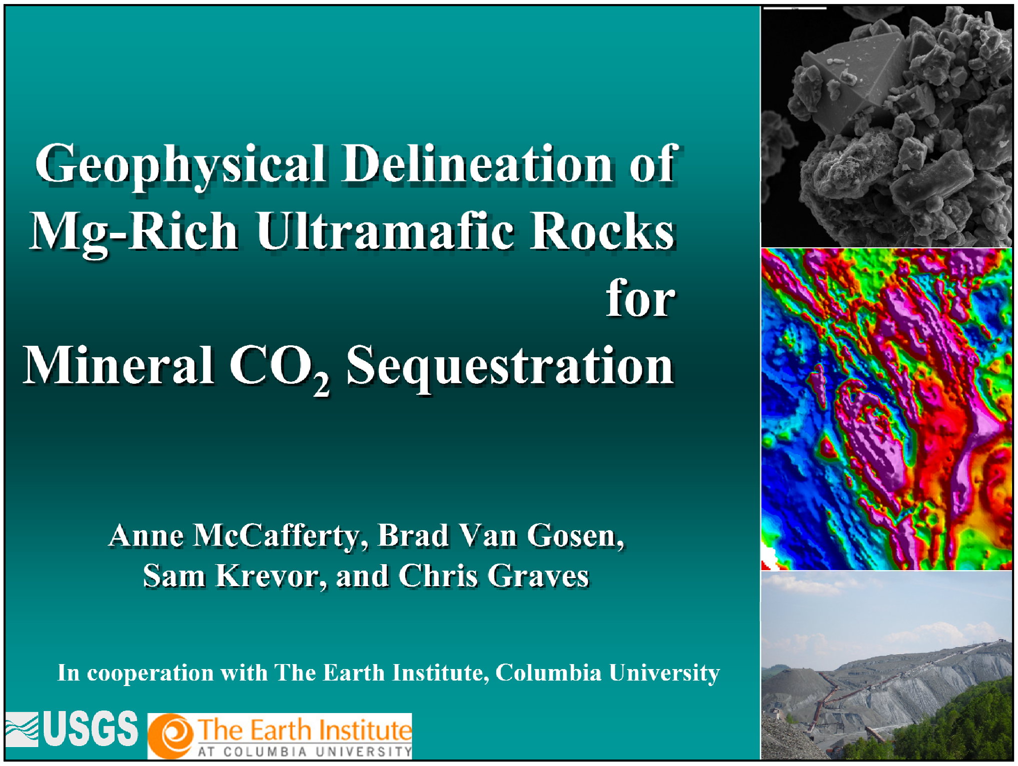
Geophysical Delination of Mg-Rich Ultramafic Rocks for Mineral Carbon Sequestration

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



Abstract

A similar version of this slide presentation was given at the 2009 Society for Mining, Metallurgy, and Exploration (SME) annual meeting in Denver, Colorado, in February 2009 (McCafferty and others, 2009). This presentation was part of the "*Industrial Minerals: Reducing Carbon Footprint in Industrial Minerals*" session. Two other related talks were presented in the same session by Sam Krevor of Columbia University. The first talk provided a status report on mineral CO_2 sequestration as an industrial process (Krevor and Lackner, 2009). The second talk presented a national-scale geologic compilation of rocks favorable for mineral CO_2 sequestration in the United States (Krevor and others, 2009). This presentation, an extension of the latter talk, shows how airborne geophysical data can be used to further refine the geologic mapping of ultramafic rocks.

Introduction

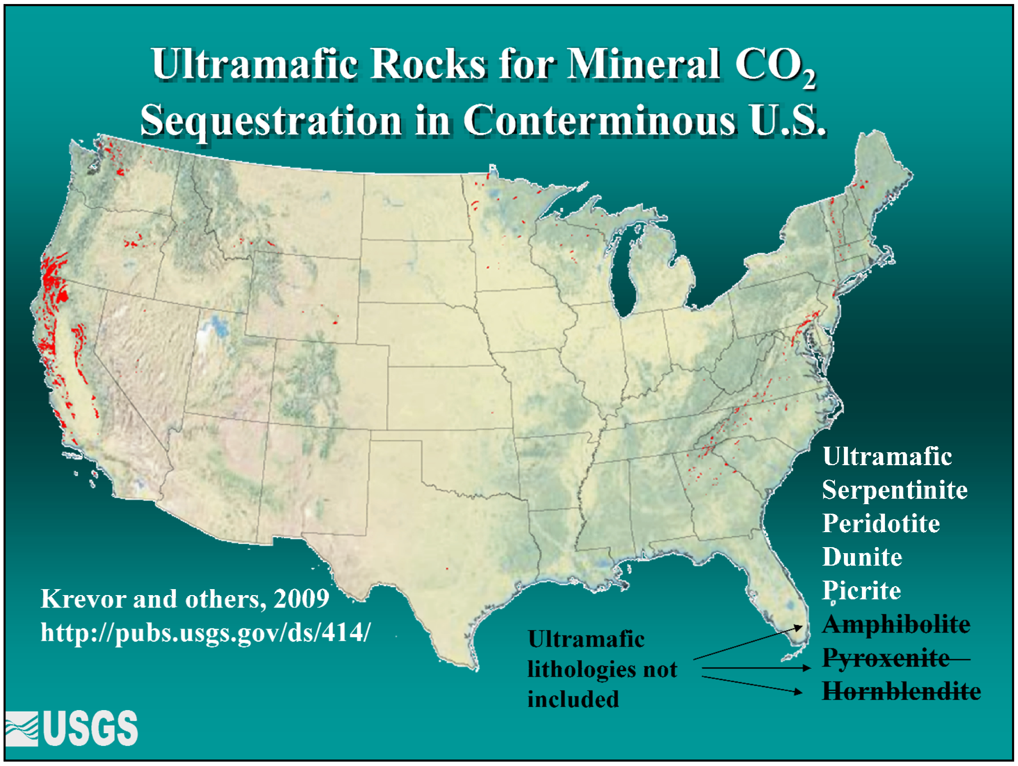
This presentation covers three general topics: (1) description of a new geologic compilation of the United States that shows the location of magnesium-rich ultramafic rocks in the conterminous United States; (2) conceptual illustration of the potential ways that ultramafic rocks could be used to sequester carbon dioxide; and (3) description of ways to use geophysical data to refine and extend the geologic mapping of ultramafic rocks and to better characterize their mineralogy.

The geophysical focus of this research is twofold. First, we illustrate how airborne magnetic data can be used to map the shallow subsurface geometry of ultramafic rocks for the purpose of estimating the volume of rock material available for mineral CO_2 sequestration. Secondly, we explore, on a regional to outcrop-scale, how magnetic mineralogy, as expressed in magnetic anomalies, may vary with magnesium minerals, which are the primary minerals of interest for CO_2 sequestration.

What is Mineral Carbon-Dioxide Sequestration?

Mineral carbon-dioxide sequestration is a process whereby carbon dioxide is either removed from the atmosphere or diverted from emission sources and stored in minerals. Mineral storage of CO_2 occurs as a natural chemical reaction in the weathering of ultramafic rocks. When it rains, the rainwater mixes with the CO_2 in the atmosphere to form a weak carbonic acid. The carbonic acid falls on the ultramafic rock, reacts with the magnesium-silicate minerals, and forms a solid magnesium-carbonate rock called magnesite ($MgCO_3$). The CO_2 gas is then permanently "locked up" in the magnesite as a solid. Magnesite is a stable mineral at the Earth's surface, it has no legacy issues such as acid drainage, and it would require no monitoring after disposal as it would remain environmentally benign over geologic time scales.

This natural mineral carbon sequestration process occurs slowly, too slowly to make it an effective means to sequester carbon dioxide from industrial sources. So, Columbia University, along with other research organizations, is exploring ways to chemically or mechanically accelerate and enhance this natural process to make it timely and economically viable. As research progresses on the industrial front, the U.S. Geological Survey (USGS) saw an opportunity to collaborate with Columbia by contributing the geologic and geophysical information necessary to underpin this important line of emerging climate change research.



Ultramafic Rocks for Mineral CO_2 Sequestration in the Conterminous United States

