Programme Area: Carbon Capture and Storage

Project: Mineralisation

Title: Work Package 1: Stage Gate 2b Report; Synthesis and Interpretation

Abstract:

A series of experiments have been carried out to determine which types of ultramafic rocks are most suitable as a feed material for CCSM, using acid leach as the method to remove Mg cations from the rock to be available for carbonation. The results show that lizardite serpentinites are by far the best with olivine giving moderate results. Rocks rich in antigorite serpentine, pyroxene, and amphibole are not suitable. The ETI is grateful for the contributions made by all participants of the Mineralisation project; Perkins Engines Company Limited, Shell Global Solutions International B.V., Natural Environment Research Council as represented by the British Geological Survey, and the University of Nottingham.

Context:

CCS by mineralisation has been identified as a promising additional method of sequestering CO2 emissions. Minerals and CO2 can react together to permanently store CO2 as a solid carbonate product, which can then be safely stored, used as an aggregate or turned into useful end products such as bricks or filler for concrete. This £1m project, launched in May 2010 carried out a detailed study of the availability and distribution of suitable minerals across the UK along with studying the technologies that could be used to economically capture and store CO2 emissions. The project consortium involved Caterpillar, BGS and the University of Nottingham. The objective was to investigate the potential for CCS Mineralisation to mitigate at least 2% of current UK CO2 emissions and 2% of worldwide emissions over a 100- year period. The project has found that there is an abundance of suitable minerals available in the UK and worldwide to meet these mitigation targets. However, challenges remain to make the capture process economically attractive and to reduce its energy use. Significant niche opportunities exist where waste materials are used as feedstock and/or the process produces value-added products, but markets would not be at the level required to meet the mitigation targets.

Work Package 1: Stage Gate 2b Report; Synthesis and Interpretation

CCSM Programme

Internal Report WP1 SG2b Deliverable 1.10

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Work Package 1: Stage Gate 2b Report; Synthesis and Interpretation

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Foreword

This report is the published product of part of a study carried out for the ETI Carbon Capture and Storage Mineralisation FRP. This volume contains a synthesis and interpretation of the work carried out by BGS towards Stage Gate 2b. The detailed data and findings are presented in the Appendices.

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This report interprets data produced by Nottingham University and the original data are reported in the companion WP2 report on the Technology aspects of the Project.

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Contents

Foreword i

Acknowledgements i

Contents i

Summary 1

1 Task 1.6 Resource definition 3
- 1.1 Executive summary 3
- 1.2 Introduction 3
- 1.3 The rocks tested 3
- 1.4 Experimental results. 5
- 1.5 Conclusions 7

2 Task 1.7 Detailed assessments of obstacles to mineral accessibility and availability 8
- 2.1 Executive summary 8
- 2.2 Introduction 8
- 2.3 The planning system 8
- 2.4 Environmental Impact Assessment 9
- 2.5 Potential sites for CCSM 11

3 Task 1.8 UK resources 20
- 3.1 Executive summary 20
- 3.2 Introduction 20
- 3.3 Ballantrae Area 20
- 3.4 Belhelvie Area 23
- 3.5 Portsoy Area 25

3.6 Lizard Area ... 27
3.7 Shetland Area ... 29
3.8 Summary of UK resources ... 31

4 Task 1.9 Global resource review ... 33
4.1 Executive summary ... 33
4.2 Introduction ... 33
4.3 Background information and assumptions made for calculation of global resources ... 35
4.4 Global resource estimations by host geology ... 35
4.5 Results of global resource review ... 42
4.6 Case studies ... 44

Appendix ... 49

A.1 X-ray diffraction analyses. ... 49

A.2 X-ray fluorescence analyses. ... 51

A.3 Petrographical analysis of feed rocks. ... 52
A.3.1 Ballantrae Area ... 55
A.3.2 Belhelvie Area ... 66
A.3.3 Portsoy Area ... 71
A.3.4 Lizard Area ... 83
A.3.5 Shetland area ... 91
A.3.6 Selected samples from UAE and Norway ... 100

A.4 Planning policies ... 110
A.4.1 Protected sites designations directory ... 110
A.4.2 Online mapping tools used: ... 116
A.4.3 Lizard peninsula as an example of local planning policies ... 117

A.5 Glossary ... 120

A.6 References ... 120

FIGURES

Figure 1. The range of compositions of ultramafic rocks and the samples tested shown by yellow stars [Copyright BGS, NERC] ... 4

Figure 2. The reactivity of each mineral type as a function of the extraction time using 1.4M ammonium sulphate ... 5

Figure 3. Plot of Mg extraction for rocks of mixed mineral compositions ... 6

Figure 4. Extraction efficiencies of the tested ultramafic rocks in terms of composition — Reaction time 180 minutes [Copyright BGS, NERC]. ... 6

Figure 5. Extraction efficiencies of the tested ultramafic rocks in terms of composition — Reaction time 60 minutes [Copyright BGS, NERC]. ... 7

Figure 6. Maps showing the extent of major environmental designations in the Lizard area plus geographic and cultural features. The location of ultramafic rocks is shown in purple 12

Figure 7. Maps showing the extent of major environmental designations in the Ballantrae area plus geographic and cultural features. The location of ultramafic rocks is shown in purple . 14

Figure 8. Maps showing the extent of major environmental designations in the Shetland Isles plus geographic and cultural features. The location of ultramafic rocks is shown in purple . 15

Figure 9. Maps showing the extent of major environmental designations in the Portsoy area plus geographic and cultural features. The location of ultramafic rocks is shown in purple 17

Figure 10. The extent of major environmental designations in the Belhelvie area plus features in and around the Belhelvie area. The location of ultramafic rocks is shown in purple 18

Figure 11. A: Geological map of the area between Ballantrae and Girvan, showing two Serpentinite Belts and the location of samples collected during fieldwork in July 2011. The ultramafic rocks are shown in purple, amphibolite in brown and country rocks in grey. Red squares show sample locations[Copyright BGS, NERC]; B: typical Southern Serpentinite Belt landscape; C: landscape around mafic intrusions found between Knockdaw Hill, Breaker Hill and Craig Hill, southern belt. The small outcrop on the skyline is amphibolite.21

Figure 12. Plot of Mg extraction versus time for the Ballantrae serpentinites (ET 1, ET 2, ET 5, ET 6) and amphibolites (ET 4) 22

Figure 13. A: Geological map of the Belhelvie area, showing location of the two samples collected during fieldwork in July 2011. Legend of the lithological units is based on the BGS_GIS data[Copyright BGS, NERC]; B: General view of the Belhelvie area; C: A rare small outcrop of rock where sample ET 8 was collected. 24

Figure 14. Plot of Mg extraction versus time for the Belhevie samples (ET 7 and ET 8). 25

Figure 15. A: Simplified geological map of the Portsoy area with the ultramafic rocks shown in purple and the sample locations in red[Copyright BGS, NERC]; B: Views of the landscape around Portsoy showing the scarcity of rock outcrop. 26

Figure 16. Plot of Mg extraction versus time for the Portsoy samples (ET 10 – ET 14). 27

Figure 17. Simplified geological map of the Lizard Complex with ultramafic rocks shown in purple and mafic rocks in brown. Locations of samples studied are shown in red [Copyright BGS, NERC]. 28

Figure 18. Plot of Mg extraction versus time for the Lizard samples (ET15 – ET 18) 29

Figure 19. Simplified geology map of Unst and Fetlar with the ultramafic rocks of the ophiolite complex shown in purple. The darker shade denotes serpentinites derived from harzburgite and the lighter shade from dunite [Copyright BGS, NERC]. 30

Figure 20. Plot of Mg extraction versus time for the Shetland samples (ET 19 – ET 22). 31

Figure 21. Ultramafic rocks and CO_2 emitters of southern Europe [Copyright BGS, NERC]. 45

Figure 22. Ultramafic rocks and CO_2 emitters of India; A: Area location for Figure 23; B: Area location for Figure 24. [Copyright BGS, NERC] 46

Figure 23. Ultramafic rocks and CO_2 emitters of eastern India [Copyright BGS, NERC]. 47

Figure 24. Ultramafic rocks and CO_3 emitters of southern and central India [Copyright BGS, NERC]. 48

Figure 25. Geological map of the area between Ballantrae and Girvan, showing two Serpentinite Belts and the location of samples collected during fieldwork in July 2011, ultramafic rocks are shown in purple and mafic rocks in brown [Copyright BGS, NERC]. 55

Figure 26. Images showing: a) typical Southern Serpentinite Belt landscape (Fig 1 for location); b) landscape around mafic intrusions found between Knockdaw Hill, Breaker Hill and Craig Hill, southern belt (Fig 1 for location). The small outcrop on the skyline is amphibolite 56

Figure 27. Images showing, a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET1 outcrop, recent excavation adjacent to a landfill site NE from Lendalfoot. ... 57

Figure 28. Images of sample ET1: a) hand specimen; b) polished thin section scan; c) crossed polarised light optical photomicrograph showing mesh texture serpentine with scattered large (up to 5 mm) orthopyroxene pseudomorphs – bastites; d) reflected light optical photomicrograph showing crystal of chromite with embayed crystal edges (holly-leaf texture). Minute (<5 µm) fractures of magnetite were commonly observed crosscutting the chromites ... 58

Figure 29. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET2 outcrop, found S of a lake belonging to Fishery located c. 1km NW of Garnaburn Farm, nr Colmonell ... 59

Figure 30. Photographs of ET2 serpentinite: a) several hand specimens fragments; b) a holly-leaf crystal of chromite surrounded by blue-green chlorite; c&d) polished thin section scanned images of SL2a and SL2b respectively; e) crossed polarised light photomicrograph of SL2a serpentinite with apparent fracture cleavage running through serpentine mesh exclusively, bastites (centre of field of view) are not deformed; f) crossed polarised light photomicrograph of SL2b serpentinite showing only faint fracture cleavage and large bastites with relict pyroxene in the centre ... 61

Figure 31. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET5 outcrop, found c. 5km S of Girvan and S of Byne Hill Caravan Park. ... 62

Figure 32. Photographs of ET5 serpentinite: a) few hand specimens fragments; b) polished thin section scanned images; c) crossed polarised light photomicrograph of SL5 serpentinite with apparent bastites with mesh texture serpentine, crosscut by serpentine-infilled fractures; d) plain polarised light photomicrograph showing chromite crystals and bastite within mesh serpentine ... 63

Figure 33. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET6 outcrop, found on a track running subparallel to A77, N of the B734. ... 64

Figure 34. Photographs of ET6 serpentinite: a) selection of hand specimen fragments; b)scanned polished thin section; c) crossed polarised light photomicrograph showing mesh texture serpentinite hosting several bastite crystals; d) plain light photomicrograph showing black, altered holy-leaf chromite within mesh serpentinite. ... 65

Figure 35. Geological map of the Belhelvie area, showing location of the two samples collected during fieldwork in July 2011. The ultramafic rocks are shown in purple [Copyright BGS, NERC]. ... 66

Figure 36. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) heavily overgrown ET7 outcrop, found c. 500 m E from Braeside Farm.67

Figure 37. Photographs of ET7 serpentinised plagioclase-rich wherlite showing: a) hand specimen with distinctive white patches of altered plagioclase; b) scanned polished thin section; c) crossed polarised light photomicrograph showing poikilotopic clinopyroxene and interstital altered plagioclase within a groundmass of serpentinised olivine; d) plane polarised light photomicrograph showing chlorite- amphibole corona that occurs between altered plagioclase and serpentinised olivine. ... 68

Figure 38. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) distant view and a close up of the heavily overgrown ET8 outcrop, found NE of B999 road, near Longdrum 69

Figure 39. Photographs of sample ET8, serpentinised melatroctolite showing: a) hand specimen with distinctive white patches of altered plagioclase; b) scanned polished thin section with distinctive bands of mafic and ultramafic composition; c) crossed polarised light photomicrograph showing poikilotopic clinopyroxene and olivine-inclusion rich orthopyroxene within a groundmass of serpentinised olivine; d) plane polarised light photomicrograph showing troctolite band dominated by serpentinised olivine set in a groundmass of interstitial altered plagioclase 70

Figure 40. Simplified geological map of the Portsoy area with the ultramafic rocks shown in purple and the sample locations in red [Copyright BGS, NERC]. 71

Figure 41. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) heavily overgrown ET10 outcrop, found c. 5 km SW of Portsoy, Damheads Quarry (disused). 72

Figure 42. Photographs of sample ET10, chlorite-rich serpentinite: a) hand specimen with distinctive shear zones; b) scanned polished thin section showing scattered chromites (black) in shear groundmass of serpentine and chlorite; c) plane polarised light photomicrograph showing bladed crystals of chlorite in a groundmass of serpentine mesh, note the augen texture around chromite marked by red-dotted line; d) plane polarised light photomicrograph showing finely-crystalline bladed crystals of chlorite and mesh serpentine with scattered Fe oxide/oxyhydroxide 73

Figure 43. Arial photograph (Google Earth) and site location for sample ET 11 74

Figure 44. Photographs of sample ET11, chlorite-rich serpentinite: a) hand specimen; b) scanned polished thin section; c) plane polarised light photomicrograph showing mesh serpentine, patchy Fe oxide/oxyhydroxide and scattered chromites; d) plane polarised light photomicrograph showing crystals of chromite rimmed with bladed crystals of chlorite, all within mesh serpentine 75

Figure 45. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) serpentinite ET12 cropping out on the beach of Links Bay, Portsoy. 76

Figure 46. Photographs of sample ET12, chlorite-rich serpentinite: a) hand specimen; b) scanned polished thin section; c) plane polarised light photomicrograph showing mesh serpentine, Fe oxide/oxyhydroxide remobilised to the grain boundaries of newly formed crystals; d) plane polarised light photomicrograph showing association of talc, chlorite and Mg, Fe +-Mn, Ca hydrous silicate (probably Chl alteration product); f) detailed plane polarised light photomicrograph showing the Mg, Fe +-Mn, Ca hydrous silicate overgrowing bladed crystals of chlorite, all within serpentine groundmass 78

Figure 47. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) serpentinite outcrop at Portsoy Marble Quarry (disused) 79

Figure 48. Photographs of sample ET13, chlorite-rich serpentinite: a) hand specimen; b) plane polarised light photomicrograph showing bladed chlorite intergrown with serpentine minerals; c, d) scanned polished thin section of ET13 a and ET 13b respectively; e) plane polarised light photomicrograph showing sheared serpentinite with foliation clearly determined by chlorite and chromite/magnetite deformed zones, ET13a; f) crossed polarised light photomicrograph showing sheared serpentine mesh and chlorite patches. 81

Figure 49. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) small serpentinite exposure at the W end of Meikle Toux farm 81

Figure 50. Photographs of sample ET13, chlorite-rich serpentinite: a) hand specimen; b) scanned polished thin section; c) crossed polarised light photomicrograph showing sheared serpentine mesh; d) altered chromite (now magnetite) and distinctive chlorite halo 82

Figure 51. Topographical image (Google Earth) of Cornwall with the site of interest marked by white rectangle; and generalised geological map showing the location of 4 Lizard samples analysed in this study. The ultramafic rocks are shown in purple and the mafic rocks in brown [Copyright BGS, NERC]. 83

Figure 52. Arial photograph (Google Earth) and site location for sample ET 15 [Copyright BGS, NERC]. 84

Figure 53. Photographs of sample ET15, serpentinite: a) scanned polished thin section; b) crossed polarised light photomicrograph showing fibrous and partially recrystalised serpentine crystals; c) reflected light photomicrograph showing corroded chromite displaying sieve-like texture 85

Figure 54. Arial photograph (Google Earth) and site location for sample ET 16 [Copyright BGS, NERC]. 86

Figure 55. Photographs of sample ET16, serpentinite: a) scanned polished thin section; b) plane polarised light photomicrograph showing assemblage of chlorite and amphibole in mesh and partially recrystalised serpentine; c) crossed polarised light photomicrograph showing mesh serpentinite (bottom) and recrystalised serpentine in veins, both cross cut by micro-fractures of quartz 87

Figure 56. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) Massive partially serpentinised peridotite cut by numerous veins, Balk quarry. 88

Figure 57. Photographs of sample ET17, serpentinite: a) scanned polished thin section; b) crossed polarised light photomicrograph showing two generations of serpentine minerals, recrystallised serpentine occurring adjacent to a fracture and relict mesh serpentine further away from the fracture. The rock is crosscut by veins of carbonate; c) plane polarised light photomicrograph fresh crystal of chromite surrounded by mesh serpentine. The field of view also shows a fragment of a bastite crystal and scattered amphibole crystals 89

Figure 58. Arial photograph (Google Earth) and site location for sample ET18 [Copyright BGS, NERC]. 90

Figure 59. Photographs of sample ET18, serpentinite: a) scanned polished thin section showing veins; b) plane polarised light photomicrograph showing a large crystal of orthopyroxene adjacent to an aggtregate of amphibole after clinopyroxene in a matrix of partially serpentinised olivine.Shetland Area 91

Figure 60. Geology map of Unst and Fetlar with the ultramafic rocks of the ophiolite complex shown in purple, the darker shade is serpentinites derived harzbugite and the lighter shade from dunite [Copyright BGS, NERC]. 92

Figure 61. Google Earth image of northern Unst showing the low undulating topography and almost complete lack of exposed rocks. Geology map of the northern part of Unst, colours as Figure 60 and with pods of pyroxene-rich rocks in brighter purple and rocks extensively altered to talc in pink. The locations of the boreholes from which samples were taken are also shown [Copyright BGS, NERC]. 93

Figure 62. Photographs of sample ET19, serpentinite: a) scanned polished thin section; b) crossed polarised light photomicrograph showing partially carbonate-replaced serpentine groundmass; c) plane polarised light showing altered chromite in antigorite-dominated groundmass 94

Figure 63. Photographs of sample ET20: a) scanned polished thin section; b) crossed polarised light photomicrograph showing relict of fresh olivine and chromite within partially carbonate-replaced groundmass of antigorite and lizardite; c) plane polarised light photomicrograph showing partially altered chromite crystal within a antigorite-dominated groundmass; d) carbonate replacing serpentine minerals 96

Figure 64.Scanned polished thin section image of the rock analysed and optical microscopy light image showing mesh texture serpentinite and chromites (black) surrounded by distinctive rim of chlorite. 97

Figure 65. Scanned polished thin section and optical microscopy photomicrograph (cross-polarized light) showing partially carbonate replaced serpentinite 99

Figure 66. Scanned polished thin section image and optical microscopy photomicrograph showing the characteristics of the olivine aggregate. The sample contains small amounts of phases, such as: serpentine, chromite, chlorite, amphibole, talc, carbonate, and pyroxene .100

Figure 67. Scanned polished thin section image (3 cm longer edge) and optical microscopy photomicrograph showing large crystals of pyroxene in a finer matrix of olivine and serpentine 101

Figure 68. Scanned polished thin section image (3 cm longer edge) pyroxenite veinlet and optical photomicrograph showing crystals of spinel in a matrix of olivine and serpentine 102

Figure 69. Scanned polished thin section image and optical microscopy photomicrograph showing large crystals of pyroxene in association with plagioclase and olivine 104

Figure 70.Scanned polished thin section image and optical microscopy photomicrograph showing the amphibole-prehnite-rich rock 105

Figure 71. Scanned polished thin section image and optical microscopy photomicrograph showing sheared and locally recrystallised serpentinite..... 106

Figure 72. Scanned polished thin section image. Optical microscopy photomicrographs showing b) microgabbro fragment (left side) c) relics of olivine d) co-existing lizardite and antigorite .107

TABLES

Table 1. The bulk mineralogy of samples tested determined by XRD 5

Table 2. Revised estimates of the potential resources of ultramafic rocks suitable for CCSM using an acid leach Mg extraction 32

Table 3. Ultramafic complex types (modified from Krevor et al. 2009) 33

Table 4. Ultramafic rock resource estimates for the UK; British Columbia, Canada; USA; France; and the World. 34

Table 5. Compilation of properties of layered intrusions in relation to CCSM feedstock materials.36

Table 6. Compilation of properties of ophiolite rocks in relation to CCSM feedstock materials. 39

Table 7. Percentage of komatiite rocks in Archæan greenstone belts 40

Table 8. Serpentine minerals in komatiites 41

Table 9. Resources of ultramafic rocks in layered intrusions. 42

Table 10. Resources of ultramafic rocks in ophiolites 43

Table 11. Resources of ultramafic rocks in Archæan greenstone belts 43

Table 12. Summary of global resources of ultramafic rocks 43

Table 13. Mass of ultramafic rocks in southern Europe (depth of 35m) (totals may not match due to rounding) . 44
Table 14. Quantitative mineralogy determined by X-ray diffraction 50
Table 15. Chemical composition of rock samples used for Mg leaching experiments 51
Table 16. Details of the samples studied. 53
Table 17. Optical petrography summary table . 108

Summary

This report documents the BGS contribution to Work Package 1. This comprises:

- Defining a suitable resource for CCSM (Task 1.6)
- A detailed assessment of obstacles to mineral accessibility and availability in the UK (Task 1.7)
- An assessment of UK resources from the target areas identified in Phase 1; the Lizard, Ballantrae, Portsoy, Belhelvie and Shetland (Task 1.8)
- A more refined assessment of global resources that focuses on the geological controls of ultramafic rocks and revised criteria for suitability arising from Task 1.6 (Task 1.9)

To define a suitable resource for CCSM, a series of experiments were carried out to determine which types of ultramafic rocks are most suitable as a feed material, using an acid leach method to remove Mg cations from the rock to be available for carbonation (leach experiments were undertaken by UoN). The results show that lizardite serpentinites are by far the best with olivine-rich rocks giving moderate results. Rocks rich in antigorite serpentine, pyroxene, and amphibole are not suitable.

In the areas rated as most promising in the Stage Gate 1 report, a study was carried out to assess possible constraints on exploitation of feedstock material for CCSM. It covers aspects of the locations that might pose obstacles to the exploitation, including practical features such as topography. Regulations related to planning and permission to operate at these locations were also investigated. The analysis shows that no areas have any particular constraints from the point of view of accessibility and logistics. The Lizard and to a lesser extent Shetland have a range of planning restrictions according to current planning rules for quarries, but Ballantrae, Portsoy and Belhelvie have few restrictions. It is pointed out that if CCSM was considered an important application and very large quarries were required, planning would most likely be dealt with by the new Infrastructure Planning Unit not local planning authorities.

The initial assessment of UK resources assumed that all ultramafic rocks would be suitable for CCSM; no account of mineralogical and geological variability was made. Thus, to see how these variables may affect feed materials for CCSM from UK sources a detailed mineralogical characterisation and Mg-leaching experiments on the target localities were undertaken. The results show that the lizardite serpentinites from Ballantrae, Portsoy, and Belhelvie are good feed materials. The studies also show that some of the rocks from Shetland have a large proportion of antigorite serpentinites that have poor reactivity and the volume of resource is downgraded by 50%. The rocks from the Lizard have substantial amphibole peridotite/serpentinites that also have poor reactivity and the resource is downgraded by 40%. The revised estimate, based on a better knowledge of the rock types and actual experimental tests of reactivity, gives a resource of 9.5 Gt, roughly 4 times the target for the project.

To examine the applicability of CCSM worldwide, a desk-based global resource review was undertaken to provide an estimate of the amount of ultramafic rocks available according to the major geological controls identified in the Stage Gate 1 Report. These were ophiolites, layered igneous intrusions, komatiites and other Archæan ultramafic rocks. In addition, two case studies – south-eastern Europe and India – were undertaken to examine the spatial relationship between point source emitters and available ultramafic rock; the areas were chosen as they do not have ready access to underground storage. The results for the global resources assessment show significant resources – potentially up to c. 30 Tt for a 35 m quarry depth. Of these approximately 20 Tt is serpentinite suitable for the CCSM process considered here. Around 60% of this comes

from ophiolites and the remainder from Archæan rocks. Serpentinites associated with ophiolites often represent large volumes of comparatively homogeneous lizardite serpentinite so offer attractive targets for CCSM feedstock material. On a global scale, the amount of material available in layered igneous rock is relatively small (<1 Gt). The total resource could capture global CO_2 emissions at 2006 levels for nearly 400 years.

For the two case studies, the analysis showed that for southern Europe 75% of the point source emitters were within 60 km of a serpentinite resource, potentially making this a good location for the deployment of CCSM. In India the scope for CCSM using serpentinite was less favourable and would probably represent a niche deployment of the technology. However, if different feedstocks could be used (e.g. olivine) there is good potential.

1 Task 1.6 Resource definition

1.1 EXECUTIVE SUMMARY

A series of experiments have been carried out to determine which types of ultramafic rocks are most suitable as a feed material for CCSM, using acid leach as the method to remove Mg cations from the rock to be available for carbonation. The results show that lizardite serpentinites are by far the best with olivine giving moderate results. Rocks rich in antigorite serpentine, pyroxene, and amphibole are not suitable.

1.2 INTRODUCTION

The Stage Gate 1 report (Zimmermann et al. 2010) described the range of mineralogical compositions of ultramafic rocks and reviewed the literature about testing of rocks for their suitability for CCSM. The conclusion was that:

- only a limited range of rock compositions had been tested
- the characterisation of the rocks tested was often poor
- the experiments carried out had been by various methods and at a range of conditions
- it was not possible to meaningfully compare and synthesise the data

To address this problem a range of rocks were selected to cover the broad range of ultramafic rocks and a series of Mg-leaching experiments were carried out, all under exactly the same conditions. The only variable in these experiments was the composition of the starting material and the purpose was solely to evaluate the relative leachability. The experimental method and full set of data are given in the main *Carbon Capture and Sequestration by Mineralisation (CCSM) Stage 2B Report* along with a separate set of experiments to optimise the leaching conditions. These results are for leaching using ammonium sulphate but are probably applicable to other acid leaching processes.

1.3 THE ROCKS TESTED

The ranges of rock types tested are shown on Figure 1, the basis of which was described in detail in the Stage Gate 1 report (Zimmermann et al. 2010). The figure shows the main minerals that are found in ultramafic rocks at the corners, and indicates the composition fields of the commoner rocks, with the composition of the actual rocks tested shown as stars. We tried to use rocks as close as possible to the pure end members, together with two intermediate compositions for the ophiolite mantle as this is likely to be the largest potential source rock on a global scale.

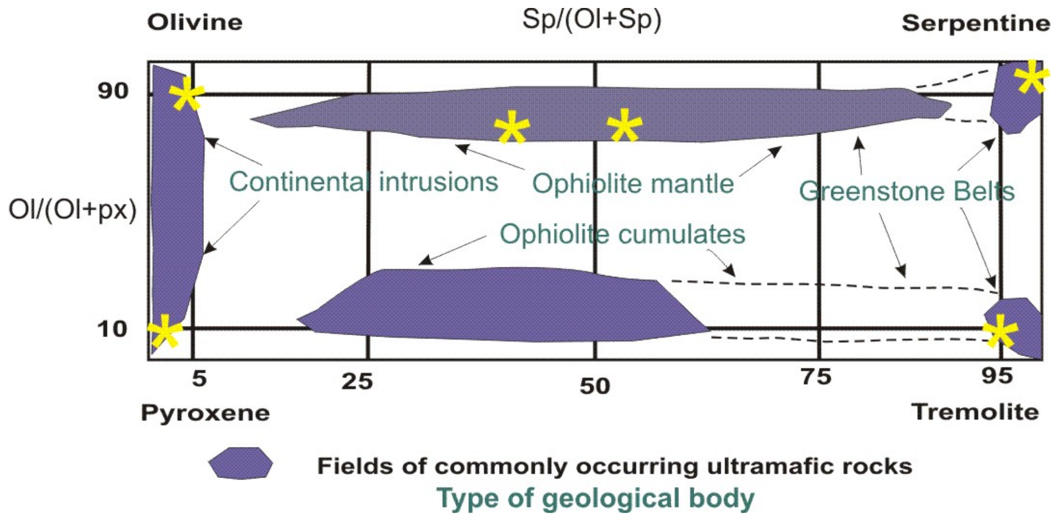


Figure 1. The range of compositions of ultramafic rocks and the samples tested shown by yellow stars [Copyright BGS, NERC]

For most compositions, a single sample was tested. To define the reactivity of serpentine we tested several samples as there are two main types, lizardite and antigorite, and there is considerable confusion about which type has better leaching properties. All samples used have been subjected to a detailed geological characterisation that included examination of hand specimens, study of thin sections by optical, petrographic microscope, bulk mineralogy by XRD and chemical composition by XRF. Full results are given in the Appendices. The composition of the samples is best illustrated by the mineralogy determined by quantitative XRD and the results are given in Table 1. We had some difficulty getting a pure amphibole rock within the time available and the one used contains prehnite, an alteration mineral similar to anorthite feldspar.

We paid particular attention to the types of serpentine. We used a lizardite serpentinite collected from Ballantrae as part of this project and the results for similar samples described elsewhere in the report show that it is typical and representative. For antigorite, we used a very pure sample previously collected by BGS from Italy (ET 29) and a sample from Cedar Hills, USA (ET 30). The latter was originally used by the ARC laboratories and has been supplied by them as a 'standard rock' and used by various laboratories for experiments. We have examined two samples of this rock that were supplied via Nottingham University on two separate occasions and both are shown in the table. The data show that the sample used for the experiments has a high antigorite content (85%) but no lizardite, and also contains a fragment of microgabbro as well as 8% quartz and clay which must be due to contamination (possibly during field sampling) and alteration. In contrast, the sample tested previously had 18% lizardite but no quartz and clay. There is clearly significant variation in the rocks being used as 'standard' antigorite serpentinite and this could partly explain the confusing results reported previously.

It is also pertinent that samples with substantial amounts of lizardite report quite large amounts of amorphous material from the quantification process. BGS are fully aware of this issue connected to poor fundamental data in the databases of XRD profiles of lizardite. The problem has yet to be solved, but we currently think that the amorphous material is actually an underestimate of lizardite. This problem is part of the PhD research topic recently started by Alicja Lacinska (a co-author of this report) at Nottingham University in collaboration with BGS and Caterpillar.

Table 1. The bulk mineralogy of samples tested determined by XRD .

ETI prefix	ETI Sample	Area	Rock name	Lizardite-1M	Lizardite-1T	Antigorite	Forsterite	Enstatite	Cpx (Diopside)	Amphibole (Tremolite)	Clinochlore	Magnetite	Hematite	Anorthite	Prehnite	Amorphous
ET	1	Ballantrae N	lizardite serpentinite	32	41.7							1.1				25.2
ET	29	Italy	antigorite serpentinite			93.8					4.2	1.4	0.6			0
ET	30	USA	antigorite serpentinite			85.3	5.2					1.6		1.3		0
		USA	antigorite serpentinite		18.4	61.5	8.1				1.8	1				7.6
ET	27	UAE	clinopyroxenite		3.4		10.9	6.4	72.7	1.1				5.5		0
ET	28	UAE	amphibole rock							58.9	10.2				27	0
ET	25	UAE	harzburgite		22		34.4	12.6	8.1	1.4	6					12.3
ET	26	UAE	harzburgite		37.2		15.6	19.5	4.2	0.3	8.6					13.7
ET	9	White Hill	Amphibolite		0.3				4.3	67.5	0.3			27.6		

1.4 EXPERIMENTAL RESULTS.

The full experimental methodology and results are presented in *Carbon Capture and Sequestration by Mineralisation (CCSM) Stage 2B Report* Appendix volume, but the data of most importance to this part of the report are the results of the Mg extraction with increasing time. The data are plotted on Figure 2 and for simplicity the dominant mineral is referred to rather than the rock. This shows that lizardite has the best properties with a lot of Mg extracted in a very short time (nearly 80% after 1 hour, and nearly 90% after 3 hrs). Olivine also shows a high total extraction, but the short-term extraction rate is much lower with only 55% Mg extracted after 1 hour. The data show that antigorite is far inferior to lizardite, with total extraction less than 60% and only 40% after 1 hour.

Pyroxene and amphibole-rich rocks have very similar properties, with a total extraction around 30% but little increase after 1 hour. This possibly reflects an early release of Mg from the minor constituents of these rocks such as serpentine and chlorite; pure minerals might have a lower total extraction. Samples of gabbro and amphibolite, that are composed of amphibole with abundant feldspar (that does not contain Mg), show even lower extraction. This reflects both the lower starting content of Mg and the low efficiency of leaching.

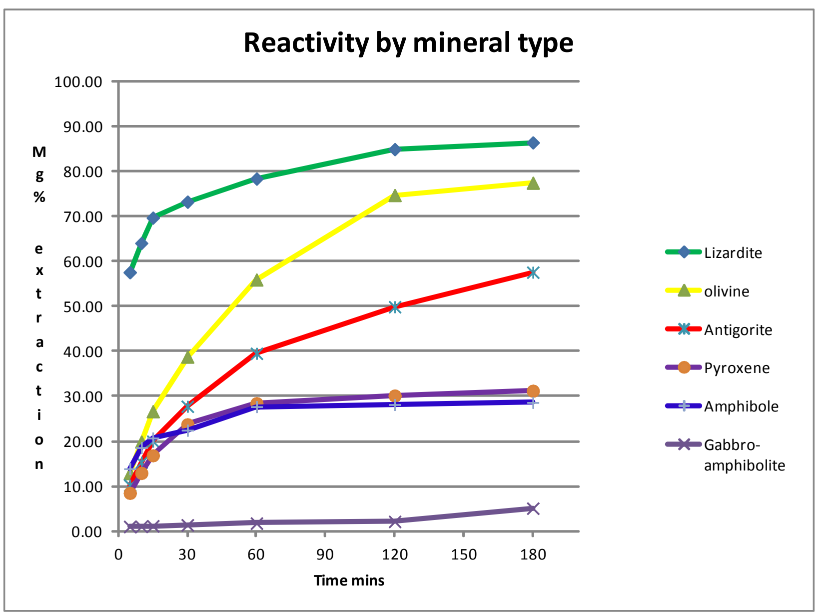


Figure 2. The reactivity of each mineral type as a function of the extraction time using 1.4M ammonium sulphate .

The data shown here for end member compositions can essentially be used in a predictive way to estimate the reactivity of any combination of these minerals. This is demonstrated by the results from samples with mixed compositions shown in Figure 3. This shows that rocks with higher contents of olivine and particularly pyroxene have progressively lower extraction efficiencies. After 1 hour the early release from serpentine gives these mixed rocksbetter extraction than pure olivine but after longer periods the low extraction from pyroxene and amphibole makes them worse than olivine.

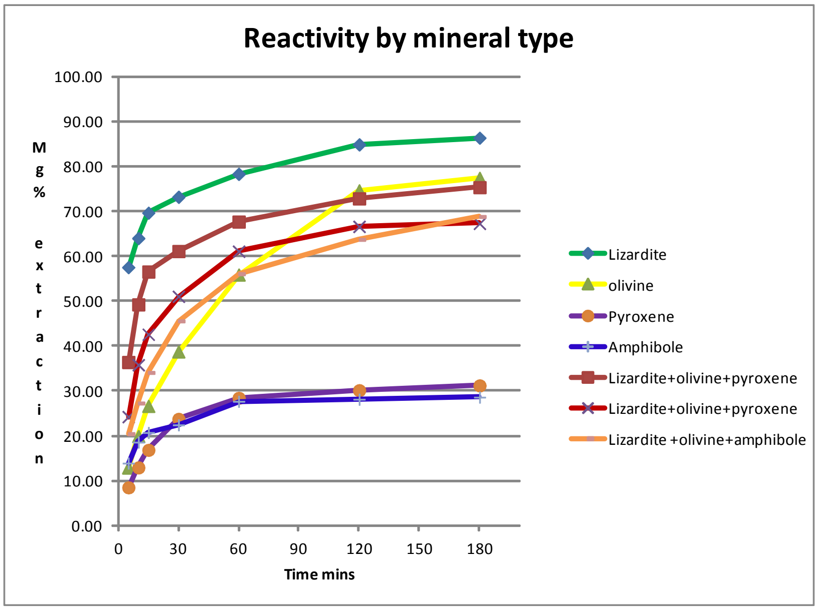


Figure 3. Plot of Mg extraction for rocks of mixed mineral compositions .

The extraction efficiencies of the range of rocks tested are shown on the classification rectangle with data for extraction after 180 minutes in Figure 4. It is possible that an extraction time around 60 minutes might be more appropriate for an industrial process and hence this is shown in Figure 5.

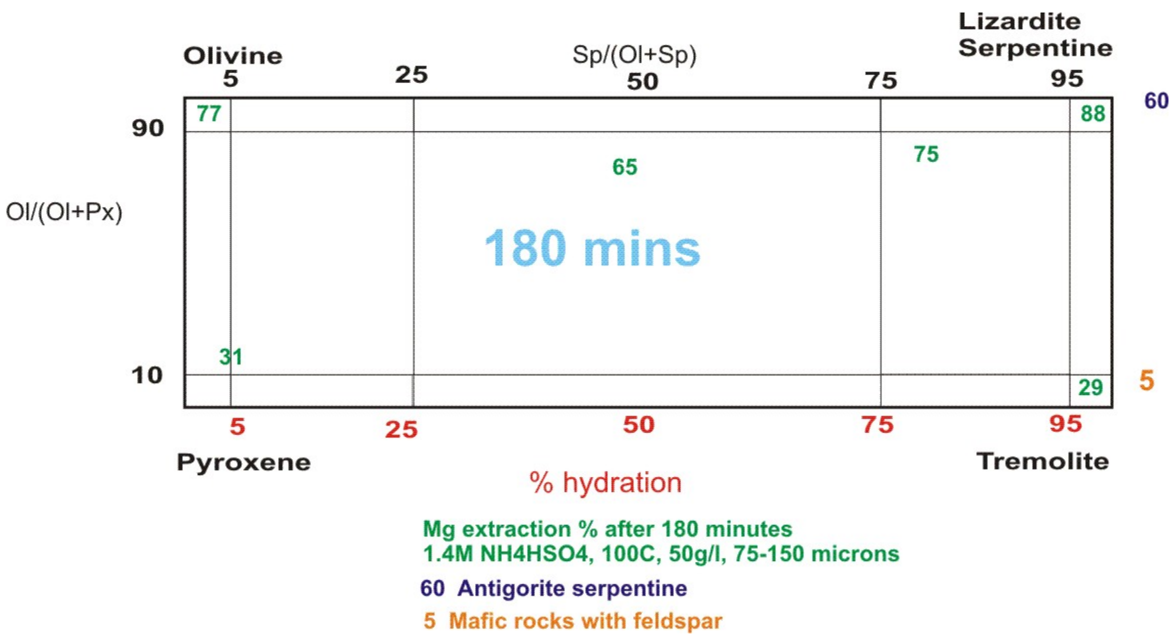


Figure 4. Extraction efficiencies of the tested ultramafic rocks in terms of composition — Reaction time 180 minutes [Copyright BGS, NERC].

