An assessment of global resources of rocks as suitable raw materials for carbon capture and storage by mineralisation

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KEYWORDS: Ultramafic rocks; Carbon dioxide sequestration by mineralization; Serpentine; Olivine.

Abstract

Carbon capture and storage by mineralisation (CCSM) is a method proposed for capturing CO_2 by reacting it with magnesium in ultramafic rocks to form carbonate minerals and silica. Large quantities of magnesium silicate rocks are required for this process and to demonstrate the feasibility, and adequately plan for the development and supply of mineral resources, their locations and quantities must be known. This study attempts to globally define the spatial extent and quantity of resources that could be used for the CCSM processes and to asses, if based on resources, this could be a viable, widely applicable CO_2 sequestration process. It has been estimated that around 90 teratonnes of material is available. This is sufficient to capture global CO_2 emissions for over 700 years at current levels of output and highlights the enormous resource. Even if only a small part is utilised, it could make a significant impact on CO_2 reduction. The majority of the resource is contained within ophiolitic rocks. The study further attempts to split CCSM resources into altered (serpentine-rich rocks) and unaltered (olivine-rich rocks) due to the different processing requirements for these rock types. CCSM is likely to be of most use in areas with no access to underground geological CO_2 storage or for small operations where underground storage is not practical. This study demonstrates that substantial resources are available and their supply is unlikely to be a constraint.

1. Introduction

Carbon capture and storage (CCS), is a process considered vital for controlling the rise in anthropogenic CO_2 emissions and, thereby mitigating, climate change. This is largely focused on geological sequestration by injection of CO_2 into porous sedimentary rocks where the CO_2 is held in pore spaces or dissolved in intragranular fluids. Rock sequences with sufficient storage capacity and minimal potential for leakage are typically contained within sedimentary basins, the global distribution of which, are shown on Figure 1. This demonstrates that large areas of the globe do not have access to geological storage. CCSM is a potential method of CO_2 capture and storage that might be particularly applicable in those places that lack nearby sedimentary basins suitable for CO_2 injection. The CCSM process has received less scientific research and technological development than geological storage, thus it is difficult to anticipate the relative cost and efficiency of the two processes in the future. It is possible that CCSM could be a complementary CO_2 capture and storage technology and may provide a viable alternative for countries without suitable opportunities for geological storage or for smaller local CO_2 sequestration. However, if the CCSM technology develops to a point, where it imposes a similar cost to underground storage, it could be much more widely applicable, either in parallel or as an alternative. The main advantage of CCSM is that the CO_2 is permanently captured in solid minerals that are stable for millions of years, with no possibility of leakage. This in turn makes the technology less risky and more acceptable to the general public.

The principle of CCSM, the process by which CO_2 reacts with divalent metal cations (mainly magnesium and calcium) to form carbonate minerals, was first proposed by Seifritz (1990). The basis of the process is the reaction of magnesium and calcium silicate feedstock minerals with CO_2 to form respective carbonate minerals.

Large quantities of feedstock material, rich in divalent cations, are required for the carbonation reaction as 2-4 tonnes of rock are required for each tonne of CO_2 stored. The only elements present in sufficient quantities that form stable insoluble carbonates are magnesium and calcium. Most of the calcium, near the earth's surface, is already in the form of carbonate, in limestone, hence the main candidate as a source of cations is magnesium, that is largely present in silicate minerals. Some calcium might be sourced from industrial waste materials (Renforth *et al*., 2011, Sanna *et al.,* 2012), but the amounts available are relatively small and could only supply local CO_2 capture plants. To achieve significant CO_2 capture on a global scale, feed material must come from naturally occurring Mg-rich silicate rocks, known as ultramafic rocks.

For CCSM to be considered as a viable option for carbon sequestration on a large scale the location, volumes and properties of resources suitable for feedstock material must be known. Several regional studies on the distribution of these resources and matching known resource areas to CO_2 emitters have been undertaken (Picot *et al.,* 2011, Krevor *et al.,* 2009, Voormeij and Simandl, 2004, Mani *et al.,* 2008, Bodénan *et al.,* 2006 and Renforth 2012). However, to date, no study on quantification of the potential resources available for CCSM on a global scale has been performed. Information on global resources will increase confidence as to the feasibility of this method of capturing CO_2 emissions and will assure the industry developing the technology that sufficient resources exist to make the process viable.

This study estimates the total global resources of land-based ultramafic rocks at or near the earth's surface that are suitable for CCSM feedstock material. Information from regional and global geological maps were combined with assumptions regarding the spatial distribution, typical composition and bulk properties of the resources, based on type localities and published literature. These assumptions are detailed in the methodology section. This information will allow industry and policy makers to make informed decisions regarding the viability and suitability of CCSM as a method of carbon capture and as an alternative to geological storage. Also, by mapping the global distribution of CCSM feedstock material further spatial analysis was possible, such as the relationship of resources to areas with potential for, or lack of, geological storage and the relationship of resources to CO_2 emitters. This is of significant importance when considering the large quantity of feedstock materials required and the associated environmental / economic cost of transport and disposal of material (although this may be offset if a commercial use is found for end-products). The total resource estimated in this study is the available geological resource calculated mostly using generalised information from published literature and geological mapping. The method employed could be used for country wide or regional estimates where more detailed and specific information is available and economic and environmental aspects can be factored in; but this is not realistic on a global scale.

1.1 Fundamentals of the CCSM process

The mineral transformations involved in CCSM occur spontaneously in nature (Seifritz, 1990). Methods to promote and enhance natural weathering have been proposed, e.g. studies by Schulling and Krijgsman (2006) and Renforth (2012). Reactions under the conditions at the earth's surface are relatively slow and the capacity for natural CO_2 sequestration is limited, therefore a faster engineered process must be used to achieve a major impact. One proposed method, currently in the early stages of testing, involves the pumping of CO_2-rich solutions down boreholes in to rock formations that contain silicate minerals with the requisite cations that are expected to undergo carbonation reactions. This is referred to as *in situ* CCSM and has been described by Kelemen and Matter (2009) and extensively studied by researches of CarbFix pilot project in Iceland (Gislason *et al*., 2010, Matter *et al.,* 2009 and references therein).

The main CCSM method proposed, that has also seen the most research, is for feed materials, commonly silicates, to be processed in an industrial plant. This is referred to as *ex situ* mineralisation and involves significant thermo-chemo-mechanical pre-treatment of the resource material to strip out the cations and make them available for combination with CO_2 to form carbonate minerals (Lackner *et al.,* 1995). A range of methods have been proposed and tested at the lab scale (see Sanna *et al*., 2014a for review) involving single and multistage processes, aqueous and gas reactions. For an industrial process a throughput time of a few hours might be necessary. A process that has had substantial development and success involves acid leaching as a means of material pre-treatment (Sanna *et al.,* 2014b) and resources for this type of process are the main focus of this study.

The previous section showed that the largest concentrations of requisite cations (20-30wt% Mg) are present in the magnesium silicate minerals found in ultramafic rocks. The ultramafic rocks are defined by their abundance (>90%) of mafic (dark) minerals with high magnesium and concomitant low silica contents (Le Maitre *et al*., 2002). These rocks, composed almost entirely of mafic minerals, constitute the predominant resource for CCSM.

The main magnesium-rich silicate minerals contained within ultramafic rocks include:

- Olivine, commonly forsterite, chemical formula Mg_2SiO_4 (Mg content ca. 30%).
- Orthopyroxene, commonly enstatite, chemical formula $MgSiO_3$ (Mg content ca. 21%).
- Clinopyroxene, commonly diopside, chemical formula $(Mg,Ca)SiO_3$ (Mg+Ca content ca. 25%).
- Serpentine group, commonly lizardite, chemical formula $Mg_3Si_2O_5(OH)_4$ (Mg content 25%)

- Amphibole group, commonly tremolite, chemical formula $Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$ (Mg+Ca content 25%)
- Brucite, chemical formula $Mg(OH)_2$ (Mg content 42%)

Although all ultramafic rocks contain a large proportion of magnesium silicate minerals, these minerals can occur in a wide variety of mineral combinations, not all of which may be suitable for CCSM. The original mineral assemblages that are characteristic of fresh, unaltered, ultramafic rocks, may be altered by geological processes during or subsequent to the rocks emplacement. This is most commonly associated with hydration of originally anhydrous minerals to form their hydrated equivalents and other phases. Degrees of hydration vary greatly and can reach as much as 100%, forming new hydrous magnesium silicate minerals, such as serpentine and brucite from olivine or amphibole from pyroxene.