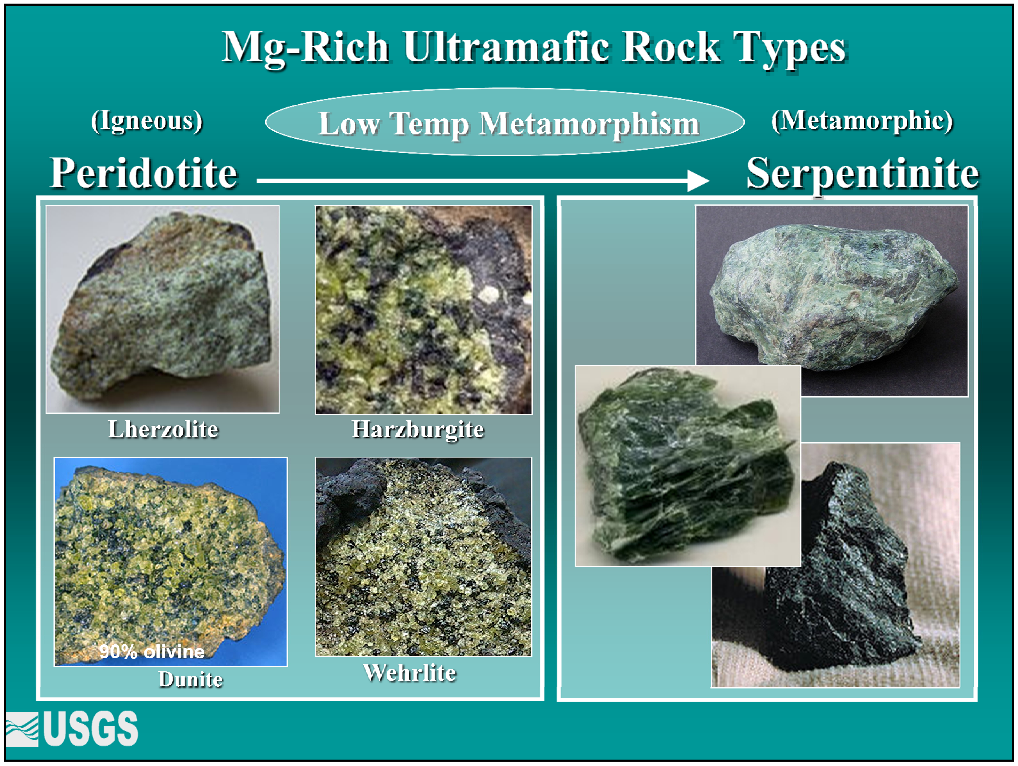
In 2007, scientists at the USGS and Columbia University began a joint effort to compile a national-scale map showing the locations of magnesium-rich ultramafic rocks in the conterminous United States that might be available for mineral CO_2 sequestration. The USGS had recently completed a series of integrated geologic map databases that cover the entire United States as part of a National Surveys and Analysis (NSA) Project (http://minerals.usgs.gov/projects/surveys_and_analysis/). As a result of the NSA project, digital geologic information was readily available to augment research and address land management issues at national scales.

The national map of ultramafic rocks was primarily compiled from the NSA data and augmented by new digital compilations from other state geological survey sources and existing paper geologic maps that were digitized. The ultramafic rock data used in our compilation came from geologic maps that range in scale from 1:50,000 to 1:750,000--most of the originating maps had a scale of 1:250,000. For specifics and details behind the map compilation, sources used, and scale of maps, see Krevor and others (2009a).

In February of 2009, the USGS, in cooperation with the Earth Institute at Columbia University, released the ultramafic rock map for mineral CO_2 sequestration in both report and digital map form (Krevor and others, 2009a available at http://pubs.usgs.gov/ds/414). Our report identifies the largest known sources of ultramafic bedrocks in the continental United States. The largest and most numerous ultramafic rock bodies occur in the west coast States of California, Oregon, and Washington. Also, a belt of ultramafic rocks extends northeastward through the eastern states from western Georgia through the southern Appalachians, up through the Middle-Atlantic States, in Staten Island, then to western New England, Vermont and Maine. Smaller ultramafic outcrops exist in the interior of the United States in Minnesota, Michigan, Wisconsin, Montana, Wyoming, and Texas. In total, the map shows 16,263 square kilometers (km_2) of ultramafic rock, an area roughly equivalent to the state of Hawaii including all its islands.

Ultramafic rocks suitable for mineral carbonation are rich in magnesium-silicate minerals, primarily olivine and serpentine. Several rock lithologies fall under the category of ultramafic rock. However, not all ultramafic rock lithologies were deemed magnesium-rich enough to be suitable for CO_2 sequestration. Hence, only those ultramafic rock types that contain a high proportion of magnesium minerals (greater than 18 weight percent) are included in the geologic compilation. Specific lithologies that met these criteria are peridotite, dunite, serpentinite and picrite (a rare olivine-rich volcanic basalt).

Ultramafic rock types not included in the geologic compilation are amphibolite, pyroxenite, and hornblendite.

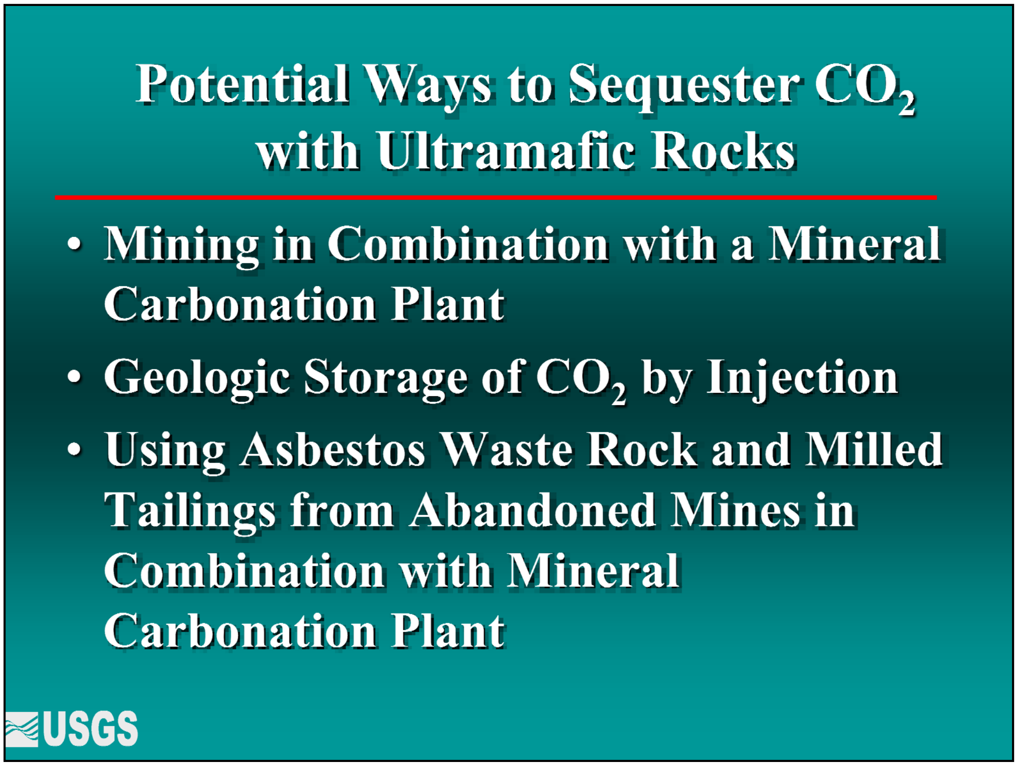


Mg-Rich Ultramafic Rock Types

In general, magnesium-silicate rich ultramafic rocks that are permissive for mineral CO_2 sequestration include various types of peridotite (an igneous rock) and serpentinite (its altered metamorphic equivalent). Peridotites include -- lherzolite, harzburgite, dunite, and wehrlite; the magnesium comes primarily from high concentrations of the mineral olivine, typically greater than 40 percent. Dunite can contain 90 percent or more olivine.

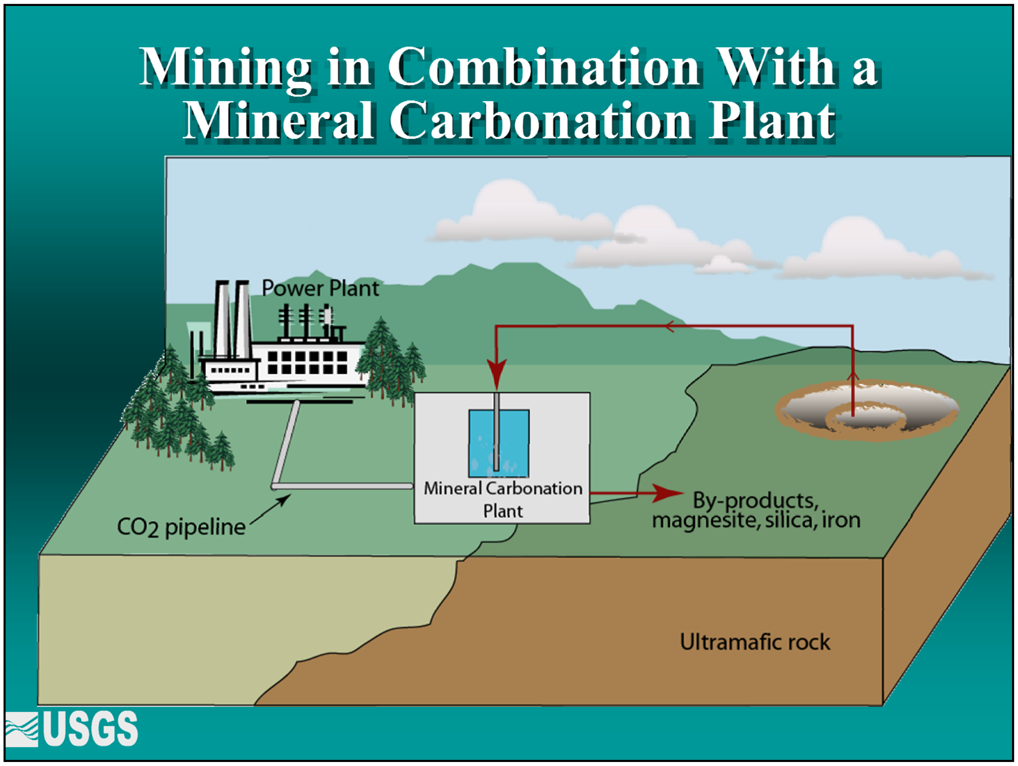
Serpentinite produced from peridotite contain magnesium-rich serpentine minerals, including chrysotile, lizardite, and antigorite.

In addition to the magnesium-silicate minerals, ultramafic rocks contain magnetite (Fe_3O_4), which is ubiquitous in both unserpentinized and serpentinized ultramafic rocks. Magnetite typically occurs as an accessory mineral in amounts less than 1 weight percent, but it can be present in amounts greater than 10 weight percent. Even small amounts of magnetite (1/4 weight percent) can produce significant magnetic anomalies. In later slides, we discuss the presence of magnetite in both peridotites and serpentine rocks and its effect on producing magnetic anomalies.