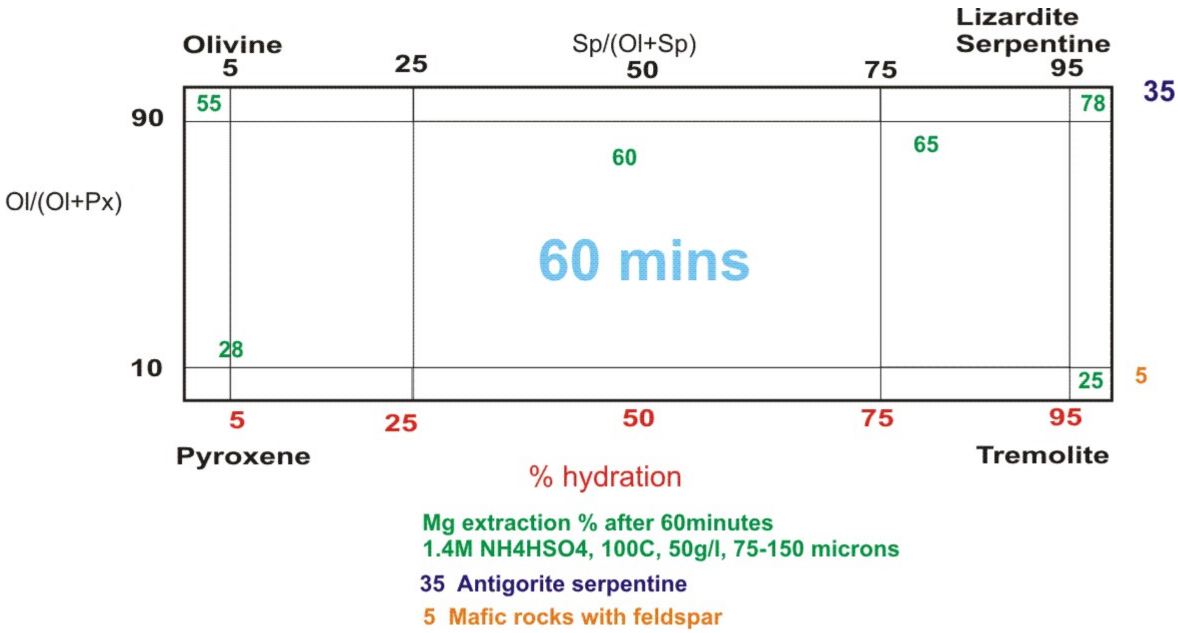


Figure 5. Extraction efficiencies of the tested ultramafic rocks in terms of composition — Reaction time 60 minutes [Copyright BGS, NERC].

These plots show clearly that, considering a 60 minute leach time, rocks rich in lizardite serpentine are best. The extraction rate decreases significantly as the proportion of olivine increases, and reaches unacceptably low values as the antigorite serpentine or particularly the pyroxene and amphibole increase.

1.5 CONCLUSIONS

A set of Mg extraction experiments has been carried out using an ammonium sulphate leach. This is the first time a series of consistent experiments have been carried out on well-characterised starting materials. This is a major step forward in knowledge of the technology and enables the behaviour of many types of ultramafic rocks to be predicted. These results are probably applicable to other acid leach treatments but not other methods.

From the testing over a 60 minute Mg extraction period the conclusions are:

- The most suitable rocks are lizardite serpentinites, with 80% extraction
- Olivine gives reasonable results, 55% extraction
- Serpentinised peridotites, a mixture of olivine and lizardite with some pyroxene (probably the largest resource worldwide), give results between these extremes with typically 65% extraction
- Antigorite serpentinites are poor (40% extraction)
- Rocks rich in amphibole and pyroxene are poor (typically 25% extraction)
- Mafic rocks with 50% feldspar are worst, with 5% extraction

The data obtained show that rocks rich in antigorite, pyroxene and amphibole should no longer be considered as suitable resources for utilisation by this leaching method.

If the method could be modified to improve the extraction from antigorite, pyroxene and amphibole the volume of possible resources would be significantly increased.

2 Task 1.7 Detailed assessments of obstacles to mineral accessibility and availability

2.1 EXECUTIVE SUMMARY

This section addresses possible constraints on exploitation of resource rocks in the areas rated as most promising in the Stage Gate 1 study. This analysis shows that no areas have any particular constraints from the point of view of accessibility and logistics. The Lizard and to a lesser extent Shetland have a range of planning restrictions according to current planning rules for quarries, but Ballantrae, Portsoy and Belhelvie have few restrictions. It is pointed out that if CCSM was considered an important application and very large quarries were required, planning would most likely be dealt with by the new Infrastructure Planning Unit, not local planning authorities.

2.2 INTRODUCTION

The Stage Gate 1 report (Zimmermann et al. 2010) identified the size and locations of ultramafic rocks that could be used as a source material for CCSM. These rock bodies were ranked according to their size and location including simple criteria regarding remoteness, topography, and transport. The Phase 2 activities have been concerned solely with the locations rated A and the largest rated A/B at Portsoy. This section of the report addresses those aspects of the locations that might pose obstacles to the exploitation of a resource, including practical features such as topography, and also regulations related to planning and permission to operate at these locations.

2.3 THE PLANNING SYSTEM

In the UK, the use and development of land is controlled through the planning system. The planning system seeks to resolve conflicting interests in land use in economically, socially and environmentally sustainable ways – a balance that market forces alone would not deliver.

The planning system for most development is governed by European and UK legislation, implemented through Government policy, and incorporated into development plans at the local level. These are prepared by local planning authorities in consultation with local communities and set out the broad framework for development within their area. Using this 'plan-led' system, local planning authorities are responsible for administering their development plan and granting approval on most applications for developments based on it, except where there are other overriding considerations.

However, for nationally significant infrastructure, there is a specific set of national policy documents, which apply to development proposals, and applications for development are determined by a national planning body. At present, this is the Infrastructure Planning Commission, although this is soon to change to a democratically accountable Infrastructure Planning Unit (IPU). It is likely that applications for Carbon Capture and Sequestration by Mineralisation (CCSM) projects would be determined by the IPU, as they would be vital for energy developments, which will also be decided by the IPU. Despite this high-level decision making, local policies are still taken into account, and projects need to be carried out to high environmental standards, including the application of appropriate requirements to mitigate the effects of the development as far as possible.

For the purpose of analysing the possible planning and environmental issues that should be considered when evaluating potential sites for the mineralisation methods proposed, parallels are drawn, throughout this document, with the minerals extractive industry (quarrying). It has to be borne in mind that for CCSM to be operated on a meaningful scale in the UK, using UK-sourced feed material, this would require the operation of quarries as large or larger than any currently in existence in the UK.

2.4 ENVIRONMENTAL IMPACT ASSESSMENT

A large development, such as any proposed quarry to be used for CCSM, is likely to have significant effects on the surrounding area. Therefore, planning applications for this size of development will require an Environmental Impact Assessment (EIA) in accordance with the European Commission Council Directive 85/337/EEC, as amended and transposed into UK regulations. EIA is a process by which information about the environmental effects of a project is collated, evaluated, and presented in a form that provides a basis for consultation and enables decision makers to take account of these effects when determining whether a project should proceed. The output from this process is a document called an **Environmental Statement** (ES). Box 1 provides more detail about what should be included in an EIA.

Box 1 Information for inclusion in environmental statements[1]

SCHEDULE 4 Information for inclusion in environmental statements

PART 1

1. Description of the development, including in particular—
   (a) a description of the physical characteristics of the whole development and the land-use requirements during the construction and operational phases;
   (b) a description of the main characteristics of the production processes, for instance, nature and quantity of the materials used;
   (c) an estimate, by type and quantity, of expected residues and emissions (water, air and soil pollution, noise, vibration, light, heat, radiation, etc) resulting from the operation of the proposed development.
2. An outline of the main alternatives studied by the applicant or appellant and an indication of the main reasons for the choice made, taking into account the environmental effects.
3. A description of the aspects of the environment likely to be significantly affected by the development, including, in particular, population, fauna, flora, soil, water, air, climatic factors, material assets, including the architectural and archaeological heritage, landscape and the inter-relationship between the above factors.
4. A description of the likely significant effects of the development on the environment, which should cover the direct effects and any indirect, secondary, cumulative, short, medium and long-term, permanent and temporary, positive and negative effects of the development, resulting from—
   (a) the existence of the development;
   (b) the use of natural resources;
   (c) the emission of pollutants, the creation of nuisances and the elimination of waste,
   and the description by the applicant or appellant of the forecasting methods used to assess the effects on the environment.
5. A description of the measures envisaged to prevent, reduce and where possible offset any significant adverse effects on the environment.
6. A non-technical summary of the information provided under paragraphs 1 to 5 of this Part.
7. An indication of any difficulties (technical deficiencies or lack of know-how) encountered by the applicant or appellant in compiling the required information.

PART 2

1. A description of the development comprising information on the site, design and size of the development.
2. A description of the measures envisaged in order to avoid, reduce and, if possible, remedy significant adverse effects.
3. The data required to identify and assess the main effects which the development is likely to have on the environment.
4. An outline of the main alternatives studied by the applicant or appellant and an indication of the main reasons for the choice made, taking into account the environmental effects.
5. A non-technical summary of the information provided under paragraphs 1 to 4 of this Part.

Environmental impacts can be positive or negative, direct or indirect, short, medium or long term, and temporary or permanent. Impacts will vary for the different stages of the development (development and commissioning, operation, closure and decommissioning). Impacts may result from visual intrusion, noise, dust and fine particulates, blasting and traffic, dewatering, water

[1] Source: http://www.legislation.gov.uk/uksi/2011/1824/schedule/4/made

pollution, and/or visual intrusion. A quarry as envisaged by the project will include potential impacts on different aspects of the environment such as:

- population
- fauna and flora
- soil
- water
- air
- climatic factors
- material assets, including the architectural and archaeological heritage
- landscape

All the effects of the development will need to be considered and any control measures to prevent impacts or to mitigate impacts will need to be put forward in the EIA. As part of the EIA process, national policies and local policies will be used to guide the decision maker in an assessment of whether impacts are 'acceptable' and the development can, therefore, be permitted. There is a great deal of baseline environmental data to collect in accordance with EIA practice and procedure.

2.4.1 Protected areas

There are certain aspects of the baseline environment that are relatively easy to identify and document – such as the environmental designations or protected areas present in an area. This would be done as part of the assessment on flora and fauna, and also as part of the assessment on material assets.

National policy documents in the UK that are particularly relevant to any areas that are recognised in planning policy for their landscape, ecology or heritage interests are given below:

Scotland	Wales	England
Scottish Planning Policy	Planning Policy Wales Minerals Planning Policy Wales	Planning Policy Statement 9: Biodiversity and Geological Conservation Minerals Policy Statement 1: Planning and Minerals

Any development that takes place in areas that these policies relate to will need to take account of the relevant documents that are listed above.

2.4.2 Management of development in protected areas in the UK

Within the UK, there are numerous statutory and non-statutory protected areas such as National Parks and Sites of Special Scientific Importance (SSSIs). The Joint Nature Conservation Committee[2] provides a directory of UK protected sites. In addition, protected areas are now widely available to view online using interactive maps or to download for use in Geographical Information Systems. This information is provided in Appendix 4.

The presence of one or more protected areas does not necessarily preclude development. It is the significance of any 'harm' to the protected area that is important (Box 2). The purpose of the planning process is to try to reconcile the competing uses of land for development and environmental protection.

[2] http://jncc.defra.gov.uk/Default.aspx

Box 2 Planning Policy Statement 9: Biodiversity and Geological Conservation[3]

'The aim of planning decisions should be to prevent harm to biodiversity and geological conservation interests. Where granting planning permission would result in significant harm to those interests, local planning authorities will need to be satisfied that the development cannot reasonably be located on any alternative sites that would result in less or no harm. In the absence of any such alternatives, local planning authorities should ensure that, before planning permission is granted, adequate mitigation measures are put in place. Where a planning decision would result in significant harm to biodiversity and geological interests which cannot be prevented or adequately mitigated against, appropriate compensation measures should be sought. If that significant harm cannot be prevented, adequately mitigated against, or compensated for, then planning permission should be refused.'

page 3

'Where a proposed development on land within or outside a SSSI is likely to have an adverse effect on an SSSI (either individually or in combination with other developments), planning permission should not normally be granted.'

page 5

2.4.3 Other sites that are not protected by statute

In addition to areas protected in statute, there are also areas that are important at a local level, and that are protected through local policies. This applies to local wildlife and geological sites. As identified above, these will still need to be taken into account if an application is submitted for a nationally significant project.

2.5 POTENTIAL SITES FOR CCSM

Five potential areas for large scale CCSM have been identified by project geologists. It was not within the remit of this project to undertake a full planning review or an EIA. However, it is necessary to have an awareness of the environmental and planning issues associated with a development such as those envisaged. It is possible at an early stage to collate and view protected area (or designation) data in the immediate and surrounding environment of potential sites for CCSM. This may give an early indication of which potential sites will be more or less acceptable, in planning terms, in the long-term. Features of the areas of interest, such as the transport network, the topography and tree cover, can also give an indication of the suitability of each site for CCSM. A local policy review focussing on minerals policies has also been undertaken for the Lizard, in order to demonstrate the type of local policies that an application will be considered against. A summary is shown in *Work Package 1: Stage Gate 2 Report Appendix Chapter A4.3: Planning Policies–Lizard peninsula as an example of local planning policies*. This has been used as an example of all the types of possible restrictions. For the other locations, only the more important aspects have been included.

For each of the five potential sites the major designations in the area are described, coupled with a short description of the access to and topography of each area (Figures 6 to 10).

2.5.1 The Lizard, Cornwall

Figure 6 shows the location of the Lizard, the international and national protected areas in and around the ultramafic rock bodies, and the general geographical and cultural features of the area[4].

[3] Source: http://www.communities.gov.uk/publications/planningandbuilding/pps9

[4] Please note that the 'features maps' have been created to provide context for the reader. The scale of map that was used to analyse the topography and road network was 1:50,000.

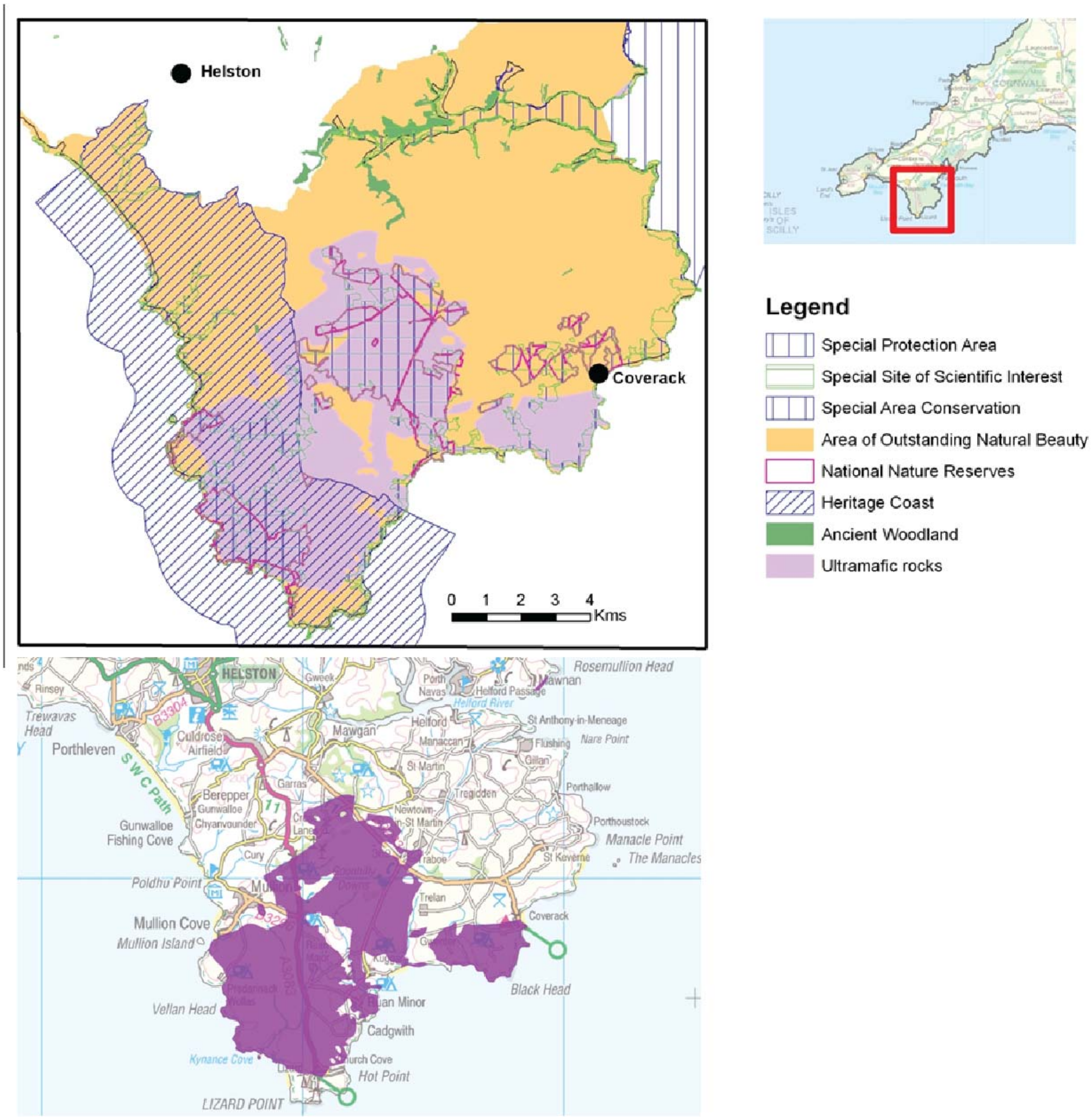


Figure 6. Maps showing the extent of major environmental designations in the Lizard area[5] plus geographic and cultural features[6]. The location of ultramafic rocks is shown in purple

All of the Lizard bodies are within an Area of Outstanding Natural Beauty. The south-western body is also mostly designated as Heritage Coast and largely covered by National Nature Reserves, Special Protection Areas, and Special Areas of Conservation. The coastal boundary of the entire peninsula is designated as a Site of Special Scientific Interest. The central body is fragmented by National Nature Reserves, Special Protection Areas and Special Areas of Conservation. The most easterly body is less fragmented by designations, but is still encircled by them.

The Lizard bodies occur at the southernmost part of the mainland of Britain and therefore they have very good access for transport by sea (English Channel). There are several private fishing ports and harbours in the vicinity, however only Porthoustock is listed as being for private,

[5] © Natural England (2011), reproduced with the permission of Natural England. OS Topography, © Crown Copyright 2011
[6] Grid squares 10 km. OS Topography, © Crown Copyright 2011

commercial use[7]. This has been used in recent years for the export of rock from a quarry at Porthoustock. The nearest major port, defined as *'any port with two or more berths and facilities and equipment capable of discharging 100,000 tons of cargo per month from ocean-going ships'* (http://www.thefreedictionary.com/), is located at Plymouth, 100 km away.

Onshore the access would be limited in most areas by the need to use B roads, which feed into the main A roads. The majority of these A and B roads are single carriageway, and a traffic impact assessment would be necessary to assess the impacts on the roads of increased heavy goods vehicle movements, including any impacts on the safety of residents in towns and villages en route.

Most of the area identified with suitable rocks is relatively low lying (<90mAOD), with gentle gradients except at the coast where there are cliffs and where rivers have eroded steeper valleys. It seems unlikely that there would be any exploitation issues as a result of the topography of the area.

The numerous designations covering most of the area could lead to considerable opposition and obstacles to the operation of a very large quarry at the Lizard, particularly in the western part.

2.5.2 Ballantrae

Figure 7 shows the international and national protected areas in and around the Ballantrae ultramafic rocks in southwest Scotland, and the general geographic and cultural features of the area.

The northerly ultramafic rock body is approximately 30% covered with Sites of Special Scientific Interest, Special Protection Areas, and Special Areas of Conservation. The southerly body hosts separate discrete areas with the same designations, which account for around 25% of the surface area. However, in the west, nearer the coast, there are less designations. The coastline between Ballantrae and Girvan is mostly designated as Sites of Special Scientific Interest, though it is not continuous.

The Ballantrae ultramafic rocks are situated on the west coast of Scotland, neighbouring the waters of the Irish Sea. Although there are a few fishing ports and harbours close to the area, the closest commercial major port is in Ayr to the north[8].

The network of roads in the area of Girvan–Ballantrae is reasonable and the use of a combination of A and B roads would provide fairly good access to the site of interest. A transport impact assessment would identify whether these roads are suitable to support the volume of heavy goods vehicles that would be necessary for any CCSM development to proceed.

The whole area is covered by hills, which are around 200 m in height, with varying gradients. In general, the hills that comprise the area of interest near Ballantrae are less steep and lower in the west and more steep and higher in the east. The area of woodland / forest lying to the west of the A174 and north of the B734 will need to be considered at the planning stage, as it may provide screening, but removal of the trees for access may not be acceptable.

In general the overall topography and access and limited number of areas covered by environmental designations indicate that Ballantrae might encounter fewer obstacles to development than the Lizard.

[7] www.ports.org.uk
[8] http://planningportal.marinemanagement.org.uk/#

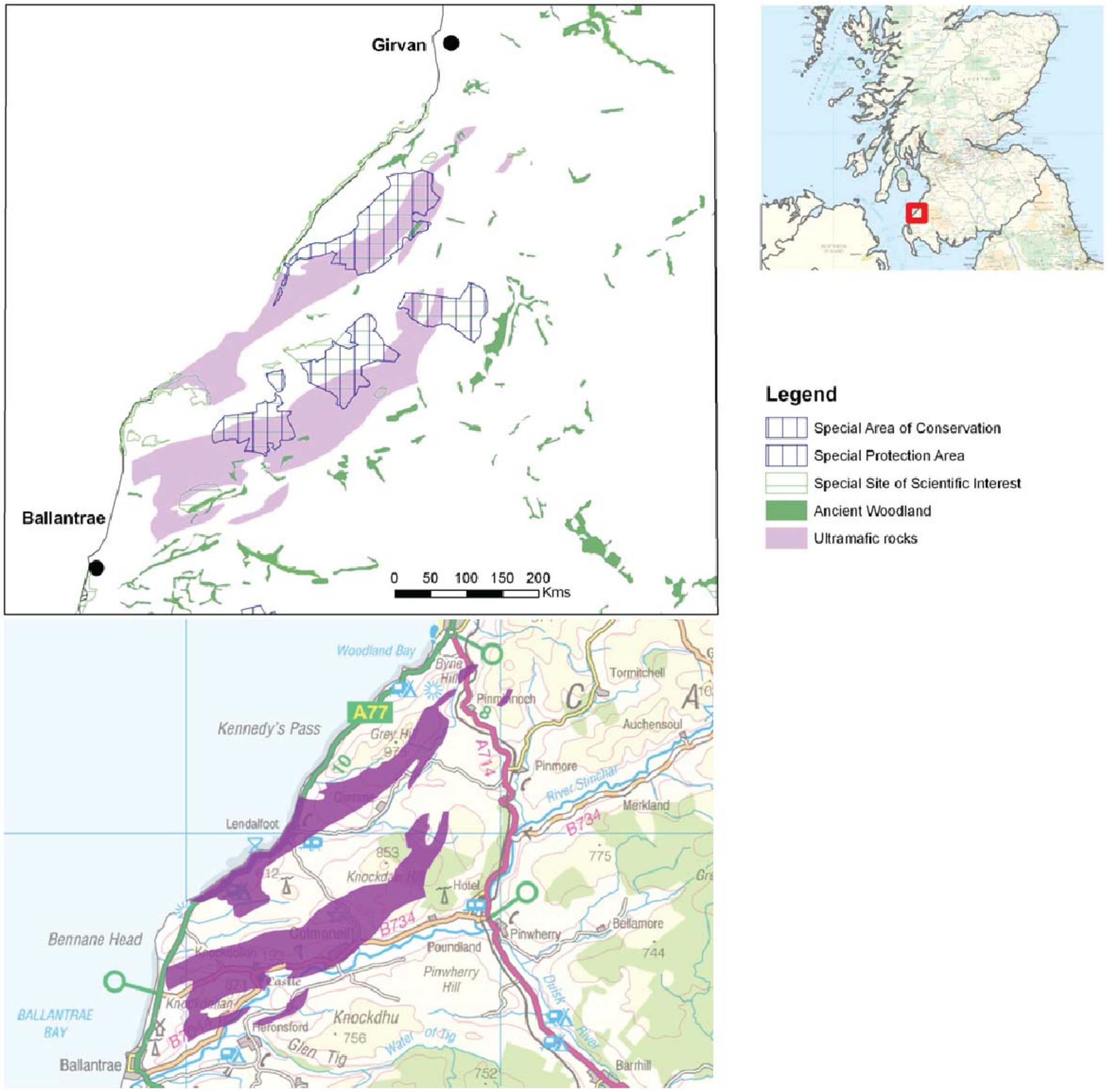


Figure 7. Maps showing the extent of major environmental designations in the Ballantrae area[9] plus geographic and cultural features[10]. The location of ultramafic rocks is shown in purple

[9] © Crown copyright and database right (2011). All rights reserved
[10] Grid squares 10 km. OS Topography, © Crown Copyright 2011

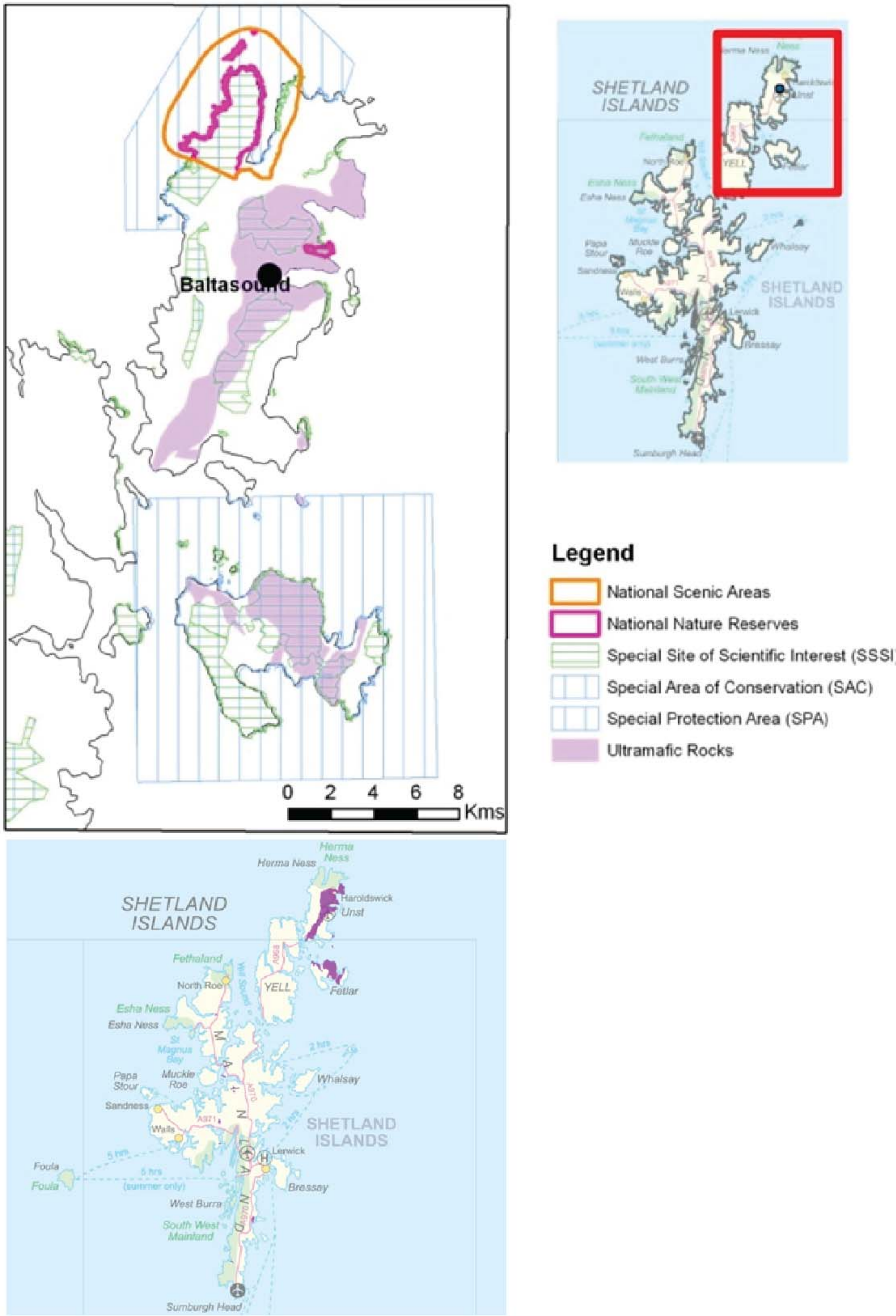


Figure 8. Maps showing the extent of major environmental designations in the Shetland Isles[11] plus geographic and cultural features[12]. The location of ultramafic rocks is shown in purple

[11] © Crown copyright and database right (2011). All rights reserved

[12] Grid squares 10 km. OS Topography, © Crown Copyright 2011

2.5.3 Shetland Isles

Figure 8 shows the international and national protected areas in and around the Shetland Isles ultramafic rocks and the general geographical and cultural features of the area. The Isle of Fetlar ultramafic body is almost entirely covered with major designations for protected areas (Sites of Special Scientific Interest, Special Protection Areas and Special Areas of Conservation). The Isle of Unst ultramafic body is partly covered by two Sites of Special Scientific Interest. Along the east coast there are also some Sites of Special Scientific Interest.

The virtually treeless islands lie about 180 km northeast of the Scottish mainland. There are two ports/harbours identifiable on the Isle of Unst (www.ports.org.uk/). Neither is listed as commercial, although Baltasound is listed as a leisure, fishing, and ferry terminal. On the Isle of Fetlar, only Oddsta is listed, which is a ferry terminal. There are no major ports on the Isle of Unst or Fetlar[13].

Despite its geographical isolation, the road network is fairly good on Unst (a combination of A and B roads) but less satisfactory on the island of Fetlar, where there is only one B road running NW across the island. There is an existing quarrying industry on Unst, but not on the scale envisaged for CCSM. A transport impact assessment would be necessary to ascertain whether the roads are suitable for haulage vehicles. Both islands are covered with hills, some reaching 100–150 m AOD.

In general, the Isle of Fetlar has drawbacks from both logistical and planning aspects, but the main Isle of Unst may have areas suitable for the location of a quarry.

[13] http://planningportal.marinemanagement.org.uk/#

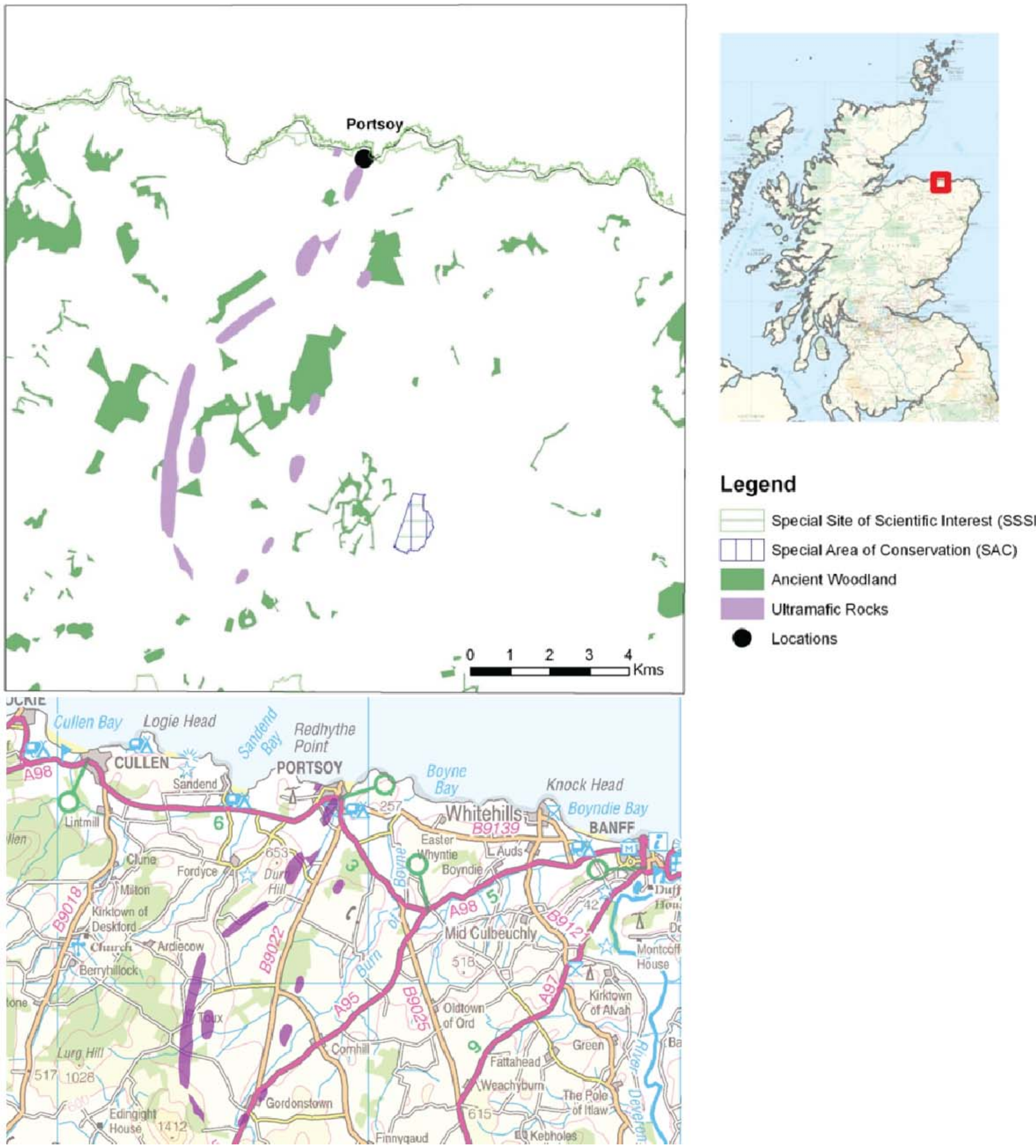


Figure 9. Maps showing the extent of major environmental designations in the Portsoy area[14] plus geographic and cultural features[15]. The location of ultramafic rocks is shown in purple

2.5.4 Portsoy

Figure 9 shows the international and national protected areas in and around the Portsoy ultramafic rocks in north-east Scotland, plus the general geographic and cultural features of the area. The ultramafic bodies mostly underlie areas without designations. Ancient Woodland does intersect at places, but the bodies are not fragmented. Sites of Special Scientific Interest are present along the coast.

There are several leisure/fishing harbours/ports around Portsoy[16] but no major ports[17]. The area is readily accessible by a network of A, B, and unclassified roads. The ground underlain by

[14] © Crown copyright and database right (2011). All rights reserved
[15] Grid squares 10 km. OS Topography, © Crown Copyright 2011
[16] http://www.ports.org.uk/area.asp?area=57
[17] http://planningportal.marinemanagement.org.uk/#

ultramafic rock is, overall, fairly low-lying, undulating farmland. However, the town of Portsoy is an exception as it is underlain by the ultramafic rocks located close to the Moray Firth coast. There are many areas of woodland / forest in the vicinity that would need to be considered during the planning process.

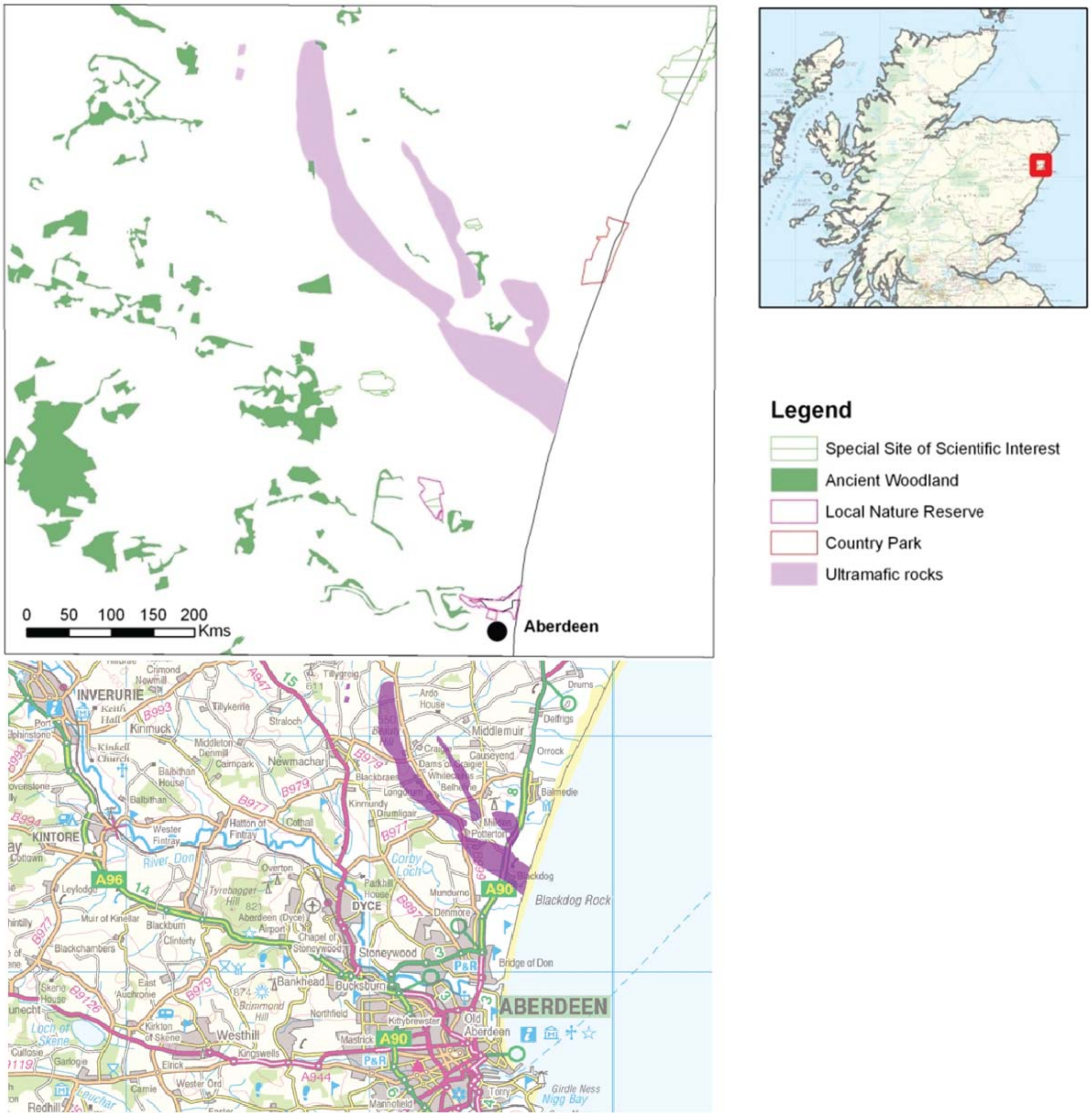


Figure 10. The extent of major environmental designations in the Belhelvie area[18] plus features in and around the Belhelvie area[19]. The location of ultramafic rocks is shown in purple

2.5.5 Belhelvie

Figure 10 shows the international and national protected areas in and around the Belhelvie ultramafic rocks in north-east Scotland plus the general geographic and cultural features of the area.

The ultramafic bodies are mostly free from any major environmental designations. Ancient Woodland does intersect at places, but the bodies are not fragmented. The coastal area is also largely free of any protected areas.

[18] © Crown copyright and database right (2011). All rights reserved
[19] Grid squares 10 km. OS Topography, © Crown Copyright 2011

There are no major ports or harbours in the immediate vicinity of the sites of interest, although there is a large port in Aberdeen, which is listed for commercial and fishing uses[20]. Road access is reasonable to good, via the B977, B979, A947, and the A90 dual carriageway. Although pre-existing settlements will likely preclude full exploitation of this resource, the contours suggest that the land is relatively flat with low inclines in most places.

[20] http://planningportal.marinemanagement.org.uk/# and www.ports.org.uk).