A range of laboratory experiments have been carried out to investigate the ease of liberation of cations from various rocks and minerals (O'Connor *et al.,* 2005, Styles *et al.,* 2014). The ease and efficiency of cation leaching (reactivity) define the suitability of a feed material for the CCSM process. Laboratory experiments have shown that olivine has good leaching properties but pyroxenes are poor. Their hydrated equivalents behave in a similar way and serpentine is generally good and amphibole poor. The exception is antigorite, a variety of serpentine that has poor leaching properties (Sanna *et al.,* 2014b, Styles *et al.,* 2014 and references therein). Consequently, rocks rich in pyroxene, amphibole and antigorite are not regarded as suitable feedstock material for an *ex situ* acid leach process (considered in this study) but could possibly be used if an alternative efficient Mg-extraction process was identified. Brucite is a common, but normally only a very minor, constituent of serpentinites. However, as it is a hydroxide rather than a silicate, with a high Mg content and releases the cations very readily, its presence is beneficial to the overall leaching properties of the rock.

The carbonation reactions of olivine and serpentine are as follows:

Olivine (forsterite): $Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$

Serpentine (lizardite): $Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$

Although the carbonation reactions for both these magnesium-rich minerals are broadly similar, their different physical properties and structures mean that they might need to be treated separately. Some CCSM processes can be optimised for olivine or serpentine but are not often applicable to both (Styles *et al.,* 2014). If olivine and serpentine occur in different rock types, in different areas they can easily be mined to extract a particular type and direct the products to a specific processing route. However, if they are present in the same rock, they are usually inter-grown on a fine (<cm) scale making their separation uneconomic if not impossible. Therefore, the technological process either has to be able to cope with mixed mineral feed, or, if one component is not effectively utilised, the risk of reducing the overall efficiency of the process will be significantly increased.

Some rocks contain relatively high magnesium and calcium contents and occur abundantly in nature but are less suitable for *ex situ* CCSM processes. For example basalt, although abundant, does not contain as much magnesium and calcium as ultramafic rocks and is not as reactive in the *ex situ* acid leach processes that are currently being developed. Experiments by O'Connor *et al.,* (2005) and Styles *et al*., (2014) show that the main constituent minerals, clinopyroxene ($CaMgSi_2O_6$) and plagioclase feldspar ($CaAlSi_3O_8$), are much less reactive than olivine and serpentine. This means that basalt is less suitable for an *ex situ* process where speed of reaction is essential. Slower reaction kinetics may be acceptable in an *in situ* situation such as that being investigated by the CarbFix project in Iceland.

Calcium silicates can potentially be used, however they are rare in nature and only occur in significant quantities in waste materials, such as recycled concrete and steel slags (Sanna *et al.,* 2012 and references therein). The mineral wollastonite ($CaSiO_3$) has good reactivity (O'Connor *et al.,* 2005) but only low tonnages are available and its prices can be as high as > US$100 per tonne (Verta, 2013), as it is used for industrial processes, particularly in the production of ceramics. Consequently, on the basis of low abundance and high cost, wollastonite has not been considered as a potential resource in this study.

To constitute a resource a suitable feedstock material needs to contain a high proportion of minerals that are reactive in the CCSM process and be abundant. Future technological advances in chemical processing, changing economics of the process, allied to increases in the carbon price under carbon trading schemes means that CCSM may become comparable in cost to underground CCS. Development of *in situ* CCSM techniques may make it is possible that basaltic rocks or rocks high in feldspar may become more prospective CCSM resources in the future. Another implication for potential resources is that the in situ method can only be carried out at the location of the rock body and the CO_2 must be taken to the disposal site, making co-location with CO_2 emitters important. In contrast, the ex situ method could involve transport of CO_2 or large volumes of rock to a suitable site. In this instance, co-location is less important but transport costs are a critical factor.

2. Methodology for resource volume calculation

2.1 Outline

The methodology used to calculate CCSM resources is similar to other large-scale resource reviews, for example MacDonald *et al.,* 2012, in that resource quantity is calculated by a simple multiplication of estimated area and thickness and this figure appropriately modified using known properties of the rock types in question, estimated from analysis of published literature. On a global scale many assumptions must be made on the 'typical' properties of rock types, but as studies become smaller scale and more focused, better, more-locality specific data can be used and improve confidence in results generated.

2.2 Types of ultramafic rocks

Ultramafic rocks occur in a variety of geological settings and have different proportions of constituent minerals. These need to be considered separately when calculating resource volumes. Table 1 outlines the broad resource types and associated geological settings this study has used to quantify resources of CCSM feedstock materials.

In Table 1, Alaskan-type deposits are treated as a separate category. However, they have a restricted global distribution compared to the other ultramafic rock types and, in terms of CCSM feedstock resources, are broadly similar to ophiolites in some respects and layered igneous intrusions in others. Therefore, in the following analysis, Alaskan-type deposits are classified depending on which category they best match. For example, the Alaskan-type deposits of the Urals are considered as ophiolites due to their structure and high degree of alteration and Alaskan-type deposits in Alaska and British Columbia are considered as layered igneous intrusions due to their lower degree of alteration, dunite core, high levels of magmatic differentiation and association with platinum group minerals.

2.3 Layered igneous intrusions

The datasets used to define the resources in the layered igneous intrusions category consist of discrete points with an average spatial extent assigned to them. Point data are the best available information as no comprehensive dataset showing the spatial extent of individual layered igneous intrusions with global coverage exists in a readily available format.

Two datasets containing information on the global distribution of layered igneous intrusions were used and the results compared to validate the methodology. They were platinum group mineral (PGM) resources complied by Natural Resources Canada (NRCAN) (2012) and a dataset containing information on the global distribution of major deposits of PGMs compiled by the British Geological Survey (BGS) (published in Gunn, 2014). The presence of PGMs was used as a proxy for the location of layered igneous intrusions as they are the main location of PGM ore bodies. A similar approach was taken by Picot *et al.*, (2011), in their study of worldwide potential for mineral carbonation, using existing PGM mines as locations for potential CCSM feedstock resources. However, this study only considered existing mine sites rather than total global resources. For both datasets only PGM occurrences that had associations with magmatic or lateritic deposits overlying magmatic deposits were selected thereby eliminating non-magmatic PGM occurrences with no potential for ultramafic rocks. These two datasets have significant differences. The NRCAN dataset is comprehensive and global. It contains 1040 records of magmatic- or laterite-associated PGM occurrences. The BGS database contains only 47 records of major PGM occurrences associated with magmatic deposits, many of which host established prospects or mines. Both datasets contain caveats related to their use. Whilst the Natural Resources Canada dataset is much more comprehensive than the BGS dataset it is not selective and so contains many occurrences linked to minor intrusions that may be too small or not contain significant quantities of ultramafic rocks to be suitable for CCSM feedstock material. The BGS dataset captures all the major layered igneous intrusions with large volumes of ultramafic rocks (up to 100 000 km^3) that are deemed the most prospective for CCSM. However, smaller-scale intrusions (less than 100 km^3), which still may have resource potential, are not included. The distribution of these intrusions for the BGS and NRCAN datasets is shown on Figure 3.

2.3.1 Assumptions required for resource volume calculation

For volume calculation the spatial extent of layered igneous intrusions needs to be estimated from the point information in the databases. Two figures for the ‘typical’ size of a layered igneous intrusion were estimated, one for the BGS dataset and one for the NRCAN dataset. For the NRCAN dataset, a figure of 100 km^2 was used for areal extent. This was based on the areal extent of the Skaergaard layered igneous complex, which is 100 km^2 (McBirney, 1996). For the BGS dataset, an average figure of 2000 km^2 was taken to represent the much larger intrusions included in this dataset, for example Muskox, Great Dyke, Rincón del Tigre and Stillwater, which all have areas between 1000 and 3000 km^2 (Table 2).

Not all rocks within these layered igneous intrusions will be suitable as a feedstock material for CCSM as they do not comprise 100% ultramafic rocks and not all ultramafic minerals are equally reactive during the CCSM processes. Based on information about both the surface outcrop and the internal stratigraphy of some typical major intrusions, it was assumed that 15% of a layered intrusion may be a suitable resource. This figure was derived by the review of well-studied intrusions (sources are listed in Table 2). The key information used is collated in Table 2 and a comparison of the internal stratigraphy of selected major intrusions is shown in Figure 2.

Although a figure of 15% was considered representative, these deposits are varied in nature with the range encompassing the Great Dyke, Zimbabwe, that has a surface outcrop consisting of 70–80% ultramafic rocks (Wilson, 1996) to the Bushveld Complex, one of the largest layered igneous intrusions in the world, having a surface outcrop with less than 10% ultramafic rocks (Cawthorn *et al.,* 2002).