Potential Ways to Sequester CO_2 With Ultramafic Rocks

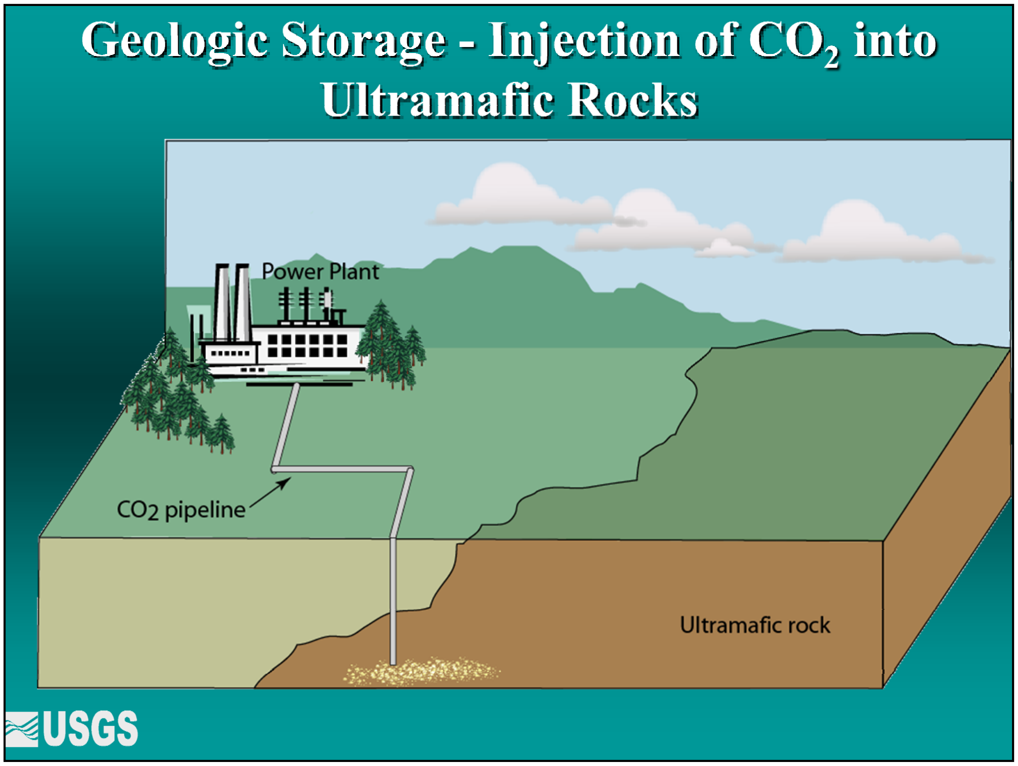
Using magnesium-rich ultramafic rocks to mitigate CO_2 is unique in comparison with other greenhouse gas storage approaches in that there are multiple options to use these rocks to sequester captured carbon dioxide. All carbon sequestration approaches have technological, financial, societal, and political challenges to overcome before successful implementation. That said, conceptual models oftentimes act as starting points for establishing a framework from which these challenges can be addressed. The next three slides provide illustrations of the concepts provided above.



Mining in Combination With a Mineral Carbonation Plant

This illustration shows an "ex-situ" approach to mineral CO_2 sequestration. It is one of the original scenarios proposed by Lackner and others (1995) in which ultramafic rock is mined, crushed, and reacted with captured carbon dioxide in a mineral carbonation plant. Carbon dioxide is captured at a power, cement, or iron and steel plant and then piped or otherwise transported to a mineral carbonation plant. At the mineral carbonation plant, dissolved magnesium-silicate minerals are combined with aqueous carbon dioxide to precipitate magnesium carbonate (magnesite). Because ultramafic rocks contain other minerals that are not part of the processing, by-products such as silica, iron, and accessory minerals are generated. The magnesite and by-products could be relocated back to the mined area. Alternately, the solids produced as part of the mineral carbonation process may have uses as industrial reagents.

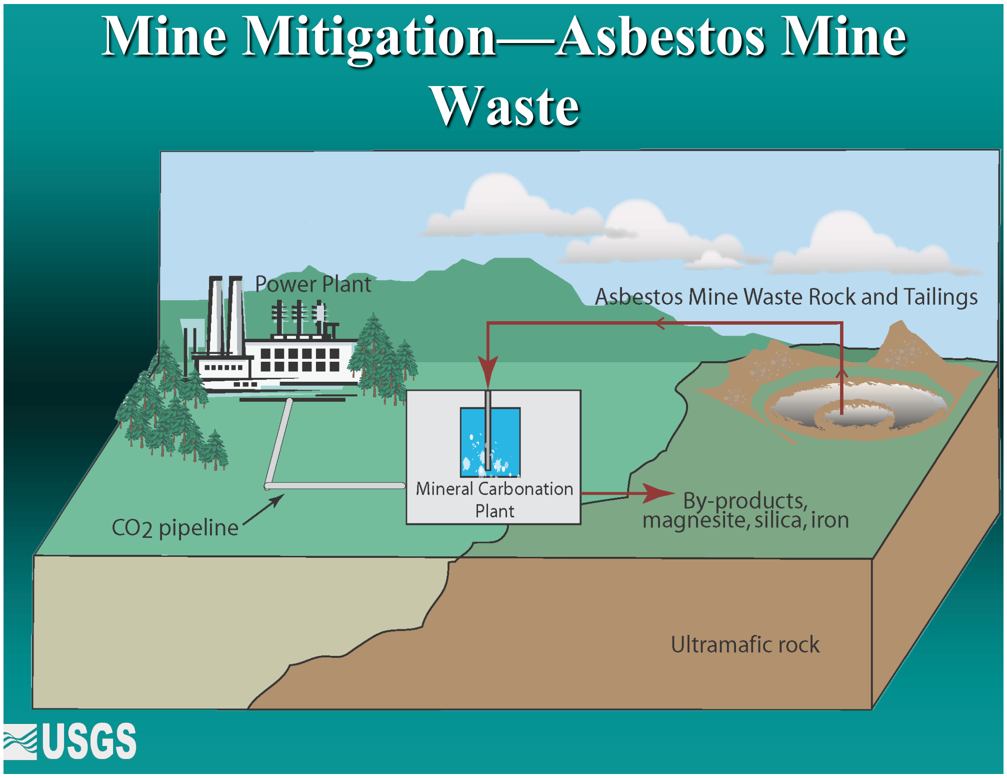
Areas of active chemical engineering research for this type of mineral carbonation focus on the reactions that occur at the mineral carbonation plant. Engineers are researching and testing ways to perform the chemical dissolution and precipitation to make this an economically feasible greenhouse gas mitigation technology. Krevor and Lackner (2009) provide a progress report on advances in the chemical dissolution part of the process.



Geologic Storage – Injection of CO_2 Into Ultramafic Rocks

This slide illustrates a geologic storage option in which carbon dioxide is captured at the point of emission, in this case, a power plant, and pumped either in liquid or gaseous form into the ultramafic rock. Ideally the point source of emission is located near the ultramafic bedrock in order to reduce transportation costs.

Researchers with Columbia University have recently proposed an “in-situ” mineral carbonation of CO_2 by using peridotite in Oman (Keleman and Matter, 2008). In their research, they propose that heated water combined with pressurized CO_2 could be injected into deep hydro-fractured ultramafic rocks, thereby speeding up the natural mineral carbonation process.

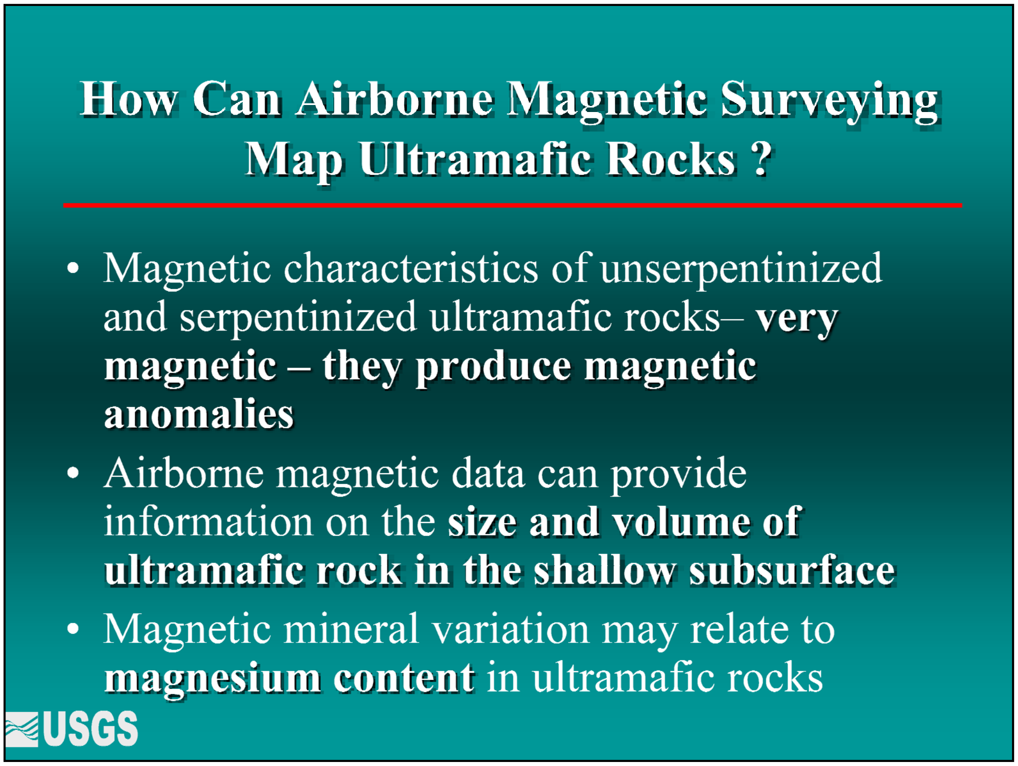


Mine Mitigatation — Asbestos Mine Waste

Natural deposits of asbestos such as chrysotile are commonly hosted by ultramafic rocks. Chrysotile is a magnesium-silicate mineral and as such, a candidate for mineral carbonation. Some former asbestos mines in the United States contain large volumes of excavated, crushed and processed ultramafic rock. Finding ways to safely mitigate the waste rock and mine tailings from abandoned or closed mines in order to prevent the asbestos minerals from entering the air, water, and soil is a challenge to state and federal regulatory agencies.