3 Task 1.8 UK resources

3.1 EXECUTIVE SUMMARY

Potential feed materials for CCSM from UK sources have undergone detailed mineralogical characterisation and Mg-leaching experiments. The results show that the lizardite serpentinites from Ballantrae, Portsoy, and Belhelvie are good feed materials. The studies show that the rocks from Shetland include a large proportion of antigorite serpentinites that have poor reactivity and the volume of resource is downgraded by 50%. The rocks from the Lizard have substantial amphibole peridotite/serpentinites that also have poor reactivity and the resource is downgraded by 40%. The revised resource based on a better knowledge of the rock types and actual experimental tests of reactivity gives a resource of 9.5 Gt, roughly 4 times the target for the project.

3.2 INTRODUCTION

The Stage Gate 1 report (Zimmermann et al. 2010) identified a number of areas of potential source rocks and rated them according to various parameters. This produced a shortlist of areas rated A or A/B that were considered the main resource areas. The resource of 13.5 Gt was based on the assumption that all rock types were equally suitable. The purpose of this Task was to use the information gained from resource definition studies (Task 1.6) to refine the resource estimate according to geological rock type and to carry out leaching experiments on actual samples of UK rocks to confirm that they showed similar characteristics to those studied for resource definition.

BGS had samples in the archive collection, of sufficient size (several kg) for experiments, from the most distant locations of the Lizard in Cornwall and the Shetland Isles. Suitable samples from Ballantrae, Belhelvie, and Portsoy were lacking and hence were collected on a field visit in July 2011. In addition to these samples, one sample of 100 kg was collected from Ballantrae to be available for a suite of tests all on a rock of the same composition, a 'typical' UK serpentinite.

All samples have been carefully and comprehensively characterised by optical microscope, X-ray diffraction, and bulk chemistry by XRF. It is critical to know exactly what is being used in the experiments to make meaningful interpretation of the data. This has been a serious weakness in much previously published data.

3.3 BALLANTRAE AREA

3.3.1 Geological summary

The ultramafic bodies of Ballantrae are located on the coast, *c.* 75 km SW from Glasgow, in between the towns of Girvan and Ballantrae. There are two SW–NE trending belts:

a) Northern Serpentinite Belt [NX 1810 9487] – up to 1.5 km wide, extends over an area of 12.8 km^2

b) Southern Serpentinite Belt [NX 092 859 – NX 183 905] – up to 2 km wide, occupies an area of *c.* 19.1 km^2.

Both belts were investigated during fieldwork in July 2011. The serpentinite bodies are in fault-bounded blocks amongst sedimentary and volcanic rocks in the Midland Valley Terrane of central Scotland (Figure 11A). The topography of the area is undulating hills with several areas of low crags (Figure 11B–C). The extent of the amphibolite bodies is an important feature as these rocks are not suitable for carbonation. They are harder than the surrounding serpentinites and form most of the low crags shown on the photo in Figure 11C. It is assumed that this means their extent is fairly accurately shown on the existing geological maps. Their size and different appearance, and the occurrence in discrete bodies, all suggest that they could be avoided during a quarrying operation and possibly even used as an aggregate by-product. The area of ultramafic rocks has been recalculated using more accurate data as shown on Figure 11A and after removal of the amphibolites is only 2% less than the original estimate.

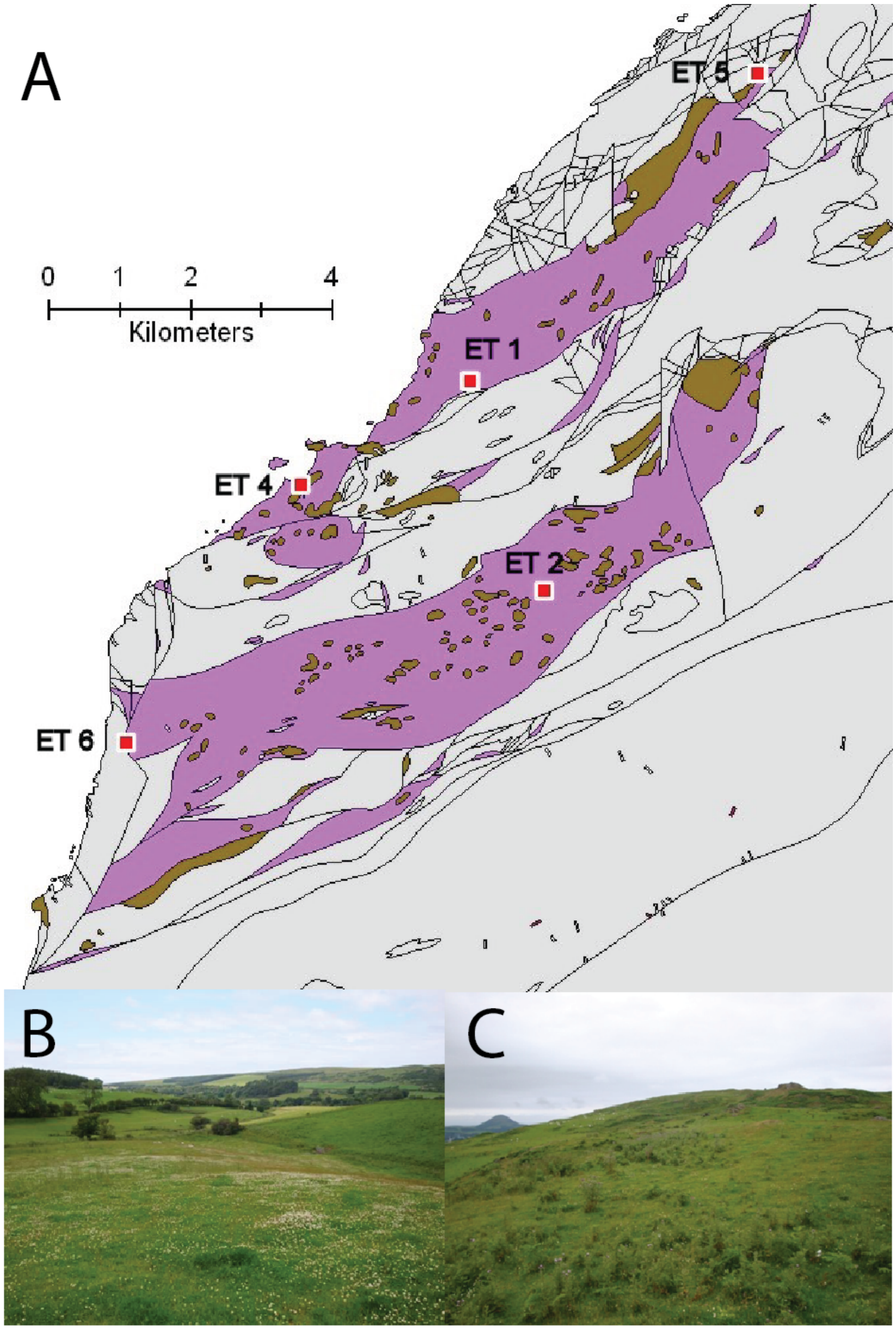


Figure 11. A: Geological map of the area between Ballantrae and Girvan, showing two Serpentinite Belts and the location of samples collected during fieldwork in July 2011. The ultramafic rocks are shown in purple, amphibolite in brown and country rocks in grey. Red squares show sample locations[Copyright BGS, NERC]; B: typical Southern Serpentinite Belt landscape; C: landscape around mafic intrusions found

between Knockdaw Hill, Breaker Hill and Craig Hill, southern belt. The small outcrop on the skyline is amphibolite.

3.3.2 Mineralogical summary

The petrographic analysis of the thin sections of the samples collected showed that all the ultramafic rocks are serpentinites with traces of chlorite but no relics of the original olivine and pyroxene.

A study of 130 sections from the BGS collection showed that good serpentinites, similar to those tested, are present throughout the area. In areas close to faults there are rocks that have already undergone partial or extensive carbonation due to natural processes, but these are thought to be of very limited areal extent. There are also a few samples of pyroxene-containing ultramafic rocks in the northern part of both belts that make them less suitable. These rock types are not shown separately on the existing maps and it is thought that they are of limited extent. Sections of various mafic rocks, those shown in brown on Figure 10, confirmed that they are not suitable.

The mineralogy determined by quantitative XRD showed very similar results to the thin sections and indicated that all the serpentine is the lizardite polymorph. One sample had traces of amphibole (1.7%) and prehnite, an alteration product of plagioclase feldspar.

3.3.3 Results of reactivity experiments.

Four samples of serpentinite and one amphibolite from Ballantrae have been used for Mg leaching experiments and the results are shown in Figure 12.

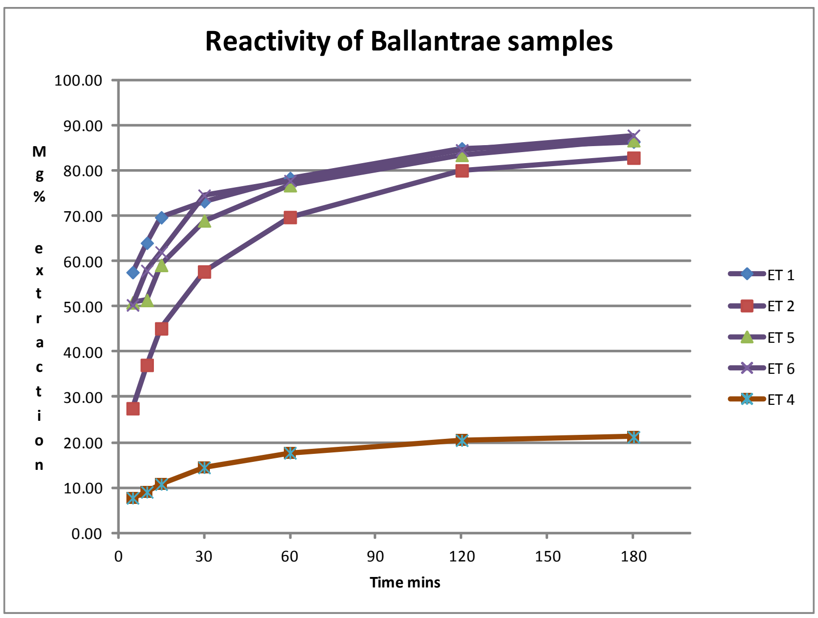


Figure 12. Plot of Mg extraction versus time for the Ballantrae serpentinites (ET 1, ET 2, ET 5, ET 6) and amphibolites (ET 4)

These results show that all the serpentinites have very good leaching properties with nearly 80% extracted after 60 minutes. In stark contrast, the amphibolite releases less than 20% and hence is not suitable for carbonation.

3.3.4 Summary

Mineralogical analysis of samples from Ballantrae shows that the serpentinites are all lizardite and broadly similar. They have good reactivity and are highly suitable for mineral carbonation. This is a large potential resource and alone is roughly the target amount for the project. There are areas of amphibolite within the serpentinite that need to be avoided but they appear to be of a size where they could be quarried separately and used for aggregate. If this is not possible, the overall grade of the deposit might be reduced by around 10%.

3.4 BELHELVIE AREA

The Belhelvie intrusive mass, located around 10 km to the north of Aberdeen, occupies an onshore area of *c.* 25 km^2. Of this 25 km^2, just over 10 km^2 are accounted for by ultramafic lithologies. The ultramafic rocks occur principally as two NW–SE trending strips, one lying along the southern flank of the intrusion, with the second being found towards its centre. The remainder of the intrusion comprises gabbroic rocks that are not suitable for carbonation

The Belhelvie intrusion is part of the Newer Gabbro suite of intrusions in NE Scotland. These are a group of gabbros and minor peridotites that occur in a series of intrusions within the metasedimentary rocks of the Scottish Highlands (Figure 13A). They are part of the ‘Layered Intrusion Group’ (see Section 4.2 below) and have a different origin to the ‘Ophiolite mantle Group’ that includes all the other rocks studied here.

The area is farmland with low rolling hills and actual rock outcrop is rare (Figure 13B–C). It is difficult to be sure of the actual extent of the ultramafic rocks and it is assumed that the existing geological maps are the best estimate.

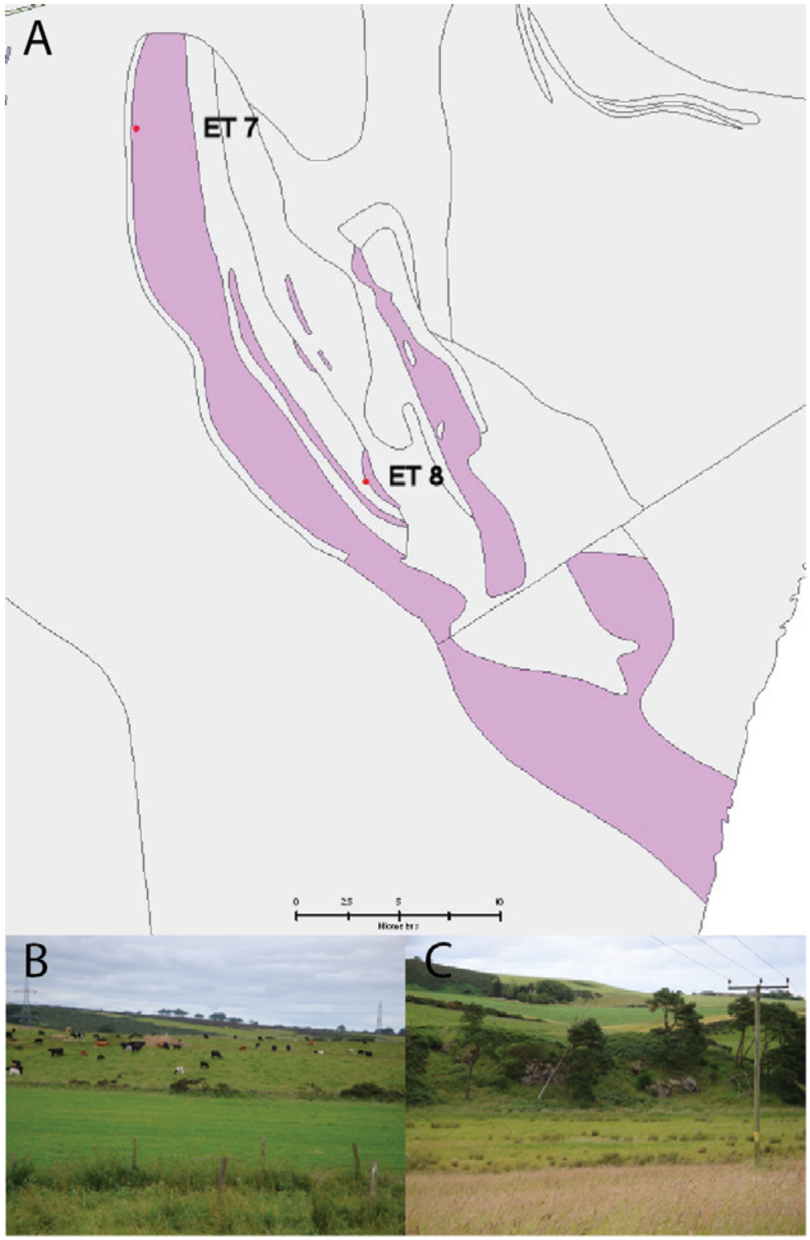


Figure 13. A: Geological map of the Belhelvie area, showing location of the two samples collected during fieldwork in July 2011. Legend of the lithological units is based on the BGS_GIS data[Copyright BGS, NERC]; B: General view of the Belhelvie area; C: A rare small outcrop of rock where sample ET 8 was collected.

3.4.1 Mineralogical summary

Two thin sections of samples collected in July 2011 have been examined. These are peridotites that have been serpentinised to around 50% but still contain substantial amounts of olivine and pyroxene (20-30%) and minor amounts of chlorite. One sample has around 25% clay minerals, probably replacing original feldspar.

A study of the few sections from the BGS collection shows that the rocks are partially serpentinised peridotite. There is not sufficient extra information to modify interpretation.

The mineralogy determined by quantitative XRD showed a high proportion of serpentine (70-80%) and less relict olivine, pyroxene and amphibole than was observed in the thin section. The serpentine is lizardite. The clay alteration was not detected. The apparent discrepancy between the results is a function of the sample size; the thin section is point data from less than a gram of rock while the XRD is an average of several kg and likely to be more representative of a bulk source rock.

3.4.2 Results of reactivity experiments.

Two samples of the ultramafic rocks were tested and the results shown in Figure 14.

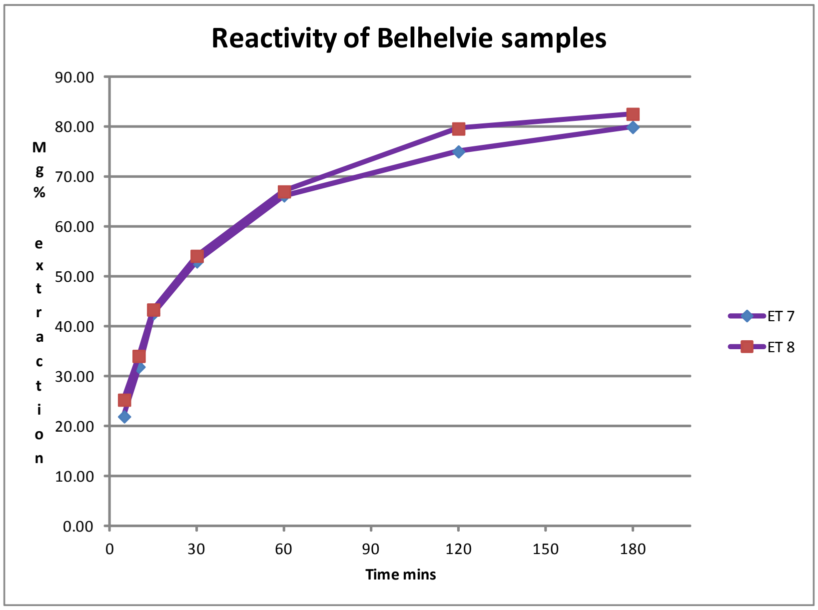


Figure 14. Plot of Mg extraction versus time for the Belhevie samples (ET 7 and ET 8).

The results show that the reactivity of both samples is almost identical with nearly 70% Mg released after 60 minutes. The proportion of less reactive olivine and pyroxene is slightly higher in ET 7.

3.4.3 Summary

The samples from Belhelvie are partially serpentinised peridotites. The proportion of serpentine in samples analysed is 70–80% and the higher presence of the less reactive olivine and pyroxene, makes them inferior to the rocks from Ballantrae with around 10% less Mg extracted after 60 minutes. The rocks here are part of a layered complex and likely to be less homogenous on a regional scale than the rocks from the ophiolite group. The lack of surface outcrop makes it impossible to assess this possible variation with any certainty. If this were to be considered as a resource, considerable geological investigation would be required. There is no new information about the area and the estimate of the resource is left unchanged.

3.5 PORTSOY AREA

The Portsoy ultramafic bodies exist as a discontinuous NNE–SSW trending belt, which extends for around 10 km inland from the Moray Firth coast. Estimating the true extent of these bodies is problematic due to poor exposure, but together they are thought to occupy an area of *c.* 4.7 km^2. For this phase of the study more detailed geological maps have been used (1:50,000) and these show a slightly larger area of ultramafic rocks which leads to a larger resource estimate.

The geology of the Portsoy area is complicated structurally and lithologically. The area comprises a wide range of metamorphic and igneous rocks. The ultramafic rocks occur as a linear belt c. 10 km long but less than 1 km wide (Figure 15A). The bodies are thought to be part of the disrupted mantle sequence of an ophiolite complex that has been tectonically emplaced along a major fault zone known as the Portsoy lineament (Styles 1994).

The area around Portsoy is farmland and woodland on rolling hills with few rock outcrops as shown in Figure 15B–C.

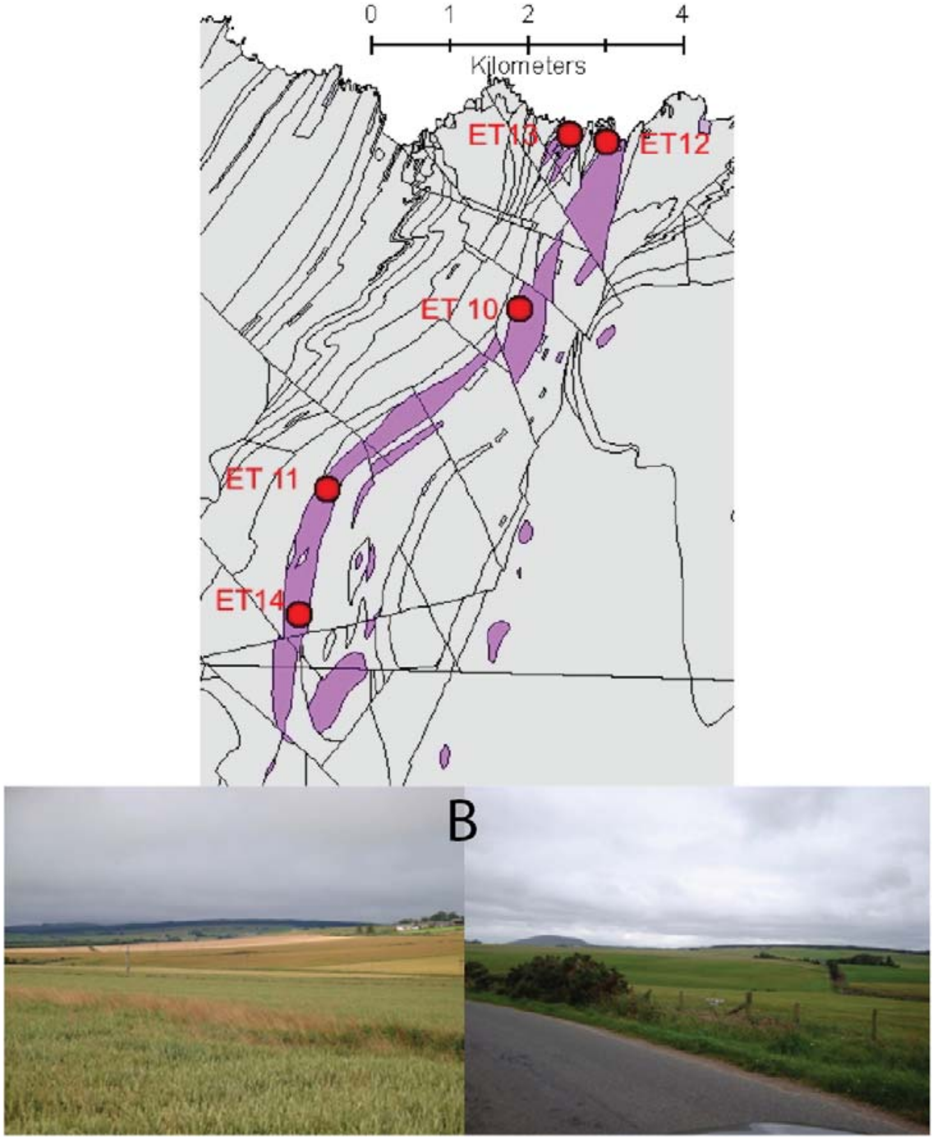


Figure 15. A: Simplified geological map of the Portsoy area with the ultramafic rocks shown in purple and the sample locations in red[Copyright BGS, NERC]; B: Views of the landscape around Portsoy showing the scarcity of rock outcrop.

3.5.1 Mineralogical summary

The petrographic analysis of the thin sections of the samples collected showed that all the ultramafic rocks are serpentinites with no relics of the original olivine and pyroxene but contained more chlorite than other samples, with 10-20% compared to around 5% in other areas.

Examination of 65 thin sections from the BGS collection shows that most are serpentinites with substantial amounts of chlorite, similar to the samples tested. Some samples from close to the western margin of the ultramafic body show significant amounts of carbonate alteration; the extent is not known but is probably relatively localised. A few samples contain significant amphibole (10-20%) suggesting that some parts are derived from a different parent rock. These rocks are likely to have a lower reactivity but there is no way to estimate how extensive they are due to the poor exposure and small numbers of samples. However it is thought that they might be of relatively local extent.

3.5.2 Results of reactivity experiments.

Five samples of serpentinite have been tested and the results are shown in Figure 16.

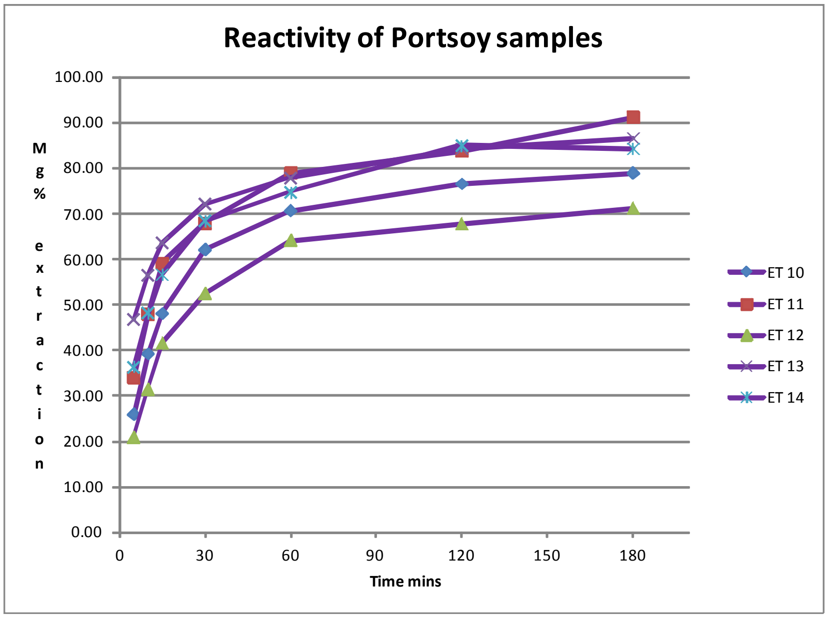


Figure 16. Plot of Mg extraction versus time for the Portsoy samples (ET 10 – ET 14).

The results from the Portsoy samples show that most are very similar to the Ballantrae samples with 70-80% extraction after 60 min. It is interesting that the samples such as ET 13 and 14 with 15% chlorite show similar extraction to pure serpentinite. ET 12 contains 3.2% talc, which contains Mg, but possibly is not leached and could explain the slightly lower extraction. It appears that chlorite does not have a negative effect on Mg leaching.

3.6 LIZARD AREA

The Lizard Complex in SW Cornwall consists of ophiolitic mafic and ultramafic rocks that are in faulted contact with the sedimentary rocks to the north. The ultramafic rocks cover an area of 54 sq km and comprise various rock types that are shown on Figure 17. The 'primary' peridotites are shown in dark purple, occur in the eastern part, and are now largely serpentinites with various remnants of olivine and pyroxene (usually less than 10% and very rarely up to 50%). Serpentinites derived from dunite (olivine rock) are shown in dark maroon and occur in the northern parts; they only rarely contain remnants of olivine. Recrystallised peridotites occur in the western part; these contain substantial amounts of amphibole after pyroxene and plagioclase feldspar, and often only around 60% serpentine.

The topography of the Lizard is a peninsula with cliffs around the coast up to 90m, and inland a relatively flat platform dissected by a few valleys. In the west much of this is moor and heath land but in the east dominantly farmland.

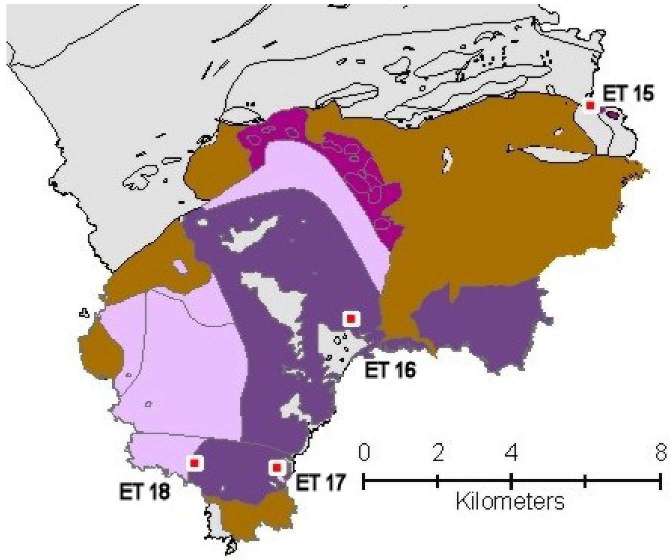


Figure 17. Simplified geological map of the Lizard Complex with ultramafic rocks shown in purple and mafic rocks in brown. Locations of samples studied are shown in red [Copyright BGS, NERC].

3.6.1 Mineralogical summary

Petrographical examination of the thin sections of the samples used for experiments reflects the variation in rock types. ET15, a dunite serpentinite, consists of serpentine with a few % of chlorite and chromite. ET16 and 17, the 'primary' peridotite serpentinites are broadly similar consisting of around 90% serpentine with ET16 having higher proportions of chlorite and amphibole, around 5% of each. In contrast the recrystallised peridotite ET18 is much less serpentinised and contains only 40% serpentine with amphibole at 25%, olivine 20% and orthopyroxene 15%.

Examination of several hundred thin sections in the BGS collection shows that rocks with a relatively low proportion of serpentine (<50%) could be common in the western area. The dunite samples from the north are all extensively/totally serpentinised. Many samples from the eastern area show more relict olivine and pyroxene than ET16 and 17 with 60-70% serpentine being quite common and some as low as 50%. It should be stressed that these samples from previous scientific projects probably tried to collect the freshest rocks to gain most information about the original rock type. These samples therefore indicate a worst-case scenario rather than a typical composition that probably has much more serpentine.

The mineralogy determined by quantitative XRD showed slightly different results. ET 15 has about 15% chlorite, higher than the thin section and consistent with results from previous studies. ET 16 and 17 are both largely serpentine but by this method, ET 17 had a higher proportion of amphibole. The data for ET18 showed a much higher proportion of serpentine 75% and proportionately lower olivine, pyroxene, and amphibole. These results highlight the heterogeneity of these rocks and, as previously stated, the XRD is probably more representative of a bulk sample.

3.6.2 Results of reactivity experiments.

Four samples of serpentinite have been tested and the results are shown in Figure 18.

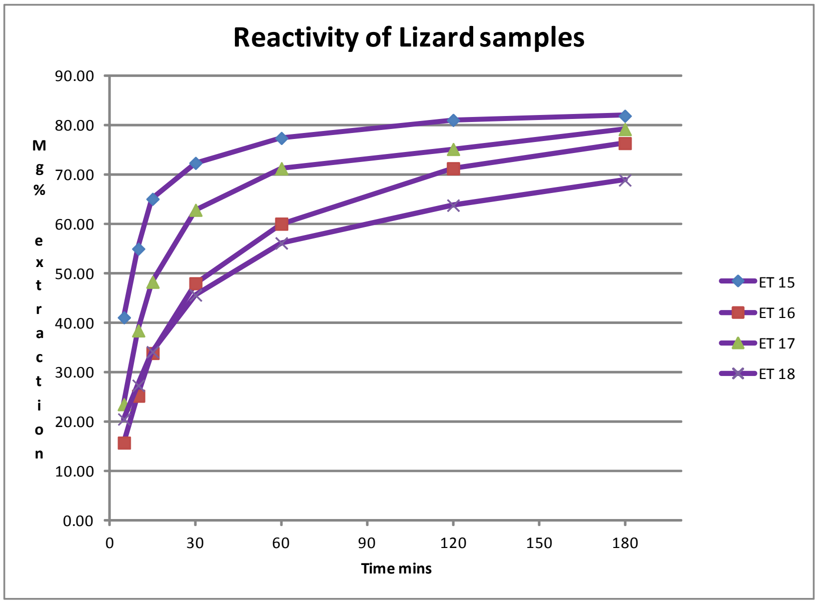


Figure 18. Plot of Mg extraction versus time for the Lizard samples (ET15 – ET 18) .

The reactivity results show that the completely serpentinised rock ET 15 gives very similar results to the serpentinites from Ballantrae and Portsoy with 80% after 60 minutes. ET 18 gives far inferior results with only 55% extracted after 60 minutes. The other rocks give results between these two reflecting the increasing amount of less reactive amphibole, pyroxene, and olivine.

3.6.3 Summary

The results of the geological studies and leaching experiments show that the rocks in the western part of the Lizard have much inferior leaching properties when compared with other localities, and hence cannot be considered a good resource rock. The resource estimate has to be reduced to the areas covered by the ‘primary’ peridotite and dunite serpentinites, 32 sq km - roughly 60% of the original estimate. The better resource rocks are fortunately in the areas with fewer planning restrictions

3.7 SHETLAND AREA

The ultramafic rocks in Shetland occur on the northernmost islands of Unst and Fetlar. They form the Shetland ophiolite Complex (Figure 19). The ultramafic rocks cover an area of 54.6 km^2 on the two islands. There are two main rock types: serpentinites derived from mantle harzburgite on the western side of the Unst body and on Fetlar; and serpentinites largely derived from dunite on the eastern side of the Unst body. Samples from the BGS Collection were selected for analysis. Only samples from the northern part of Unst were of sufficient size for all the experiments, but these cover both the dunite and harzburgite types.

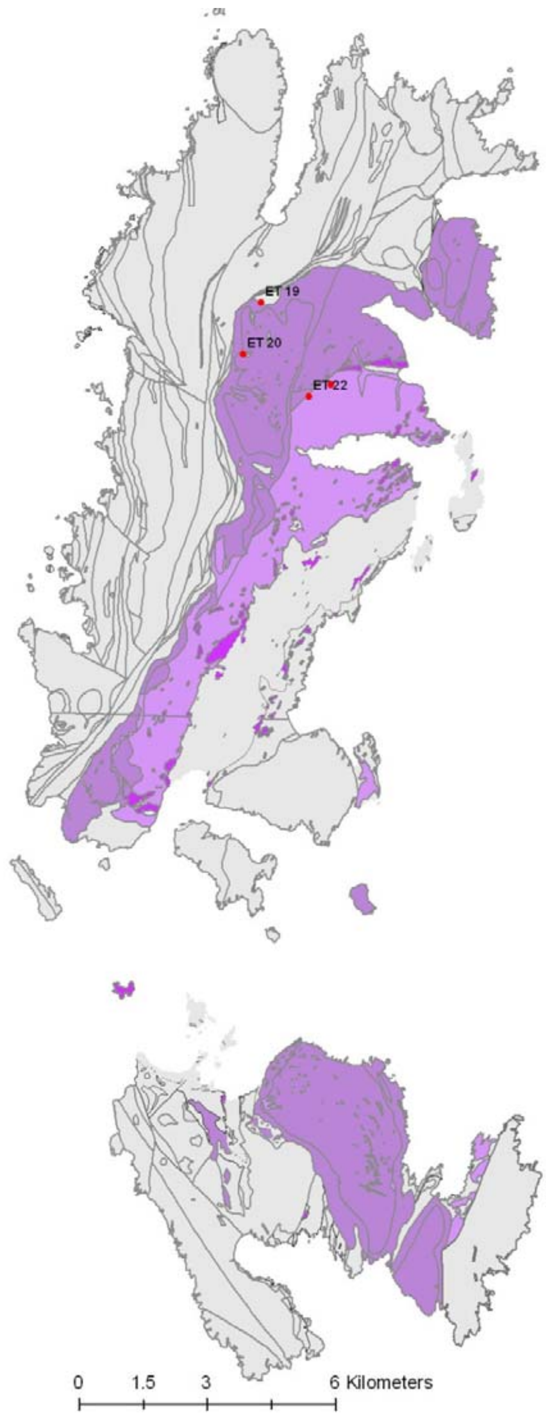


Figure 19. Simplified geology map of Unst and Fetlar with the ultramafic rocks of the ophiolite complex shown in purple. The darker shade denotes serpentinites derived from harzburgite and the lighter shade from dunite [Copyright BGS, NERC].

3.7.1 Mineralogical summary

The petrographical analysis, of the selected samples shows significant variation. They are all essentially serpentinites, but two samples ET19 and ET22 show substantial alteration to carbonate (30 and 45% respectively). The carbonate is intimately intergrown with the serpentine and this was not at all obvious in the hand specimen during sample selection. The samples show variation in the proportion of the serpentine types present; ET 19 and 20 contain both types with antigorite dominant while ET 21 only contains lizardite and ET22 only antigorite.

All samples contain minor amounts of chromite and chlorite.

Examination of 53 thin sections available from the BGS collection, all from Unst, shows that carbonation is very variable from place to place as is the proportion of antigorite and lizardite. There is no clear pattern to the distribution of the two types.

The mineralogy determined by quantitative XRD showed slightly different results. In particular the degree of carbonation was lower: in ET19 it was only 10% and in ET22 it was down to 25%. This probably means that the experimental results are representative of a rock likely to be found. The proportions of the serpentine types are similar to those estimated from optical microscopy.

3.7.2 Results of reactivity experiments.

Four samples of serpentinite have been tested and the results are shown in Figure 20.

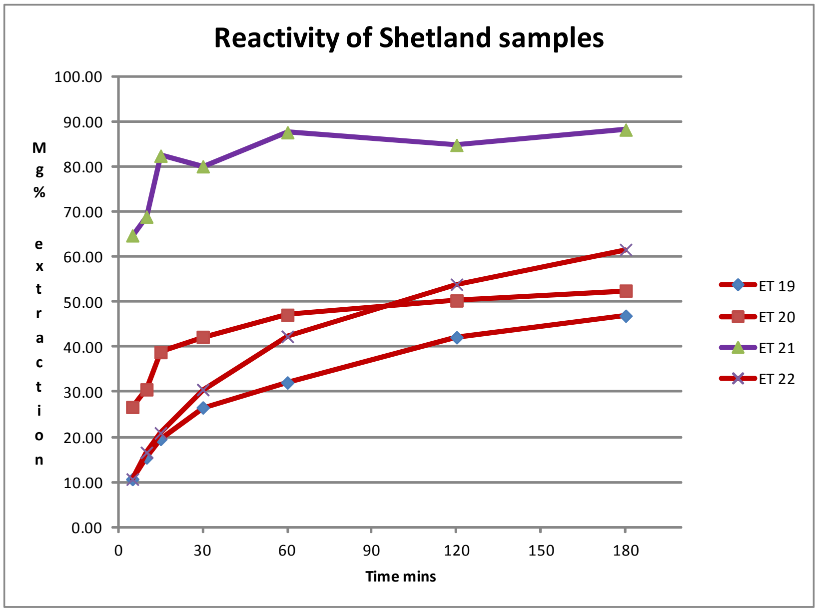


Figure 20. Plot of Mg extraction versus time for the Shetland samples (ET 19 – ET 22).

The leaching results show that the lizardite serpentinite ET19 gives good results with over 80% extraction after 60 minutes, very similar to lizardite serpentinites from other areas. The antigorite-rich serpentinites show much lower leaching with 30-45% leaching after 60 minutes. ET 20 has a much higher early release of Mg as it contains about 45% lizardite.

3.7.3 Summary

The results of the leaching experiments show that the antigorite serpentinites have much lower reactivity than the lizardite variant and hence should not be considered as a good resource. There are no maps showing the distribution of the serpentinite types and the samples we possess at BGS are too few to make a realistic assessment. It is clear that a substantial and possibly dominant proportion is antigorite, but until reliable information is available, a simplistic downgrade of the resources by 50% is suggested. A better estimate would require a detailed geological survey.

3.8 SUMMARY OF UK RESOURCES

The analysis and experiments carried out in Task 1.8 have enabled a more realistic estimate of the potential resources of ultramafic rocks that are suitable for use in the acid leach ammonia-based process that is under investigation in Work Package 2. The result is a revised estimate of the resources that is shown in Table 2.