It was assumed, based on the type sections, that the ultramafic rocks within layered igneous intrusions are forsteritic olivine peridotites and harzburgites with a low degree of serpentinisation. Where information has been available (generally the larger intrusions) ultramafic rocks that are not suitable for CCSM feedstock materials, such as orthopyroxenite and clinopyroxenite (due to the low olivine content and lower leachablity of pyroxene), have been discounted. Many layered igneous intrusions have been serpentinised to some degree. However, this is difficult to estimate on a global scale. Typically, the large layered igneous intrusions are mostly unaltered and smaller intrusions are more susceptible to alteration as the peripheral alteration envelope will be proportionately larger relative to the total mass of the intrusion. Little alteration is recorded at major intrusions such as Stillwater, Duluth and the Bushveld Complex (McCallum, 1996; Miller and Ripley, 1996 Eales and Cawthorn, 1996). Serpentinisation is commonest at the boundaries of intrusions and along fault and shear zones, where fluids have circulated. For example, dunite from the Great Dyke, Zimbabwe is 100% serpentinised at the surface but the degree of serpentinisation decreases significantly with depth (Wilson, 1996) or the Twin Sisters Dunite, USA, which has a serpentinised zone up to 700 m thick around an unaltered dunite core (Ragan, 1967). As a result serpentinisation is deemed to be insignificant at depth in the majority of layered igneous intrusions and, therefore, for calculation purposes all rocks are considered as unaltered.

The mass of ultramafic rocks contained within layered igneous intrusions was calculated based on the densities of the most common constituent ultramafic rock types, such as peridotite and pyroxenite, a density of 3.2g/cm^3 was used.

2.4 Ophiolites

Ophiolites are fragments of former ocean crust that have been obducted during the collision of tectonic plates. They consist of an upper part composed of crustal mafic rocks and a lower part of mantle derived ultramafic rocks that can be several kilometres in thickness. The global extent of ophiolites is shown in Figure 4, which was compiled from Asch (2005), Krevor *et al.,* (2009), Voormeij and Simandl (2004) and Exxon Production Research Company and The American Association of Petroleum Geologists (1985) (Table 3).

Ophiolites occur in a variety of different settings, which in turn can affect their potential for CCSM feedstock material. Therefore, different assumptions have been made for European and Asian Tethyan ophiolites, ophiolites from the rest of the World and ophiolitic rocks of the Urals.

Characteristics of ophiolites from these settings have been compiled in Table 4, and used to make assumptions regarding typical attributes.

2.4.1 Assumptions required for resource volume calculation

Where possible, only the ultramafic component of ophiolites has been included in the calculation. However, this refinement was not always possible due the resolution of some data sets and the complexity of tectonic settings in which ophiolite complexes are found. As a result assumptions have been made regarding the proportion of the ultramafic component. For Tethyan ophiolites, a value of 45% was used to represent the volume percent of the proportion of ultramafic rocks, taken from the average composition for type sections (Coleman 1971, Robinson *et al.,* 2003, Dilek and Furnes 2009, Hawkins 2003).

For USA and British Columbian ophiolites, a value of 50% was used, as the proportions of mantle to crustal rocks are generally higher (Table 4). Some Alaskan-type intrusions (e.g. those of the Urals), although technically not ophiolites, have been considered in this category as they occur in similar tectonic settings. For ophiolites of the rest of the world a value of 40% was used based on the average composition of representative sections (Coleman 1971, Hawkins 2003, Komor *et al.,* 1985, Ulrich *et al.,* 2010 and Hopson *et al.,* 2008) (Table 4).

For ophiolites, it was assumed that all ultramafic rocks could constitute a feedstock for CCSM processes as the proportion of unreactive pyroxene-rich rocks is generally low. Therefore these figures represent maximum values as any dilution due to the presence of other minerals (e.g. pyroxene, amphibole and feldspar) has not been factored in. Quantitative data about the proportions of rock types is generally not available on a global scale.

This study has attempted to calculate an average degree of serpentinisation for ophiolite rocks, despite the problems due to their diverse and varied nature. Across the global spectrum of ophiolite compositions the degree of serpentinisation can range from 0 to 100%. For European Tethyan ophiolites a value of 50% has been taken based on reported values from typical ophiolites (Coleman 1971, Robinson 2003, Dilek and Furnes 2009 and Hawkins 2003) (Table 4). The same value has been used for rest of the world ophiolites. This most likely represents a minimum value. A value of 80% is used for ophiolites of the USA and British Columbia, based on Table 4, as these ophiolites are generally older and more altered than Tethyan ophiolites. No attempt has been made to calculate the degree of serpentinisation for the ultramafic rocks of the Urals as serpentinisation is not thought to be significant for these large dunite bodies (Zohan, 2002).

There are three common members of the serpentine mineral group: lizardite, chrysotile and antigorite and they have different properties with regards to CCSM processes. The type of serpentine will depend largely on the temperature of formation. Lizardite and chrysotile were formed at lower temperatures, have similar properties, and are the most suitable for CCSM feedstock material. They are particularly associated with the younger ophiolites that have been subjected to fewer metamorphic events, possibly only the emplacement event, and cooler conditions, for example ophiolites of Oman-UAE, New Caledonia and Papua (Nicolas and Boudier, 2003) or European Tethyan ophiolites (Onen, 2003). The serpentine type antigorite is much less reactive (Sanna *et al.* 2014b, Styles *et al.,*2014) and less suitable for CCSM. However, antigorite, formed at higher temperatures, is only reported from the small number of ophiolites that have been affected by moderate grade regional metamorphism, often subsequent to obduction. An example is the ophiolites of Vermont which, although heavily serpentinised, have undergone regional metamorphism and contain only antigorite (Jahns, 1967). However, as few publications contain information about the proportions of the specific type of serpentine present, all serpentine is assumed to be lizardite and therefore suitable. All calculations therefore represent the maximum figure.

The density of a pure serpentine rock is 2.6g/cm^3, while the density for unaltered ultramafic rocks is 3.2g/cm^3 as per assumptions made for layered igneous intrusions. The average density for partially serpentinised rocks was taken to be 2.9g/cm^3 based on the most common mineral assemblages that are a mixture of fresh minerals and serpentine with around 50% serpentine.

2.5 Archaean Greenstone Belts

Ultramafic rocks also occur within Archaean metamorphic terrains, these are remnants of ancient crustal rocks (older than 2.5 billion years). The ultramafic component of these rocks includes metamorphosed igneous intrusions, but the most common and most prospective for CCSM feedstock resources is komatiites, which are ultramafic lavas. The CGMW Geological Map of the World (Commission for the Geological Map of the World - CGMW, 2000) delineates terrains of Archaean plutonic, metamorphic and extrusive rocks, some of which are ultramafic (Figure 5). Only Archaean rocks have been used for the purposes of this study. However, Paleoproterozoic greenstone belts containing ultramafic rocks, such as those of the Fennoscandinavian shield or the Flin-Flon Greenstone Belt, Canada, could also be a prospective resource for CCSM feedstock material.

Only a small percentage of the Archaean terrains depicted on the CGMW Geological Map of the World (2000) comprise rocks of ultramafic composition that may be suitable as CCSM feedstock material. The percentage of suitable CCSM resources has been derived by a comparison of the areas covered by the Geological Map of the World with Archaean greenstone belts prospective for CCSM feedstock material derived from more detailed mapping (Geological Survey of India, 1993). This showed that of the areas of exposed Archaean rocks, only 20% comprise greenstone belts or metavolcanosedimentary belts, and of this only 10% is likely to be ultramafic rocks (Table 6). As a result a value of 2% has been used to represent the quantity of ultramafic rocks within these Archaean terrains.

The majority of ultramafic Archaean rocks have been altered by metamorphic processes which can significantly affect the types of Mg-rich minerals present. The alteration minerals depend on the temperature of metamorphism and original composition of the source rocks (Blais and Auvray, 1990). For low temperature alteration the end product is largely dependent on the MgO content of the rock.

The range of MgO contents found in most komatiite deposits is 25–35% (Table 5), so it can be assumed that low temperature metamorphism (typically greenschist facies) will lead to serpentinisation. Higher temperature metamorphism will alter ultramafic minerals to amphiboles (Stiegler *et al.,* 2010), which are of little use in CCSM due to their resistance to the release of Mg during processing. Based on information in Table 7 and examples of well-known komatiites a value of 50% has been used to represent the proportion of ultramafic minerals altered to serpentine minerals suitable for CCSM feedstock material. This figure is based on approximately 30% of deposits being metamorphosed amphibolites and of the remaining 70%, around 20% are altered to antigorite or other minerals which are not suitable for the CCSM process. Table 7 gives the range of serpentinisation in komatiites, which has been used to derive the percentage of komatiite that has been serpentinised. Resources of ultramafic rock not metamorphosed to lizardite serpentine have not been incorporated in the calculation as these are unlikely to be a resource for CCSM feedstock material; these resources are also not significant in size.

2.6 CCSM resource thickness

Many of the resources described above have considerable thicknesses, well in excess of that feasible to economically extract low-value bulk resources. For the purpose of this study a thickness of 100 m has been used for resource estimates, a typical depth of a medium-sized hard-rock quarry. This is a conservative estimate and very large bodies of rock may be able to accommodate large open pits with much greater working depths. Estimates of resources by researchers in other countries have used depths of up to 500 m (Lackner *et al.*, 2008). These maximum depths are further complicated if the ultramafic rocks are located in an existing mine site (for example many nickel deposits contained within layered igneous intrusions). In these cases the maximum depth of working will be greatly increased and constrained by the economics of the higher value commodity being worked. As a result, for more focused studies looking at CCSM resources in existing mine sites, much greater depths may be appropriate.