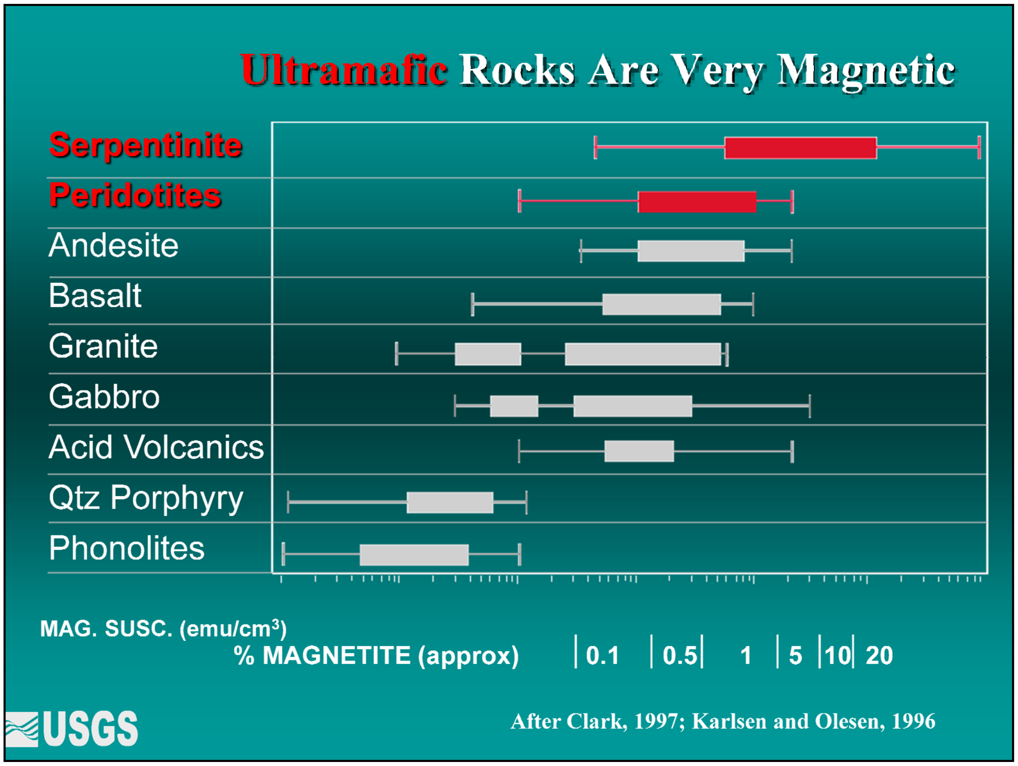
The process would work similar to the original scenario proposed by Lackner and others (1995) but the source material for the mineral carbonation of CO_2 would be the already mined waste rock sitting at the former asbestos mine and mill sites. Safe handling and transport practices would have to be put in place to safely combine the asbestos waste with the CO_2.

Using asbestos mine waste in a mineral carbonation process to mitigate the negative environmental effects of carbon dioxide would have at least two environmental benefits: it would improve air quality, and it would reduce health risks for those living near the abandoned mines. Carbon dioxide would be permanently sequestered from the atmosphere and the asbestos minerals, which are some of the first to dissolve in the mineral carbonation process, would be permanently removed from entering the air, water, and soil.



How Can Airborne Magnetic Surveying Map Ultramafic Rocks?

The next few slides will illustrate how aeromagnetic surveying can augment the geologic characterization of ultramafic rocks.

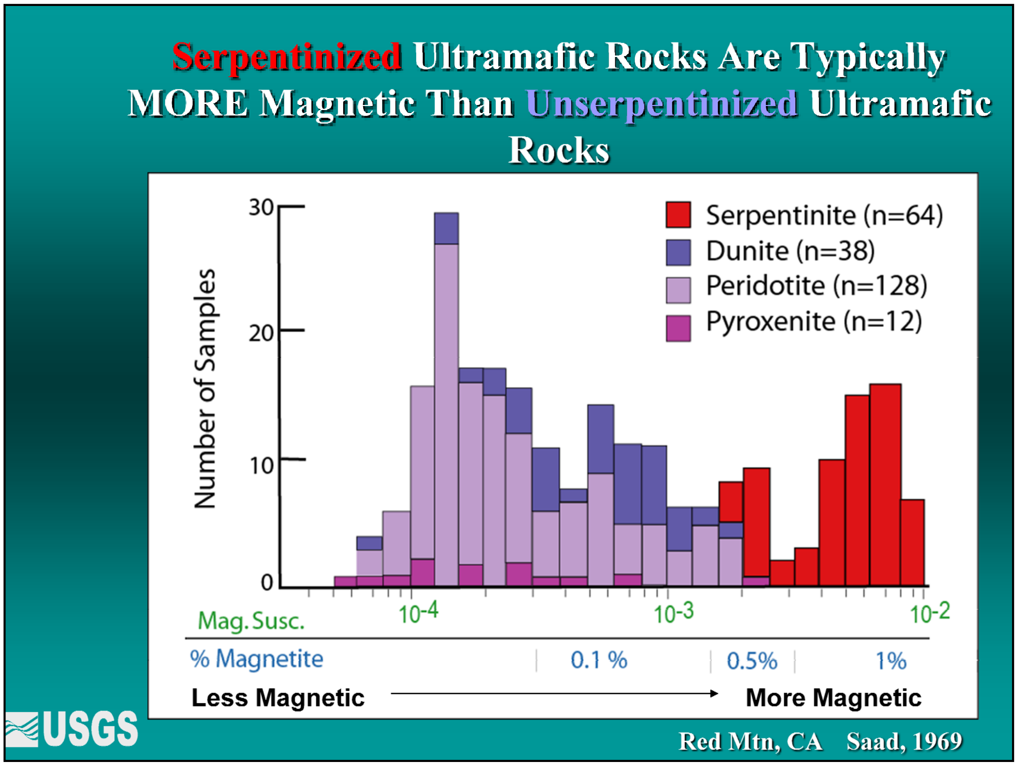


Ultramafic Rocks Are Very Magnetic

Serpentinite and peridotite rocks have some of the very highest magnetic susceptibilities in comparison with other common igneous and metamorphic rock types (Karlsen and Olesen, 1996; Clark, 1997). This fact makes them especially attractive targets for aeromagnetic surveying. Magnetic susceptibility is the physical property that relates the amount of magnetite in a rock to aeromagnetic anomalies. Also, magnetic susceptibility can be roughly equated to magnetite content as is shown on the lower part of the graph. In general, the more magnetite per volume of rock, the higher the magnetic susceptibility and the larger the amplitude of magnetic anomaly.

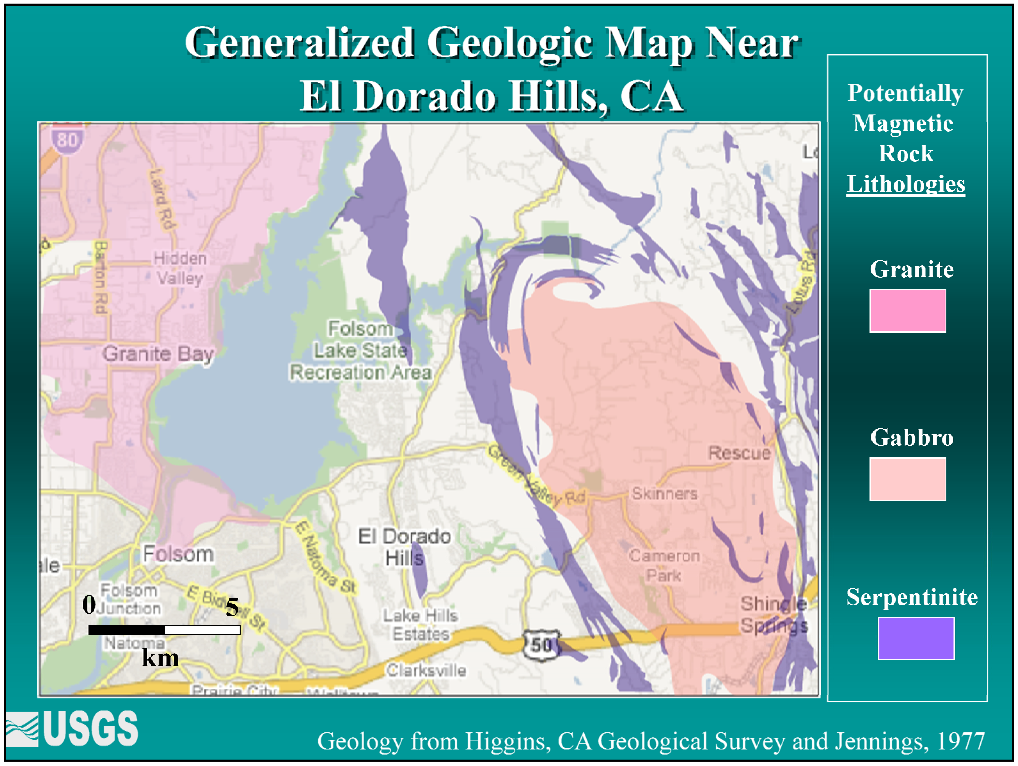
The graph above also illustrates that there is overlap in magnetic susceptibility for different rock types. This kind of information becomes important when one interprets aeromagnetic anomalies. One needs to have a solid understanding of the mineralogy and specifically of the magnetic properties related to the various lithologies that are or may be present in an aeromagnetic survey area in order to accurately interpret magnetic anomalies. For example, there is considerable overlap in typical magnetic susceptibilities of peridotites and gabbros. Therefore, these rock types will likely look similar in an aeromagnetic anomaly map, so a solid understanding of the known geology will help to properly interpret the geophysical data.