Table 2. Revised estimates of the potential resources of ultramafic rocks suitable for CCSM using an acid leach Mg extraction

Location	Rock type	Rating	Area sq km	Resource (Mt)	Revised area	Revised resource (Mt)	% original estimate
Lizard Peninsula, Cornwall	Meta-peridotite, serpentinite	**A**	53.7	5073	**32**	**3024**	**60**
Ballantrae	Serpentinite	**A**	26.1	2421	**25**	**2363**	**98**
Belhelvie	Meta-peridotite, serpentinite	**A**	10.3	951	**10.3**	**951**	**100**
Portsoy	Serpentinite	**A/B**	4.7	439	**5.9**	**439**	**100**
Shetland Isles (Unst)	Serpentinite, meta-peridotite	**A**	38.2	3500	**19**	**1750**	**50**
Shetland Isles (Feltar)	Serpentinite, meta-peridotite	**A**	16.4	1499	**8**	**750**	**50**
Total revised resources				**13883**	**100**	**9276**	**67**

The results of the leaching experiments show that some rock types included in the original estimate are no longer considered suitable. The geological control on the extent of the unsuitable rocks is fairly good for the Lizard and the estimate is probably reliable. In the case of Shetland this is much less certain. It has to be borne in mind that we are making extrapolations based on a limited number of samples, not all of which were collected to make this evaluation, and hence not always suitable for this purpose. In the case of the Lizard, as an example, leaching of 4 samples that total around 100 g is being extrapolated to 5 x 10^9 tonnes of rock. In the case of Portsoy, newer versions of the geological maps gave a larger area (about 25%) but as the study of thin sections showed that some rocks are not suitable the estimate of the resource is not changed.

The outcome of the re-evaluation is that the overall amount of suitable resources is reduced to around 9.3 x 10^9 tonnes. This is still well above the target of around 2.5 x 10^9 tonnes. The combination of suitable rock type, good logistics, and fewer planning restrictions suggest that Ballantrae would be the best site for a pilot operation.

4 Task 1.9 Global resource review

4.1 EXECUTIVE SUMMARY

The desk-based global resource review was undertaken to provide an estimate of the amount of ultramafic rocks available according to the major geological controls identified in the Stage Gate 1 Report. These were ophiolites, layered igneous intrusions, komatiites and other Archæan ultramafic rocks. In addition, two case studies – south-eastern Europe and India – were undertaken to examine the spatial relationship between point source emitters and available ultramafic rock; the areas were chosen as they do not have ready access to underground storage. The results for the global resources assessment show significant resources – potentially up to c. 30 Tt for a 35 m quarry depth. Of these approximately 20 Tt is serpentinite suitable for the CCSM process considered here. Around 60% of this comes from ophiolites the amount of material available in layered igneous intrusions is relatively small (<1 Gt) and the remainder comes from Archæan rocks. Serpentinites associated with ophiolites often represent large volumes of comparatively homogeneous lizardite serpentinite so offer attractive targets for CCSM feedstock material.

For the two case studies, the analysis showed that for southern Europe 75% of the point source emitters were within 60 km of a serpentinite resource, potentially making this a good location for the deployment of CCSM. By contrast, in India the scope for CCSM using serpentinite was less favourable and would probably represent a niche deployment of the technology. However, if different feedstocks could be used (e.g. olivine) there is good potential.

4.2 INTRODUCTION

The Stage Gate 1a report provided: (i) a high-level overview of the geological controls on the distribution of ultramafic rocks, (ii) a review of previous country and region specific studies for the potential of CCSM (Voormeij and Simandl, 2004; Krevor et al., 2009; Bailly 2004; Mani et al. 2008) and (iii) a crude estimate of global resources.

Table 3. Ultramafic complex types (modified from Krevor et al. 2009)

Geological setting	Complex type	Description	Distribution of ultramafic minerals	Examples
Orogenic	Ophiolite (Alpine-type)	The basal section of the oceanic crust has been thrust onto continental crust	Tectonised part contains harzburgite and lherzolite hosting pods of dunite. Cumulate part contains layers of dunite. Rocks are often highly serpentinised, but some are fresh and can represent significant sources of olivine	Troodos, Cyprus; Semail, Oman/UAE
	Volcanic arc plutons (Alalskan-type)	Intrusion formed in an island-arc complex accreted onto continental crust	Concentrically zoned distribution of minerals comprising a core of dunite with zones of clino and ortho pyroxenite	Union Bay, Alaska, USA, Nizhny-Tagil, Russia (also a Pt deposit)
Intra cratonic	Layered 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	Bushveld, South Africa; Great Dyke, Zimbabwe; Duluth, Canada; Stillwater, Montana, USA

			faults and shear zones. Though ultramafic layers occur, mafic layers predominate	
	Komatiitic metavolcanic rocks	Differentiated flows and sub-volcanic intrusions in Archæan or Proterozoic mafic volcanic complexes	The basal parts of lava flows and sills are generally peridotitic. Degree of serpentinisation is highly variable	Central Lapland Greenstone Belt, Finland; Kambalda Greenstone Belt, Australia

The high-level overview of the geological controls identified that the most common occurrences of ultramafic rocks are located in mountain building zones where the Earth's tectonic plates collide. Ultramafic bodies are also located in extensional zones (rifts) within continental plates, and include layered intrusions and smaller sills and dykes (Wyllie, 1967). In addition, ultramafic rocks can be found in continental margin settings associated with continental break-up. These include sills and dykes as well as ultramafic lavas. Finally, in some of the oldest parts of continental plates (cratons), metamorphosed ultramafic lava flows (komatiites) and related subvolcanic intrusions are locally found. Furthermore, all of these rocks have distinct geological histories and show differences in location, mineralogy, and mineralogical distribution (Table 3). These different setting and rock types form the basis for the more detailed global resources review presented below

The Stage Gate 1a report (Zimmermann 2010) also identified four country / region-specific studies (USA, France, India and British Columbia [Canada]) on potential resources of ultramafic rock for CCSM. These were scaled-up to form the basis for a crude estimate of global resources (Table 4)

Table 4. Ultramafic rock resource estimates for the UK; British Columbia, Canada; USA; France; and the World.

Place	Favourable geology	Surface area (km^2)	% ultrabasic rock	Estimated resource (Mt)	CO_2 mineralising potential (Mt)[3]	Years of global CO_2 production[4]	Source for resource estimate
United Kingdom	very low	242,900	0.09	1,992	996	0.04	This study
British Columbia	good to high	944,735	3.00	272,792	136,396	4.8	Voormeij and Simandl (2004)
United States of America[1]	low	8,143,121	0.20	156,755	78,378	2.8	Krevor et al (2009)
France[2]	very low	543,965	0.06	3,141	1,571	0.06	Bailly (2004)
	good to high		3.00%	43,006,425	21,503,213	757.2	
World	intermediate	148,940,000	1.00%	14,335,475	7,167,738	252.4	This study
	low		0.20%	2,867,095	1,433,548	50.5	

[1]Not including Alaska

[2]Not including French dependent territories

[3]1 t rock sequesters 0.5 t CO_2

[4]2006 global CO_2 emissions @ 28.4Gt

depth of deposit 35 m

amount of minable ultra basic rock 10%

The Stage Gate 2a report recommended that to provide a more robust estimate it would be necessary to reproduce the work undertaken on UK resources at a more global scale, using a range of geological maps at scales of between 1:500,000 and 1:100,000 and published databases of the occurrences of ultramafic and related rocks . Though it was thought to be a large task for the whole globe, it was thought that a reasonably reliable figure could be produced.

This is the scope of the analysis reported here. In addition to the global resource estimate a more detailed view of two regions where there is limited scope for underground storage is given: these are the Balkan Peninsula (Europe), and India.

4.3 BACKGROUND INFORMATION AND ASSUMPTIONS MADE FOR CALCULATION OF GLOBAL RESOURCES

Although all ultramafic rocks contain high amounts of magnesium silicate minerals needed for the CCSM process, these minerals can be in a wide variety of compositions and concentrations, not all of which may be suitable for CCSM. The two commonest minerals which occur in ultramafic rocks suitable for use in CCSM processes are olivine and its alteration product, serpentine. For the purposes of this global resource review, these two categories have been used to define global quantities of source material. This is an over-simplification as olivine is contained in a variety of rock types such as harzburgite, dunite and peridotite in significant quantities, all with different properties and implications for CCSM processes. Similarly, there are a range of serpentinite minerals, including lizardite, antigorite and chrysotile, all of which exhibit different properties during Mg-leaching for CCSM (Section 1.4). The calculations used here take account of the results of the suitability study (Section 4.1, Task 1.6) and do not consider pyroxene rocks as source rocks. The suitability study also identified that antigorite serpentine is poor compared to lizardite. The high-level data used for this study and probably most detailed reports and publications will not have information on the variety of serpentine. This is because making accurate identification of the serpentine type is time-consuming and expensive (XRD), but rarely considered to be of any importance. It is therefore impossible to make a realistic estimate of the proportions of the minerals from the published literature. However from the authors` general knowledge and experience we suggest that a very rough estimate might be that antigorite is roughly 10-20% of all serpentine on a global scale. The process considered by this study requires lizardite serpentinite as a feedstock, but other studies and processes have considered olivine as a feedstock.

To calculate tonnages, it was assumed that the average specific gravity (SG) of fresh ultramafic rocks was 3.2 g/cm^3. However, the SG is dependent on composition and state of hydration and this can range down to 2.6 for serpentinites. For the more altered rocks 50% serpentinisation is assumed, giving a SG of 2.9. The maximum quarry depths of 35 and 100 metres were assumed. These represent two possible scenarios of extracting these minerals via open pit methods; 100 metres is a depth that open bit mining for low value bulk materials is unlikely to exceed, although a large nickel mine in serpentinite in Australia has mined to a depth of 400m.

4.4 GLOBAL RESOURCE ESTIMATIONS BY HOST GEOLOGY

4.4.1 Layered intrusions

For layered intrusions, such as Bushveld, South Africa; the Great Dyke, Zimbabwe; Duluth, Canada; and Stillwater, Montana, USA, two datasets were used for the calculations. These concern the global distribution of platinum group mineral (PGM) deposits and occurrences as, if non-magmatic occurrences are excluded; these are a proxy for the locations of layered igneous intrusions. The first dataset was obtained from Natural Resources Canada (Natural Resources Canada, 2012). This is a comprehensive global dataset containing information on many recorded occurrences of PGE mineralisation. It contains 1040 records of magmatic or laterite associated PGE occurrences (a laterite PGM deposit is formed by the weathering of PGM-bearing ultramafic rocks). Though comprehensive this contains many occurrences linked to small intrusions that may not be suitable for use in CCSM. The second dataset was compiled by the BGS and documents the locations of major occurrences of PGM, many of which host established prospects or mines; this database contains 47 records of PGE occurrences associated with magmatic deposits. Both datasets were used in the estimations as each individual merits the results can be compared and contrasted.

4.4.1.1 Estimation of outcropping area and average ultramafic rocks content of layered igneous intrusions

The data in the two datasets are point data, no comprehensive dataset showing the spatial extent of layered igneous intrusions globally exists in a readily available format. Therefore, an estimate of the average outcropping area of a layered intrusion is required. Two figures were approximated for each dataset. For the National Resources Canada dataset the outcropping area – c. 100 km^2 – of Skaergaard (McBirney 1996) was taken as the size of an average layered intrusion. For the BGS information, a figure of 2000 km^2 was taken to represent the much larger intrusions covered by this dataset. For example, the Muskox, Great Dyke, Rincon del Tigre and Stillwater intrusions all have areas between 1000 and 3000 km^2 (Table 4).

It was estimated that around 15% by volume of any layered igneous intrusion comprises ultramafic rocks. This is based on the surface outcrop and the internal stratigraphy of some typical major intrusions (Table 5). This estimate considered ultramafic rocks that may be suitable for CCSM processes,e.g olivine-rich rocks with high magnesium contents, rather than ultramafic rocks as a whole, wherever such information was available (for example from detailed stratigraphic logs through intrusions). Although a figure of 15 % was considered representative due to the varied nature of these deposits, there are some notable exceptions to this. The Great Dyke, Zimbabwe, has a surface outcrop consisting of 70–80 % ultramafic rocks (Wilson 1996) and the Bushveld complex, one of the largest layered intrusions in the world, contains less than 10% ultramafic rocks (Cawthorn *et al.,* 2002).

4.4.1.2 Composition of ultramafic rocks within layered intrusions

For the purposes of this study, it was assumed that the ultramafic rocks within layered intrusions were high forsteritic olivine peridotites and harzburgites with a low degree of serpentinisation. Ultramafic rocks not prospective for CCSM such as pyroxenite have been discounted in the previous step where information has been available. Many layered intrusions have likely been serpentinised to some degree, altering their proprieties as a CCSM feedstock material. This degree of alteration is difficult to estimate on a global scale. Typically layered intrusions may be largely unaltered; little alteration is recorded at major intrusions such as Stillwater, Duluth and the Bushveld complex. Serpentinisation and alteration is commonest at the boundaries of intrusions, where fluids have circulated. For example, dunite from the Great Dyke, Zimbabwe is 100 % serpentinised at the surface, but the degree of serpentinisation does decrease significantly with depth (Wilson 1996). Similarly, the Twin Sisters Dunite, USA, has a serpentinised zone up to 700 m thick around an unaltered dunite core (Ragan 1967).

Table 5. Compilation of properties of layered intrusions in relation to CCSM feedstock materials.

Name	Area (km^2)	Total thickness (m)	Thickness of ultramafic rocks (m)	Type of ultramafic rocks	Source
Rincon del Tigre	3000	4600	2600	Mainly dunite with bands of harzburgite and orthopyroxenite	Annells 1979
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	65000	7000-9000	1600-2100	Harzburgite, dunite (around 800m) Pyroxenite (around 1500m)	Eales and Cawthorn 1996, Cawthorn *et al.,* 2002.
Duluth	5000	-	-	Olivine cumulates	Miller and Ripley 1996
Great Dyke	3300	3000	2000	Dunite (often serpentinised) (900m) Pyroxenite 1100m)	Wilson 1996, Oberthur 2002

4.4.2 Volcanic arc (Alaskan-type) deposits

This deposit type is geographically restricted when compared to other sources of ultramafic rocks and does not contain as large a volume of feedstock materials as either ophiolites or layered intrusions. Their ultramafic component consists mainly of dunite or serpentinised dunite, much the same as many layered intrusions (Himmelberg and Loney 1995, Zohan 2002). For this reason, these deposits are not treated separately but have been included in the calculations for either ophiolite-related ultramafic rocks or layered intrusions, or sometimes both (see caveats) as they share many similarities with these two categories.

There is a small degree of double counting involved; some magmatic PGE deposits are associated with ophiolite complexes, Alaskan type intrusions, and komatiites. As a result, some igneous intrusions may also be included in the calculations for ophiolite-related and greenstone belt ultramafic rocks. Regarding the Alaskan type deposits, their contribution to global resources is comparatively small, so this is unlikely to give a significant overestimation.

4.4.3 Ophiolites

Spatial data have been generated for the global extent of ophiolite rocks; this has come from several sources (Asch 2005, Krevor *et al.*, 2009, Voormeij and Simandl 2004, Exxon Production Research Company and The American Association of Petroleum Geologists 1985). A slightly different approach has been taken for each of these sources due to the different scales and caveats associated with each dataset and due to the different geological terrains they represent. As a result, four different sets of calculations have been produced:

- Tethyan ophiolites based on Asch 2005
- Ophiolites in the USA and British Columbia based on studies by Krevor *et al.,* 2009 and Voormeij and Simandl 2004.
- Ophiolite rocks of the Urals based on Asch 2005 (strictly speaking these rocks are Alaskan type igneous intrusive complexes, which is why they are treated separately)
- Ophiolites in the rest of the world from Exxon Production Research Company and The American Association of Petroleum Geologists 1985

For ophiolite rocks the weights of both the unaltered and altered rocks have been calculated, as they may require different processes for CCSM. For the ammonia acid leach processes considered in this study, ultramafic rocks that have been altered to serpentinite are most favourable.

4.4.3.1 AREA OF ULTRAMAFIC MANTLE ROCKS WITHIN OPHIOLITE ROCKS

For all ophiolites, it was assumed that all unaltered mantle rocks could constitute a feedstock for CCSM processes. As a result, these figures represent maximum values, as impurities such as pyroxenes are likely to be present in some mantle rocks in amounts (up to 20%) that render them less suitable . This has not been factored in, as quantitative data are not readily available, on a global scale, on the amount of pyroxene.

Tethyan ophiolites: A value of 45% was used to represent the quantity of ultramafic mantle rocks within these ophiolites; this was taken from the average composition for type sections of Tethyan ophiolites (Table 6)

Ophiolites in the USA and British Columbia: A value of 50% was used for these ophiolites, as proportions of mantle to crustal rocks are generally higher for ophiolites in the tectonic regimes found in North America. (Table 6)

Ophiolite rocks of the Urals: Although these are in an ophiolite setting these deposits are not technically ophiolites and are classed as intracratonic Alaskan type intrusions and so have been treated slightly differently to other ophiolite types. Studies on this type of deposits show that around 15% of the deposit comprises dunite (Zohan 2002, Voormeij and Simandl 2004).

Rest of the world ophiolites A value of 40% was used based on the average composition of representative samples of ophiolites (Table 6). Although typically it seems that ophiolites outside the European Tethyan belt have greater proportions of mantle rocks (around 50% rather than the 45% used for Tethyan ophiolites) the mapping used to define these areas did not differentiate igneous and ophiolite-related sedimentary rocks. As a result, these areas will include sediments as well as the igneous component of ophiolites, and thus ultramafic rocks will represent a lower proportion of the total area,

Table 6. Compilation of properties of ophiolite rocks in relation to CCSM feedstock materials.

Name of ophiolite	Source	Thickness of crustal rocks (km)	Thickness of mantle (ultramafic) rocks (km)	% ultramafic rocks	Degree of serpentinisation
Cyprus – Troodos[1]	Coleman 1971	2.75	2.00	42	13% "lizardite common antigorite rare"
Cyprus - Troodos[1]	Robinson 2003	7.00	5.00	42	-
Cyprus - Troodos[1]	Dilek and Furnes 2009	5.00	4.30	46	"mainly serpentinised harzburgite"
Vourinous[1]	Coleman 1971	2.30	3.70	62	15%
Vourinous[1]	Hawkins 2003	4.75	7.00	60	-
Meirdita[1]	Dilek and Furnes 2009	7.13	4.38	38	-
Kizildag[1]	Dilek and Furnes 2009	4.88	4.22	46	"mainly serpentinised harzburgite"
Pindos[1]	Dilek and Furnes 2009	3.13	1.25	29	-
Pindos[1]	Karipi *et al.*, 2006	-	-	-	60-80%
Pindos[1]	Schmitt *et al.*, 2007	-	-	-	2.3-87.9%
Oman[2]	Dilek and Furnes 2009	10.25	4.60	31	-
Bay of islands[2]	Coleman 1971	5	3.5	41	"intensely serpentinised"
Bay of islands[2]	Hawkins 2003	3.6	2.4	40	-
Bay of islands[2]	Hawkins 2003	5.2	3	37	-
Bay of islands[2]	Komor *et al.*, 1985	-	-	-	25%
California coast[2,3]	Hopson *et al.*, 2008	2.75	1	27	-
Zambles	Hawkins 2003	4.8	5.5	53	-
Thetford Mines[3]	Schroetter *et al.*, 2003	5.5	6	52	-
Canyon mountain[2,3]	Coleman 1971	2.5	2.25	47	30%
Papua[2]	Coleman 1971	13	6	32	-
Papua[2]	Coleman 1977b	2.75	7	72	15%
New Caledonia[2]	Coleman 1971	0.5	7.75	94	13%
New Caledonia[2]	Ulrich *et al.*, 2010	0.4	1.4	78	10%
New Caledonia[2]	Ulrich *et al.*, 2010	0	0.95	100	30%
New Caledonia[2]	Ulrich *et al.*, 2010	0	1.9	100	15%
New Caledonia[2]	Ulrich *et al.*, 2010	0	2.6	100	10%
Typical ocean crust[2]	Hawkins 2003	4.5	4.5	50	-
Typical ocean crust[2]	Coleman 1971	6.5	5.5	46	-

Source of spatial data: [1]Asch 2005; [2]Exxon Production Research Company 1985; [3]Krevor et al., 2009

4.4.3.2 EXTENT OF SERPENTINISATION

Globally, the degree of serpentinisation can range from 0–100% across the highly varied spectrum of ophiolite compositions. Defining a typical value is problematic due to the diverse and varied nature of these rocks. This study has attempted to calculate an average degree of serpentinisation for ophiolite rocks. For European Tethyan ophiolites a value of 50% has been taken based on reported values from typical ophiolites, (Table 6) and the knowledge and experience of the team members. The same value has been used for ophiolites in the rest of the world; this may represent a minimum value, but, due to the diverse nature of global ophiolites, there is little evidence to support a precise value or a higher percentage. A value of 80% is used for ophiolites of the USA and British Columbia based on Table 6 as these ophiolites are generally older and more altered then Tethyan ophiolites. Following the same procedure as for layered intrusions no attempt has been made to calculate the degree of serpentinisation for the ultramafic rocks of the Urals.

4.4.3.3 COMPOSITION OF SERPENTINE MINERALS

Not all serpentine minerals are suitable for the CCSM process, and this study is primarily focused on deposits of lizardite serpentine. The serpentine mineral group consists of lizardite, antigorite and chrysotile, and these occur in variable proportions in serpentinised rocks (Coleman 1977a). Lizardite serpentinite is typical of lower temperature metamorphism with the proportion of antigorite increasing in higher temperature regimes. As the type of serpentine will depend on the temperature of metamorphic conditions, lizardite is more associated with younger ophiolites. These have been subjected to fewer metamorphic events through geological time and cooler conditions, for example Oman-UAE, New Caledonia and Papua (Nicolas and Boudier 2003) or European Tethyan ophiolites (Onen 2003). The opposite is true for older rocks, which may have undergone numerous metamorphic events and/or regional metamorphism. Examples include the Liguria (northern Italy) and Trinity (NW USA) ophiolites (Nicolas and Boudier 2003) or the ophiolites of Vermont which, although heavily serpentinised, contain only antigorite and no lizardite (Jahns 1967). For this study, due to the difficulty in obtaining quantitative data on the type of serpentine minerals, the proportion of lizardite was not estimated. All calculations therefore represent the maximum figure for lizardite.

4.4.4 Komatiites and other Archæan ultramafic rocks

The datasets used to define the spatial extent of komatiites and other Archæan rocks are from the geological map of the world (Commission for the Geological map of the World, 2000).

Table 7. Percentage of komatiite rocks in Archæan greenstone belts .

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	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

This global geology map delineates terrains of Archæan plutonic, metamorphic and extrusive rocks; these terrains are the hosts of komatiites and other Archean ultramafic rocks and can be used to estimate their spatial extent. Table 7 shows how the average percent of komatiites contained within greenstone belts has been calculated and Table 8 shows how the percentage of komatiite that has been serpentinised has been derived.

Table 8. Serpentine minerals in komatiites .

Name	Significant amounts of serpentinite minerals present?	Serpentine	Degree of serpentinisation
Black Swan	Yes	Lizardite & antigorite	Minor (mainly carbonate minerals)
Honeymoon Well	Yes	Lizardite	No fresh olivine
Kambalda	No	None – amphibolite grade metamorphism	-
Marshall Pool	Yes	Lizardite	Local preservation of fresh olivine
Mt Keith	Yes	Mainly Lizardite, Lesser antigorite	-
Perseverance	No	None – amphibolite grade metamorphism (although some retrogressive serpentinisation)	variable
Scotia	Yes	Antigorite	-
Walter Williams	Yes	Lizardite	Locally fresh olivine
Widgiemooltha	No	None – amphibolite grade metamorphism	-
Yakabindie	Yes	-	-
Munro and Beatty	Yes	-	-
Abitibi belt	Yes	-	-
Belingwe belt	Yes	-	-
Kuhmo belt	No	None – amphibolite grade metamorphism	-
Barberton belt[1]	Yes	-	50-100%

[1]source Stiegler *et al.,* 2010; all other data Barnes 2000

4.4.4.1 ULTRAMAFIC ROCKS WITHIN ARCHÆAN TERRAINS

A value of 2% has been taken to represent the quantity of ultramafic rocks within Archæan terrains from the data set used. This has been derived from a comparison of prospective greenstone belts from more detailed mapping (Geological Survey of India 1993) to the areas contained within the geological map of the world. This showed that of the large areas of Archæan rocks in the geological map of the world only 20% was likely to be prospective for ultramafic rocks (the remainder comprising mainly granitic rocks). Of this 20% only 10% was likely to be ultramafic rocks suitable for the CCSM process (Table 7).

4.4.4.2 ALTERATION OF ULTRAMAFIC ROCKS WITHIN ARCHÆAN TERRAINS

The majority of komatiites have been altered by metamorphic processes which can significantly affect the form in which ultramafic minerals are present (Arndt 1982). The altered minerals depend on the temperature of metamorphism and original composition of the source rocks (Blais and Auvray 1990). If low temperature secondary alteration of these rocks has occurred, it is most likely to have formed serpentinite minerals and is dependent on the MgO content. If the MgO content of the rock is less than 25% chlorite minerals are formed and if values are above 35%, brucite will form. Serpentinite minerals will form if MgO contents are between 25–35%, which is the range found in most komatiite deposits (Arndt *et al.*, 2008) so it can be assumed that low temperature metamorphism will lead to serpentinisation. Higher temperature metamorphism will alter ultramafic minerals to amphiboles (Stiegler *et al.*, 2010), which are of no use in the CCSM processes. A value of 50% has been used to represent the proportion of ultramafic minerals altered to lizardite serpentinite based on approximately 30% of deposits being metamorphosed to amphibolite facies, and of the remaining 70% around 20% are altered to antigorite, or other serpentine minerals of no use for the CCSM process.

The weight of ultramafic rock not metamorphosed to lizardite serpentinite has also been calculated. However this is unlikely to be a resource for CCSM as in many cases minerals have been altered to forms not compatible with known CCSM processes. These resources are also not nearly as significant in size and do not have the consistent properties associated with ultramafic rocks from layered intrusive deposits.

4.5 RESULTS OF GLOBAL RESOURCE REVIEW

The results of the global resource review are in Table 9 to Table 11 and summarised in Table 12. This shows that significant resources are available, the largest being from unaltered ophiolite rocks. However, as discussed above, this represents a maximum value, as not all unaltered mantle ophiolite rocks would be suitable as a CCSM feedstock. In addition, these olivine-rich rocks are not suitable for the process considered by this study and different methods of processing would be required. Quantities of similar olivine-rich feedstock material associated with ultramafic layered intrusions are much lower, around 0.5 billion tonnes (Table 9). However, as a resource the value of these rocks could be much higher as they are often associated with existing mines and material could be readily available from mine waste and tailings.

Table 12 shows that out of global resources of serpentinised ultramafic rocks, the target for feedstock material for the process, around 60% comes from ophiolites and 40% comes from Archæan rocks. This is due to the extensive occurrence of ophiolites globally and the fact that they are often extensively altered. Serpentinites associated with ophiolites often represent large volumes of comparatively homogeneous lizardite serpentinite and hence offer attractive targets for CCSM feedstock material.

Table 9. Resources of ultramafic rocks in layered intrusions.

Layered intrusions				
			Source: BGS dataset	**Source: NRCAN**
Average size of intrusion (km^2)			2000	100
Number of intrusions			47	1040
Total area (km^2)			94000	104000
Area of ultramafic rocks[1] (km^2)			14100	15600
Quarry depth	Volume	Volume of ultramafic rocks (km^3)	141	156
35 m	Mass	Mass of ultramafic rocks (Mt)	451,200	499,200
Quarry depth	Volume	Volume of ultramafic rocks (km^3)	493	546
100 m	Mass	Mass of ultramafic rocks (Mt)	1,579,200	1,747,200

[1]Assumes ultramafic rocks comprises 15 % of the layered igneous complex

Table 10. Resources of ultramafic rocks in ophiolites .

	Ophiolite type		
	European Tethyan	**USA and British Columbia**	**Rest of world**
	Total vol. of rock serpetinised = 50%	**Total vol. of rock serpetinised = 80%**	**Total vol. of rock serpetinised = 50%**
Total area	48458km^2	59823 km^2	367980 km^2
Area of mantle rocks	21806 km^2	29911 km^2	165591 km^2
Area serpentinised	10903 km^2	23929 km^2	82795 km^2
Volume unaltered ultramafic rocks (35m depth)	381.6 km^3	209 km^3	2898 km^3
Volume unaltered ultramafic rocks (100m depth)	1090 km^3	598 km^3	8280 km^3
Volume serpentinised ultramafic rocks (35m depth)	382 km^3	838 km^3	2898 km^3
Volume serpentinised ultramafic rocks (100m depth)	1090 km^3	2393 km^3	82795 km^3
Weight unaltered ultramafic rocks (35m depth)	1.2 Tt	0.7 Tt	9.3 Tt
Weight unaltered ultramafic rocks (100m depth)	3.5Tt	1.9 Tt	26.5 Tt
Weight serpentinised ultramafic rocks (35m depth)	1.1 Tt	2.4 Tt	8.4
Weight serpentinised ultramafic rocks (100m depth)	3.2 Tt	6.9 Tt	24.0 Tt

Table 11. Resources of ultramafic rocks in Archæan greenstone belts .

Greenstone belts		
Total area of prospective Archæan rocks (km^2)		7659841
Area of ultramafic rocks in greenstone belts (km^2)		153196.8
Area of ultramafic rocks serpentinised (km^2)		76589.4
Quarry depth 35 m	Volume serpentinised ultramafic rocks(km^3)	2680.9
	Mass serpentinised ultramafic rocks (Tt)	6.4
Quarry depth 100 m	Volume serpentinised ultramafic rocks (km^3)	7659.8
	Weight serpentinised ultramafic rocks (Tt)	18.4

Table 12. Summary of global resources of ultramafic rocks .

		Geological setting			Totals		
		Ophiolite (including Urals)	**Archæan greenstone belt**	**Layered intrusion (NRCAN data)**		**Co_2 mineralising potential Tt**	**Years of global Co_2 (2006)**
Quarry depth 35 m	Mass serpentinised ultramafic rocks (Tt)	11.9	7.8	-	19.7		
	Mass unaltered ultramafic (Tt)	11.4	-	0.5	11.9		
	Total resources				**31.6**	**10.5**	**371**
Quarry depth 100 m	Mass serpentinised ultramafic rocks (Tt)	34.1	22.2	-	56.3		
	Mass unaltered ultramafic (Tt)	32.6	-	1.8	34.3		
	Total resources				**90.7**	**30.2**	**1,065**

Tt 10^{12} tonnes **Global emissions $28.4*10^9$ tonnes**

4.6 CASE STUDIES

All data on CO_2 point source emitters has been sourced from the International Energy Agency's (IEA) 2006 global emissions database (IEA 2006) and (where coordinates are available) has been spatially projected into a GIS.

4.6.1 South-eastern Europe

The Tethyan ophiolite belt in this area runs through Croatia, Bosnia Herzegovina, Serbia and Montenegro, Albania, Macedonia and Greece; these countries have little access to geological CO_2 storage and are largely reliant on coal fired power stations. The large quantity of ultramafic rocks, lack of alternative storage options and quantity of significant point source CO_2 emitters means there is potential for CCSM in this region. These countries are not large emitters on a global scale; combined, they contribute 0.5% of the worlds CO_2 emissions and 1.3% of Europe's[21]. They do, however, still contain numerous small to medium point source emitters, in the form of smelters, cement works and power stations, to which CCSM processes would be suited.

Ultramafic rocks of the Tethyan ophiolite belt are the source of all CCSM feedstock material in these countries, and 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 (Table 13).

Table 13. Mass of ultramafic rocks in southern Europe (depth of 35m) (totals may not match due to rounding) .

Country	Area of mafic/ultramafic ophiolite rocks (km^2)	Weight of serpentinised rocks(Gt)	Weight of unaltered olivine rich rocks (Gt)
Croatia	392	8.2	8.9
Serbia and Montenegro	5960	123.9	135.2
Bosnia and Herzegovina	1771	36.8	40.2
Albania	4345	90.3	98.5
Macedonia	783	16.3	17.8
Greece	3419	71.1	77.5
Total	**16669**	**346.6**	**378.1**

The properties of the Tethyan ophiolites of southern Europe are similar to those throughout the Tethyan ophiolite belt and are outlined in Section 4.3 above along with the assumptions used for weight calculations.

The ultramafic component of the ophiolite consists of lherzolites, harzburgites, and dunites in both ultramafic cumulate rocks and mantle rocks. The degree of serpentinisation is variable, from between a few per cent to 100% serpentinised as can be seen in Table 13. Studies on ophiolite rocks in Serbia, Bosnia and Herzegovina (Bazyev *et al.,* 2003, Trubelja *et al.,* 1995) state that all olivine in both mantle and cumulate rocks for these areas has been replaced by serpentine so the 50% used in weight calculations could represent a minimum value. Serpentinite minerals in Tethyan ophiolites are likely to be in the form of lizardite rather than antigorite, (Nicolas and Bodier 2003, Trubelja *et al.*, 1995). Other limiting factors in the use of these rocks as a CCSM feedstock is the presence of detrimental minerals such as pyroxene and amphibole. Data from ophiolite rocks in Bosnia (Trubelja *et al.*, 1995) show that pyroxenes are present in harzburgites, but not in significant quantities, and metamorphism is to greenschist facies

[21] http://www.iea.org/textbase/nppdf/free/2011/key_world_energy_stats.pdf

(generally leading to the presence of lizardite serpentinite) with amphibolite facies (leading to the replacement of lizardite with antigorite) only found locally.

4.6.1.1 RELATIONSHIP OF ULTRAMAFIC ROCKS TO CO_2 EMITTERS

Figure 21 shows a number of point source CO_2 emitters in close proximity to, or sited on top of, ultramafic rocks. The largest of these are coal fired power stations in Serbia and Greece, but there are also numerous small power stations, cement works and refineries with access to ultramafic rocks, all of which may be suitable for the CCSM process. A buffer of 60 km was used as the distance that CCSM feedstock material could be transported. This is the maximum distance low value bulk materials can be practically transported by road before transportation and fuel costs become prohibitive. If rail, or in extreme cases pipeline infrastructure, was used to transport material 200 km may be a more feasible distance (Highley et at 2004). It can be seen in Figure 21 that around 75% of CO_2 point source emitters are within this buffer. Three sites lie directly on ultramafic rocks: two small power stations in Bosnia Herzegovina, both emitting around 7000 thousand tonnes of CO_2 per year; and a refinery in central Serbia with undisclosed CO_2 emissions.

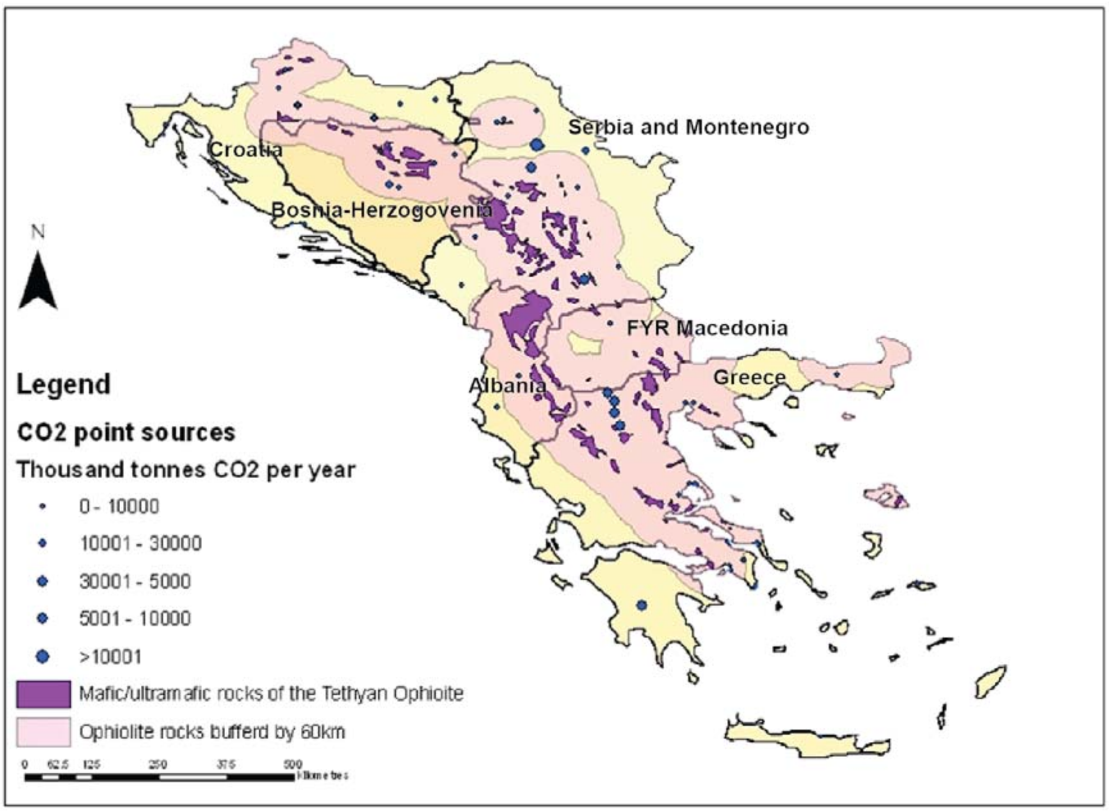


Figure 21. Ultramafic rocks and CO_2 emitters of southern Europe [Copyright BGS, NERC].

4.6.2 India

India contains a large volume of ultramafic rocks in the form of komatiites and other Archæan intrusions (Figure 21). The country also has little access to geological CO_2 storage but emits over 5% of the worlds CO_2[22]. As a result, CCSM could be a viable way to capture some of these CO_2 emissions.

Ultramafic rocks in India are concentrated in around 25 major Archæan greenstone belts (Rogers and Giral 1977); these are mainly located in the south west and north east of the country. They

[22] http://www.iea.org/textbase/nppdf/free/2011/key_world_energy_stats.pdf

have been spatially defined for the purposes of this study by 1:5 000 000 geological mapping by the geological survey of India (geological survey of India 1993). These greenstone belts are very variable in composition and are described in detail in Mani *et al.*, 2008 and Rogers and Giral 1977 but almost all contain some form of ultramafic component. Komatiites and other Archæan ultramafic igneous rocks from these greenstone belts contain lithologies prospective for CCSM including dunite and serpentinite. There are also however ultramafic rocks with low prospectivity for CCSM feedstock material such as pyroxenites and amphiboles. Also occurring are non-ultramafic rocks of gabbros, basalts and schists.

In eastern India, the two largest areas of greenstone belts are associated with the Singhbhum Craton and the Sonakhan greenstone Belt. The Sonakhan greenstone belt (Figure 22), located in the north eastern part of the Bhandara Craton, contains no komatiites but does have a mafic to ultramafic component of around 2:3 (Rogers and Giral 1977).

The Singhbhum Craton in Northern Orissa covers a significant area but is not prospective for ultramafic rocks. Archæan rocks in this craton comprise mainly metasedimentary or felsic rocks, no komatiites are recorded and amphibolite grade metamorphism prevalent (Rogers and Giral 1977).

The most prospective Archæan Craton is the Dharwar Cratonic Belt of Southern India (Figure 23); this is split into the Eastern and Western Dharwar Cratonic blocks. Greenstone belts within these are all much more prospective for ultramafic rocks then the Archæan rocks to the north and east.