3. Results of global resource calculations

Taking into account all the assumptions, caveats and discussions made previously, the values for the global resources of CCSM feedstock material from ultramafic rocks are presented in Table 8 to Table 11. Table 8, which provides details regarding the calculation of tonnage of CCSM feedstock from layered igneous intrusions, shows that both the BGS and NRCAN data gives similar values and boosts confidence in the assumptions made for each dataset. For the final totals the more conservative BGS data was used. Table 9 presents the detail regarding the calculation of tonnage of CCSM feedstock material derived from ophiolite rocks, giving a breakdown of ophiolite resources within different areas. Table 10 shows the calculation of tonnage of CCSM feedstock material from Archaean greenstone belts. The tables show estimated resources for serpentinised and fresh rocks separately to give an indication of possible resources if they were used in a process that could only utilise one type. If this were the case, the caveat discussed previously, that often these may not be in separate rock bodies, it must be borne in mind and that the resource might be substantially less. A summary of the results is shown in Table 11.

4. Confidence in global resources calculations

This study has made a number of assumptions to calculate global volumes of ultramafic rocks. One of the most important of these is that the volumes are based on the surface mapping, at a global or regional scale, for both ophiolites and Archaean ultramafic rocks. The assumption made for the area of layered igneous intrusions was that they were associated with PGM mineralisation, however this would disregard intrusions that are barren for PGM. Therefore the estimate should be regarded as a minimum. Volumes for layered igneous intrusions are based on average size of intrusions, but these can be made with some confidence, as similar results are obtained from two separate datasets with different assumptions applied. All volumes were calculated using a conservative thickness of 100 m, this can be considered as shallow compared to the deep profiles of many of the types of deposit, particularly the ophiolites and the depth of many modern open-pit mines. The assumption is made that lithologies mapped and properties recorded at the surface are representative of those at depth. However, confidence in this assumption would decrease with depth.

The final tonnages depend substantially upon assumptions made on the proportion of CCSM feedstock materials from ultramafic rocks within the mapped or assumed extents of layered igneous intrusions, ophiolitic rocks and Archaean rocks. The geological settings of these resource types are all extremely varied, when considered on a global scale. The approach taken was to consider classic well documented examples and use average values from these. Layered igneous intrusions are the most variable with the amount of ultramafic rocks present in the case studies varying between 20% and 70% (Table 2). This is further complicated by the presence of rocks, such as pyroxenites, that do not constitute a CCSM feedstock resource (by most processes considered) but can form a significant proportion of some intrusions. Hence, a conservative estimate of only 15% was used for the proportion of suitable resources which is likely to represent a minimum value. The same principle of a minimum value is also applied to the figure of only 2% used for the Archaean rocks calculation. In contrast, the assumption that 40-50% of ophiolite deposits could be used for CCSM feedstock resources (depending on the type of ophiolite) potentially leads to an over estimation of resource volumes as areas defined as ophiolite rocks may contain non-ultramafic rocks. This figure could be more accurate and probably decrease if further work identified unsuitable ultramafic rocks from within the datasets used to define ophiolite resources.

There are also mineralogical and geological unknowns which may render ultramafic rocks within the areas defined as unsuitable for CCSM feedstock material. For example variations in mineralogy with depth and local impurities may make the rock unsuitable. Without detailed geological, geochemical and mineralogical analyses these are impossible to identify. It is beyond the scope of this global scale study to consider these factors. Regional scale studies are more suited to this level of detail, an example of which has been undertaken for India by Mani *et al.,* (2008).

5. Application: A case study for south and eastern Europe

Regional case studies are useful in demonstrating how data from resources assessments such as this might be used to indicate the locations where CCSM could practically be applied. Southern and Eastern Europe is one such example; the Tethyan ophiolite belt runs through Croatia, Bosnia Herzegovina, Serbia, Montenegro, Albania, Macedonia and Greece. These countries have little access to geological CO_2 storage and are largely reliant on coal fired power stations, often fuelled by high CO_2 emitting brown coal. The large quantity of ultramafic rocks, lack of alternative storage options and number of significant point source CO_2 emitters means there is potential for CCSM in this region.

Data from the International Energy Agency's (IEA) 2006 global emissions database (IEA 2006) show that although these countries are not large emitters on a global scale, they contain numerous small to medium point source emitters and combined they contribute 0.5% of the world's CO_2 emissions and 1.3% of Europe's. These are in the form of smelters, cement works and power stations, all of which would be suited for CCSM processes.

Ultramafic rocks of the Tethyan ophiolite belt are the source of all CCSM feedstock material in these countries. Mafic and ultramafic rocks, as defined by Asch (2005), cover large surface areas, especially in Serbia and Albania, which are all considered prospective for CCSM feedstock material. Albania alone is estimated to contain 280,000 million tonnes of serpentinised rocks and 310,000 million tonnes of olivine rich rocks based on the criteria used to calculate global resources.

These resources can be linked to individual point source emitters. Figure 6 shows a number of point source CO_2 emitters in close proximity, or sited on top of, ultramafic rocks. The largest of these being coal fired power stations in Serbia and Greece. Based on the IEA's global emissions database (IEA 2006) there are also numerous small power stations, cement works and refineries with access to ultramafic rocks, all of which may be suited to a CCSM process. It can be seen in Figure 6 that around 75% of CO_2 point source emitters are within 60 km of a potential CCSM feedstock resource (60 km being the maximum transport distance for bulk commodities, as explained in the discussion). Three sites lie directly on ultramafic rocks; two small power stations in Bosnia Herzegovina, both emitting around 7,000 thousand tonnes of CO_2 per year, and a refinery in central Serbia with undisclosed CO_2 emissions.

6. Discussion

The estimates made here show that potentially 90 teratonnes of material suitable for CCSM feedstock material may be present globally if the process can deal with mixtures of different minerals. Studies of the process of CCSM estimate that between 1.6 and 3.7 tonnes of feedstock material are required to capture 1 tonne of CO_2 (Lackner *et al.,* 1995, IPCC 2005). Using estimates from the Global Carbon Project (2012) for annual global CO_2 emissions (for 2011, 34.7 billion tonnes of emissions came from power generation from fossil fuels and cement manufacture), this study shows that there are potential resources of CCSM feedstock material to capture global CO_2 emissions for between 700 and 1,600 years based on the current rate of global CO_2 emissions.

The figure of 90 teratonnes is the total available resource based only on geological factors and extraction to 100 m depth. If operational, economic and environmental considerations are factored in the figure will be much lower. However, it demonstrates that there are sufficient resources of CCSM feedstock material for CCSM to be considered as an option that could make a significant impact on global CO_2 levels, if an economically acceptable technology for processing can be developed. Any development would also need to be coupled with an incentive to utilise the technology in the form of a regulatory framework for controlling emissions.

Implementation of CCSM on a large scale would entail the mining, processing and transport of vast amounts of material. Industries that deal with large volumes of material are already well established, such as those for coal and iron ore, showing that the technology and infrastructure exists with acceptable economic constraints. A comparison can be made with the coal industry, this is, by tonnage, one of the largest mineral industries globally and produced nearly 8 billion tonnes of coal in 2011 (British Geological Survey 2013). Global reserves are around 860 billion tonnes (BP 2013). No resource estimates are available for recent years but would be an order of magnitude larger than this. If the global coal industry were to be compared to CCSM resources, an industry producing 8 billion tonnes of ultramafic material could capture between 5 and 15% of emissions from fossil fuel power generation and cement manufacture. Resources of 90 teratonnes has potential to sustain an industry at least an order of magnitude larger than the global coal industry, however the environmental and economic constraints of developing such an industry would be substantial.

The environmental constraints of developing an industry based on the construction of new mines to extract CCSM feedstock material would be a considerable. The substantial size of pit required coupled with the necessary infrastructure and associated heavy industry could have a significant effect on the local environment, including visual impact, noise, dust and loss of habitat. The carbonation process will use considerable amounts of water and other chemical reagents that will have consequences for both water supply and industrial waste disposal. If the process reaches a pilot scale, the use of tailings of ultramafic rocks from existing mine sites could minimise many of these hurdles as much of the environmental mitigation measures and permitting will already be in place.

An example of the possible implementation on a local scale uses the case study of southern Europe used earlier. The largest emitter in this example is a coal burning power station which emits 9 million tonnes of CO_2 per year. This means that between 14 million and 30 million tonnes of ultramafic material would be required every year to sequester this CO_2. A quarry 100 m deep and with a surface area of 1 km^2 would supply CCSM feedstock for 10 years. This demand could be met from ophiolitic ultramafic rocks 15 km south of the site, however the requirement of a mine of this magnitude would have planning and environmental constraints.