In a following slide, we will show an aeromagnetic anomaly map over an area in California containing serpentinite juxtaposed with a similarly magnetic gabbro.



Serpentinized Ultramafic Rocks Are Typically More Magnetic Than Unserpentinized Ultramafic Rocks

The transformation of a peridotite to a serpentinite markedly changes the magnetic susceptibility. The process of low-temperature serpentinization remobilizes iron to create magnetite, which gives serpentinized ultramafic rock higher magnetic susceptibilities than its unmetamorphosed counterpart. A study conducted by Saad (1969), which shows the variability of magnetic susceptibility of four ultramafic rock types that occur in proximity at Red Mountain, Calif., east of San Francisco, illustrates this effect**.** Unserpentinized ultramafic rock types that were sampled include peridotite, dunite, and pyroxenites and are shown in the purple colors. Serpentinite (red) clearly shows a shift toward higher magnetic susceptibilities and magnetite content.



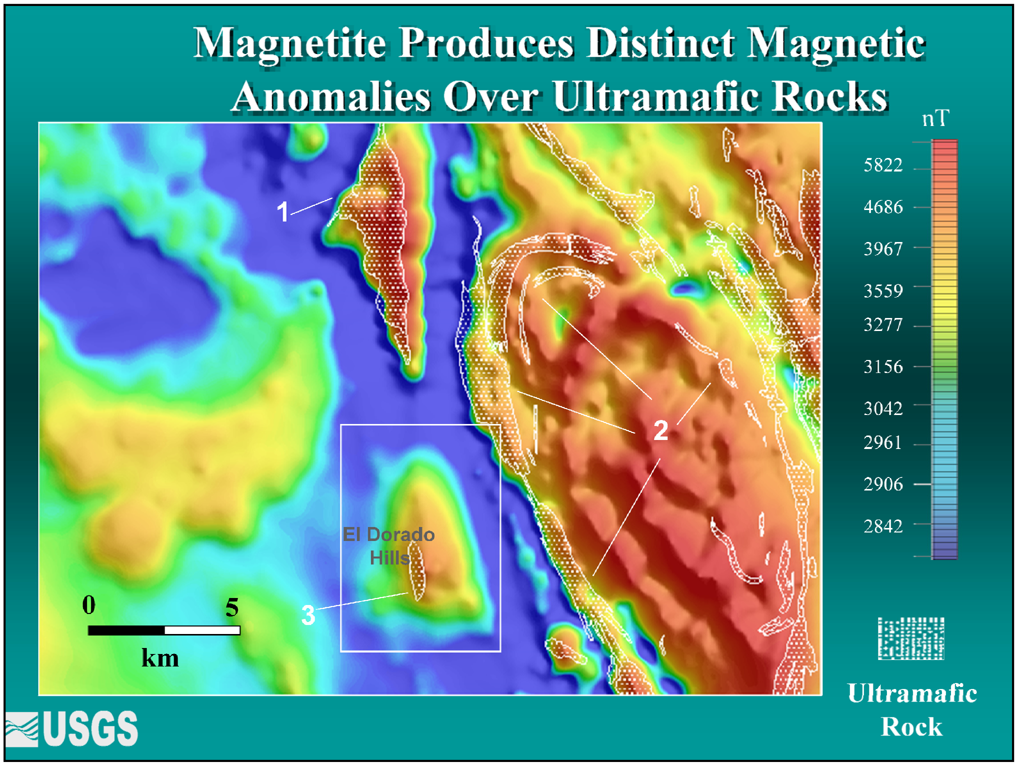
Generalized Geologic Map Near El Dorado Hills, California

To illustrate the magnetic anomaly signature of various igneous and metamorphic rock types, we look at the geology of another area in north-central California near El Dorado Hills. The area is in the foothills of the Sierra Nevada Mountains in western El Dorado County, approximately 30 miles northeast of Sacramento.

Outcrops of ultramafic serpentinite (in purple from C. Higgins, California Geological Survey, written commun., 2007), gabbroic (peach), and granitic rock (pink) are surrounded by either nonmagnetic metavolcanic rocks or Quaternary sediments (Jennings, 1977).

The ultramafic rocks are serpentinized and were most likely derived from peridotite (Churchill and others, 2000). They are part of the western Sierra Nevada metamorphic belt, which ranges in age from 160 to 300 million years old. The gabbro and serpentinite are in contact with nonmagnetic metavolcanic rocks of Mesozoic age. Outcrops of Mesozoic granite are present in the northwestern part of the map.

Some of the serpentinite outcrops have been intruded by the Pine Hill intrusive complex gabbro, which is approximately 165 million years in age (Springer, 1971). As shown in the earlier slide, gabbro and serpentinite can have similar magnetic properties and it can be challenging to distinguish between these two rock types with magnetic anomaly data. Fortunately, at least in most other parts of California, gabbro occurs in much less volume than the ultramafic rocks. The Pine Hill intrusion is one of the larger outcrops in the state.



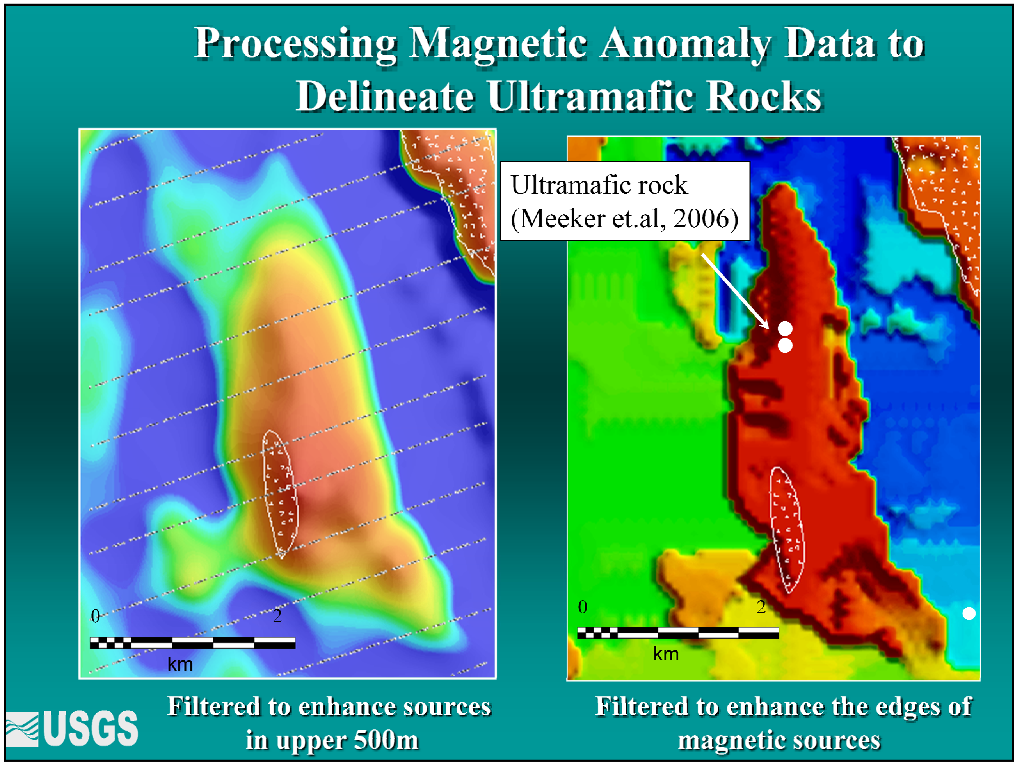
Magnetite Produces Distinct Magnetic Anomalies Over Ultramafic Rocks

This slide shows an aeromagnetic anomaly map for the area around the El Dorado Hills region. The airborne magnetic data are from part of a survey flown over the northern Sierra Foothills (U.S. Geological Survey, 2002). Data were collected along northeast-southwest-trending flight lines spaced 800 meters (m) apart and flown at an elevation of approximately 300 m above topography. The flight line data were gridded and processed to correct for anomaly shift at this magnetic latitude. This processing is called a reduction-to-the pole (RTP) filter and results in a magnetic anomaly map that has all anomalies correctly positioned over the rocks causing them.

The warmer colors in the map show the magnetic anomaly response of rocks with more magnetite. The cooler blue colors indicate rocks that have little to no magnetite. The area includes ultramafic rocks that crop out along a northwest-trending belt within the Sierra Foothills. Ultramafic rocks are serpentinized and mapped outcrops are shown in the stippled white pattern.