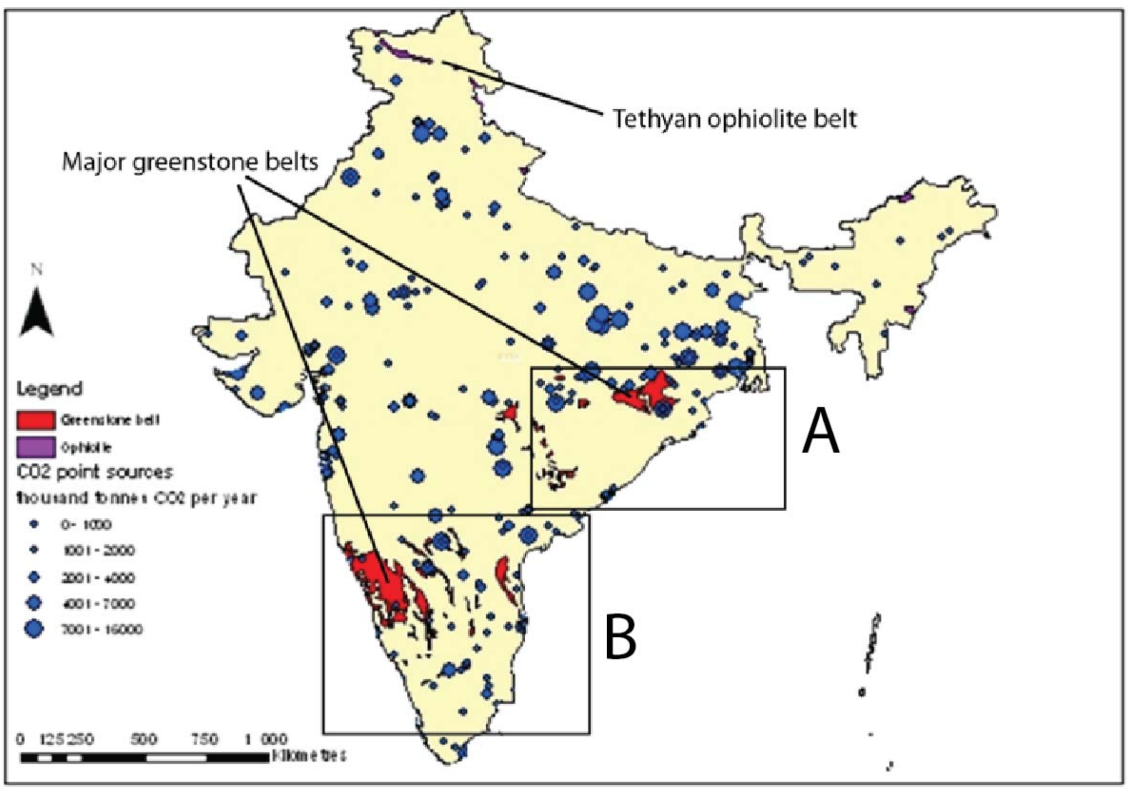


Figure 22. Ultramafic rocks and CO_2 emitters of India; A: Area location for Figure 23; B: Area location for Figure 24. [Copyright BGS, NERC]

The Eastern Dharwar Cratonic Block consists of numerous linear greenstone belts, comprising mainly volcanic rocks, including komatiites and layered intrusions. One of the largest igneous provinces in this block is the Kolar greenstone belt; this is representative of many of the greenstone belts from this block and comprises 90% mafic and ultramafic rocks and 10% komatiites. However, the metamorphic grade is well into amphibolite facies resulting in ultramafic minerals potentially being in forms not suitable for CCSM processes such as antigorite serpentinite (Rogers and Giral 1977).

The Western Dharwar Cratonic Block consists of the mainly igneous Sargur formation in the south, which shares many similarities with the Kolar greenstone belt (Rogers and Giral 1977), and the Chitradurga and Bababundan groups, both related to major basins. The younger, basin related Archæan rocks consist of metasediments and mafic to felsic volcanic rocks (Mani *et al.*, 2008). Ultramafic rocks are present but not in large quantities, compared to the older Sargur Formation. For example, the Chitradurga belt comprises 50% mafic and ultramafic rocks; less than 50% of this is likely to be ultramafic. Komatiites are also rare and comprise less than 1% of the belt (mainly located in a western arm near Kibbanahalli) (Rogers and Giral 1977). Metamorphic grade is lower and greenschist facies rocks are present so any ultramafic minerals present are more likely to be in forms suitable for CCSM processes.

4.6.2.1 RELATIONSHIP OF ULTRAMAFIC ROCKS TO CO_2 EMITTERS

Significant sources of CO_2 (Figure 21) are spread evenly across India (IEA GHG 2006) and many are in close proximity to ultramafic rocks contained within the greenstone belts.

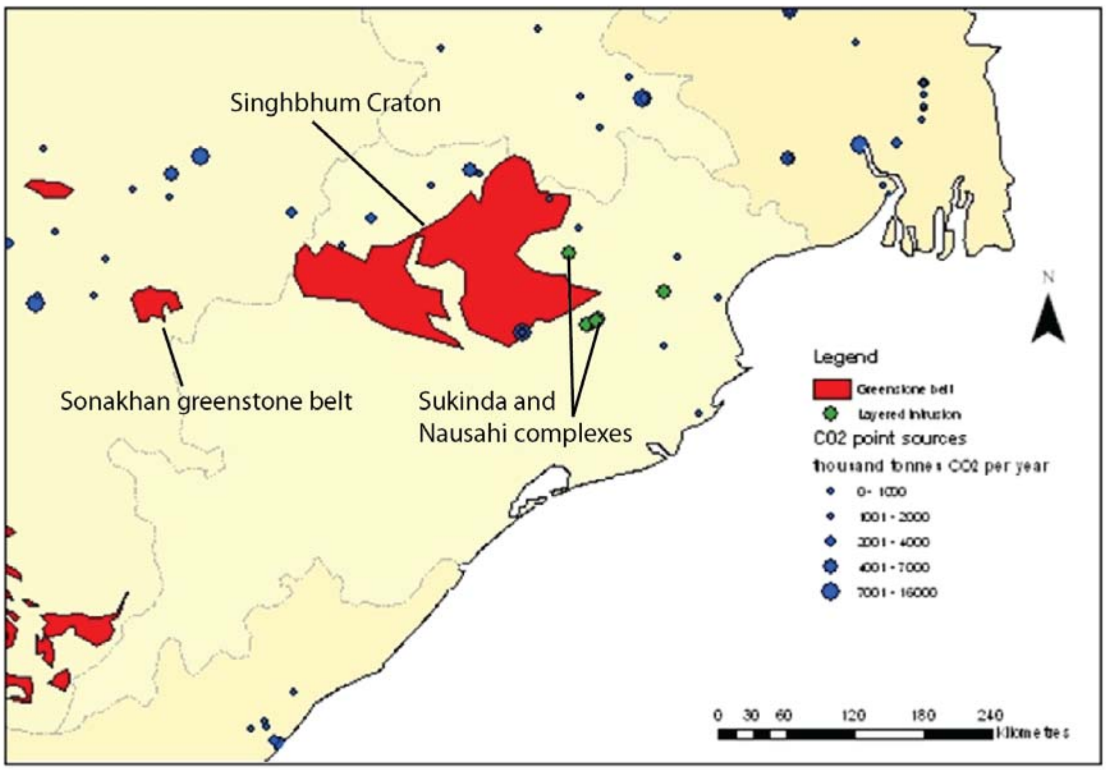


Figure 23. Ultramafic rocks and CO_2 emitters of eastern India [Copyright BGS, NERC].

The Singhbhum cratonic block (Figure 22) in north eastern India underlies a major coal fired power station at Talchar with CO_2 emissions of over 20000 kt per year and is 20–30 km from two steel plants and another coal fired power station with emissions between 3-4000 kt of CO_2 per year. Smaller emitters are also very near or adjacent to the greenstone belt including two steelworks and two cement works. Although this greenstone belt is not prospective for ultramafic rocks, at its eastern edge there are the ultramafic igneous bodies of the Sukinda and Nausahi complexes. These bodies host several mines for nickel laterites and chromite and consist of Archæan ultramafic cumulate rocks, most commonly serpentinised dunite. They are of a significant size, the Sukinda complex covering $42km^2$ and the Nausahi complex covering 3.5 km^2 (Page *et al.*, 1985). These ultramafic intrusions could provide feedstock minerals for CO_2

sequestration in the vicinity and it is possible that material from tailings from active workings at Saraubil where chromite is currently mined could be an easily assessable source of material.

Several major CO_2 emitters are also in close proximity to ultramafic rocks in the Dharwar Craton. The most prospective rocks within this craton are the older, mainly mafic and ultramafic Sargur formation, such as the Kolar greenstone belt (Figure 23). The other greenstone belts, although covering a large surface area, are significantly less likely to contain ultramafic rocks suitable for CCSM feedstock material. There are three major point source emitters within 40 km of these rocks, two coal fired power stations and a large steel works, all with CO_2 emissions of between 5–9000 kt per year. There are also numerous smaller point source emitters in close proximity to these rocks, including four cement works, two steel works and a coal fired power station with emissions less the 1000 kt per year. The Kola greenstone belt has a surface area of 320 km^2: using the assumptions made in Section 4.4.4 above and taking a value of komatiite content of 10% (Mani *et al.*, 2007) shows that this area alone could host 3840 Mt of material suitable for CCSM processes.

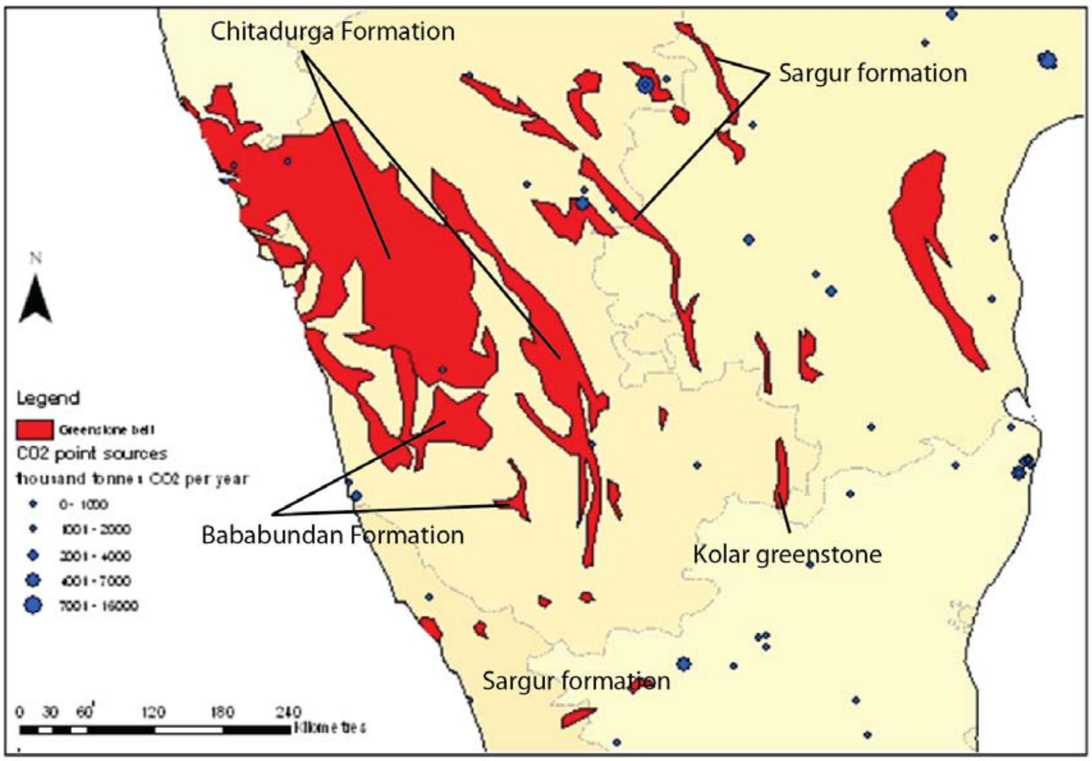


Figure 24. Ultramafic rocks and CO_3 emitters of southern and central India [Copyright BGS, NERC].

Ultramafic rocks are also available from Tethyan ophiolites in the north of the country. These occur in linear south west-north east trending belts cutting from Pakistan through India and across to China. As described in Section 4.4.3 these rocks are prospective for CCSM feedstock material, especially lizardite serpentinite. However this area is sparsely populated, mountainous and contains few CO_2 emitters. There is a small gas fired power station around 20 km from the outcrop of these rocks in Kashmir and a cement works 100 km to the south. The remote and inaccessible nature of this area means CCSM is unlikely to be feasible.

Appendix

Introduction

A detailed desk study assessing several sites of ultramafic and mafic rocks was performed during the ETI Project Phase (Stage) 1. Following the assessment sites were graded according to their potential for source rocks. All sites with a high ranking were selected for further study, material suitable for this was available for the most distant sites at The Lizard in Cornwall and Unst in Shetland. However three sites had inadequate samples and these were chosen as destinations for reconnaissance fieldwork that took place in July 2011. The sites were: ***Ballantrae*** ophiolite (South Ayrshire), ultramafic and mafic intrusions around ***Belhelvie*** (Aberdeenshire) and serpentinites of ***Portsoy*** (Banffshire coast). The fieldwork was undertaken by two geologists from British Geological Survey. This appendix contains the data produced by BGS during studies for stage gate 2B for Task 1.10. The data covers sample collection and selection, mineralogical characterisation that included optical microscopy, scanning electron microscopy, X-ray diffraction analysis, and X-ray fluorescence bulk chemical analysis.

There is also data in support of the study of planning and logistical constraints in the areas of the UK where potential resources of ultramafic rocks are situated and the studies of global resources of ultramafic rocks.

A.1 X-ray diffraction analyses.

Analysis was carried out using a PANalytical X'Pert Pro series diffractometer equipped with a cobalt-target tube, X'Celerator detector and operated at 45 kV and 40 mA. The samples were scanned from 5-85°2θ at 0.33°2θ/minute. Diffraction data were initially analysed using PANalytical X'Pert Highscore Plus version 2.2a software coupled to the latest version of the International Centre for Diffraction Data (ICDD) database.

Following identification of the mineral species present in the sample, mineral quantification was achieved using the Rietveld refinement technique (e.g. Snyder & Bish, 1989) also using the PANalytical X'Pert Highscore Plus version 2.2a software.

There is a problem with the quantification of serpentinite samples as they report unrealistically large amounts of amorphous material that is almost certainly spurious. BGS is aware of this problem and previous studies suggest that treating the amorphous as an underestimate of the lizardite component gives reasonable results. Investigation of this problem is a topic of the PhD studies recently started by Alicja Lacinska.

Table 14. Quantitative mineralogy determined by X-ray diffraction .

ETI prefix	ETI Sample	Area	Rock name	Amorphous	Lizardite-1M	Lizardite-1T	Antigorite	Amphibole (Actinolite)	Clinochlore	Cpx (Diopside)	Enstatite	Forsterite	Talc	Magnesite	dolomite	Calcite	Magnetite	Hematite	Anorthite	Phrenite	Quartz	Thomsonite	Smectite	Epidote	ETI prefix
ET	1	Ballantrae N	Serpentinite	25.2	32	41.7											1.1								ET
ET	2	Ballantrae S	Serpentinised Harzburgite	22.9	23.9	51.4											1.2				0.6				ET
ET	4	Ballantrae N	Metagabbro (amphibolitised?)					33.7	2.6											63.2	0.5				ET
ET	5	Ballantrae N	Serpentinite	14.7	27.6	48.5		1.7									2.5			5					ET
ET	6	Ballantrae S	Serpentinite (hematite-rich)	28.1	28.2	40.7									0.4			2.6							ET
ET	7	Belhelvie	Mela troctolite	15.1	20.4	37.4		6	4.5	4.8		11.8													ET
ET	8	Belhelvie	Serpentinised peridotite ?Pyroxenite	18.3	23.3	41.8			6.4	2.2	1.1	4.1					1.3					1.5			ET
ET	9	White Hill	Pyroxenite or amphibolitised pyroxenite			0.3		67.5	0.3	4.3									27.6						ET
ET	10	Portsoy	Serpentinite	11.9	30.7	33.9			19.3								4.2								ET
ET	11	Portsoy	Serpentinite	14.9	28.9	41.6			13.6								1								ET
ET	12	Portsoy	Serpentinite	7.7	25.1	49.5			7.6				3.2			3.2		3.7							ET
ET	13	Portsoy	Serpentinite	15.5	27.3	39.4			16.2								1.1	0.5							ET
ET	14	Portsoy	Serpentinite	14.3	26.6	43.3			15								0.8								ET
ET	15	Lizard	Dunite serpentinite	14.8	30.5	36.6			12.4							0.6	0.5	3			1.6				ET
ET	16	Lizard	serpentinised lherzolite	31.8	23.2	42.7										0.2		2.1							ET
ET	17	Lizard	serpentinised lherzolite	17.8	21.7	49.3		1.1	5.9							0.1	0.4	2.8					0.9		ET
ET	18	Lizard	serpentinised lherzolite	10.6	18.7	44.2		9.5			7.7	8.6									0.7				ET
ET	19	Shetland	antigorite serpentinite	0	18.2	10.4	61.2							8.3	1.1		0.8								ET
ET	20	Shetland	antigorite serpentinite	0	19	26.6	46.7							4.8	0.4		2.5								ET
ET	21	Shetland	serpentinite	17.8	40	39.8											2				0.4				ET
ET	22	Shetland	antigorite serpentinite	0			71.9							25.4	0.3	0.2	2.2								ET
ET	23	Norway	olivine concetrate (Minelco)			1.3		3	3.2		6.4	84.2	1.7								0.2				ET
ET	25	UAE	harzburgite	12.3		22		1.4	6	8.1	12.6	34.4			3.2										ET
ET	26	UAE	harzburgite	13.7		37.2		0.3	8.6	4.2	19.5	15.6			0.9										ET
ET	27	UAE	clinopyroxenite	0		3.4		1.1		72.7	6.4	10.9							5.5						ET
ET	28	UAE	amphibole rock	0				58.9	10.2											27	0.2			3.7	ET
ET	29	Italy	antigorite serpentinite	0			93.8		4.2								1.4	0.6							ET
ET	30	USA	antigorite serpentinite	0			85.3					5.2					1.6		1.3		2.4		4.2		ET

A.2 X-ray fluorescence analyses.

The bulk composition of all the samples has been determined by X-ray fluorescence at the BGS laboratories in Keyworth. The results are given in Table 15.

Table 15. Chemical composition of rock samples used for Mg leaching experiments .

	SiO2	MgO	Al2O3	Fe2O3t	Mn3O4	CaO	TiO2	Cr2O3	NiO	Na2O	K2O	P_2O_5	V2O5	LOI	Total
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
ET1	37.70	38.56	1.40	7.48	0.13	0.03	0.01	0.36	0.26	<0.05	<0.01	<0.01	0.01	14.40	100.34
ET2	40.54	37.43	0.88	7.91	0.11	0.18	<0.01	0.47	0.27	<0.05	0.01	<0.01	0.01	12.89	100.70
ET4	44.90	5.72	17.38	6.77	0.12	20.65	0.30	0.02	<0.01	0.21	0.06	0.02	0.04	3.83	100.02
ET5	39.85	38.47	0.51	7.99	0.09	0.06	<0.01	0.38	0.31	<0.05	<0.01	<0.01	<0.01	12.82	100.48
ET6	38.93	37.73	0.67	8.23	0.11	0.31	<0.01	0.53	0.34	<0.05	<0.01	<0.01	<0.01	13.47	100.32
ET7	37.53	32.32	3.94	12.98	0.17	2.61	0.23	0.46	0.21	0.12	0.03	0.01	0.01	9.89	100.51
ET8	37.48	33.38	3.73	12.55	0.19	0.93	0.06	0.11	0.30	0.09	0.02	0.01	<0.01	11.55	100.40
ET9	41.20	7.34	18.13	15.91	0.23	14.17	0.76	0.01	<0.01	1.14	0.04	0.03	0.09	1.12	100.17
ET10	38.40	36.90	1.26	10.31	0.07	0.08	0.02	0.76	0.31	<0.05	<0.01	<0.01	<0.01	12.37	100.48
ET11	39.34	37.60	1.33	7.64	0.16	0.03	0.02	0.38	0.29	<0.05	<0.01	<0.01	<0.01	13.65	100.44
ET12	37.92	37.19	0.59	8.20	0.23	1.65	0.03	0.36	0.28	<0.05	0.03	<0.01	0.01	13.80	100.29
ET13	40.21	39.12	0.58	6.40	0.15	0.08	<0.01	0.26	0.26	<0.05	<0.01	<0.01	<0.01	13.62	100.68
ET14	38.81	37.14	1.83	7.74	0.16	0.03	0.04	0.35	0.29	<0.05	<0.01	<0.01	<0.01	13.63	100.02
ET15	39.24	38.22	1.14	7.42	0.12	0.41	0.01	0.32	0.28	<0.05	0.01	<0.01	<0.01	13.21	100.38
ET16	39.50	37.94	1.42	7.41	0.11	0.20	0.03	0.36	0.28	<0.05	<0.01	<0.01	<0.01	13.08	100.33
ET17	39.86	36.48	1.99	8.54	0.13	0.27	0.04	0.39	0.26	<0.05	<0.01	<0.01	<0.01	12.39	100.35
ET18	40.53	35.31	3.12	8.60	0.14	1.78	0.11	0.33	0.26	0.18	0.04	<0.01	0.01	9.77	100.18
ET19	37.80	37.49	1.17	7.39	0.11	0.46	<0.01	0.46	0.27	<0.05	0.01	<0.01	<0.01	14.89	100.05
ET20	36.96	38.91	0.22	8.18	0.10	0.31	<0.01	0.44	0.31	<0.05	0.01	<0.01	<0.01	14.80	100.24
ET21	32.54	40.03	0.74	9.52	0.13	0.15	<0.01	0.78	0.30	<0.05	<0.01	<0.01	<0.01	15.80	99.99
ET22	33.05	37.62	0.74	8.51	0.11	0.19	<0.01	0.98	0.28	<0.05	<0.01	<0.01	<0.01	18.65	100.13
ET23	41.88	48.07	0.38	7.69	0.11	0.42	0.01	0.48	0.36	<0.05	0.04	<0.01	<0.01	0.77	100.21
ET25	40.51	38.39	1.91	8.50	0.14	3.02	0.03	0.37	0.28	<0.05	<0.01	<0.01	<0.01	7.82	100.97
ET26	40.92	37.91	0.96	8.24	0.14	1.68	<0.01	0.55	0.27	<0.05	<0.01	<0.01	0.01	10.06	100.74
ET27	49.33	20.63	4.53	6.29	0.14	17.22	0.07	0.28	0.03	0.12	<0.01	<0.01	0.03	1.12	99.79
ET28	45.86	12.11	12.96	9.34	0.19	14.94	0.16	0.14	0.02	0.17	0.04	<0.01	0.05	3.73	99.71
ET29	39.88	36.22	2.41	8.36	0.14	0.41	0.07	0.39	0.29	<0.05	<0.01	<0.01	<0.01	11.25	99.42
ET30	39.68	38.80	1.16	7.24	0.09	0.49	0.07	0.37	0.29	0.19	0.14	<0.01	<0.01	12.30	100.82

A.3 Petrographical analysis of feed rocks.

This section describes the petrographical analysis of the samples used for Mg leaching experiments under standard conditions. These samples cover two aspects of the project. Firstly, the samples were used in testing their leachability from areas of interest across the UK. These were a mixture of samples collected specifically for this project and samples from the BGS collection. Secondly, ultramafic rock types with a wide range of compositions were assessed; these included some of those collected but mostly ones from the BGS collection

In July 2011, two geologists from BGS visited a few sites that could potentially provide a source rock for mineral carbonation processes. Based on the results from a detailed desk study of ultramafic rock resources within the UK that was conducted for the ETI Stage Gate 1 report, three regions of interest were identified and subjected to detailed investigation in July 2011: ***Ballantrae*** (South Ayrshire) ophiolite, ***Belhelvie*** (Aberdeenshire) ultramafic and mafic intrusions and serpentinites of ***Portsoy*** (Banffshire coast).

Collectively, 14 ultramafic and mafic rock samples were collected from selected areas, out of which the 11 most representative samples were selected to be used in further laboratory investigation (Table). The sampling locations were chosen based on the existing geological data, mainly BGS geological memoirs and maps together with the use of Google Earth, where the potential exposures were identified and localised. In addition, during the fieldwork a reconnaissance of the regions selected was undertaken in terms of the presence of additional exposures (e.g. in new road cuttings or on the coast), the present state of road infrastructure, and the degree of vegetation that often obscured access to the outcrops.

In general, the outcrops of the lithologies of interest were scarce and in places poorly exposed. These sites were usually located on private premises, examples of which are: a landfill site, a fishery, a caravan park, farms and household; therefore every time prior to entering the place verbal permission was obtained from a land owner. Elsewhere, the lithologies were exposed on the shore, top of hills or in disused quarries that were usually fenced off, heavily overgrown and acted as dump sites for local farmers.

Table 16. Details of the samples studied.

ETI Sample Number	Region	Locality	OS grid ref. *x*	*y*	Lithology	Weight (kg)	Kappa meter reading	Analysis performed *Petrography*	*XRD*	*XRF*	*UoN Experiments*
ET1	Ballantrae N	Lendalfoot, landfill site	NX14178	90400	Serpentinite	84.35	15-40, most >30	x	x	X	X
ET2	Ballantrae S	Fishery nr Garnaburn Farm, nr Colmonell	NX15218	87436	Serpentinite	10.9	a) 32.7 b) 30.1	x	x	X	X
ET3	Ballantrae S	Fishery nr Garnaburn Farm, nr Colmonell	NX15218	87436	Amphibolite	hand spec	0.8	N/A	N/A	N/A	X
ET4	Ballantrae N	The Whilk, S end of the N Srp Belt	NX11784	88942	Prehnite Amphibolite	9.65	0.49	N/A	x	X	
ET5	Ballantrae N	*c.* 5km S of Girvan, S of Byrne Hill Caravan Park	NX18238	94750	Serpentinite	14.6	40.5	x	x	X	X
ET6	Ballantrae S	Small cutting along A77, on the coast	NX09312	85300	Serpentinite	14.14	0.3	x	x	X	X
ET7	Belhelvie	*c.* 500m E of Braeside Farm	NJ90467	21309	Serpentinised plagioclase-rich wehrlite	17.4	38.5	x	x	X	X
ET8	Belhelvie	Longdrum	NJ92910	17560	Serpentinised melatroctolite	16.9	17.7	x	x	X	X
ET9	White Hill	Top of the hill	NJ51806	46038	Amphibolite	16	28.5	N/A	x	X	X
ET10	Portsoy	Damheads Quarry, *c.* 3km of Portsoy	NJ57786	63565	Serpentinite	17.9	92.3	x	x	X	X
ET11	Portsoy	Slackdale, *c.* 6km SW of Portsoy	NJ54742	60717	Serpentinite	16.5	25.3	x	x	X	X
ET12	Portsoy	Beach outcrops	NJ59165	66218	Serpentinite	19.05	0.33	x	x	X	X
ET13	Portsoy	Marble Quarry, on the coast	NJ58575	66335	Serpentinite	17.4	a)16.7, b)20.3	x	x	X	X
ET14	Portsoy	Meikle Toux, disused quarry	NJ54287	58731	Serpentinite	18.2	4.13	x	x	x	X
ET15	Lizard	Porthallow beach	SW79812	79812	Dunite serpentinite	5		X	X	X	X

ET16	Lizard	Gwendreath quarry	SW73331	17435	Serpentinised lherzolite	5	X	X	X	X
ET17	Lizard	Balk quarry	SW71334	13390	Serpentinised lherzolite	5	X	X	X	X
ET18	Lizard	Holestaw, Kynance	SW69079	13535	Serpentinised lherzolite	5	X	X	X	X
ET19	Shetland	Cliff N Bh UCD1	461160	1212230	Antigorite serpentinite	2	X	X	X	X
ET20	Shetland	Cliff S BH CL0	460740	1211020	Antigorite serpentinite	2	X	X	X	X
ET21	Shetland	Muckle Hoeg NE Bh NB2	462800	1210300	Serpentinite	2	X	X	X	X
ET22	Shetland	Muckle Hoeg SW BH Baltasound Hagdale 6	462275	1210029	Antigorite serpentinite	2	X	X	X	X
ET23	Norway	Minelco			Olivine rock	1	X	N/A	N/A	N/A
ET24	Norway	Minelco			Olivine rock powder	1	N/A	X	X	X
ET25	UAE	BGS collection			Harzburgite	5	X	X	X	X
ET26	UAE	BGS collection			Harzburgite	5	X	X	X	X
ET27	UAE	BGS collection			Olivine clinopyroxenite	1	X	X	X	X
ET28	UAE	BGS collection			Amphibole rock	1	X	X	X	X
ET29	Italy	Liguria			Antigorite serpentinite	0.5	X	X	X	X
ET30	USA	Cedar Hills, Pennsylvania			Antigorite serpentinite	0.5	X	x	x	X

A.3.1 BALLANTRAE AREA

The ultramafic bodies of Ballantrae are located on the coast, *c.* 75 km SW from Glasgow, in between the towns of Girvan and Ballantrae. There are two SW-NE trending belts:

a) Northern Serpentinite Belt [NX 1810 9487] – up to 1.5 km wide, extends over an area of 12.8 km^2

b) Southern Serpentinite Belt [NX 092 859 – NX 183 905] – up to 2 km wide, occupies an area of *c.* 19.1 km^2.

Both belts were investigated during fieldwork in July 2011. The topography of the area is undulating hills with several areas of low crags. The hills are covered by widespread rough grassland, pastures, and woodland. Rocky outcrops are scarce, and where identified they were accessed via private roads or tracks, always with the permission of the landowner. The network of roads in the Girvan-Ballantrae area is reasonable and the use of a combination of roads and rural tracks generally provides a fairly good access to the sites of interest.

The serpentinite bodies are in fault-bounded blocks amongst sedimentary and volcanic rocks in the Midland Valley Terrane of central Scotland.

The samples locations were chosen based on existing geological data in combination with a reconnaissance survey of the area at the start of the fieldwork. The reconnaissance showed that the number of locations with outcrop large enough to collect samples of 20 kg or more was very limited. Serpentinites are relatively soft rocks and most outcrops in the area are of other harder rocks such as amphibolites that occur within the serpentinite.

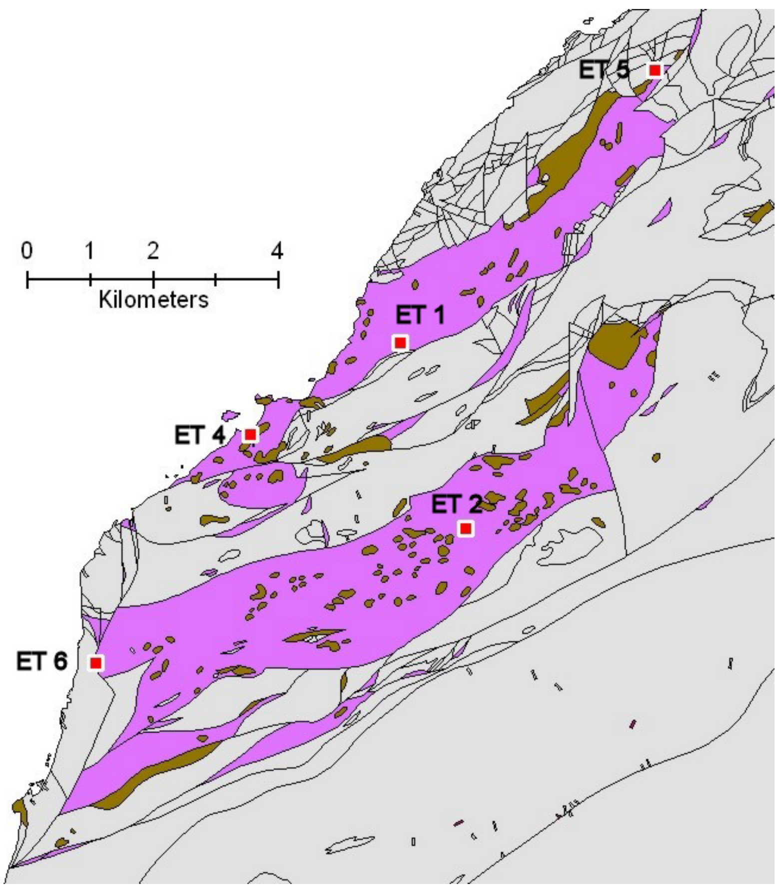


Figure 25. Geological map of the area between Ballantrae and Girvan, showing two Serpentinite Belts and the location of samples collected during fieldwork in July 2011, ultramafic rocks are shown in purple and mafic rocks in brown [Copyright BGS, NERC].

a

b

Figure 26. Images showing: a) typical Southern Serpentinite Belt landscape (Fig 1 for location); b) landscape around mafic intrusions found between Knockdaw Hill, Breaker Hill and Craig Hill, southern belt (Fig 1 for location). The small outcrop on the skyline is amphibolite .

A.3.1.1 **Sample ET 1**

Lithology:	Locality:	OS Grid Reference:
SERPENTINITE	Ballantrae N Belt Lendalfoot	(NX14178 90400)

A.3.1.1.1 FIELD SAMPLING

Sample ET 1 was collected from a small (< 3 m high), partially overgrown outcrop within the Northern Serpentinite Belt, located at a recent excavation adjacent to a landfill site near Lendalfoot. The outcrop was accessed via a private, track.

In the outcrop and hand specimen, the rock is homogenous and blocky, cut by numerous veins; of creamy green to green, locally fibrous serpentine; resulting in characteristic boxwork appearance. Kernel pattern originally from partially serpentinised peridotite mantled by serpentinite was also identified in the outcrop. In addition, several bleached zones (probably weathering - related) were seen occurring near the soil/rock contact and along some fractures.

The total weight of the sample collected was *c.* 85kg.

a *B*

Figure 27. Images showing, a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET1 outcrop, recent excavation adjacent to a landfill site NE from Lendalfoot.

A.3.1.1.2 PETROGRAPHY AND MINERALOGY

The sample studied is predominantly composed of serpentine minerals that display multi-generational textures. Texturally, by far the most abundant is mesh serpentine (pseudomorphs after olivine), making up to 83% of the thin section, with subordinate (<7%) bastite (pseudomorphs after orthopyroxene). The sample is crosscut by an array of parallel to subparallel fractures (max width 100 µm) that are infilled with finely-crystalline, locally fibrous serpentine (<2%) (Figure 28).

The mesh texture consists of tightly packed, roughly equant domains of finely intergrown, often `cross-hatched` crystals of serpentine minerals that are locally inter-woven with Fe oxide/ oxyhydroxide (<1%) and to lesser extent chlorite (< 1%). The domains normally contain an inclusions-rich core that is probably Fe oxide/oxyhydroxide relicts of the original mineral. The Fe oxyhydroxide is particularly apparent within the fracture zones, where it was either introduced to the system or remobilised during alteration of the phases adjacent to the fractures.

Bastites constitute *c.* 7 modal % of the sample analysed and occurs as either large (up to 5 mm) single crystals (orthopyroxene pseudomorphs) or clusters of several crystals.

Numerous (*c.* 5%) domains that are interstitially intergrown with serpentine mesh were found throughout the sample. These are finely crystalline and tentatively identified as a mixture of clay minerals phases (Mg, Al, Fe silicate, confirmed by SEM) and probably are relicts of original clinopyroxene.

Chromites (<1%) appear fragmented and partially altered (brownish to dark brown). Minor fractures (< 5 µm wide) filled with magnetite were locally observed.

Note on original composition.

The predominance of the serpentine mesh texture together with scattered large bastites and minor pseudomorphs after interstitial clinopyroxene suggest that the serpentinite analysed could have originated from harzburgite.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Serpentine			Chl	FeO/OH	Clay Min.
	`mesh`	bastite	vein			
% modal	83	7	2	1	2	5

a *b*

c *d*

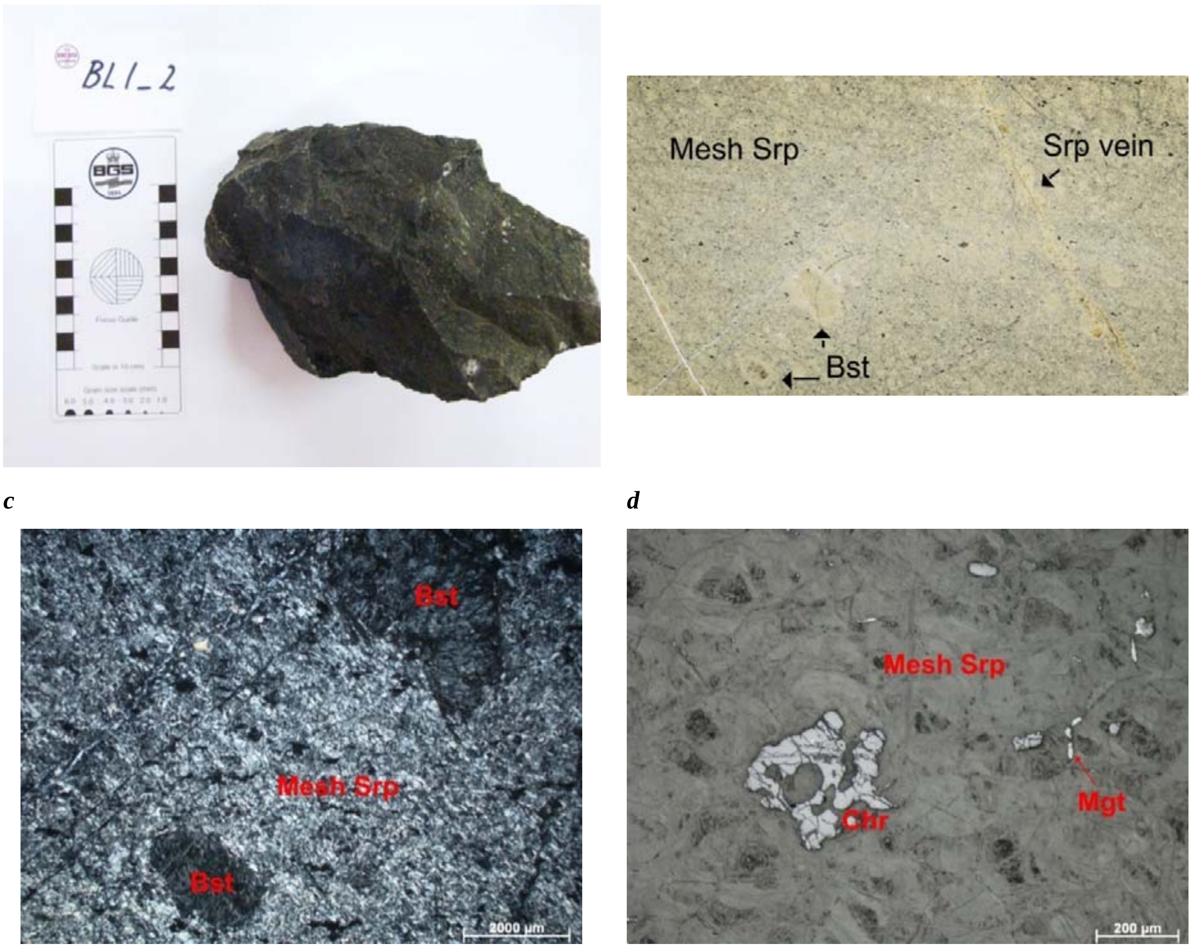


Figure 28. Images of sample ET1: a) hand specimen; b) polished thin section scan; c) crossed polarised light optical photomicrograph showing mesh texture serpentine with scattered large (up to 5 mm) orthopyroxene pseudomorphs – bastites; d) reflected light optical photomicrograph showing crystal of chromite with embayed crystal edges (holly-leaf texture). Minute (<5 µm) fractures of magnetite were commonly observed crosscutting the chromites

A.3.1.2 Sample ET 2

Lithology:	Locality:	OS Grid Reference:
SERPENTINITE	Ballantrae S Belt. Site NW of Garnaburn Farm, Colmonell.	(NX15218 87436)

A.3.1.2.1 FIELD SAMPLING

Approximately 10 kg of serpentinite sample was collected from a small outcrop (*c.* 5 m high) found near Fishery, located *c.* 1 km NW of Garnaburn Farm (nr Colmonell). The site was accessed via a track along southern shore of a lake belonging to the Fishery.