It is also important to note that, due to the low value, high volume nature of these materials, the resources would either have to be in close proximity to the emitter or have access to transport by ship to be a viable process. Moving the huge amounts of material any distance is only feasible by ship. This would require similar methods to those currently used for bulk commodities that are transported on a global scale such as coal and iron ore. As a result many remote inland ultramafic rock deposits, such as those in Northern Canada or central Africa are unlikely to be exploited for CCSM. These resources may be much better utilised in regions distant from geological carbon storage options or for small scale emitters that can be sited near CCSM resources. For areas such as these the information displayed in this study allows planners and policy makers to consider the viability of CCSM and highlights the possible future option of this method of carbon capture.

Calculation of the maximum distance for which it would be economic or feasible to transport this material is beyond the scope of this study. However, a study by Moosdorf *et al.,* 2014, has calculated efficiency in terms of CO_2 emissions of transportation of CCSM feedstock material. This study calculated transportation would only account for 0.3-0.5% of the potentiality sequestered CO_2 so, in terms of carbon budgets, transportation is not an issue. For major projects, if rail or ships were used, transport distances could be considerable whilst transportation by road might only be possible over much shorter distances. Consideration of transport distances would not be such an economic impediment if pipelines were used to transport the waste CO_2 from the emission source to the CCSM feedstock material source. This would also facilitate disposal of waste products which can be used to backfill voids left by mineral extraction. The maximum distance low value, bulk materials can be hauled by road is 60 km before transportation and fuel costs become prohibitive (Highley *et al.*, 2004). These distances may be extended however if the value of the material were to be increased, for example by the introduction of a carbon emissions trading scheme. If transported by rail, or by a pipeline infrastructure, distances up to 200 km may be feasible (Highley *et al.*, 2004). The combination of both rock resources and emitters at coastal locations could enable the process to be undertaken anywhere in the world, as the main component of sea transport is handling charges for loading and unloading while fuel for the journey is relatively minor.

CCSM technology is still at the laboratory development stage and it is possible that the first step towards implementation would be in niche markets where there are particularly favourable factors. Readily available resources are likely to be present in the form of waste dumps from metallic mineral operations and asbestos mines hosted in ultramafic rocks, as this material has already been crushed and is accessible at the surface ready for further processing. For example Mt Keith, a nickel mine in Australia produces 11 million tonnes of serpentinite waste per year (Wilson *et al.,* 2009). The Hitura nickel mine in Finland has 6 million tonnes of serpentinite stored in stockpiles and this waste has been used as a source for studies into CCSM processes (Zevenhoven *et al.,* 2011, Teir *et al.,* 2007). Examples such as these might be the most suitable locations for pilot studies or plants and if this technology were to be fully developed these mine sites would seem the most obvious locations for the installation of large scale infrastructure for industrial CCSM. Active mine sites are typically large CO_2 emitters and carbon emissions trading schemes such as are being implemented in the EU and North America could make an industrial scale CCSM process economic.

It is also possible that the production of CCSM feedstock material as a by-product could make associated nickel and PGE deposits more economically feasible, if the regulatory framework on CO_2 emissions was such that a carbon price benefit could be factored in. Studies into the Turnagain nickel deposit in British Columbia have concluded that substantial savings could be made if a CCSM plant was built on site, making this prospect economically viable to mine, based on a carbon cap-and-trade scheme with a carbon price of $200 per tonne (Hitch and Dipple, 2012). The introduction of carbon pricing would also mean the construction of mineral carbonation plants at point source emitters may become economically feasible.

To plan for the most efficient use of non-renewable mineral resources, the size, quality and location of those resources must be known. Having spatial information for CCSM ultramafic feedstock resources as well as the locations of major CO_2 emitters within a GIS allows for further analyses linking emitters to resources. The International Energy Agency's 2006 global emissions database (IEA 2006) contains information on industrial point source CO_2 emitters globally. Quantifying and showing the spatial distribution of CCSM resources in this way is vital for effective planning and policy development for future carbon capture and storage.

This analysis, based on the IEA's emitters, shows that 30% of ultramafic rocks with potential for CCSM feedstock are within 60 km of a recorded CO_2 emission point source (40% if 100 km transport distance was used). This relatively low figure is not surprising as the locations of most Archaean greenstone belts are continental interiors and ophiolite rocks are commonly in mountainous regions, neither of which are typically the densely populated, industrialised areas where CO_2 emitters are located. However, taking this into account, even if the total resource figure was reduced by 70% to represent those resources in close proximity to emitters, substantial resources remain, with the potential to capture global emissions for 200 years.

The greatest challenge to CCSM technology is to develop a commercially viable process and deal with the large quantities of carbonate and amorphous silica products (which in themselves may be a secondary resource).

7. Conclusion

This study is a first attempt to calculate an approximate global figure for ultramafic rocks that could be used as resources for CCSM. These figures provide information required to effectively plan for the use of these minerals. It shows that resources of CCSM feedstock material from both serpentinised and unserpentinised rocks are abundant and that the availability of resources is not a constraint on the development of CCSM, which could provide a way to significantly reduce anthropogenic CO_2 emissions, if commercially acceptable processes were to be developed. Although this study gives a generalised review of the abundance of specific rock types on a global scale, and as such many assumptions have been made, the results most likely represent values from the lower end of the possible available resource and are backed up by comparison with major known examples. The possible resource figure of 90 teratonnes is huge and could make a substantial impact on global emissions, if the technology can be made viable, as this could capture global emissions for hundreds of years. Using this method to capture a major proportion of global emissions would require a mining industry on a scale very much larger than anything known at present and very large open pit mines in areas where such industry had not previously existed and might be deemed unacceptable. However even if only 1% of resources were used, which is enough to capture global CO_2 emissions at current rates for over 7 years, in areas where there is an appropriate niche that makes it attractive, a significant impact on global and particularly local emissions could be made. Therefore as resources are not a constraint CCSM can be considered as an alternative method of carbon capture in those areas where geological storage is not possible and even as a viable equivalent in all areas if comparable cost is achieved.

Acknowledgment

We thank the Energy Technologies Institute (ETI) that commissioned and funded the work as part of its CCS programme. Peter Pitfield, Teresa Brown, Alicja Lacinska and the reviewers of Applied Earth Science are thanked for their valuable contributions and review. This paper is published with permission of the Executive Director of the British Geological Survey (NERC)

Tables

Resource type	Geological setting	Typical ultramafic rock types	Examples
Ophiolites	Areas where a section of the oceanic crust has been thrust onto continental crust	The lower tectonised part contains harzburgite and lherzolite, hosting pods of dunite. Cumulate part contains layers of dunite. Serpentinites are common.	Troodos, Cyprus; Semail, Oman/UAE; Bay of Islands, Newfoundland, Canada
Layered igneous intrusions	Large intrusions formed under or in continental crust	Layers of peridotite and pyroxenite can extend laterally over the whole intrusion. Serpentinisation is variable with alteration being concentrated along faults and shear zones. Ultramafic layers occur, but mafic layers tend to predominate.	Bushveld, South Africa; Great Dyke, Zimbabwe; Duluth, Canada; Stillwater, Montana, USA
Greenstone belts	Differentiated flows and sub-volcanic intrusions in Archaean mafic volcanic complexes	The basal parts of lava flows and sills are generally peridotitic. Degree of serpentinisation is variable, but generally high.	Central Lapland Greenstone Belt, Finland; Kambalda Greenstone Belt, Australia
Alaskan-type volcanic arc plutons	Intrusive magmatic rocks intruded in volcanic arcs in a subduction setting	A core of unaltered dunite surrounded by concentric zones of pyroxene-rich rocks, such as wehrlite and clinopyroxenite, with variable degrees of alteration.	Urals, Russia; Duke Island, Alaska, USA and Turnagain, British Columbia, Canada

Table 1. Ultramafic rock associations considered by this study (modified from Voormeij and Simandl 2004)

Name	Area (km^2)	Total thickness (m)	Thickness of ultramafic rocks (m)	Types of ultramafic rocks	Source
Rincón del Tigre	3000	4600	2600	Mainly dunite with bands of harzburgite and orthopyroxenite	Annells, 1986a and 1986b; Prendergast, 2000
Stillwater	1170	6500	1300	Peridotite (700m) orthopyroxenite (370m)	McCallum, 1996; Zientek *et al.,* 2002
Muskox	1670	2200	1500	Dunite, pyroxenite and peridotite	Irvine and Smith, 1967
Skaergaard	100	3500	1200	Olivine cumulates	McBirney 1996
Bushveld (Rustenburg	65000	7000-9000	1600-2100	Harzburgite, dunite (around 800m) Pyroxenite (around	Eales and Cawthorn, 1996; Cawthorn *et*

Layered Suite)				1500m)	*al.,* 2002.
Duluth	5000	4000	Not specified	Olivine cumulates	Miller and Ripley, 1996; Miller, 2011
Great Dyke	3300	3000	2000	Dunite (often serpentinised) (900m) Pyroxenite 1100m)	Wilson, 1996; Oberthür, 2002
Munni Munni	112	4450	1850	Dunite, wehrlite and pyroxenite	Barnes *et al.,* 1990; Barnes and Hoatson, 1994

Table 2. Compilation of the characteristics of selected layered igneous intrusions in relation to CCSM feedstock materials.