A close spatial association can be seen between the serpentinite outcrops and magnetic anomaly highs. Ultramafic outcrops labeled “1” and “3” are surrounded by non-magnetic metavolcanic rock at the surface that would not produce the magnetic anomaly highs that we see at locations “1” and “3.” The magnetic anomaly highs that extend beyond the mapped ultramafic rocks at locations “1” and “3” are interpreted as the magnetic expressions of shallowly buried serpentinite. Magnetic anomaly highs are also associated with the serpentinite outcrops labeled as “2.” However, these outcrops are adjacent to the Pine Hills gabbroic intrusion, a lithology that shares magnetic properties with the serpentinite. Therefore, the magnetic anomaly contrast between the gabbro and serpentinites is not as distinct as that produced at locations “1” and “3.” The anomalies associated with the serpentinite are more challenging to distinguish from the anomalies associated with the gabbro.

In the following two slides, we will illustrate how we can begin to use the magnetic anomaly data to interpret anomalies associated with serpentinitic and ultramafic rocks by starting with a less complicated anomaly located around outcrop “3.”



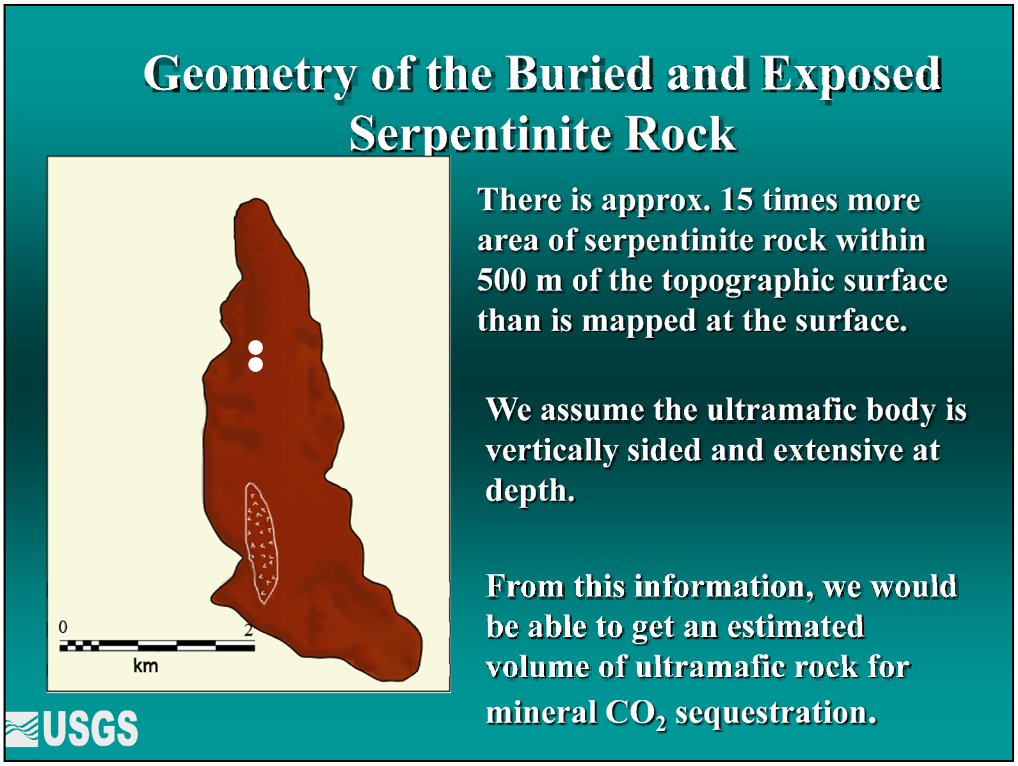
Processing Magnetic Anomaly Data to Delineate Ultramafic Rocks

The two maps displayed here show mathematical enhancements to the magnetic anomaly data over the El Dorado Hills area. The enhancements serve to improve the anomaly resolution associated with the shallowly buried extensions of the outcrop and to sharpen the outer (covered) edges of the ultramafic rock that is causing the magnetic anomaly. The northeast-trending dashed gray lines on the map on the left show the tracks of the original flight lines. Magnetic anomaly measurements were taken approximately every 30 m along the flight lines. The result is a map of the magnetic field that is well constrained so that the anomaly shape, amplitude, and size can be accurately estimated using filters such as we have used here.

Specifically, the map on the left shows the result of applying a filter to the gridded data (Phillips, 1997) that enhances magnetic anomalies caused from the magnetic properties of rocks located within the upper few hundred meters of the topographic surface. Longer wavelength anomalies associated with magnetic properties of rocks deeper than a few hundred meters have been removed.

Once the anomalies related to shallow sources were enhanced, the data were “terraced.” The map on the right shows a “terrace” map of the magnetic anomaly (Cordell and McCafferty, 1989). The terrace process transforms smoothly varying magnetic anomaly maps into maps that looks similar to a geologic map, with sources for the anomalies now having sharp, well defined boundaries in plan view.

Both enhancements provide evidence of more serpentinite at shallow depths. In addition, there is geologic evidence. Approximately 1.4 km north of the mapped outcrop, Meeker and others (2006) analyzed serpentinite rock collected at the two sites marked with white circles on the terrace map.



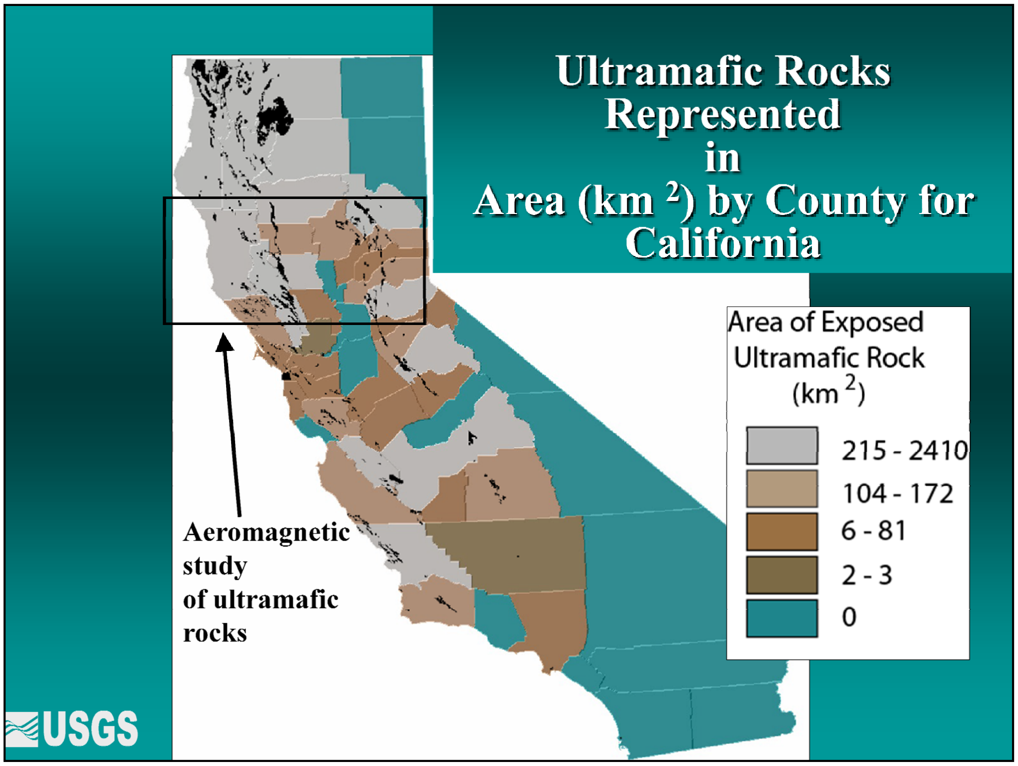
Geometry of the Buried and Exposed Ultramafic Rock

The enhancements to the magnetic anomaly data now allow for an interpretation of the anomaly related to the size, shape, and geometry of the serpentinite body. A summary of the interpretation is provided above. The next step would be to take the interpretation to a model in three-dimensions by using a combination of the geology, magnetic susceptibilities, and flight line data that cross the anomaly.

Does Magnetite Variation Within Ultramafic Rocks Relate to Magnesium Content?

The short answer to this question is…maybe. The study of how magnetite varies with magnesium is a new research direction being pursued by the USGS. Research on ultramafic rocks and soils in the Coast Range and Sierra Foothills have determined that there are positive associations between the presence of magnetite and other heavy metals, which include chromium and nickel (McCafferty and Van Gosen, in press). Magnetic anomaly variations over ultramafic rocks also show coincidence with the heavy metals.