The outcrop is lithologically heterogeneous and predominantly consists of amphibolites in contact with subordinate serpentinite.

A ***b***

Figure 29. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET2 outcrop, found S of a lake belonging to Fishery located c. 1km NW of Garnaburn Farm, nr Colmonell

A.3.1.2.2 PETROGRAPHY AND MINERALOGY

The examination of the hand specimen revealed that sample ET2 is not homogenous and amongst all the fragments collected in the field, some were distinctively sheared, whereas others were massive. In order to better describe the textural and petrographical variation two polished thin sections were prepared for this sample; \`a\` - being the apparently sheared subsample and \`b\` the massive serpentinite. XRD and chemical analysis (XRF) were however performed on the bulk ET2 sample that is a mixture of both types and more representative of the location as a whole.

Subsample ET 2a

Subsample ET2a is largely composed of serpentine minerals that display two distinctive dominant textures: bastite and mesh texture. The mesh texture serpentinite that constitutes *c.* 70% of the sample contains domains of intergrown serpentine crystals that are locally interwoven with Fe oxide/oxyhydroxide phases. Although not clearly displayed on the scanned polished thin section image, optically the mesh serpentine only displays a distinctive one directional lineation. This lineation is probably related to an early (pre-serpentinisation) development of fracture cleavage (Figure 30).

Large (0.5 mm – 5 mm), undeformed bastites are randomly scattered throughout the sample as either individual crystals (locally in mesh serpentine interstices) or clusters. Collectively the bastites constitute *c.* 25% of the sample.

In addition, both mesh serpentine and bastites are crosscut by <0.5 mm wide fractures that are predominantly infilled by serpentine with subordinate Fe oxide/oxyhydroxide and locally finely-crystalline quartz.

Chromites (<2%) in this sample are partially altered (dark red to reddish brown) and occur as large, up to 2 mm, fragmented and locally stringer-like crystals (holly leaf texture). Bright green, locally fibrous, chlorite (<0.5%) was found rimming some chromite crystals, predominantly those that were in contact with mesh serpentine. The chromite – bastite contact is, in general, sharp with no obvious alteration product. The chromite – chlorite occurrence suggest a genetic co-relation (described in detail below). Trace amount of magnetite was also observed, predominantly occurring within the serpentine mesh centres.

Subsample ET 2b

Subsample ET2b is dominantly composed of texturally diverse serpentine minerals, occurring in both bastite and mesh texture. The mesh texture serpentine, in contrast to subsample ET2a displays only minor, localised evidence for the development of a fracture cleavage. It constitutes *c.* 70% of the sample and consists of a mosaic of tightly packed serpentine crystals that are finely intergrown with Fe oxide/oxyhydroxide. In addition, the Fe oxide/oxyhydroxide (locally together with stringer-like chromite) occurs as numerous, generally randomly oriented veinlets that crosscut the mesh serpentine matrix (collectively Fe oxide/oxyhydroxide constitute *c.* 2% of the sample).

Bastites (up to 5 mm) are randomly distributed within the mesh serpentine matrix and constitute *c.* 25% of the sample. The bastites often occur clustered together. Despite random fracturing, the bastites do not display any other clear evidence for deformation.

Chromites (<2%) are fresh and display typical reddish brown colours. The crystals are large, up to 3 cm, fractured and often encountering holly leaf texture. Locally, bright green chlorite has been observed surrounding the chromites that in general are in contact with the mesh serpentine. Similarly to subsample ET2a the contact with bastite is in general sharp and there is no other phase present.

Note on origin and texture.

Mineralogically, the subsamples: ET2a and ET2b are similar. They are both essentially composed of serpentine minerals: mesh texture with scattered numerous bastites, suggesting that the rock could have originated from harzburgite. The main difference between the two subsamples is apparent in the textural arrangements and probably indicates the degree of pre-serpentinisation deformation.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Serpentine			Chr	Chl	FeO/OH	Qtz
	\`mesh\`	bastite	vein				
% modal	70	25	< 0.5	2	0.5	2	< 0.5

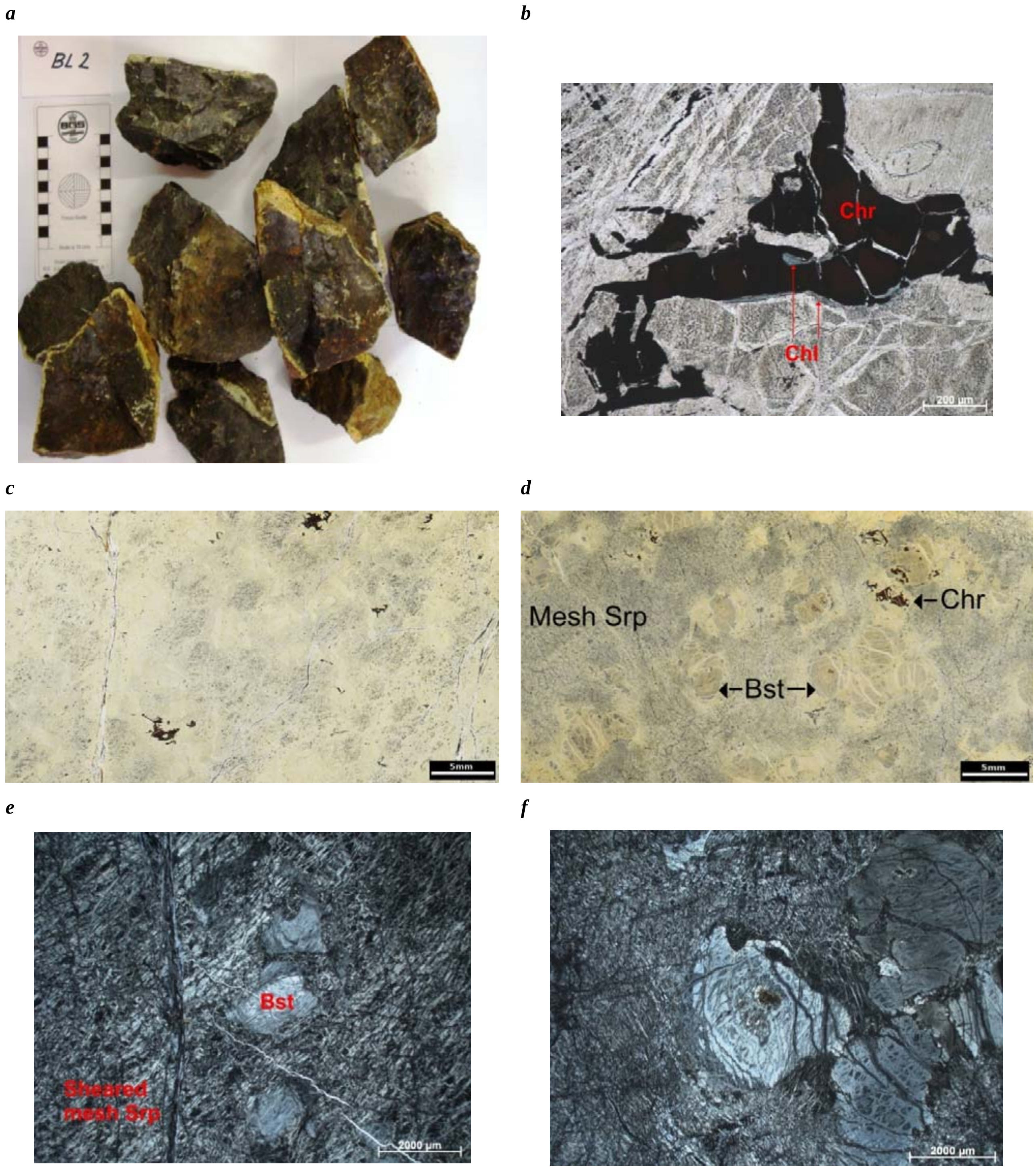


Figure 30. Photographs of ET2 serpentinite: a) several hand specimens fragments; b) a holly-leaf crystal of chromite surrounded by blue-green chlorite; c&d) polished thin section scanned images of SL2a and SL2b respectively; e) crossed polarised light photomicrograph of SL2a serpentinite with apparent fracture cleavage running through serpentine mesh exclusively, bastites (centre of field of view) are not deformed; f) crossed polarised light photomicrograph of SL2b serpentinite showing only faint fracture cleavage and large bastites with relict pyroxene in the centre

A.3.1.3 **Sample ET 5**

Lithology:	Locality:	OS Grid Reference:
SERPENTINITE	Ballantrae N Belt. Site *c.* 5km S of Girvan, S of Byne Hill Caravan Park	(NX18238 94750)

A.3.1.3.1 FIELD SAMPLING

Circa 15 kg of serpentinite was collected from a small excavation (*c.* 15 m high) in the side of the hill (Figure 31). The site was accessed via a rural track at the back of Byne Hill Caravan Park, *c.* 5km S of Girvan.

In the outcrop and hand specimen, the rock appeared black to green black with common fibrous, creamy green serpentine found on joint surfaces.

a ***b***

Figure 31. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET5 outcrop, found c. 5km S of Girvan and S of Byne Hill Caravan Park.

A.3.1.3.2 PETROGRAPHY AND MINERALOGY

Sample ET5 is a serpentinite that displays few a complex formation episodes. The rock is predominantly (*c.*75%) composed of mesh texture serpentine that hosts numerous (*c.* 20%), randomly distributed pyroxene pseudomorphs (bastites and clinopyroxene pseudomorphs). The rock is crosscut by locally anastomosing veins of serpentine (locally fibrous, possibly asbestos-like) and minor talc (<1%). The mesh texture serpentine consists of tightly packed mosaic of serpentine crystals that are intergrown and crosscut by stringers and locally box work - like Fe oxide/oxyhydroxide (*c.* 1%).

Pyroxene pseudomorphs are common (20%) in this sample and occur as large single crystals (up to 3 mm) or clusters of few crystals. In addition to commonly occurring bastites several, interstitial crystals were observed. These normally display relic pyroxene cleavage but are now composed of finely-crystalline (crystals of <100 µm) fibrous phase that has been tentatively identified as serpentine, with the relict texture possibly after amphibole, with subordinate Fe oxide/oxyhydroxide. These could be pseudomorphs after clinopyroxene that has undergone at least 2 main episodes of alteration (clinopyroxene-amphibole-serpentine). Rare, usually bladed chlorite was locally seen within these pseudomorphs.

Chromites are usually <2 mm in size. The crystals are fractured but remaining largely fresh, displaying typical reddish brown colours. Locally, they are partially surrounded by fibrous, olive green chlorite.

Note on origin.

The presence of bastites and roughly equal amount of other possibly clinopyroxene pseudomorphs (collectively up to 20%) suggest that this serpentinite could have originated from lherzolite, rather than harzburgite.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp			Chr	Chl	FeO/OH	Tlc
	`mesh`	bastite	vein				
% modal	75	20	< 1	2	<1	1	1

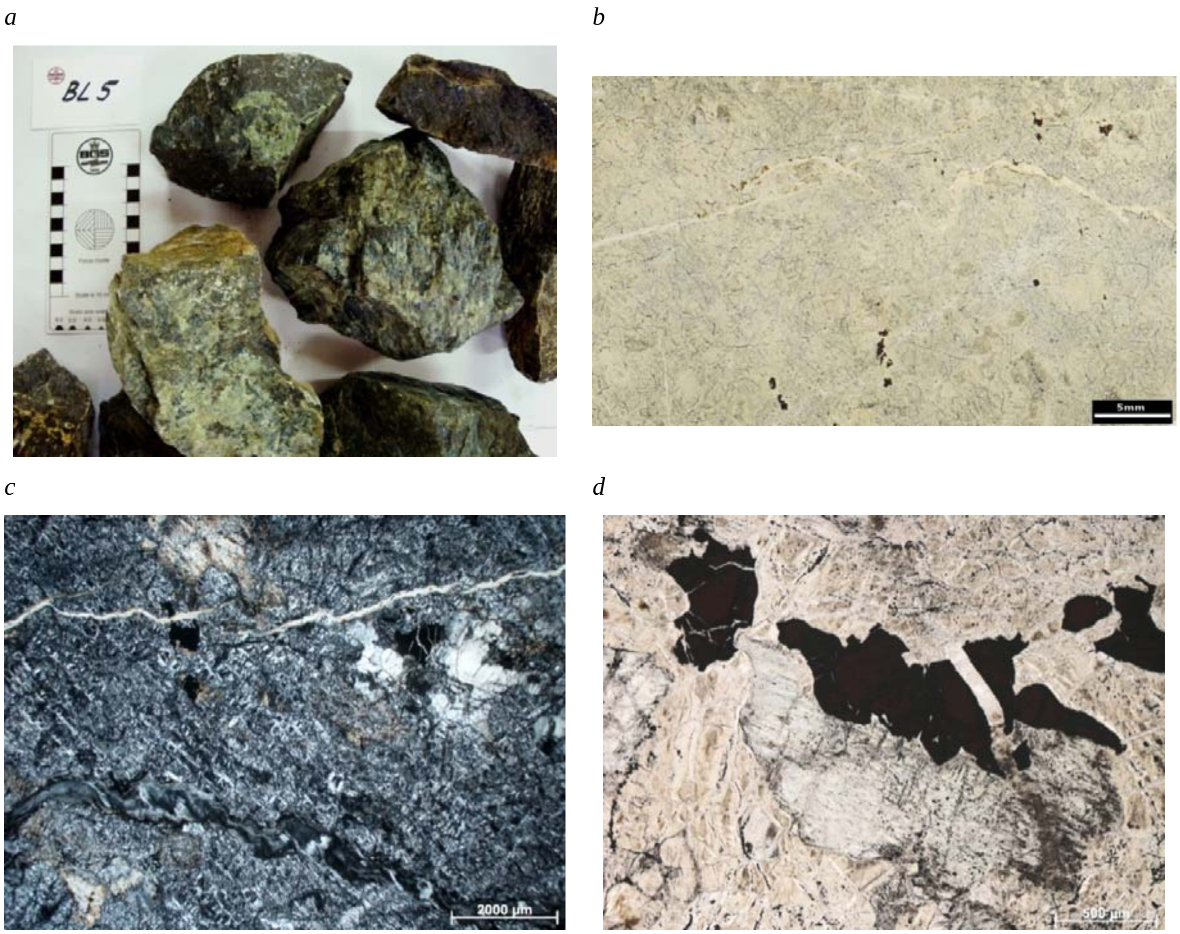


Figure 32. Photographs of ET5 serpentinite: a) few hand specimens fragments; b) polished thin section scanned images; c) crossed polarised light photomicrograph of SL5 serpentinite with apparent bastites with mesh texture serpentine, crosscut by serpentine-infilled fractures; d) plain polarised light photomicrograph showing chromite crystals and bastite within mesh serpentine

A.3.1.4 **Sample ET 6**

Lithology:	Locality:	OS Grid Reference:
SERPENTINITE	Ballantrae S Belt. Site along A77	(NX09312 85300)

A.3.1.4.1 FIELD SAMPLING

Circa 14 kg of serpentinite was collected from a small cutting encountered close to the A77coast road. The site was accessed via a track parallel to the A77 (off N from the B734) running along the foothills of S serpentinite.

The rock in outcrop and hand specimen was distinctively red stained (hematitised) and appeared brittle, often disaggregating under little pressure. This may be result of near surface weathering

a **b**

Figure 33. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) ET6 outcrop, found on a track running subparallel to A77, N of the B734.

A.3.1.4.2 PETROGRAPHY AND MINERALOGY

Sample ET6 is composed of hematite-altered serpentinite. The rock displays a typical serpentinite texture that is represented here by the presence of bastites hosted within mesh serpentine. The mesh serpentine (*c.* 70%) contains the normal tightly packed mosaic of serpentine crystals, interwoven with Fe oxide/oxyhydroxide phases. In this sample, however the amount of Fe oxide/oxyhydroxide phases, hematite in particular, is relatively higher, summing up to *c.* 3%.

The rock is crosscut by an array of randomly oriented serpentine-filled fractures (< 150 µm wide).

Bastite serpentine constitutes *c.* 25% of the sample analysed. They occur as single (200 µm – 5 mm) crystals embedded within mesh serpentine and as clusters of several crystals.

Chromite is scarce in this sample (*c.* 1 %). The crystals, usually < 1 mm, are black and locally fractured.

Trace (<0.5%) dolomite was observed occurring as <20 µm rhomb-like crystals or anhedral mass in < 50 µm wide veinlets cutting through the rock.

Note on the origin.

The rock was originally harzburgite that was serpentinised. It is brittle and significantly altered in the outcrop and hand specimen. The alteration was subsequent to the serpentinisation and probably related to local later alteration in a fault zone.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp			Chr	Chl	FeO/OH	Crb
	`mesh`	bastite	vein				
% modal	70	25	< 1	1	0.5	3	0.5

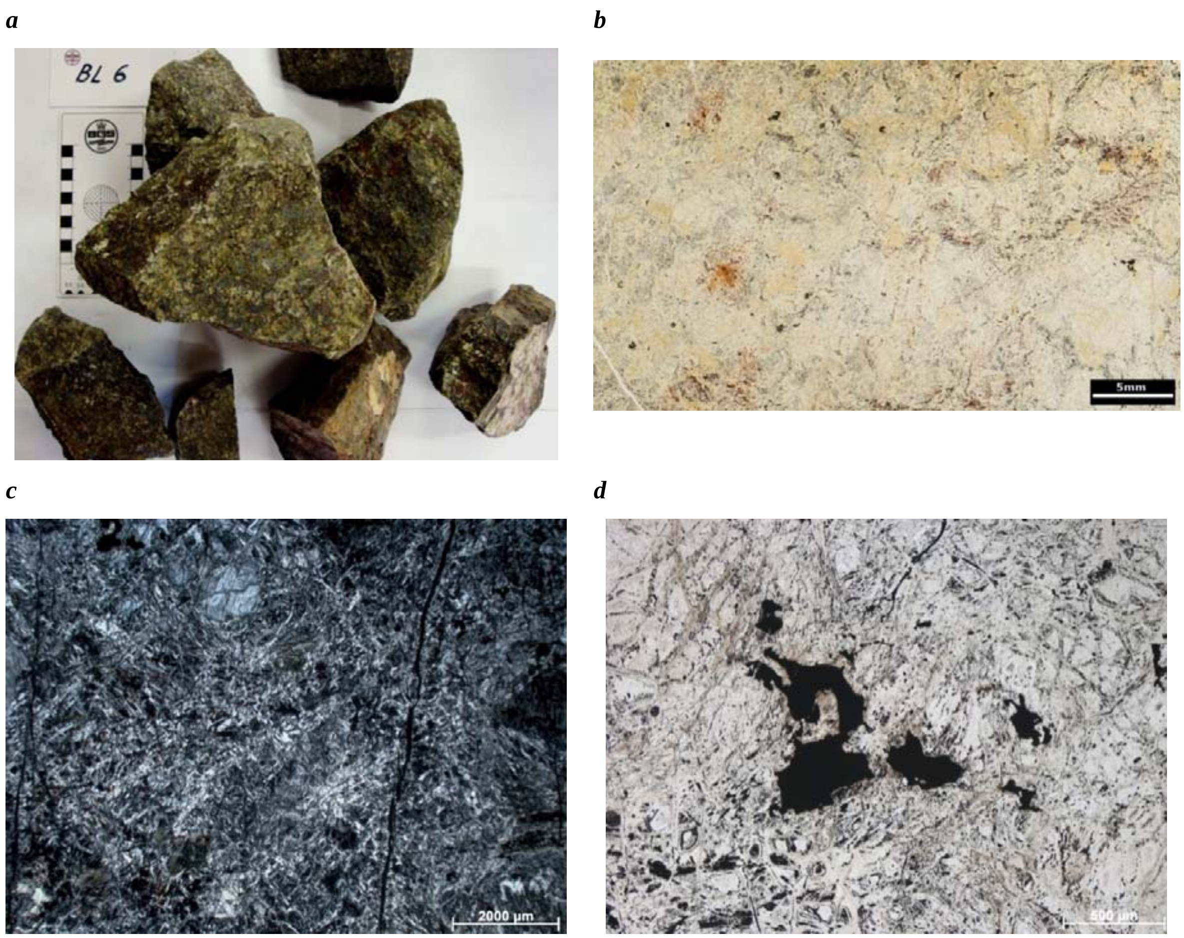


Figure 34. Photographs of ET6 serpentinite: a) selection of hand specimen fragments; b)scanned polished thin section; c) crossed polarised light photomicrograph showing mesh texture serpentinite hosting several bastite crystals; d) plain light photomicrograph showing black, altered holy-leaf chromite within mesh serpentinite.

A.3.2 BELHELVIE AREA

The Belhelvie intrusive mass, located around 10 km to the north of Aberdeen, occupies an onshore area of *c*. 25 km^2. Of this 25 km^2, just over 10 km^2 are accounted for by ultramafic lithologies. The ultramafic rocks occur principally as two NW–SE trending strips, one lying along the southern flank of the intrusion, with the second being found towards its centre.

The Belhelvie intrusion is part of the Newer Gabbro suite of intrusions in NE Scotland. These are a group of gabbros and minor peridotites that occur in a series of intrusions in to the metasedimentary rocks of the Scottish Highlands. They are part of the 'Layered Intrusion Group# (Section 4.4.1) and have a different origin to the 'Ophiolite Mantle Group' that includes all the other rocks studied.

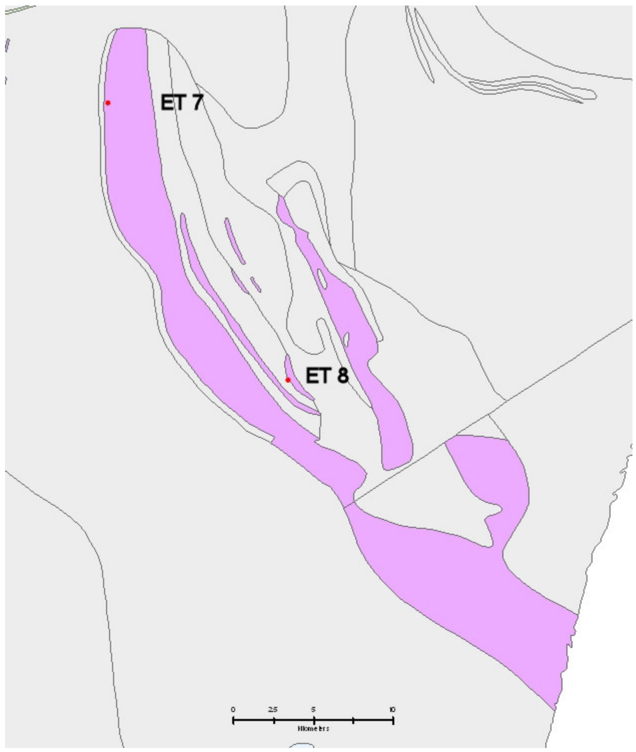


Figure 35. Geological map of the Belhelvie area, showing location of the two samples collected during fieldwork in July 2011. The ultramafic rocks are shown in purple [Copyright BGS, NERC].

A.3.2.1 **Sample ET 7**

Lithology:	Locality:	OS Grid Reference:
SERPENTINISED PLAGIOCLASE-RICH WEHRLITE	Belhelvie, nr Braeside Farm	(NJ90467 21309)

A.3.2.1.1 FIELD SAMPLING

Approximately 17 kg of rock was collected from an outcrop exposed along the road, *c*. 500 m E of Braeside Farm. The site is heavily overgrown and although adjacent to the road the access is somewhat obscured.

The outcrop belongs to the *Sites of Special Scientific Interest*; therefore particular attention was paid towards collecting the sample for this study. All the hand specimens were collected from fallen material at the bottom of the exposure and not hammered off the rock wall.

In hand specimen the lithology is characterised by white patches of interstitial plagioclase within massive, dark brown to greenish groundmass of peridotite (plagioclase peridotite). The rock weathers yellowish brown.

a ***b***

Figure 36. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) heavily overgrown ET7 outcrop, found c. 500 m E from Braeside Farm.

A.3.2.1.2 PETROGRAPHY AND MINERALOGY

Sample ET7 is a serpentinised plagioclase peridotite (serpentinised mela-troctolite). It largely consists of a serpentinised olivine groundmass (approx. 70%) containing a few large, up to 2 cm poikilotopic crystals of clinopyroxene. The groundmass contains circa 7% of relict olivine.

Clinopyroxene is largely fresh and constitutes *c.* 13% of the sample. Only minor alteration to amphibole, serpentine and chlorite (+-talc, <0.5%) was seen in places. Chlorite (approx. 4%) locally exhibits a distinctive bladed habit in this sample.

In addition, patches of very finely crystalline unidentified clay mineral (*c.* 5%) phases that are usually intergrown with finely crystalline chlorite are locally present within the interstices of serpentinised olivine crystals. These probably represent completely altered interstitial plagioclase, with relict mineral seen in only a few places (1%). The pseudomorphs usually comprise a core of intergrown clay mineral phases that at the very contact with serpentinised olivine groundmass is surrounded by a locally discontinuous rims of chlorite and amphibole. This is probably the altered relict of an original corona texture that developed between plagioclase and olivine as a result a phase equilibration during late magmatic processes.

Amphibole predominantly occurs within the altered plagioclase corona and locally as crystals in the groundmass in association with clinopyroxene. Collectively the amphibole constitutes *c.* 3% of the sample.

Chromite constitutes approximately 2% of the sample analysed and occurs as <400 microns equigranular reddish brown crystals.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp `mesh`	Ol	Cpx	Amp	Chl	Clay min. Plg-pseudo morph	Chr	Plg	Feo/oho	Tlc	Sulphides
% modal	62	7	13	3	4	5	2	1	2	<0.5	1

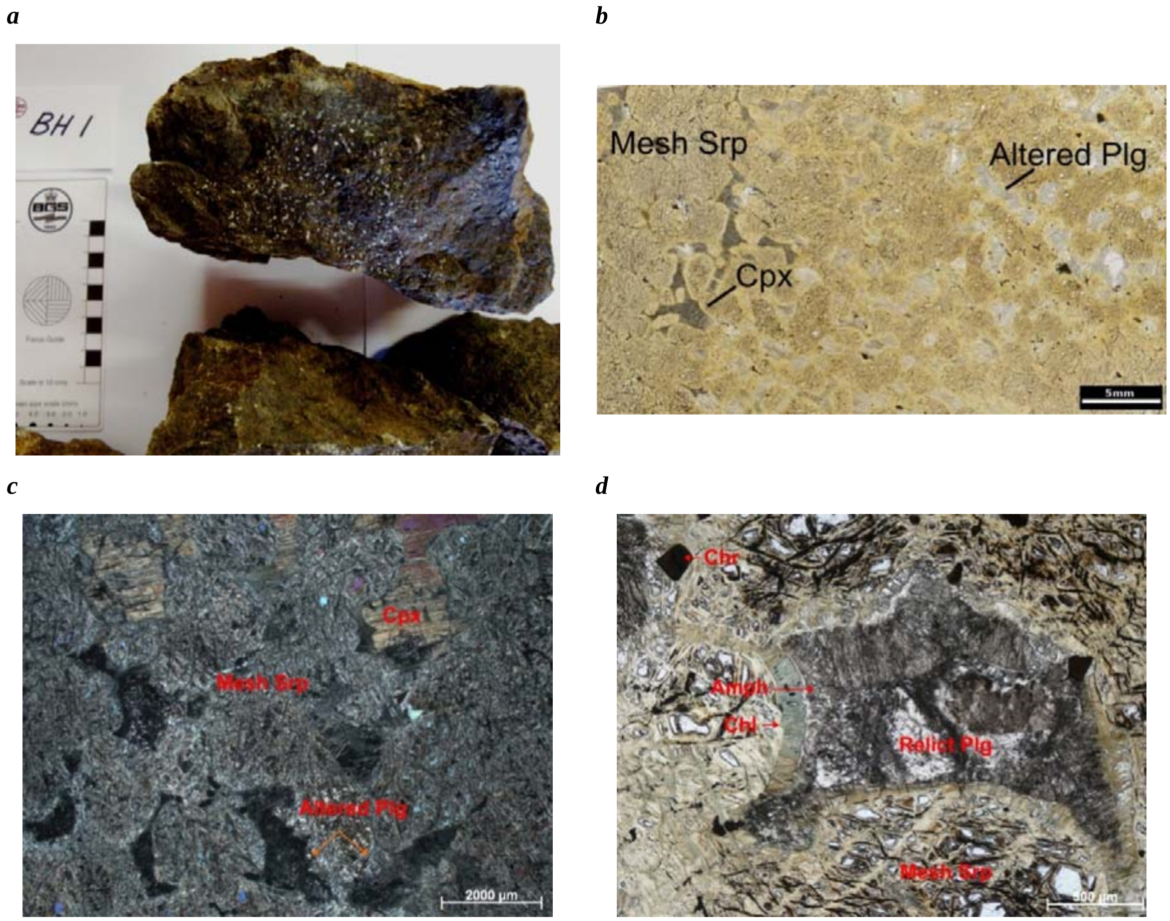


Figure 37. Photographs of ET7 serpentinised plagioclase-rich wherlite showing: a) hand specimen with distinctive white patches of altered plagioclase; b) scanned polished thin section; c) crossed polarised light photomicrograph showing poikilotopic clinopyroxene and interstital altered plagioclase within a groundmass of serpentinised olivine; d) plane polarised light photomicrograph showing chlorite- amphibole corona that occurs between altered plagioclase and serpentinised olivine.

Sample ET 8

Lithology:	Locality:	OS Grid Reference:
SERPENTINISED MELATROCTOLITE	Belhelvie, nr Longdrum	(NJ92910 17560)

A.3.2.1.3 FIELD SAMPLING

The site of interest was accessed through a grassy field NE of B999 road, near Longdrum. The exposed face of a low ridge (*c.* 15 m high) was heavily overgrown and therefore access was to some extent obscured. Approximately 17 kg of sample was collected for this study.

The lithology is characterised by the presence of bands of white interstitial plagioclase and randomly distributed greenish patches (<0.5 cm) of poikilotopic clinopyroxene. Some fragments appear black and very finely-crystalline (aphanitic), resembling recrystallised serpentinite.

a ***b***

Figure 38. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) distant view and a close up of the heavily overgrown ET8 outcrop, found NE of B999 road, near Longdrum

A.3.2.1.4 PETROGRAPHY AND MINERALOGY

Sample ET8 is a partially serpentinised and altered melatroctolite. It consists of largely serpentinised olivine (*c.* 44% with approx. 10% of fresh olivine still present) set in a matrix of virtually completely altered interstitial to poikilotopic plagioclase (*c.* 30% with possible 3% of fresh plagioclase). The rock appears somewhat banded with alternating mafic – pyroxene depleted, and ultramafic – pyroxene dominated layers.

Plagioclase is altered to finely crystalline clay mineral phase (Al, Mg, Ca, Fe, Na silicate) that is locally intergrown with chlorite. The pseudomorphs, when in contact with olivine display characteristic amphibole (<1%) and chlorite-rich (<1%) corona texture, which is probably inherited from the original corona texture of late magmatic phase equilibration. In addition, trace amount of micritic carbonate was found finely intergrown with the clay mineral phases of plagioclase pseudomorphs as well as in minor <150 μm veinlets that were seen locally.

Clusters of pyroxene were predominantly found within the ultramafic-layer. Lesser amounts of scattered single crystals were also observed within the plagioclase-rich mafic-layer. Both orthopyroxene and clinopyroxene are present within the sample analysed and occur in roughly equal amount (*c.* 10% of each). The crystals are large (up to 7 mm) and the clinopyroxene in particular is poikilotopic, enclosing numerous crystals of variably serpentinised olivine. The orthopyroxene is roughly euhedral and contains scattered olivine inclusions that are normally less serpentinised in comparison with those enclosed in clinopyroxene.

Trace amount of sulphide mineral phases was identified. These minerals were dominantly pyrite Ni, Fe (+- Cu) sulphides with variable element ratios.

	Srp `mesh`	Ol	Cpx	Opx	Plg	Amph	Chl	Clay min. Plg-pseudo morph	Feo/oho	Sulphid es
% modal	44	10	10	10	3	1	1	27	3	1

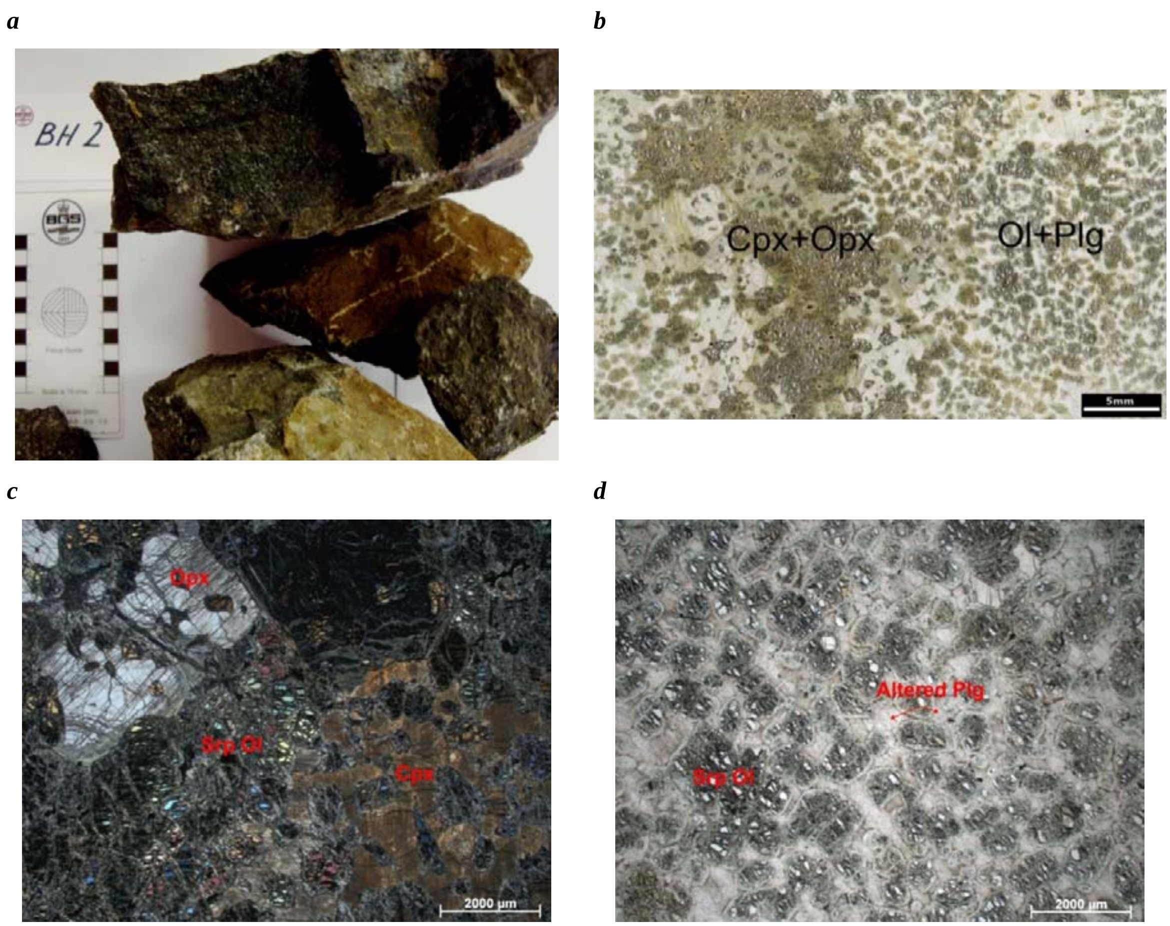


Figure 39. Photographs of sample ET8, serpentinised melatroctolite showing: a) hand specimen with distinctive white patches of altered plagioclase; b) scanned polished thin section with distinctive bands of mafic and ultramafic composition; c) crossed polarised light photomicrograph showing poikilotopic clinopyroxene and olivine-inclusion rich orthopyroxene within a groundmass of serpentinised olivine; d) plane polarised light photomicrograph showing troctolite band dominated by serpentinised olivine set in a groundmass of interstitial altered plagioclase .

A.3.3 PORTSOY AREA

The Portsoy ultramafic bodies exist as a discontinuous NNE–SSW trending belt, which extends for around 10 km inland from the Moray Firth coast. Estimating the true extent of these bodies is problematic due to poor exposure, but together they could occupy an area of *c.* 4.7 km^2.

The geology of the Portsoy area is complicated structurally and lithologicaly. The area comprises of a wide range of metamorphic and igneous rocks. The ultramafic rocks occur as a linear belt ca 10 km long but less than 1 km wide. The bodies are thought to be part of the disrupted mantle sequence of an ophiolite complex that has been tectonically emplaced along a major fault zone known as the Portsoy lineament (Styles 1994)

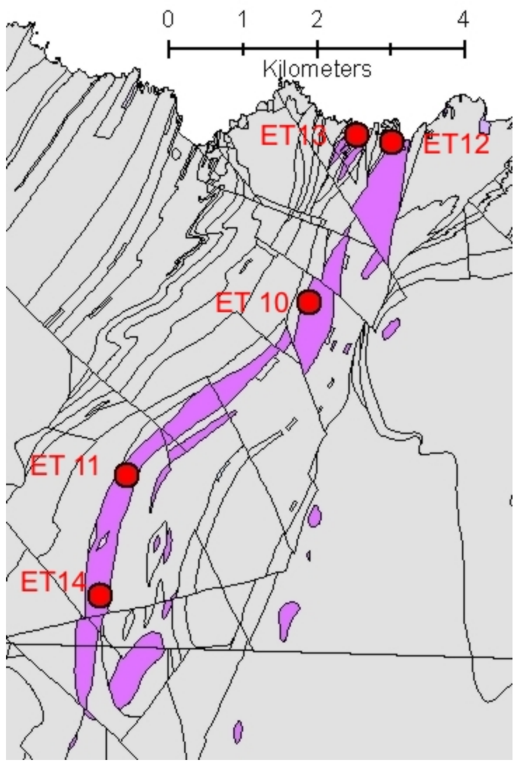


Figure 40. Simplified geological map of the Portsoy area with the ultramafic rocks shown in purple and the sample locations in red [Copyright BGS, NERC].

A.3.3.1 **Sample ET 10**

Lithology:	Locality:	Grid Reference:
SERPENTINITE CHLORITE-RICH	Damheads Quarry, *c.* 3 km SW of Portsoy	(NJ57786 63565)

A.3.3.1.1 FIELD SAMPLING

Sample ET10 was collected from a disused talc quarry found *c.* 3km SW of Portsoy (Damheads Quarry). The site was accessed through a fenced off farmland. The access to the quarry itself was difficult and obscured by heavy vegetation, rubble, and scrap metal. The quarry was also partially filled with boulders of various lithologies (dominantly gabbro) that were presumably cleared for farming in adjacent fields and therefore disposed at the site of our interest. No rocky face was therefore exposed. The samples were collected from few ultramafic boulders found in the southernmost part of the quarry (Figure 41).

Approximately 18kg of rock was collected. In hand specimen, the rock is massive black and finely-crystalline with occasional reddish patches of Fe oxide/oxyhydroxide. Locally sheared zones were observed. Creamy white, powder-like phase, possibly a mixture of carbonate, talc and other clay minerals, was often observed on the weathered surface.

a *b*

Figure 41. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) heavily overgrown ET10 outcrop, found c. 5 km SW of Portsoy, Damheads Quarry (disused).