Source	**Name of dataset**	**Use**
Asch, 2005	The 1:5 million International Geological Map of Europe and Adjacent Areas	Used to define the locations and extent of ultramafic rocks within ophiolites in Europe and the Middle East
Krevor *et al.,* 2009	Ultramafic resources of the USA	Used to define the locations and extent of ultramafic rocks within ophiolites within the USA
Voormeij and Simandl 2004	Ultramafic resources of British Columbia	Used to define the locations and extent of ultramafic rocks within ophiolites within British Columbia
Exxon Production Research Company and The American Association of Petroleum Geologists 1985	Tectonic map of the World 1:10000000	Used to define the locations and extent of ophiolitic rocks for areas not covered by more detailed regional studies

Table 3. Sources used for the spatial definition of ophiolitic resources

Name of ophiolite	Source of spatial data	Source of ophiolite characteristics	Thickness of crustal rocks (km)	Thickness of mantle rocks (km)	Percentage of ultramafic rocks	Degree of serpentinisation
Troodos (Cypress)	Asch 2005	Coleman 1971, Robinson *et al.,* 2003, Dilek and Furnes 2009.	2.75-7	2-5	42-46	80%, lizardite; antigorite rare
Vourinous (Greece)	Asch 2005	Coleman 1971, Hawkins 2003.	2.30-4.75	3.7-7	60-62	15%
Meirdita (Albania)	Asch 2005	Dilek and Furnes 2009.	7.13	4.38	38	Not specified
Kizildag (Turkey)	Asch 2005	Dilek and Furnes 2009.	4.88	4.22	46	Mainly serpentinised harzburgite
Pindos (Greece)	Asch 2005	Dilek and Furnes 2009, Karipi *et al.,* 2006.	3.13	1.25	29	60-80%
Oman	Exxon Production Research Co. 1985	Dilek and Furnes 2009. Styles *et al.* 2006	10.25	4.60	31	50-100%
Bay of islands (Canada)	Exxon Production Research Co. 1985	Coleman 1971, Hawkins 2003, Komor *et al.,* 1985.	3.6-5.2	2.4-3.5	37-41	intensely serpentinised, 67-81%
California coast (USA)	Krevor *et al.,* 2009	Hopson *et al.,* 2008	2.75	1	27	Not specified
Zambles (Philippines)	Exxon Production Research Co. 1985	Hawkins 2003	4.8	5.5	53	Not specified
Thetford Mines (Canada)	Krevor *et al.,* 2009	Schroetter *et al.,* 2003	5.5	6	52	Not specified
Canyon mountain (USA)	Krevor *et al.,* 2009	Coleman 1971.	2.5	2.25	47	30%
Papua (Indonesia)	Exxon Production Research Co. 1985	Coleman 1971, Coleman 1977.	2.75-13	6-7	32-72	15%

New Caledonia	Exxon Production Research Co. 1985	Coleman 1971, Ulrich *et al.,* 2010.	0-4.5	0.95-7.75	78-100	10-30%
Typical ocean crust	Exxon Production Research Co. 1985	Hawkins 2003, Coleman 1971.	4.5-6.5	4.5-5.5	46-50	Not specified

Table 4. Compilation of characteristics of ophiolitic rocks in relation to CCSM feedstock materials.

MgO content	Alteration product
>35%	Brucite (a magnesium hydroxide)
25-35%	Serpentine group minerals
<25%	Chlorite group minerals

Table 5. Relationship of MgO content to alteration product in komatiites, based on Arndt *et al.* (2008).

Name	% Komatiite	Source
Lapland	20-30	Ernst and Buchan 2001
Hattu	10	Ernst and Buchan 2001
Kuhmo	5	Ernst and Buchan 2001
Kostomuksha	20-30	Ernst and Buchan 2001
Eastern Dharwar	10	Ernst and Buchan 2001
Sumozero-Kenozero	10	Ernst and Buchan 2001
Belingwe greenstone belt	5	Ernst and Buchan 2001
Olondo greenstone belt	15	Ernst and Buchan 2001
Verkhovtsevo greenstone belt	7	Ernst and Buchan 2001
Nondweni	17	Ernst and Buchan 2001
Pietersburg	15	Ernst and Buchan 2001
Seerteng	5	Ernst and Buchan 2001
Kolar	10	Mani *et al.,* 2008
Chitadurga	1	Mani *et al.,* 2008

Table 6. Percentage of komatiite rocks in Archaean greenstone belts.

Name	Serpentine minerals	Degree of serpentinisation
Black Swan (Norseman-Wiluna Greenstone Belt)	Both types	Minor (mainly carbonate minerals)
Honeymoon Well (Norseman-Wiluna Greenstone Belt)	Lizardite	Wholesale: No fresh olivine
Kambalda (Norseman-Wiluna Greenstone Belt)	None – amphibolite-facies grade metamorphism	None
Marshall Pool (Norseman-Wiluna Greenstone Belt)	Lizardite	Appreciable: local preservation of fresh olivine
Mt Keith (Norseman-Wiluna Greenstone Belt)	Mainly lizardite, lesser antigorite	Appreciable
Perseverance (Norseman-Wiluna Greenstone Belt)	Amphibolite-facies grade metamorphism with some retrogressive serpentinisation	Variable
Scotia (Norseman-Wiluna Greenstone Belt)	Antigorite	Appreciable
Walter Williams (Norseman-Wiluna Greenstone Belt)	Lizardite	Appreciable: locally fresh olivine
Widgiemooltha (Norseman-Wiluna Greenstone Belt)	None – amphibolite-facies grade metamorphism	None
Yakabindie (Norseman-Wiluna Greenstone Belt)	-	Appreciable
Munro and Beatty (Abitibi Greenstone Belt)	-	Appreciable
Abitibi Belt	-	Appreciable
Belingwe Belt	-	Appreciable
Khumo Belt	None – amphibolite-facies grade metamorphism	None

Barberton Belt *	-	50-100%

Table 7. Serpentine minerals in komatiites. Source: Barnes 2000 (unless otherwise stated) - denotes not specified. * Source Stiegler *et al.,* (2010). For the location of the greenstone belts see Figure 5.

	layered igneous intrusions	
	Source: BGS dataset	**Source: NRCAN**
Average size of intrusion	2000 km^2	100 km^2
Number of intrusions	47	1040
Total area	94,000 km^2	104,000 km^2
Area of ultramafic rocks (15%)	14,100 km^2	15,600 km^2
Volume of ultramafic rocks (100m depth)	493 km^3	546 km^3
Weight of ultramafic rocks (100m depth)	1,580 billion tonnes	1,750 billion tonnes

Table 8 Resources of ultramafic rocks in layered igneous intrusions**.**

	Ophiolites			
	European Tethyan	**USA and British Columbia**	**Urals**	**Rest of world**
Total area	48,458 km^2	59,823 km^2	15,500 km^2	360,800 km^2
Area of mantle rocks	21,806 km^2	29,911 km^2	2,329 km^2	165,591 km^2
Area serpentinised	10,903 km^2	23,929 km^2	-	82,785 km^2
Volume of unaltered ultramafic rocks (100m depth)	1,090 km^3	598 km^3	233 km^3	82,796 km^3
Volume of serpentinised ultramafic rocks (100m depth)	1,090 km^3	2,393 km^3	-	82,796 km^3
Weight of unaltered ultramafic rocks (100m depth)	3,490 billion tonnes	1,910 billion tonnes	746 billion tonnes	26,490 billion tonnes
Weight of serpentinised ultramafic rocks (100m depth)	3,160 billion tonnes	6,940 billion tonnes	-	24,010 billion tonnes

Table 9 Resources of ultramafic rocks in ophiolite rocks.

Archaean greenstone belts	
Total area of prospective Archaean rocks	7,659,841 km^2
Area of ultramafic rocks within greenstone belts	153,197 km^2

Area of serpentinised ultramafic rocks	76,589 km^2
Volume of serpentinised ultramafic rocks (100m depth)	7660 km^3
Weight of serpentinised ultramafic rocks (100m depth)	22,210 billion tonnes

Table 10 Resources of ultramafic rocks in Archaean greenstone belts.

	Geological setting			
	Layered igneous intrusions (BGS data)	Ophiolites (including Urals)	Archaean greenstone belts	**Subtotals**
Weight of serpentinised ultramafic rocks (100m depth) (billion tonnes)		34,100	22,200	56,300
Weight of unaltered ultramafic rocks (100m depth) (billion tonnes)	1,600	32,600		34,200
Total for all ultramafic rocks (100m depth) (billion tonnes)				90,700

Table 11 Summary of global resources of ultramafic rocks. Figures rounded to nearest 100 billion tonnes.