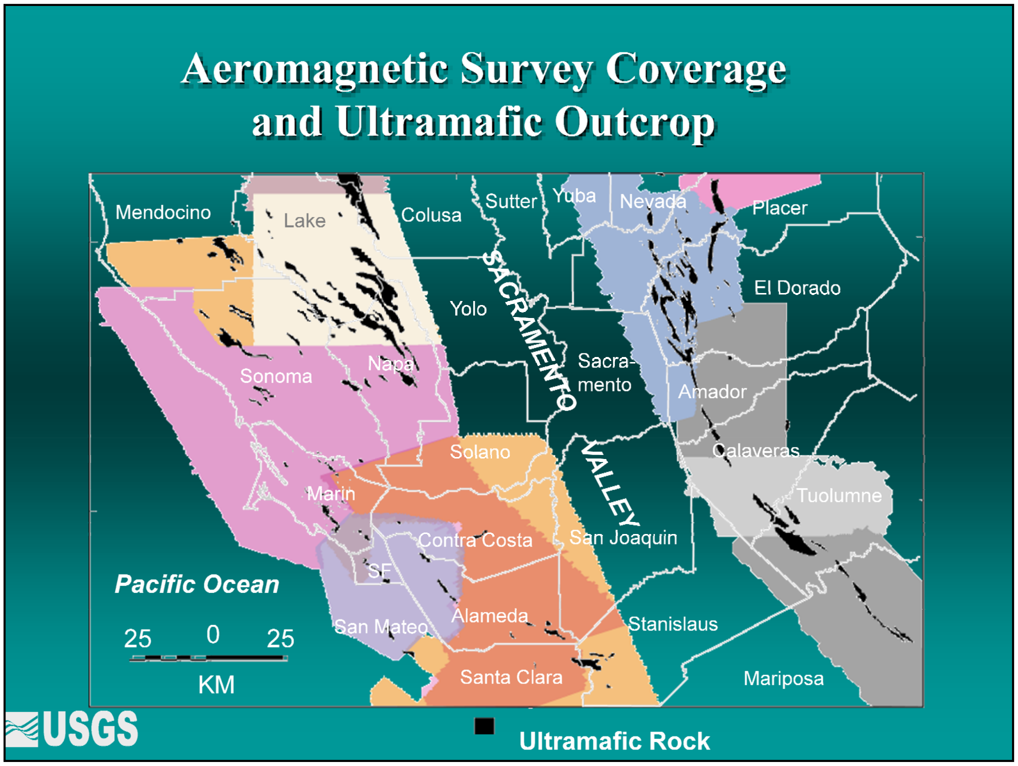
The focus of the next few slides is to illustrate significant magnetic anomaly differences from one ultramafic rock belt to another as well as differences within individual outcrops.



Area of Ultramafic Rocks by County, California

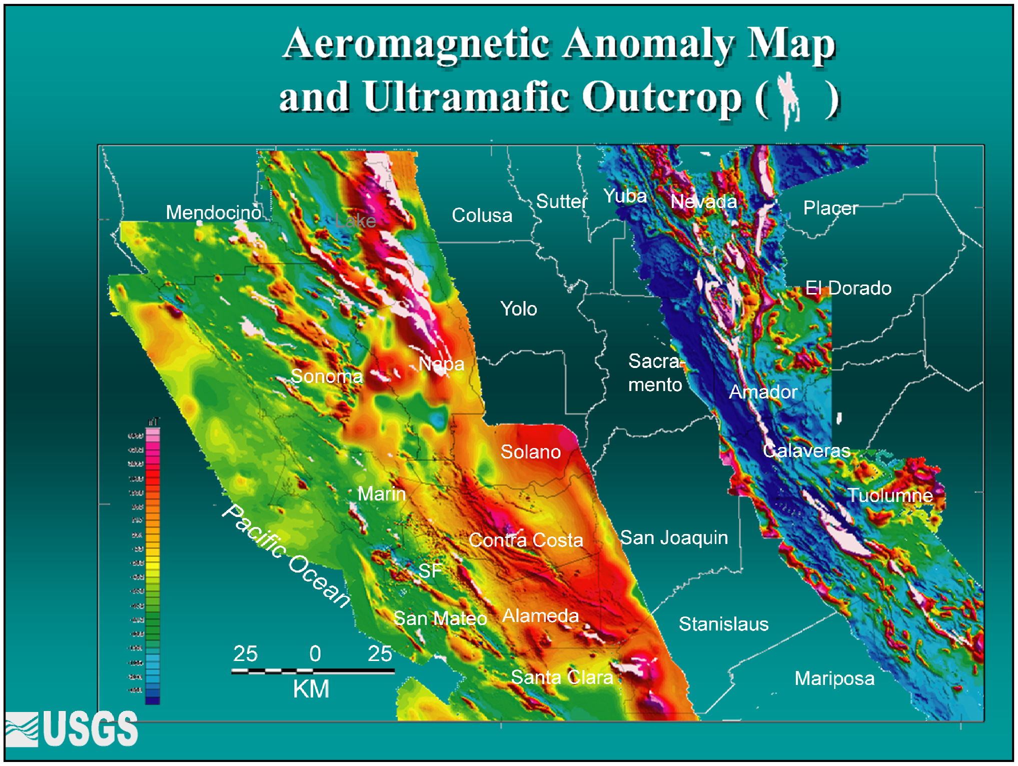
Data from the ultramafic rock map of the conterminous United States were extracted for the State of California and color coded to display the area of exposed ultramafic rock in square kilometers by county. Counties in gray have the largest area of exposed ultramafic rock while counties in green have no ultramafic rock mapped at the surface. California contains the highest amount of ultramafic rock in the conterminous United States. Forty-two of 58 counties contain some exposed ultramafic rock.

The outlined area in north-central California locates a USGS multidisciplinary study of ultramafic rocks within two belts: the Coast Range and the Sierra Nevada foothills. We use data and results from this study to illustrate the magnetic anomaly variation between the two belts and within individual ultramafic outcrops.



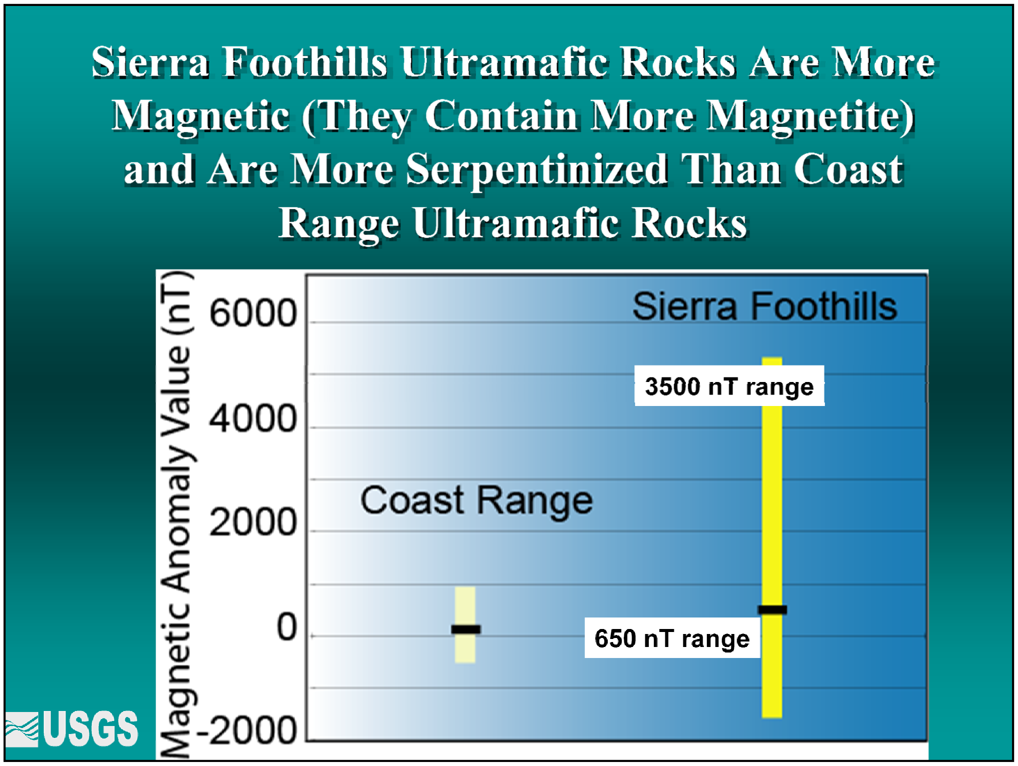
Aeromagnetic Survey Coverage and Ultramafic Outcrop

Eleven aeromagnetic surveys were compiled to obtain a composite view of the magnetic anomaly field over rocks in both ultramafic rock belts. Airborne surveys in the U.S. tend to be flown in a piecemeal fashion as shown here. They are typically designed to address specific geologic problems, thus they have varying flight specifications and are of varying quality. Surveys in colors other than gray are more recently flown and data are available digitally, meaning that the original observations along the flight lines are preserved. Surveys in gray are older (flown pre-1975) and magnetic anomaly contours have been digitized from paper maps to replicate the anomaly field for these areas. Most of the surveys were flown at an altitude of 305 m above ground and flight-line spacing ranges from 530 to 1600 m. Although magnetic surveys exist over the Sacramento Valley, they are not included in this study due to the lack of surface exposure of ultramafic rocks and the poor quality of the magnetic surveys.