A.3.3.1.2 PETROGRAPHY AND MINERALOGY

Sample ET10 is a chlorite-rich serpentinite. The rock is essentially composed of three mineral phases: serpentine (*c.* 65%), chlorite (*c.* 25%), and chromite (*c.* 8%). The groundmass is composed of serpentine mesh that consists of `cross-hatched` bladed crystals of serpentine intergrown with finely crystalline granular mass of the same mineral phase with dispersed Fe oxide/oxyhydroxide (<2%). The mesh groundmass is significantly sheared, exhibiting one directional deformational cleavage. In places the mesh serpentine texture is less apparent suggesting localised recrystallisation or presence of highly deformed relicts of original e.g. bastite- containing rock.

Chlorite is abundant in this sample. It consists approximately 25% of the rock and predominantly occurs as randomly distributed bundles of locally radiating bladed crystals and in places as lamellar-like aggregates. The blades (lamellae) vary in length from 50 µm up to 2 mm. Textural parallel to subparallel orientation of the crystals of chlorite and the cleavage in sheared serpentine is apparent in places. In addition, finely crystalline chlorite was observed dispersed within the mesh serpentine.

Chromite crystals (<5 mm) are altered (typically black) often fractured. The fractures are usually subparallel to the general orientation of the deformational cleavage and are dominated by serpentine minerals with subordinate chlorite. In places, chromite crystals and the surrounding serpentine groundmass display characteristic textural arrangement that is expressed in the presence of hard, resilient chromite core mantled by partially recrystallised serpentine with lesser chlorite. This is commonly known as augen texture, and this texture is characteristic for deformed rocks.

Note on origin.

The extent of shearing and local recrystallisation together with the occurrence of augen texture suggest that the serpentinite analysed has undergone significant deformation, most of which has probably occurred at higher temperatures and resulted in the formation of proto-mylonite. The rock was subsequently serpentinised and chloritised.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp `mesh`	Chl	Chr	Fe oxide/oho
% modal	65	25	8	<2

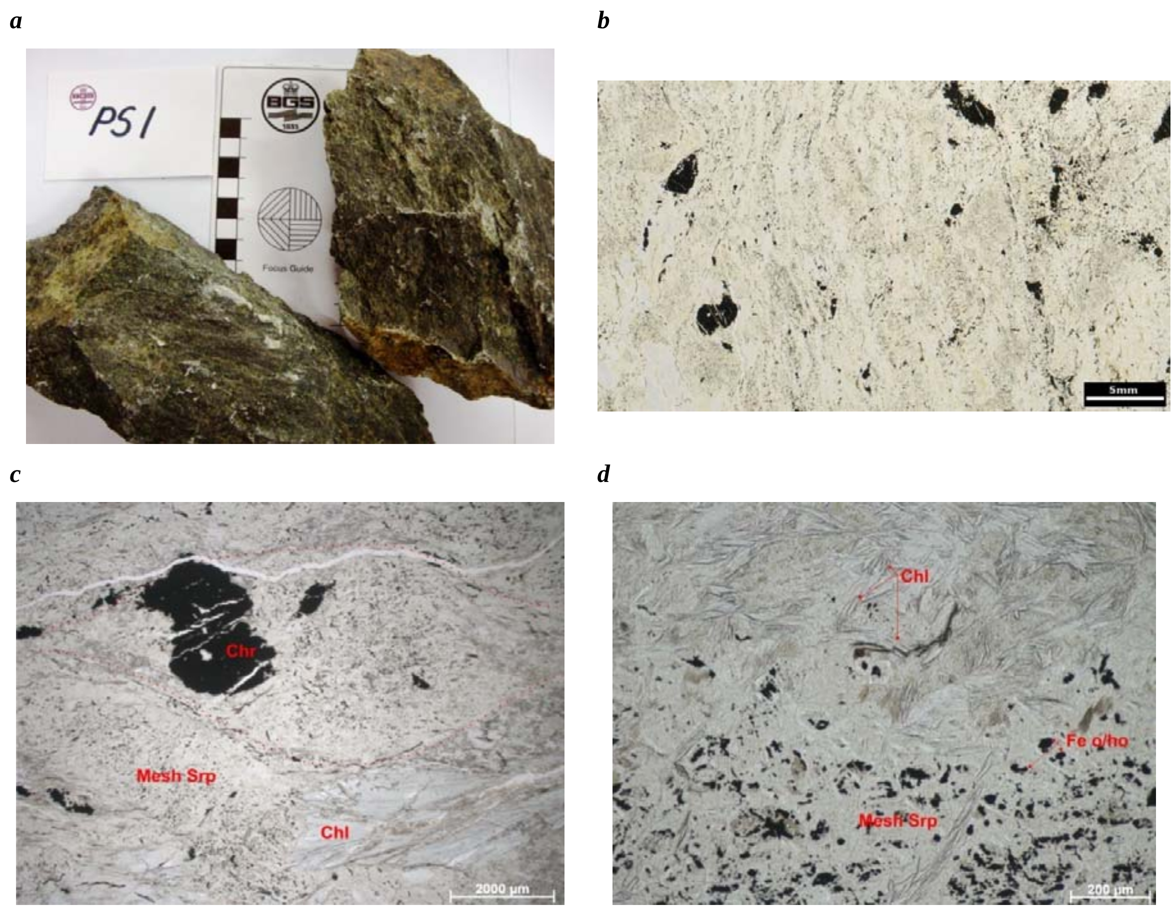


Figure 42. Photographs of sample ET10, chlorite-rich serpentinite: a) hand specimen with distinctive shear zones; b) scanned polished thin section showing scattered chromites (black) in shear groundmass of serpentine and chlorite; c) plane polarised light photomicrograph showing bladed crystals of chlorite in a groundmass of serpentine mesh, note the augen texture around chromite marked by red-dotted line; d) plane polarised light photomicrograph showing finely-crystalline bladed crystals of chlorite and mesh serpentine with scattered Fe oxide/oxyhydroxide .

A.3.3.2 **Sample ET 11**

Lithology:	Locality:	Grid Reference:
SERPENTINITE CHLORITE-RICH	Slackdale, *c.* 6km SW of Portsoy	(NJ54742 60717)

A.3.3.2.1 FIELD SAMPLING

Approximately 16 kg of serpentinite sample was collected from a small rocky face found at the back of the farm at Slackdale, *c.* 6km SW of Portsoy. The access to the exposure was largely obscured by farm equipment, plastic tubes and metal parts.

In the outcrop and hand specimen the serpentinite was black to dark green, some displaying distinct foliation.

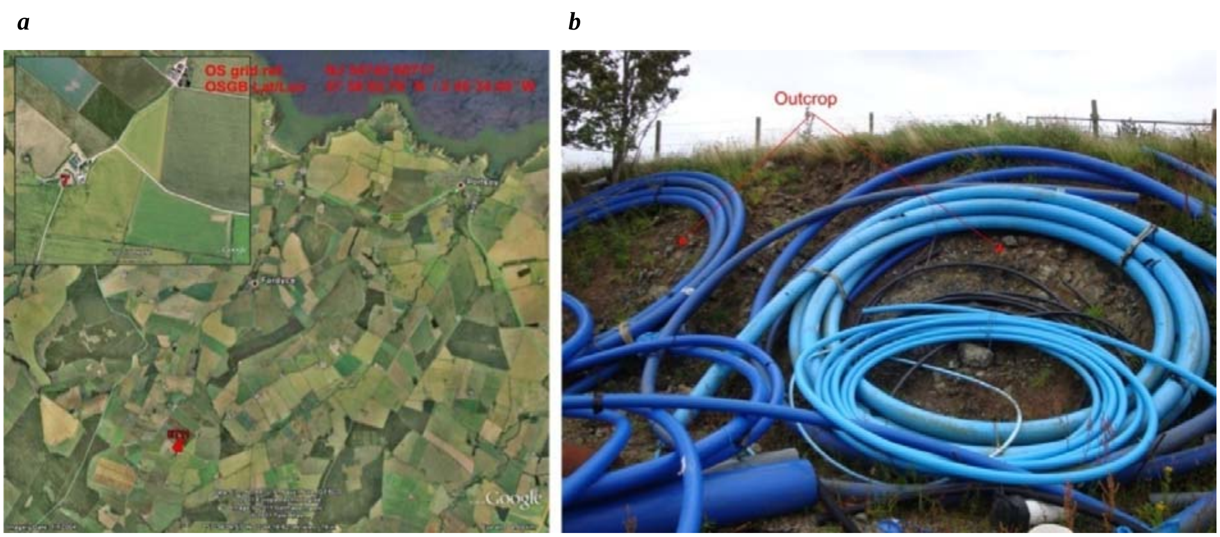


Figure 43. Arial photograph (Google Earth) and site location for sample ET 11 .

A.3.3.2.2 PETROGRAPHY AND MINERALOGY

Sample ET11 is a chlorite-rich serpentinite. The rock is predominantly composed of mesh-like serpentine minerals that are locally intergrown with chlorite. The serpentine mesh constitutes the majority of the sample analysed (*c.* 77%) and consists of roughly equant domains of `cross-hatched` bladed serpentine crystals intergrown with magnetite stringers, a texture typical for pseudomorphed olivine. Few (*c.* 3%) bastites were seen scattered within the mesh serpentine groundmass.

The rock is moderately deformed and displays faint one directional cleavage. Bands (2-3 mm thick) of recrystallised serpentine were observed aligned subparallel to the cleavage. Fracture-related yellowish brown discolouration of the rock is apparent in several places (Figure 44, scanned image). This discolouration resulted from alteration of Fe-rich phases (predominantly magnetite) and formation of Fe oxide/oxyhydroxide.

Chlorite constitutes approximately 15% of the sample analysed. It occurs as bladed (lamellar-like) crystals (< 300 µm) that are either scattered within the serpentine groundmass or more commonly associated with crystals of chromite. This association is very distinctive and consists of a halo of bladed chlorite that has evidently grown at the expense of chromite, as shown on

Figure 44. The chromite - chlorite alteration is particularly apparent within few shear zones (containing stringer-like chromite) that were subsequently reactivated by fractures.

Chromite is moderately abundant and makes up to 3% of the sample. The crystals are usually brown to dark brown when altered and < 500 µm. The majority of crystals were found within the shear zones where they occur as stringer-like aggregates. Most of the chromites observed display a low to high degree of alteration to chlorite. The degree of alteration depends on the vicinity to shear/fracture zone, with the crystals found within the shear zone exhibiting enhanced chloritisation.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp `mesh`	Bst	Chl	Chr	FeO/OH
% modal	77	3	15	3	<2

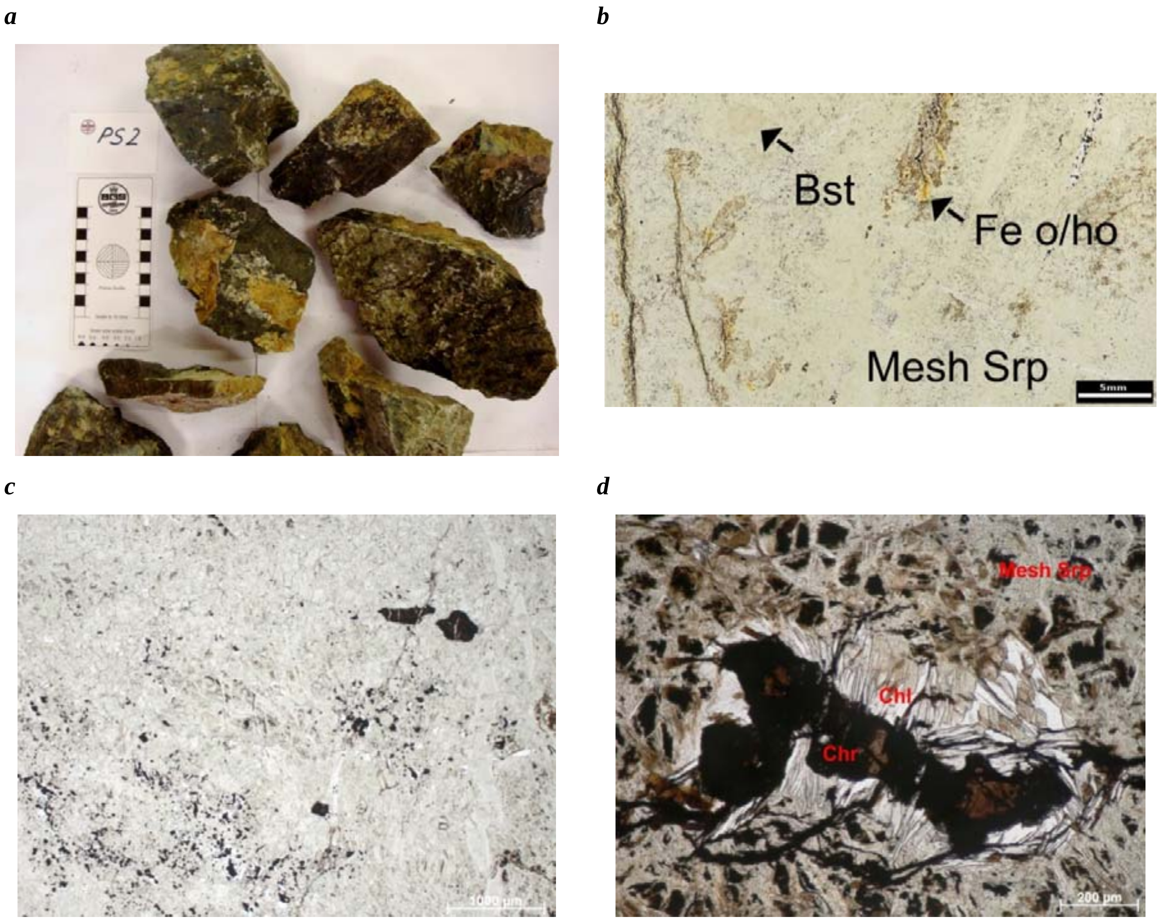


Figure 44. Photographs of sample ET11, chlorite-rich serpentinite: a) hand specimen; b) scanned polished thin section; c) plane polarised light photomicrograph showing mesh serpentine, patchy Fe oxide/oxyhydroxide and scattered chromites; d) plane polarised light photomicrograph showing crystals of chromite rimmed with bladed crystals of chlorite, all within mesh serpentine .

A.3.3.3 Sample ET 12

Lithology:	Locality:	Grid Reference:
SERPENTINITE CHLORITE-RICH	Portsoy, Links Bay, beach outcrops	(NJ59165 66218)

A.3.3.3.1 FIELD SAMPLING

Approximately 20kg of serpentinite was collected from Links Bay, Portsoy. The rocks are exposed in the central part of the intertidal zone of Links Bay.

In the outcrop and hand specimen the serpentinite is massive black on the weathered surface and dark red to greenish black on freshly cut face.

In this area the serpentinite is in contact with finely crystalline mafic rock (dominantly gabbro) and locally minor granite intrusions.

Due to its coastal location the serpentinite may contain enhanced quantities of carbonate, originating from the $CaCO_3$ shells of marine organisms on the surface.

a *b*

Figure 45. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) serpentinite ET12 cropping out on the beach of Links Bay, Portsoy.

A.3.3.3.2 PETROGRAPHY AND MINERALOGY

Sample ET12 is a chlorite-rich serpentinite. The rock is dominantly composed of mesh serpentine (*c*. 65%) that consists of tightly packed, roughly equant domains of finely intergrown, often `cross-hatched` crystals of serpentine minerals that are inter-woven with substantial amount (*c*. 5%) of Fe oxide/oxyhydroxide. In places the mesh serpentine has undergone significant recrystallisation, which resulted in remobilisation of the Fe oxide/oxyhydroxide into the newly formed crystal, boundaries giving rise to a radial-like sectors appearance (Figure 46).

Chlorite and its alteration product are secondary major phases and make up to 9% and 13% of the sample respectively. These minerals are usually intergrown forming patchy aggregates that are scattered throughout the sample. The alteration product occurs as earthy-brown finely-crystalline masses of fibrous crystals (<200 µm long) that normally display perfect basal cleavage. It is composed of unidentified Mg, Fe +-Mn, Ca hydrated silicate, possibly clay mineral. Chlorite crystals are generally coarser (up to 600 µm) and exhibit a lamellar-like texture with the lamellae usually separated by stringers of magnetite.

Talc has also been observed and constitutes *c.* 5% of the sample. It exhibits a distinctive emerald green colours and occurs as either anhedral patches or prismatic crystals, both forms are usually associated with brucite-chlorite aggregates.

Chromite is moderately abundant (*c.* 3%) in this sample; the crystals are usually large up to 2.5 mm, brown to dark brown and often fractured. The fractures are filled with magnetite and locally with intergrown serpentine-talc-chlorite. Chlorite-talc asymmetric rims are common in most chromite crystals observed.

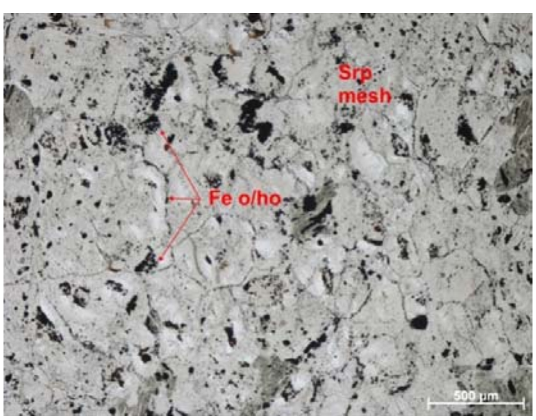
MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp `mesh`	Mg, Fe Silicate	Chl	Chr	FeO/OH	Tlc
% modal	65	13	9	3	5	5

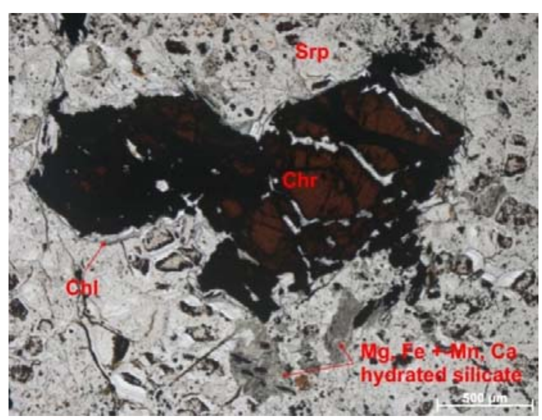
a

b

c

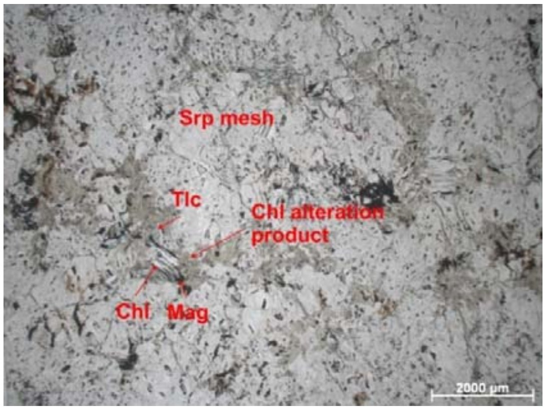


d



e

f



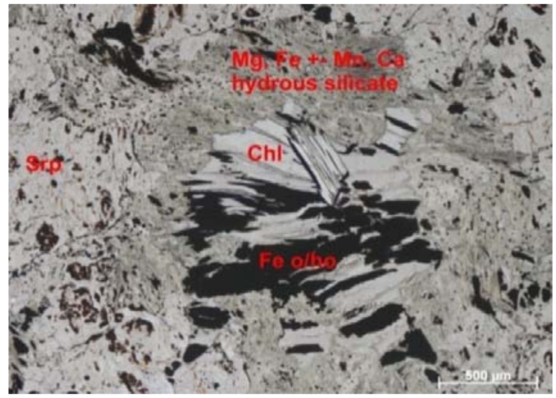


Figure 46. Photographs of sample ET12, chlorite-rich serpentinite: a) hand specimen; b) scanned polished thin section; c) plane polarised light photomicrograph showing mesh serpentine, Fe oxide/oxyhydroxide remobilised to the grain boundaries of newly formed crystals; d) plane polarised light photomicrograph showing association of talc, chlorite and Mg, Fe +-Mn, Ca hydrous silicate (probably Chl alteration product); f) detailed plane polarised light photomicrograph showing the Mg, Fe +-Mn, Ca hydrous silicate overgrowing bladed crystals of chlorite, all within serpentine groundmass .

A.3.3.4 **Sample ET 13**

Lithology:	Locality:	Grid Reference:
SERPENTINITE CHLORITE-RICH	Portsoy, Marble Quarry	(NJ58575 66335)

A.3.3.4.1 FIELD SAMPLING

Approximately 17kg of serpentinite was collected from a disused Marble Quarry at Portsoy. The quarry is located at the bottom of a cliff-dominated coastline and the usual access-providing driveway was unavailable at the time of the field work. The quarry was therefore accessed via a steep, grassy descent from a small car park found at the end of Marine Terrace, off Cullen Street. The quarry had been used for the extraction of serpentine for carving and turning in to ornamental objects at a small factory in Portsoy. Marble is usually used to describe a rock composed of calcium carbonate (calcite) but locally the rock is called marble because it is soft and easily worked, a ‘trade’ name rather than a geological description.

The rocks are very well exposed and display a variety of lithological and structural features. In hand specimen the serpentinite is green, dark green, red and black; it is massive, strongly foliated and mylonitised. The foliation is exceptionally well indicated by the subparallel alignment of crystals of chromite-magnetite.

a *b*

Figure 47. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) serpentinite outcrop at Portsoy Marble Quarry (disused) .

A.3.3.4.2 PETROGRAPHY AND MINERALOGY

The observation of the hand specimens revealed that sample ET13 is not homogenous and amongst all the fragments collected in the field some were distinctively sheared, whereas others were massive. In order to better describe the textural and petrographical variation two polished thin sections were prepared for this sample; `a` - being the apparently sheared subsample and `b` the massive serpentinite. XRD and chemical analysis (XRF) were however performed on the bulk ET13 sample a mixture of the two.

Subsample ET 13a

Subsample ET13a is a chlorite-rich serpentinite. The rock is sheared and has patchy to banded texture, which is expressed in the presence of mesh serpentine interwoven with subparallel bands and patches of chlorite and partially recrystallised serpentine. In addition, there are zones of chromite crystals that appear notably extensionally deformed.

Serpentine minerals are by far the most abundant constituting approximately 75% of the sample. These minerals are arranged in either mesh texture or to a lesser extent as finely crystalline recrystallised masses. The meshes are not deformed and consist of roughly equant domains of bladed to fibrous crystals of serpentine mantling the core of Fe oxide/oxyhydroxide (*c.* 3%). Bastites-like domains (<1 mm) are scarce (<0.5%) and partially recrystallised.

Chlorite is abundant constituting *c.* 18% of this subsample. Clusters of this finely-crystalline mineral, consisting of < 200 µm bladed crystals, show a general shear-parallel distribution trend. The arrangement of individual crystals within each separate cluster is variable, from aligned to randomly oriented.

Chromite constitutes approx. 3% of the subsample and exhibits deformational textures, expressed by distinct elongation that is parallel to subparallel to the general deformation cleavage. The crystals are black and locally fractured, with the fractures filled by magnetite.

Trace amounts (<1%) of finely-crystalline carbonate were observed intergrown with chlorite in places.

Subsample ET 13b

Subsample 13b is also a chlorite-rich serpentinite with a patchy appearance similar to ET13a. This subsample however, doesn't display clear evidence for chlorite-serpentine banding but shows a notable alignment of serpentine crystals within domains of possibly deformed mesh cells. (Figure 48).

The subsample is essentially composed of serpentine (77%) and chlorite-chlorite alteration product (18%) with subordinate altered chromite (<2%) and Fe oxide/oxyhydroxide (3%).

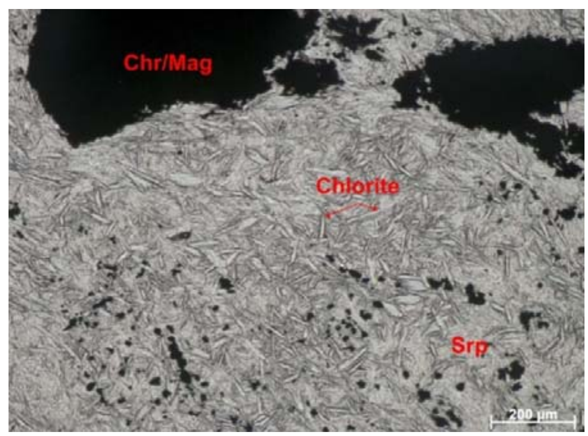
Note on origin

The presence of chlorite-serpentine patchy bands, together with distinctive deformational textures of chromite suggests that the rock has undergone significant shearing. In places, mylonitic texture is apparent. This is best observed in areas where serpentine mesh domains are in contact with chlorite and recrystallised serpentine bands.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp `mesh`	Chl	Chr	FeO/OH	Crb
% modal	76	18	<2	3	<1

a ***b***



c ***d***

e ***f***

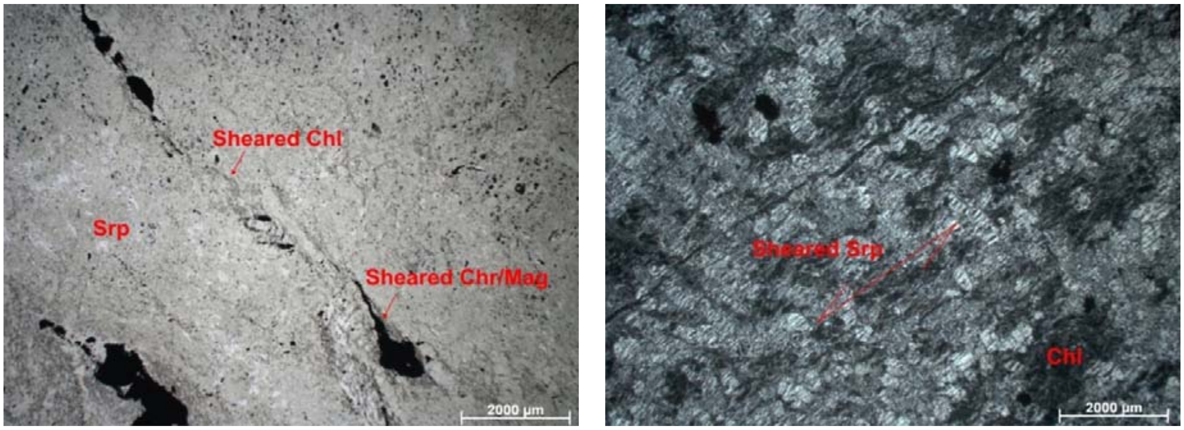


Figure 48. Photographs of sample ET13, chlorite-rich serpentinite: a) hand specimen; b) plane polarised light photomicrograph showing bladed chlorite intergrown with serpentine minerals; c, d) scanned polished thin section of ET13 a and ET 13b respectively; e) plane polarised light photomicrograph showing sheared serpentinite with foliation clearly determined by chlorite and chromite/magnetite deformed zones, ET13a; f) crossed polarised light photomicrograph showing sheared serpentine mesh and chlorite patches.

A.3.3.5 **Sample ET 14**

Lithology:	Locality:	Grid Reference:
SERPENTINITE CHLORITE-RICH	Meikle Toux Farm, *c.* 9km SW of Portsoy	(NJ54287 58731)

A.3.3.5.1 FIELD SAMPLING

Approximately 18kg of serpentinite was collected from a disused quarry found at the western end of a Meikle Toux Farm, situated *c.* 9km SW of Portsoy. The access to the outcrop was fenced off and obscured by heavy vegetation. With the permission of the land owner the rocks were collected from a small <1m wide, overgrown exposure.

In the outcrop the serpentinite was greenish brown and displayed localised bands and patches.

a ***b***

Figure 49. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) small serpentinite exposure at the W end of Meikle Toux farm .

A.3.3.5.2 PETROGRAPHY AND MINERALOGY

Sample ET14 is a chlorite-bearing serpentinite. The rock is predominantly composed of serpentine minerals that constitute approx. 85% and subordinate chlorite, making up to 7%. The rock is extensively sheared which is apparent in the texture and distribution of all the mineral phases present. For instance, mesh serpentine, the dominant form of this mineral, is still distinct however it displays development of one-directional cleavage. This was probably associated with partial recrystallisation and re-arrangement of mesh domains of the protolith, pre-deformation serpentinite. In addition, the Fe oxide/oxyhydroxide (*c.* 4%) phases appear to have been remobilised from centres of the mesh domains and concentrated in other areas, mostly fracture zones. Crystals of chromite are distinctively extensionally deformed, resulting in an elongated aggregate appearance. Chlorite crystals display a tendency to be cleavage aligned, however some randomly oriented blades were also observed.

Chlorite occurs as bladed, locally lamellae-like crystals and range in size from 50-500 µm. In most cases the crystals show a clear co-occurrence with chromite, usually forming a radial-like alteration halo.

Chromite is the least abundant, constituting *c.* 4% of the sample. The crystals are distinctively sheared and significantly altered to chlorite and magnetite

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp	Chl	Chr	FeO/OH
% modal	85	7	4	4

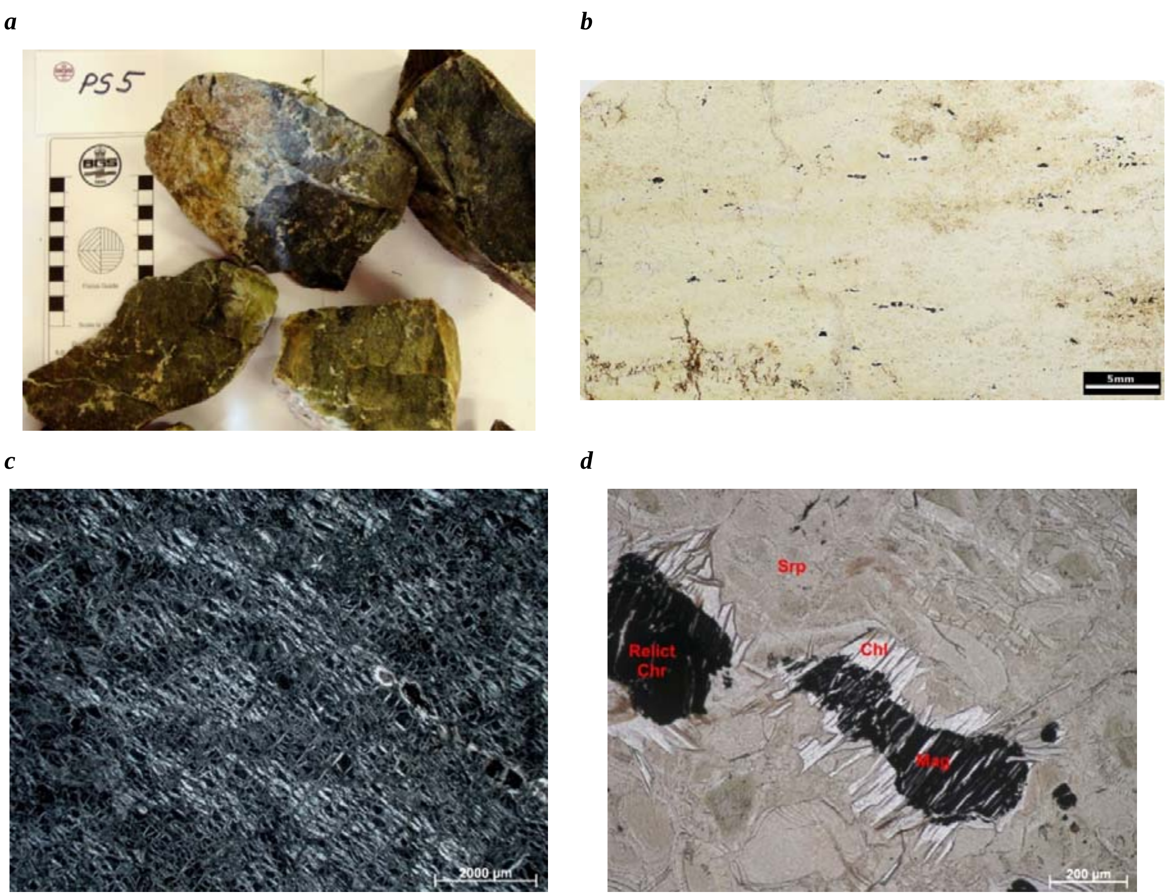


Figure 50. Photographs of sample ET13, chlorite-rich serpentinite: a) hand specimen; b) scanned polished thin section; c) crossed polarised light photomicrograph showing sheared serpentine mesh; d) altered chromite (now magnetite) and distinctive chlorite halo .

A.3.4 LIZARD AREA

The Lizard Complex in SW Cornwall consists of mafic and ultramafic rocks that comprise the Lizard ophiolite complex that is in faulted contact with the sedimentary rocks to the north. The ultramafic rocks cover an area of 54 sq km and consist of various types of rock that are shown on Figure 51. The 'primary' peridotites are shown in dark purple and occur in the eastern part and are now largely serpentinites with various remnants of olivine and pyroxene that is usually less than 10% and very rarely up to 50%. Serpentinites derived from dunite (olivine rock) are shown in dark maroon and occur in the northern parts and only rarely contain remnants of olivine. Recrystalised peridotites occur in the western part and these contain substantial amounts of amphibole after pyroxene and plagioclase feldspar and often only around 60% serpentine.

Four samples from Lizard Peninsula were chosen for further analysis. The samples are ET 15, ET 16, ET 17, and ET 18.

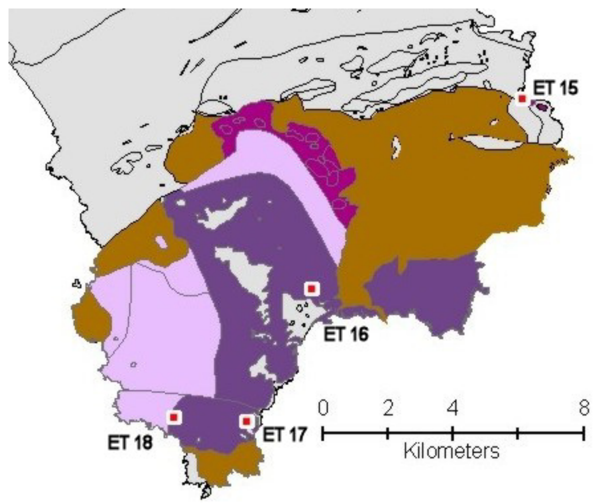


Figure 51. Topographical image (Google Earth) of Cornwall with the site of interest marked by white rectangle; and generalised geological map showing the location of 4 Lizard samples analysed in this study. The ultramafic rocks are shown in purple and the mafic rocks in brown [Copyright BGS, NERC].

A.3.4.1 **Sample ET 15**

Lithology:	Locality:	Grid Reference:
SERPENTINITE	Lizard Porthallow	(179812 23203)

A.3.4.1.1 FIELD SAMPLING

Approximately 5kg of sample of serpentinite from Porthallow, collected previously by BGS geologists, was sourced from the BGS rock collection.

a *b*

Figure 52. Arial photograph (Google Earth) and site location for sample ET 15 [Copyright BGS, NERC].

A.3.4.1.2 PETROGRAPHY AND MINERALOGY

Sample ET 15 is a serpentinite. The rock is strongly deformed (brittle deformation) and cut by numerous mutually crosscutting fractures. In places slivers of the host rock were seen to be cemented by newly grown serpentine minerals. All these features suggest that this rock was strongly brecciated, in places recrystallised and probably originates from a shear/fault zone.

The rock is predominantly composed of serpentine minerals (*c.* 90%) that exhibit several forms, such as: original mesh, bastite, and fibrous crystals. The mesh serpentine is particularly well preserved in least altered areas (yellow stained on scanned image) where the degree of recrystallisation was low. Here the serpentine minerals occur as roughly equant domains interwoven with Fe oxide/oxyhydroxide. Closer to the fracture zone the serpentine mesh appears altered and the Fe oxide/oxyhydroxide remobilised to newly formed crystal boundaries as well as along the fracture edges. The fractures vary in thickness but usually don't exceed 2.5 mm. They consist of coarse bladed and fibrous serpentine minerals intergrown with Fe oxide/oxyhydroxide. Magnetite crystals are scattered throughout the sample. Collectively, the Fe oxide/oxyhydroxide forms *c.* 5% of the sample.

Chlorite constitutes approx. 3% of the sample. The crystals are bladed, usually <100 microns and unevenly scattered throughout.

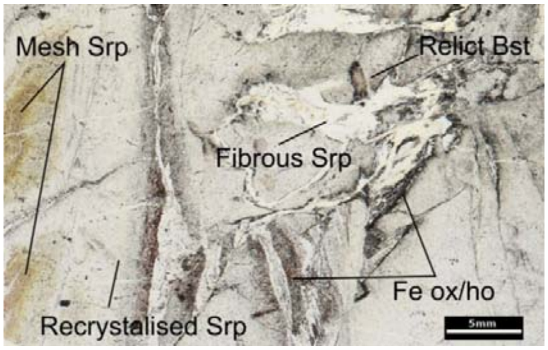
Chromite crystals are scarce, making up to 2% of the sample. The crystals (<1 mm) are in places altered to Fe oxide and largely corroded, displaying distinctive sieve-like patterns.

Trace (<1%) amount of quartz was observed in <100micron wide veins.

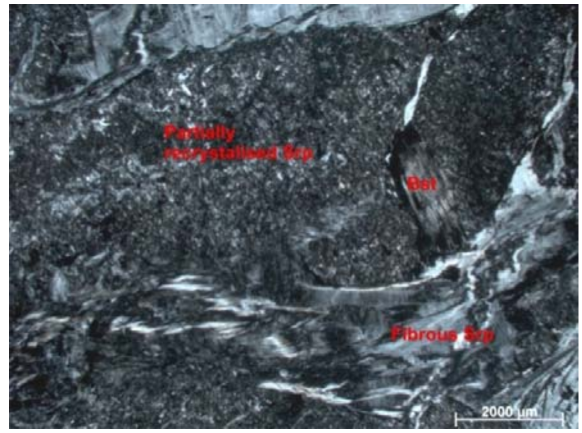
MODAL ANALYSIS - MINERAL PROPORTIONS

	Serpentine	FeO/OH	Chl	Chr	Qtz
% modal	90	5	3	2	<1

a



b



c

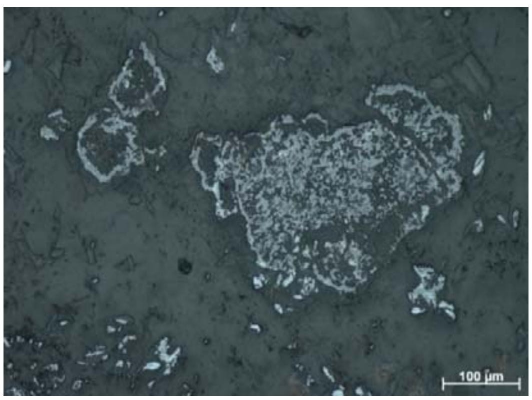


Figure 53. Photographs of sample ET15, serpentinite: a) scanned polished thin section; b) crossed polarised light photomicrograph showing fibrous and partially recrystalised serpentine crystals; c) reflected light photomicrograph showing corroded chromite displaying sieve-like texture .

A.3.4.2 **Sample ET 16**

Lithology:	Locality:	Grid Reference:
SERPENTINITE	Lizard Gwendreath Quarry	(173331 17435)

A.3.4.2.1 FIELD SAMPLING

Approximately 5 kg of sample of serpentinite from Gwendreath Quarry in Lizard, collected previously by BGS geologists, was sourced from the BGS rock collection.

a *b*

Figure 54. Arial photograph (Google Earth) and site location for sample ET 16 [Copyright BGS, NERC].