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Figures

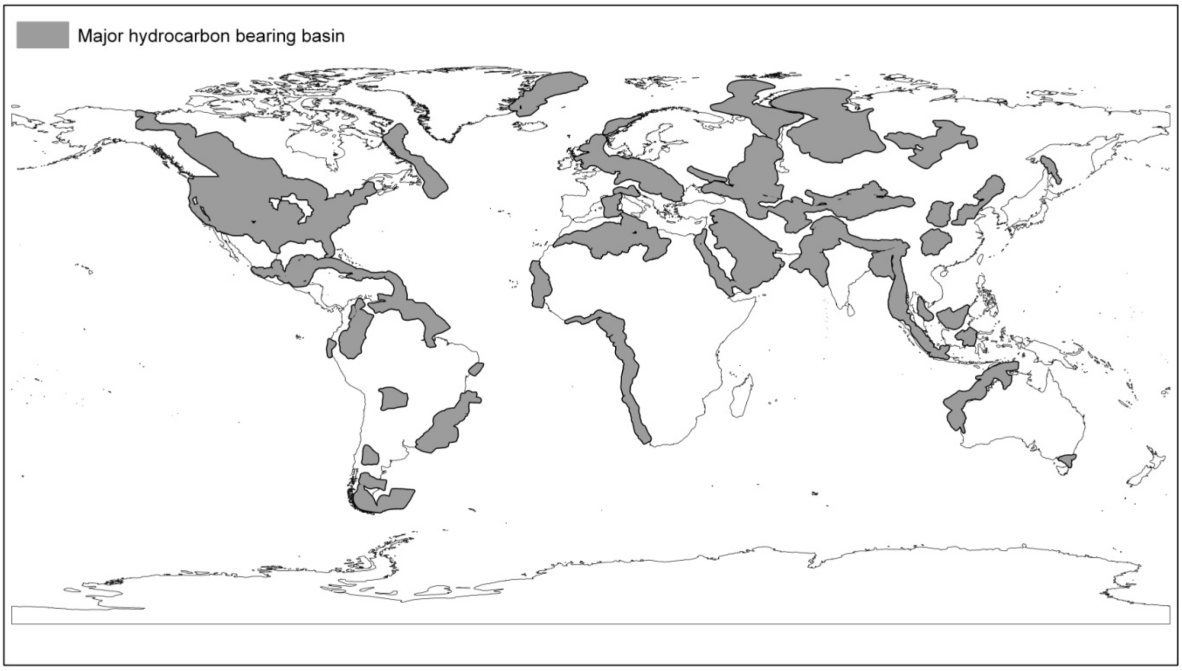

Figure 7. Global distribution of sedimentary basins (USGS 2013)

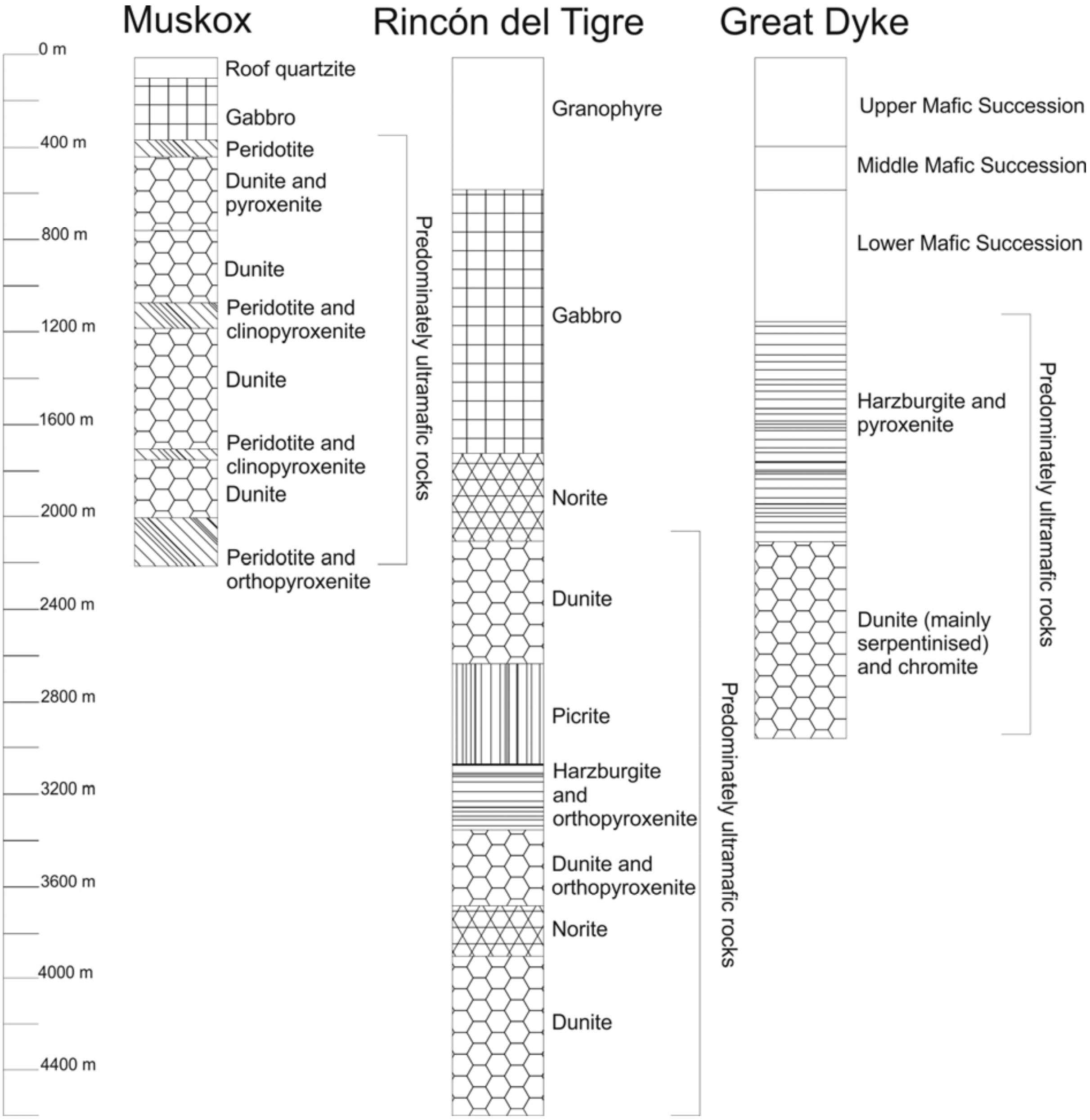

Figure 8. A comparison of major layered igneous intrusions, adapted from Wilson, 1996, Annells, 1986a and Irvine and Smith, 1967

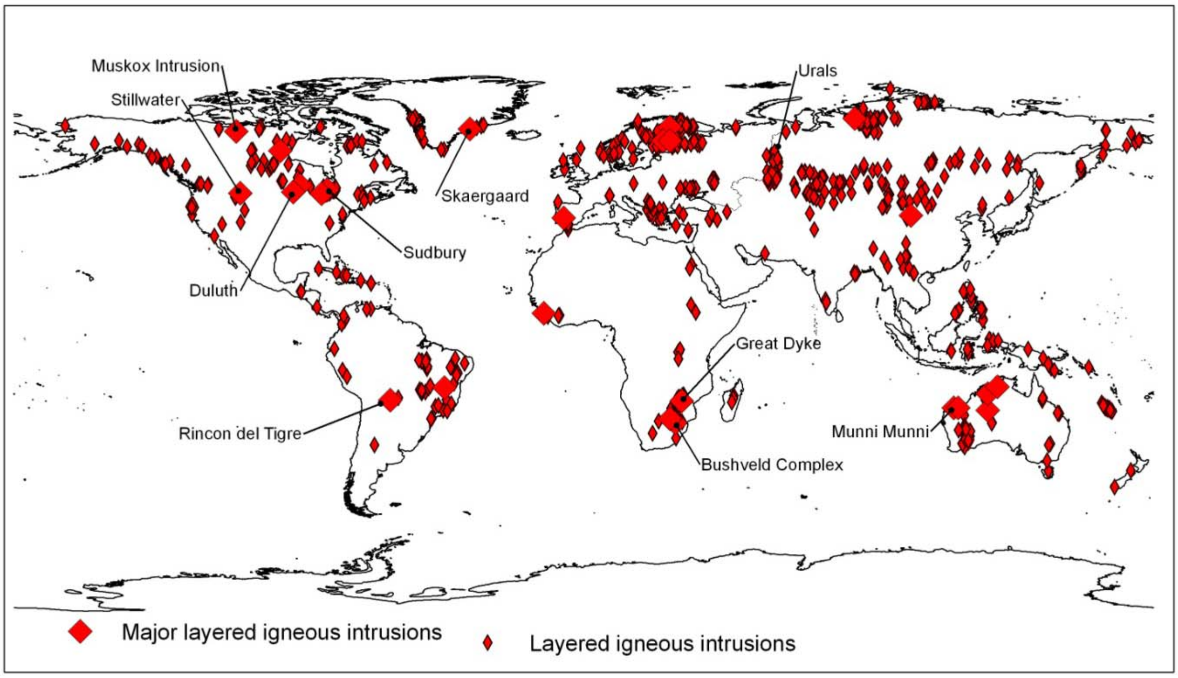

Figure 9. The distribution of resources of feedstock material from layered igneous intrusions based on BGS data.