Aeromagnetic Anomaly Map and Ultramafic Outcrops

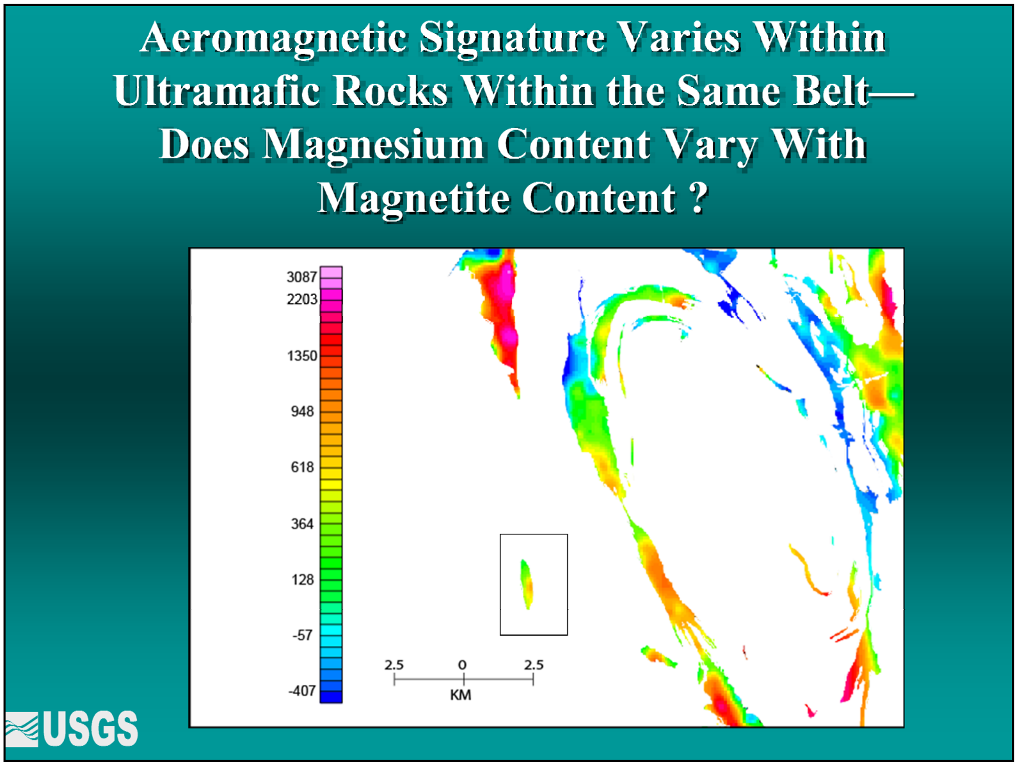
This is the map resulting from merging the magnetic data from the 11 different airborne surveys. Known ultramafic rocks are shown in white over the anomaly field colors. Magnetic anomaly maps emphasize variations in the local magnetic field caused by changes in the concentrations of various magnetic minerals, primarily magnetite. We can see that, on a regional scale, most of the ultramafic rocks coincide with linear magnetic anomaly highs. The anomalies over the Coast Range ultramafic rocks, however, have distinct differences in amplitude in comparison with anomalies over the ultramafic rocks in the Sierra Foothills.



Sierra Foothills Ultramafic Rocks Are More Magnetic and More Serpentinized Than Coast Range Ultramafic Rocks

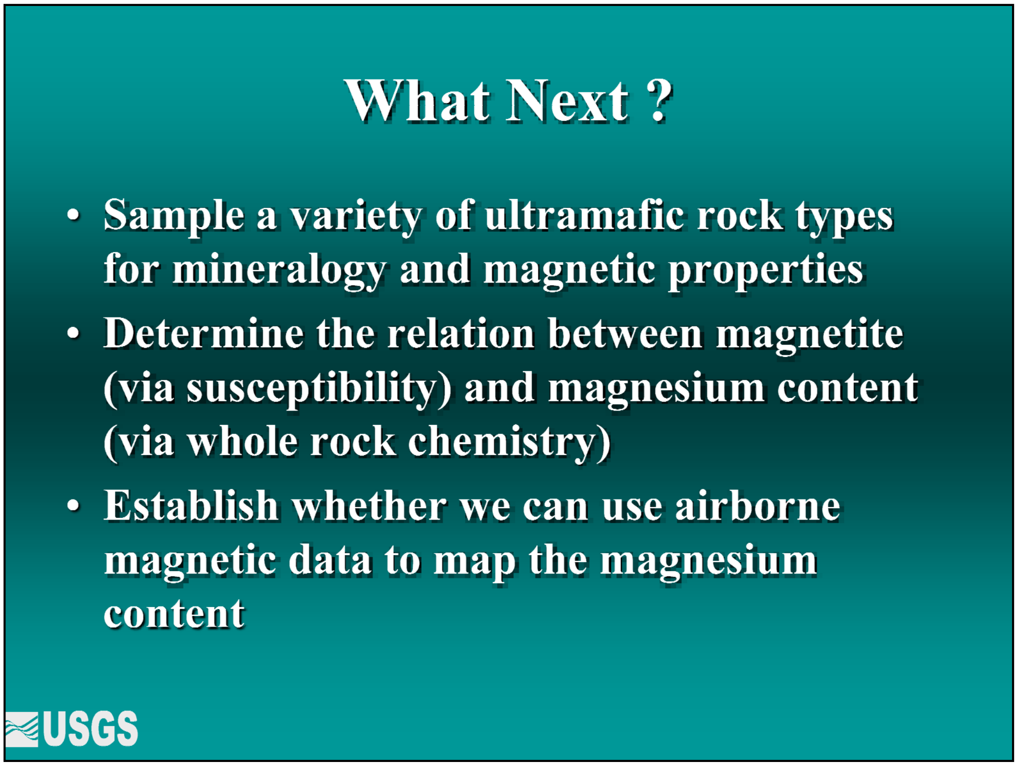
We calculated the magnetic anomaly values that occur over ultramafic outcrops in the Coast Range and the Sierra Foothills. Results of this straightforward analysis illustrate the distinct differences in magnetic anomaly magnitude between the two ultramafic rock belts. Ultramafic rocks in the Coast Range have a much smaller range of magnetic values compared to the range of magnetic values that occur over the Sierra Foothills ultramafic rocks.

We interpret the differences in magnetic properties between the two ultramafic rock belts as primarily due to variations in magnetite content. The Sierra Foothills ultramafic rocks are more serpentinized than the Coast Range. Because serpentinization produces magnetite, the Sierra Foothills ultramafic rocks would be expected to contain more magnetite and therefore have high magnetic anomaly amplitudes. In the context of mineral CO_2 sequestration, it becomes important to understand how the serpentinization process affects the magnesium content. Are less serpentinized rocks more magnesium rich? Does serpentinization favor the concentration or loss of magnesium? Is the serpentinization process a closed system so that magnesium content does not change with metamorphism?



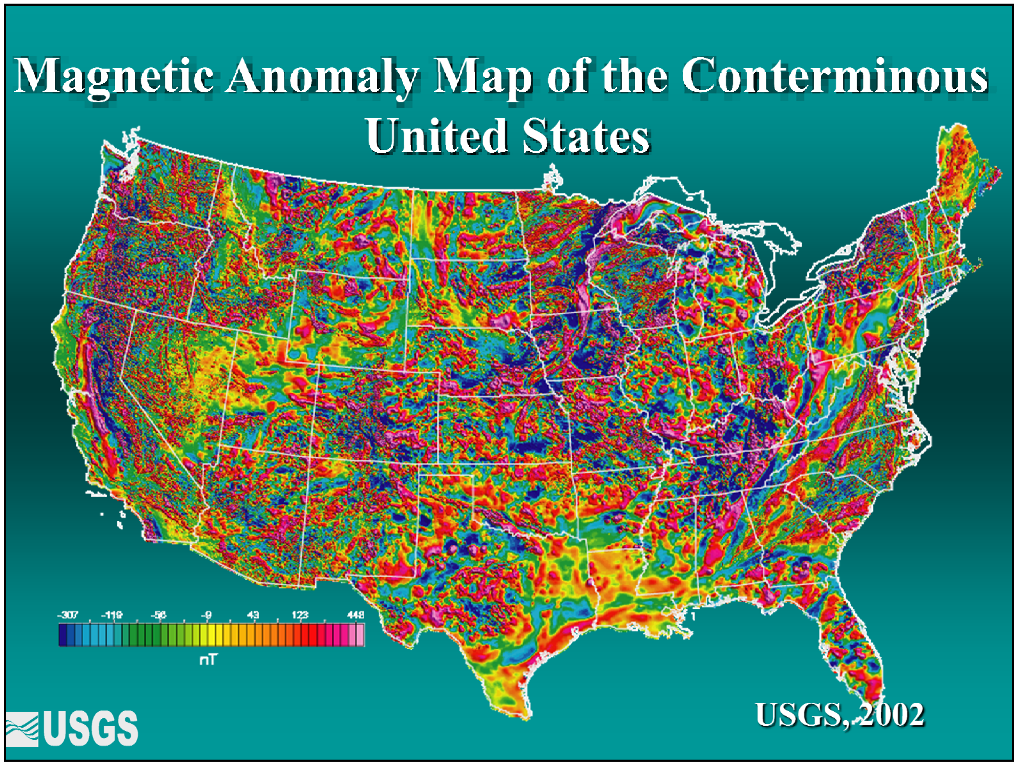
Aeromagnetic Signature Varies Within Ultramafic Rocks Within the Same Belt—Does Magnesium Content Vary With Magnetite Content?

Finally, we present the same magnetic anomaly map over the area around the El Dorado Hills region and the magnetic field mapped for only the ultramafic outcrops. The map illustrates the extreme magnetic anomaly variation within individual outcrops, indicating that magnetite content varies from one part of the outcrop to the next. If a relationship can be established between variation in magnetite content and in magnesium content, this type of map could be used to further refine a mineral resource assessment of material available for an industrial application of mineral CO_2 sequestration, or, it could be used to determine best injection sites for in-situ storage of CO_2.



What Next?

The points described above provide focus for future research efforts. Geologic and geophysical efforts will complement the chemical engineering research necessary to make mineral CO_2 sequestration a viable greenhouse gas mitigation process.



Magnetic Anomaly Map of the Conterminous United States

This national-scale aeromagnetic anomaly map of the United States (U.S. Geological Survey, 2002) shows that aeromagnetic data exist for the ultramafic rocks mapped in the conterminous United States. Similar studies to characterize the geometry and mineralogy of ultramafic rocks through magnetic anomaly interpretation could occur in any of the 29 States where ultramafic rocks have been mapped.

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