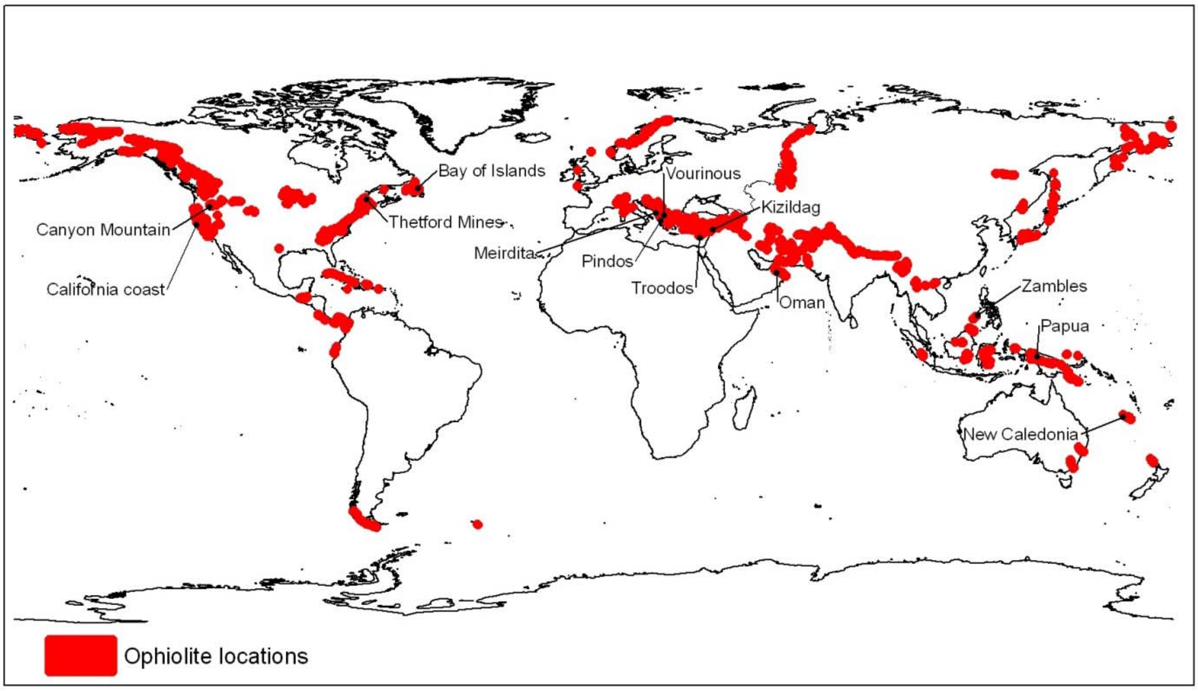

Figure 10. The distribution of resources of feedstock material from ophiolites.

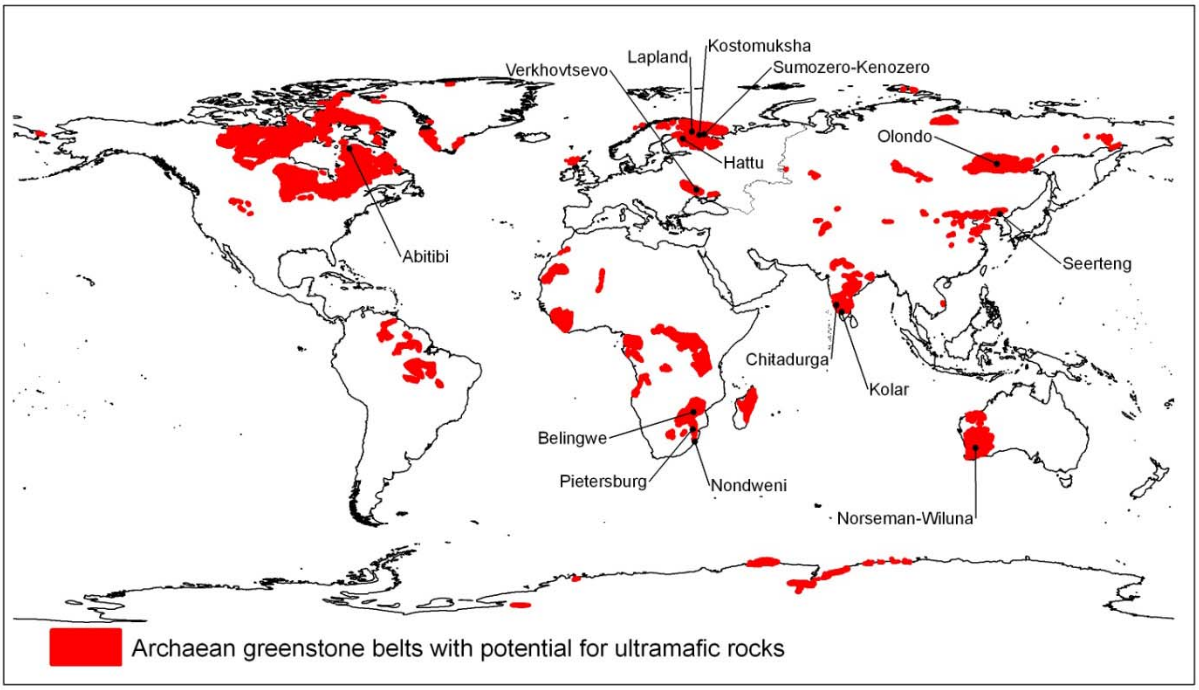

Figure 11. The distribution of resources of feedstock material from Archaean rocks.

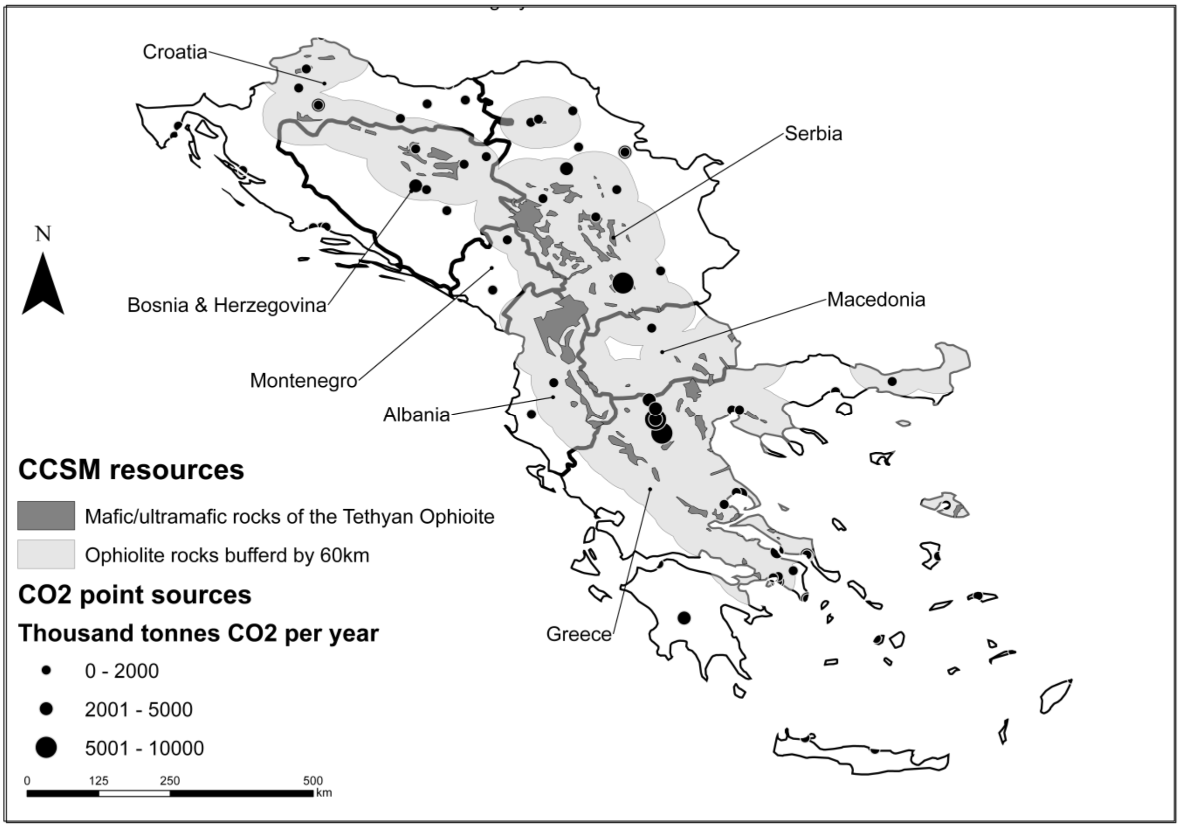

Figure 12 ultramafic rocks and CO_2 emitters of southern Europe