A.3.4.2.2 PETROGRAPHY AND MINERALOGY

Sample ET 16 is a serpentinite. Serpentine minerals are dominant, constituting *c.* 87% of the sample and occur as finely intergrown crystals in mesh cells and/or as large, up to 5 mm bastites (*c.* 5% of the total serpentine). In addition a small amount (<3% of the total serpentine) of serpentine minerals were found in <200 µm wide veins. Here, the minerals appear recrystallised, often forming the so-called hourglass texture, elsewhere in the vein the crystals exhibit a distinctively elongated, fibrous morphology (possibly chrysotile). The mesh cells usually contain Fe oxide/oxyhydroxide (up to 2% of the bulk composition) rimming serpentinised olivine relicts, all mantled by serpentine mineral phases. In places, the core of mesh cells contains trace amount of finely crystalline clay minerals, possibly talc (0.5%).

Chlorite makes up to 5% of the sample analysed and occurs as fine, <100 µm bladed crystals that are usually clustered or occur as anastomosing lamellae-like aggregates intergrown with Fe oxide/oxyhydroxide.

Amphibole constitutes about 5% of this sample. Prismatic and fine anhedral crystals were usually found within scattered patchy zones. These zones are probably relict clinopyroxene.

Trace amount of unidentified clay mineral phases were seen within, <100 µm wide veins cross cutting the sample.

Trace amounts of chromite were observed. The crystals are largely altered by Fe oxide/oxyhydroxide.

Note on origin.

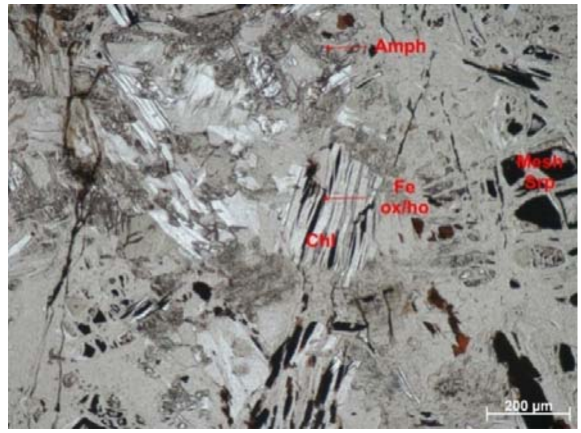
The presence of large bastite and numerous relicts of clinopyroxene (now replaced by amphibole), all set within serpentinised olivine mesh suggest that the protolith rock was lherzolitic in composition.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp \`mesh\`	Chl	Amph	FeO/OH	Tlc	Unident. clay min.	Chromite
% modal	86	5	5	2	0.5	0.5	1

a

b



c

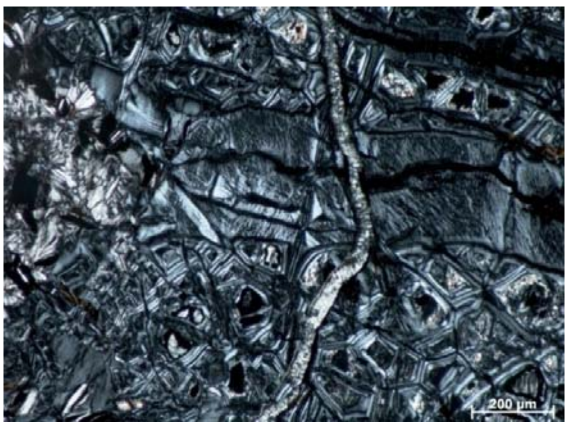


Figure 55. Photographs of sample ET16, serpentinite: a) scanned polished thin section; b) plane polarised light photomicrograph showing assemblage of chlorite and amphibole in mesh and partially recrystalised serpentine; c) crossed polarised light photomicrograph showing mesh serpentinite (bottom) and recrystalised serpentine in veins, both cross cut by micro-fractures of quartz .

A.3.4.3 **Sample ET 17**

Lithology:	Locality:	Grid Reference:
SERPENTINITE	Lizard Balk Quarry	(171334 13390)

A.3.4.3.1 FIELD SAMPLING

Approximately 5 kg of sample of serpentinite from the Balk Quarry in the Lizard, collected previously by BGS geologists, was sourced from the BGS rock collection.

a *b*

Figure 56. Images showing: a) the topographical image (Google Earth) of the site of interest and its surroundings; b) Massive partially serpentinised peridotite cut by numerous veins, Balk quarry.

A.3.4.3.2 PETROGRAPHY AND MINERALOGY

Sample ET17 is a serpentinite. This rock predominantly consists of serpentine minerals that constitute *c.* 90% of the bulk composition. The rock is texturally complicated and exhibits multigenerational mineral growth. The original texture; represented by numerous bastite crystals (20% of the bulk serpentine) scattered within mesh serpentine; is in places recrystallised, in particular within zones of enhanced veining and brecciation. The recrystallised zones display general subparallel alignment and consist of clusters and layers of randomly oriented blocky, prismatic, and/or fibrous serpentine crystals that are tightly packed and finely intergrown. Adjacent host mesh serpentine also appears partially recrystallised. Here, the recrystallisation resulted in formation of polygons (serpentine mesh-relicts) that are separated by stringers of remobilised Fe oxide/oxyhydroxide. The Fe oxide/oxyhydroxide sums up to 3% in this sample.

Trace amount (1-2%) of finely crystalline amphibole usually associated with relict clinopyroxene was observed in places.

Chromite crystals are scattered and constitute *c.* 3% of the sample analysed. The crystals are light brown (Al-rich) and usually exhibit holy leaf texture.

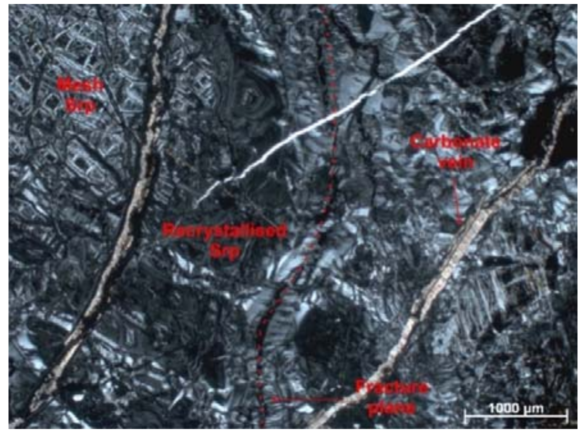
Carbonate minerals (confirmed by XRD to be calcite) constitutes only 2% of the section analysed and were predominantly found within late, <400 µm wide veins.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp \`mesh\`	Recrysta-llised Srp	Bst	Chr	FeO/OH	Amph	Cpx	Crb
% modal	40	30	20	4	3	1	<0.5	2

a

b



c

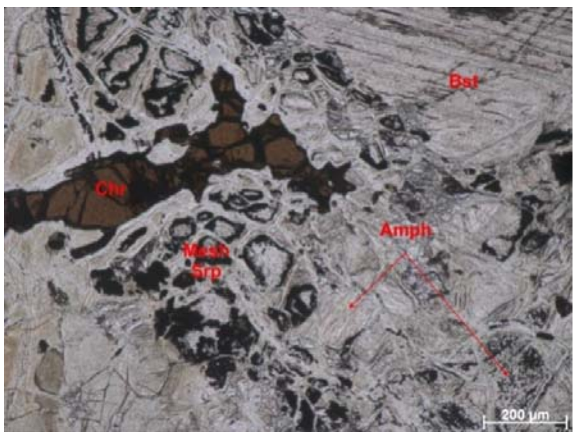


Figure 57. Photographs of sample ET17, serpentinite: a) scanned polished thin section; b) crossed polarised light photomicrograph showing two generations of serpentine minerals, recrystallised serpentine occurring adjacent to a fracture and relict mesh serpentine further away from the fracture. The rock is crosscut by veins of carbonate; c) plane polarised light photomicrograph fresh crystal of chromite surrounded by mesh serpentine. The field of view also shows a fragment of a bastite crystal and scattered amphibole crystals .

A.3.4.4 **Sample ET 18**

Lithology:	Locality:	Grid Reference:
SERPENTNITE	Holestaw Kynance	(169079 13535)

A.3.4.4.1 FIELD SAMPLING

Approximately 5 kg of sample of serpentinite from Holestaw, Kynance, collected previously by BGS geologists was derived from the BGS rocks and mineral collection.

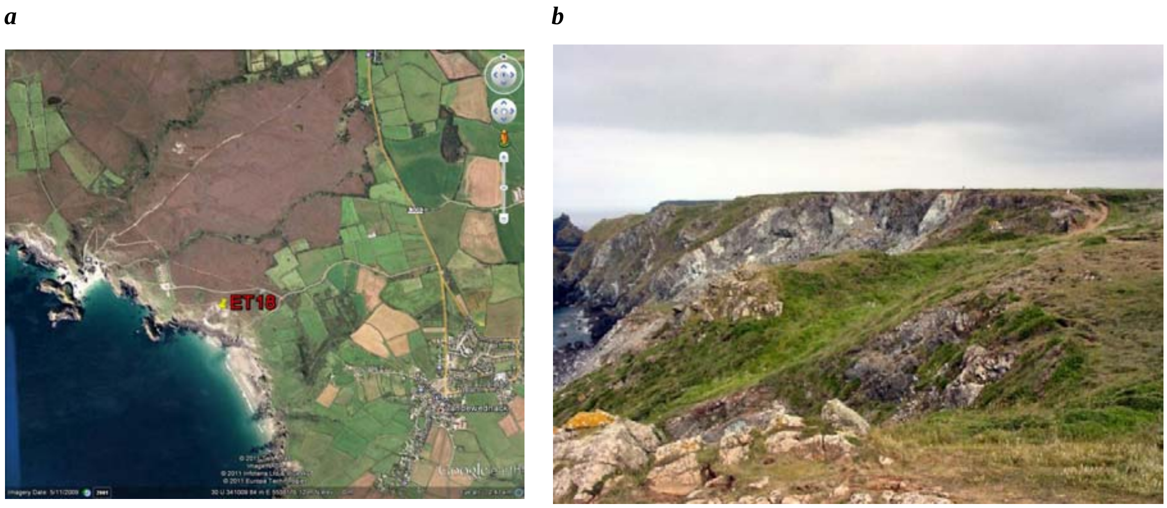


Figure 58. Arial photograph (Google Earth) and site location for sample ET18 [Copyright BGS, NERC].

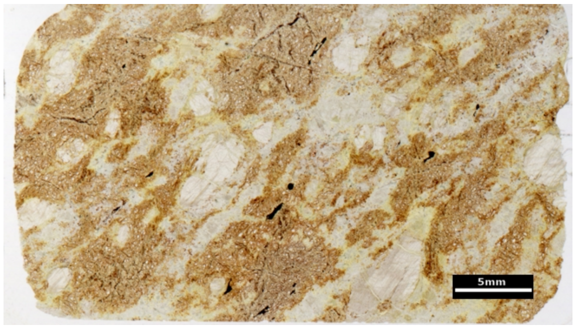
A.3.4.4.2 PETROGRAPHY AND MINERALOGY

Sample ET 18 is an amphibole-rich serpentinised lherzolite. The rock consists of c. 40% of serpentine minerals and 20% of fresh olivine, 15% of orthopyroxene and 25% of amphibole. Chromite is rare making up to 1% of the sample, it is reddish brown. Amphibole is a replacement after clinopyroxene Figure 59d and as veins Figure 59b.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Amph	Opx	Ol	Serp	Chr
% modal	25	15	20	40	1

a



b

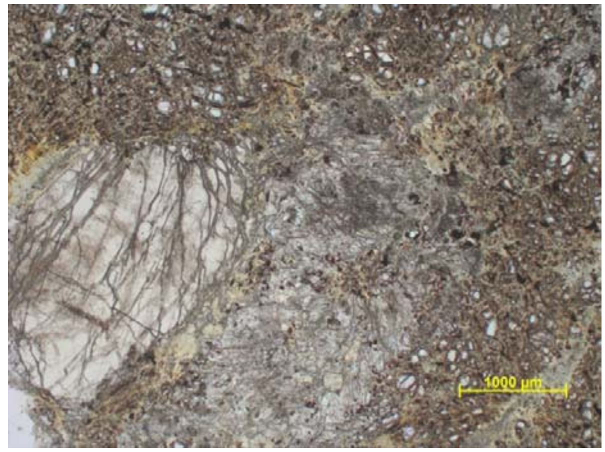


Figure 59. Photographs of sample ET18, serpentinite: a) scanned polished thin section showing veins; b) plane polarised light photomicrograph showing a large crystal of orthopyroxene adjacent to an aggtregate of amphibole after clinopyroxene in a matrix of partially serpentinised olivine.Shetland Area

A.3.5 SHETLAND AREA

The ultramafic rocks in Shetland occur on the northernmost islands of Unst and Fetlar (Figure 60). They form the Shetland Ophiolite Complex that is in faulted contact with a range of metamorphic rocks. The ultramafic rocks cover an area of 55 sq kms on the two islands. There are two main rock types serpentinites derived from mantle harzburgite on the western side of the Unst body and on Fetlar and serpentinites largely derived from dunite that are found on the eastern side of the Unst body(Figure 60). A particular feature of the rocks on Unst is that the ultramafic rocks are thrust over the top of carbonate-rich rocks, limestones and marbles. During metamorphism fluids rich in CO_2 have invaded the serpentinites, particularly along the lower parts and along faults and caused alteration to carbonate and in some places talc.

Samples of sufficient size were only available from borehole cores in the northern part of Unst, two near the base of the complex and two towards the middle (Figure 61).

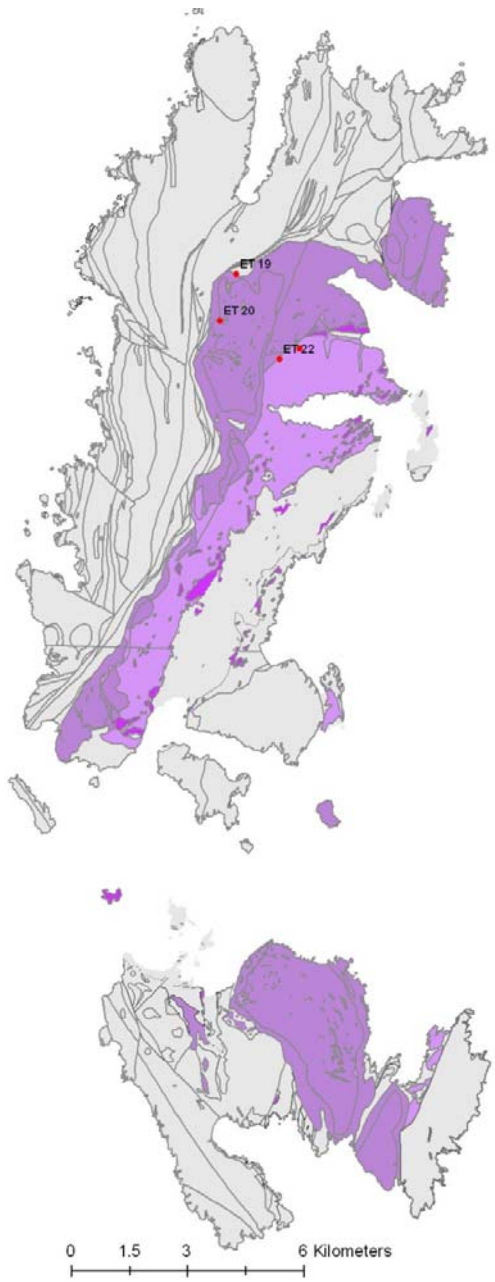
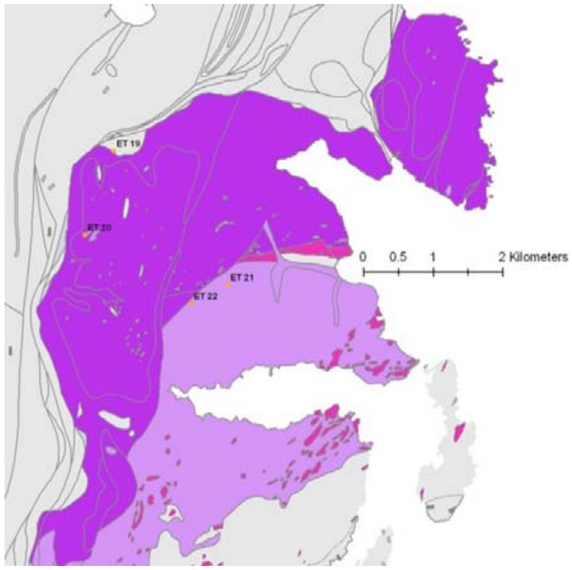


Figure 60. Geology map of Unst and Fetlar with the ultramafic rocks of the ophiolite complex shown in purple, the darker shade is serpentinites derived harzbugite and the lighter shade from dunite [Copyright BGS, NERC].

a



b

Figure 61. Google Earth image of northern Unst showing the low undulating topography and almost complete lack of exposed rocks. Geology map of the northern part of Unst, colours as Figure 60 and with pods of pyroxene-rich rocks in brighter purple and rocks extensively altered to talc in pink. The locations of the boreholes from which samples were taken are also shown [Copyright BGS, NERC].

A.3.5.1 **Sample ET 19**

Lithology:	Locality:	Grid Reference:
CARBONATE REPLACED SERPENTINITE	Shetland	461160 1212230

A.3.5.1.1 SAMPLING

Approximately 2 kg of sample of serpentinite was derived from the BGS rocks and mineral collection. It is from a depth around 130 m in a borehole close to the northern margin of the ophiolite, on Unst, Shetland.

A.3.5.1.2 PETROGRAPHY AND MINERALOGY

Sample ET19 is a serpentinite that is extensively replaced by carbonate. The serpentine minerals remain dominant, constituting approx. 75% of this sample. The groundmass serpentine comprises two morphologically different types of crystals, occurring in roughly equal amounts: A granular finely intergrown type (probably lizardite 25%) and a bladed to locally fibrous type (probably antigorite 45%), altogether forming a tightly packed mosai*c*. The serpentine mosaic generally displays one-directional alignment that is also determined by the distribution of stringer-like Fe oxide/oxyhydroxide (*c.* 5%). The pseudomorphic mesh texture is absent and the majority of textures observed are probably a result of shearing and recrystallisation. Scarce (<3% of the total serpentine content) scattered, partially recrystallised bastites were observed in places. Veins (<1mm thick) of fine equant to fibrous serpentine locally crosscut the rock.

Carbonate is abundant in this sample constituting *c.* 30%. Two predominant morphological forms were observed; finely crystalline mass and coarse (sparry) crystals. Both forms are evidently pseudomorphic replacing former serpentine minerals, recrystallised mesh texture, and bastites respectively.

Chromite crystals are moderately abundant, making up to 5% of the sample analysed. The crystals are dark red-brown, usually euhedral to subhedral and vary in size from 100 µm to 400 µm.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Ant	Liz	Crb	Chr	FeO/OH
% modal	45	25	20	5	5

a

b

c

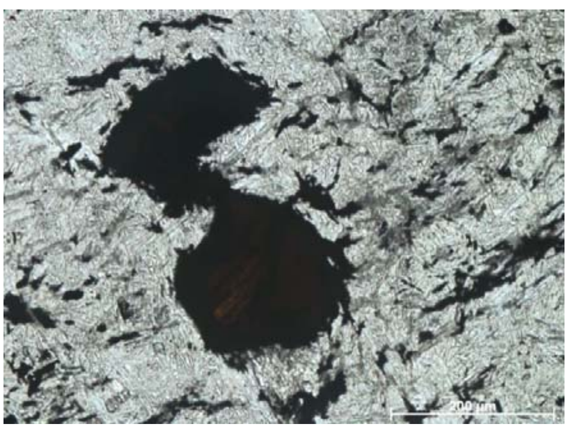


Figure 62. Photographs of sample ET19, serpentinite: a) scanned polished thin section; b) crossed polarised light photomicrograph showing partially carbonate-replaced serpentine groundmass; c) plane polarised light showing altered chromite in antigorite-dominated groundmass .

A.3.5.2 **Sample ET 20**

Lithology:	Locality:	Grid Reference:
CARBONATE REPLACED SERPENTINITE	Shetland	460740 1211020

A.3.5.2.1 SAMPLING

Approximately 2 kg of sample of serpentinite was sourced from the BGS rocks collection. It came from a depth around 15m from a borehole near the northern margin of the ophiolite on Unst, Shetland.

A.3.5.2.2 PETROGRAPHY AND MINERALOGY

Sample ET20 is a serpentinite that has been partially replaced by carbonate. Serpentine minerals are the major constituents making up to 75% of the sample. Three distinctive forms of these minerals were distinguished: serpentine mesh, bastite and bladed to plate-like crystals. The mesh cells (*c.* 23% of the total serpentine) consist of roughly equant serpentine domains, commonly containing fresh olivine (up to 7%), intergrown and crosscut by stringers of Fe oxide/oxyhydroxide. Relict bastites (*c.* 5% of the total serpentine) are scattered throughout the sample, they are large, up to 6 mm and normally rimmed by fibrous serpentine. The majority of the bulk serpentine (*c.* 47%) is represented by bladed to plate-like crystals (possibly antigorite) that commonly occur as randomly oriented bundles. These contain several tens of locally radiating parallel blades, usually < 200 µm long. Elsewhere, the blades appear to be finely intergrown with the mesh serpentine, usually overwriting the latter texture.

The Fe oxide/oxyhydroxide, which in total makes up to 7% of the sample, appears to have been largely remobilised and now occurs as patches and stringers that are generally associated with relicts of pyroxene pseudomorphs. Locally a foliation-parallel trend is faintly displayed.

The serpentine analysed is deformed and displays distinctive one-directional cleavage (foliation).

The carbonate constitutes approx. 7% of the sample and occurs as fine, anhedral to subhedral crystals replacing serpentine minerals. The crystals usually occur as subparallel stringers that generally delineate the rock’s foliation.

Chromite crystals (*c.* 2% remaining) are largely replaced by magnetite. The crystals are usually <1 mm and locally display holy leaf texture. The relicts of fresh chromite are characteristically dark reddish brown, as opposed to black when completely altered. The alteration progressed from the crystal boundaries and along the fracture. In places, the crystals are surrounded by bladed chlorite (2%)

MODAL ANALYSIS - MINERAL PROPORTIONS

	Ant	Srp Liz	Bst Liz	Crb	Ol	FeO/OH	Chr	Chl
% modal	47	23	5	7	7	7	2	2

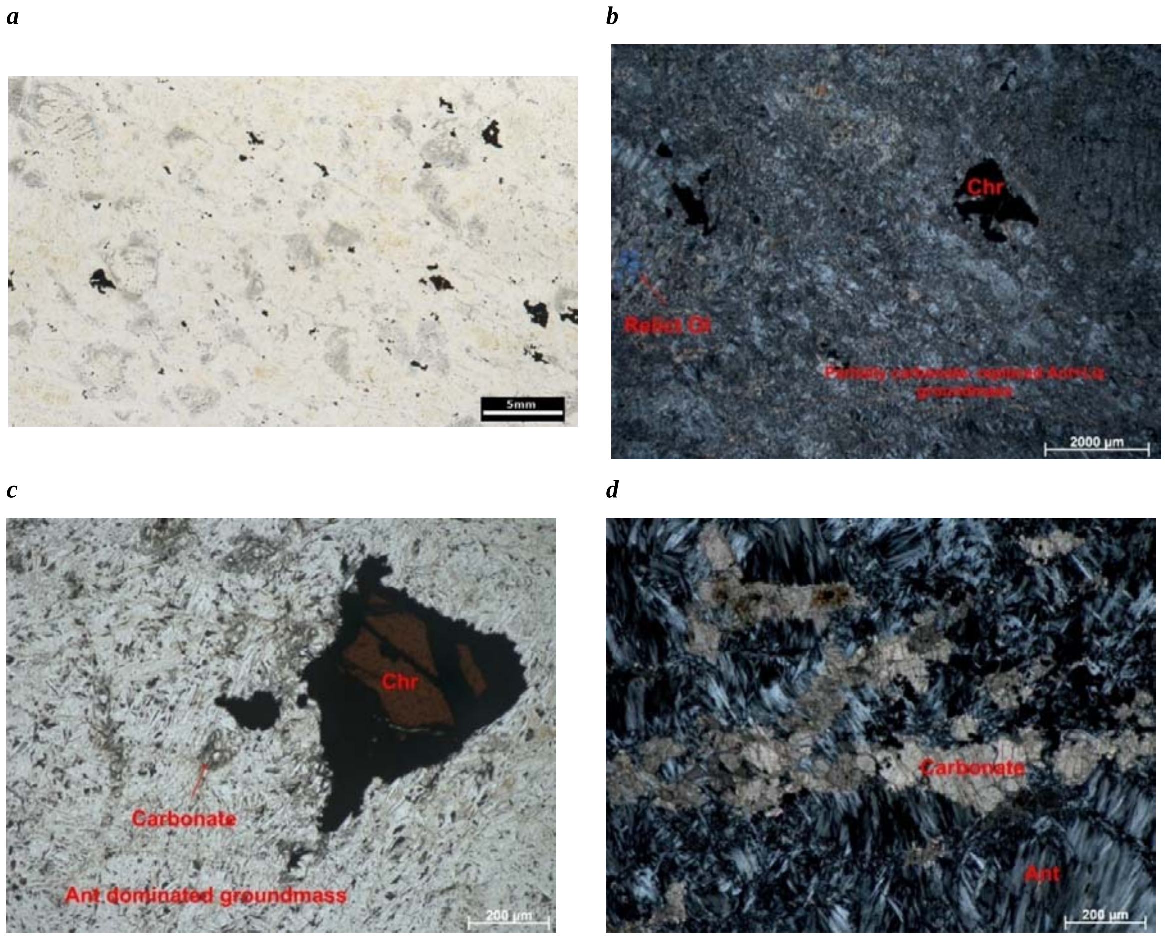


Figure 63. Photographs of sample ET20: a) scanned polished thin section; b) crossed polarised light photomicrograph showing relict of fresh olivine and chromite within partially carbonate-replaced groundmass of antigorite and lizardite; c) plane polarised light photomicrograph showing partially altered chromite crystal within a antigorite-dominated groundmass; d) carbonate replacing serpentine minerals .

A.3.5.3 **Sample ET 21**

Lithology:	Locality:	Grid Reference:
SERPENTINITE CHROMITE-RICH	Shetland	462800 1210300

A.3.5.3.1 SAMPLING

Approximately 2 kg of sample of serpentinite was sourced from the BGS rocks collection. It is from a depth around 45 m from a borehole in the central part of the ophiolite on Unst, Shetland.

A.3.5.3.2 PETROGRAPHY AND MINERALOGY

Sample ET21 is a chromite-rich serpentinite. The mesh serpentinite constitutes approx. 80% of the bulk rock. The olivine-originated meshes (trace amount, <1% of olivine remaining) are well preserved in this sample and a display characteristic texture of tightly packed serpentine domains that are rimmed and interwoven with Fe oxide/oxyhydroxide (*c.* 3%). Locally, the centres of mesh cells exhibit a distinctive pattern of laminated (commonly book-like) polygons that are supposedly composed of clay mineral phases inter-layered with serpentine minerals. Elsewhere in the rock, these polygons appear to have been partially replaced by finely crystalline phase, not identified optically.

Chromite constitutes approx. 10% of this sample. The crystals are brown, usually euhedral to subhedral and range in size from 100 µm to 1 mm. They display distinctive association pattern with chlorite, with the latter forming roughly regular concentric rims around core chromite.

Chlorite makes up to 5% and occurs as either finely crystalline mass or fibrous crystals surrounding chromites. In addition, stacks of parallel chlorite fibres and granular chlorite mass were observed partially filling fractures (<300 µm wide) that randomly cross-cut the serpentinite. The fractures also contain unidentified clay mineral phases and trace amount of hematite.

Sulphides and native metals occur in trace amounts, collectively up to 2% of the sample analysed. They exhibit stringer-like multiphase clusters and display fracture-related distribution. Magnetite, pentlandite, Ni Fe oxide, native copper, and trace amount of native Ag were identified using optical and electron microscopy measures.

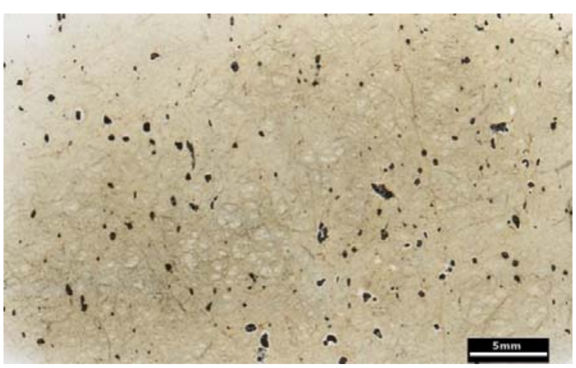
Note on origin.

The predominance of olivine-originating serpentine mesh texture and the virtual absence of bastites and clinopyroxene pseudomorphs suggest that the protolith rock was dunite. The fracture-related distribution of sulphides and native metals suggest that these mineral phases are not magmatic; such is e.g. chromite in this sample and probably represent later mineralisation event related to element remobilisation during hydrothermal processes.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp `mesh`	Chl	Chr	FeO/OH	Sulphides
% modal	80	5	10	3	2

a



b

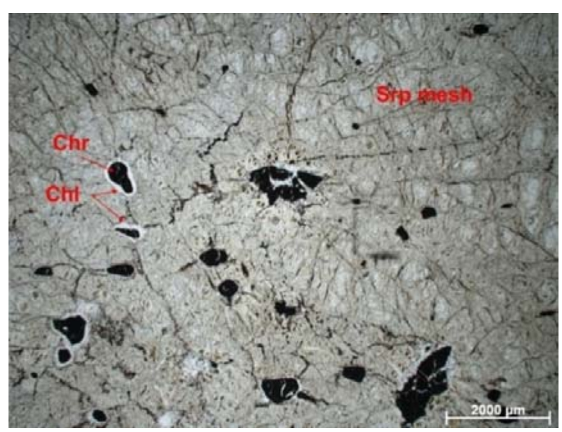


Figure 64.Scanned polished thin section image of the rock analysed and optical microscopy light image showing mesh texture serpentinite and chromites (black) surrounded by distinctive rim of chlorite.

A.3.5.4 **Sample ET 22**

Lithology:	Locality:	Grid Reference:
CARBONATE REPLACED SERPENTINITE	Shetland	462275 1210029

A.3.5.4.1 FIELD SAMPLING

Approximately 2 kg of sample of serpentinite was sourced from the BGS rock collection. It is from a depth around 13 m from a borehole in the central part of the ophiolite on Unst, Shetland.

A.3.5.4.2 PETROGRAPHY AND MINERALOGY

Sample ET22 is a carbonated serpentinite. It is predominantly composed of serpentine and very finely crystalline carbonate (crystals generally <5µm) that is evidently pseudomorphic after serpentine minerals. In addition, carbonate minerals occur in few, <1mm wide anastomosing veins. Here, the crystals are equant and coarser, with size ranging from 5-80 µm. Collectively, the carbonate minerals constitute approx. 45% of the sample analysed.

Serpentine minerals form *c.* 40% of the sample and predominantly occur as blades (probably antigorite) and finely crystalline masses that display distinctive sutured crystal margins. There is no pseudomorphic texture preserved in the groundmass, the serpentine is recrystallised, and heavily corroded and replaced by carbonate. The Fe oxide/oxyhydroxides are largely remobilised, they constitute *c.* 3% of the rock.

Chromite is common forming about 10% of the rock. The crystals are black, euhedral to subhedral and vary in size from 100 µm-1 mm. The chromite crystals may have been partially altered to magnetite.

Chlorite is minor constituent, making up <2% of the rock. It is usually associated with chromite, forming asymmetric rims.

Trace amount of sulphide mineral phases, predominantly pyrite was identified.

Note on origin.

The rock displays evidence for ductile and brittle deformation. The carbonation processes postdate the deformation, often utilising fracture cleavage and plastically deformed laminae.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Ant	Crb	Chl	Chr	FeO/OH
% modal	40	45	2	10	3

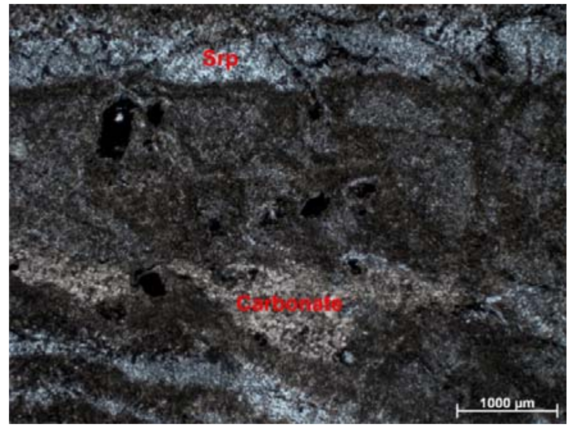


Figure 65. Scanned polished thin section and optical microscopy photomicrograph (cross-polarized light) showing partially carbonate replaced serpentinite .

A.3.6 SELECTED SAMPLES FROM UAE AND NORWAY

A.3.6.1 Sample ET 23

Lithology:	Locality:	Grid Reference:
OLIVINE CONCENTRATE	Norway	()

A.3.6.1.1 SAMPLING

Approximately 2 kg of olivine concentrate, originating from Norway, was obtained from Minelco Ltd, United Kingdom. This was mostly as fine milled powder (ET24) with some coarser 5 mm size pieces that were used to make a thin section.

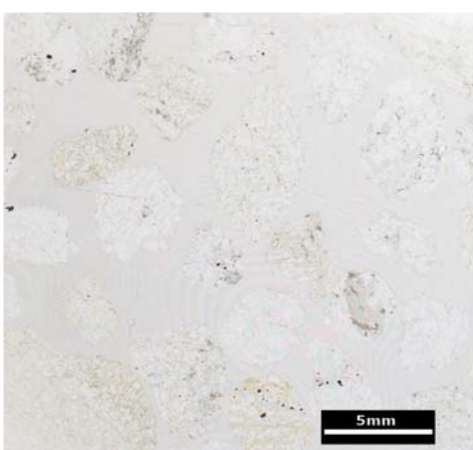
A.3.6.1.2 PETROGRAPHY AND MINERALOGY

The sample analysed is an aggregate of several rock fragments, varying in size from 3-10mm. The fragments are compositionally different and consist of serpentinised dunite, dunite, chlorite rich dunite and partially carbonate-replaced dunite. In general, the average collective modal analysis, including all the fragments, shows that olivine minerals consists c. 83%, followed by serpentine, chlorite, clinopyroxene, orthopyroxene, with trace amounts of chromite. Fe oxide/oxyhydroxide, amphibole, and talc were also observed in places. In addition, some fragments showed significant alteration to carbonate.

Texturally, the rock fragments display evidence for significant deformation that is mainly pronounced by the presence of strained crystals of olivine and pyroxene, with localised development of subgrains.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Ol	Cpx	Opx	Srp	Chl	Chr	Carb	Fe o/ oho	Amp	Talc
% modal	83	3	1	5	3	1	2	1	0.5	0.5



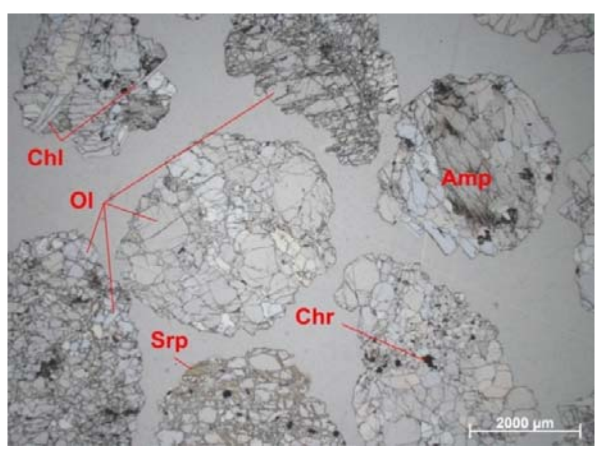


Figure 66. Scanned polished thin section image and optical microscopy photomicrograph showing the characteristics of the olivine aggregate. The sample contains small amounts of phases, such as: serpentine, chromite, chlorite, amphibole, talc, carbonate, and pyroxene .

A.3.6.2 **Sample ET 25**

Lithology:	Locality:	Grid Reference:
HARZBURGITE	UAE	()

A.3.6.2.1 SAMPLING

Approximately 5 kg of sample of harzburgite from the ophiolite in the UAE was sourceed from the BGS rock collection.

A.3.6.2.2 PETROGRAPHY AND MINERALOGY

Sample ET25 is a harzburgite. The rock is fresh partially serpentinised and composed of 40% olivine, 20% orthopyroxene, about 10% of clinopyroxene and about 30% of serpentine replacing olivine and to a lesser extent orthopyroxene. The pyroxene crystals are coarse and range in size to 6 mm in a matrix of finer olivine and serpentine.

Olivine (up to 4mm in size) is fragmented to < 0.5 mm grains. These are surrounded by mesh texture serpentine.

In addition there is about 2 - 3% of brown reddish chromite. The section is cut by late, thin (about 50 µm thick) carbonate, and crack-seal vein, filled with fibrous crystals. The carbonate vein is locally recrystalised. In addition serpentine veins (up to 250 µm thick

MODAL ANALYSIS - MINERAL PROPORTIONS

	Cpx	Ol	Opx	Srp	Fe o/ oho
% modal	9	40	20	30	<1

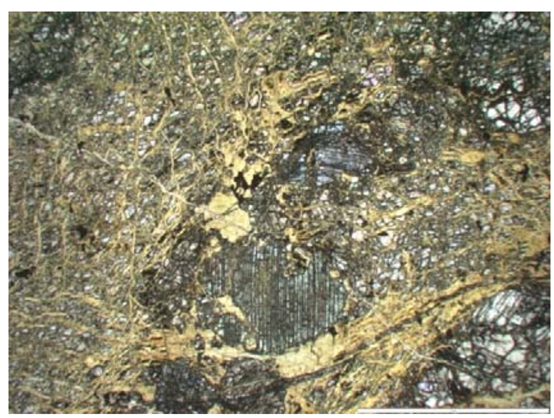


Figure 67. Scanned polished thin section image (3 cm longer edge) and optical microscopy photomicrograph showing large crystals of pyroxene in a finer matrix of olivine and serpentine .

A.3.6.3 **Sample ET 26**

Lithology:	Locality:	Grid Reference:
HARZBURGITE	UAE	()

A.3.6.3.1 SAMPLING

Approximately 5 kg of sample of harzburgite from the ophiolite in the UAE was sourceed from the BGS rock collection.

A.3.6.3.2 PETROGRAPHY AND MINERALOGY

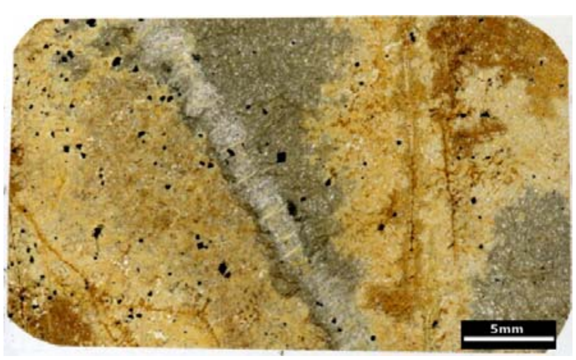
Sample ET26 is a serpentinised dunite. There are about 20% of fragmented olivine relicts (<0.5 mm grains), pyroxene is rare. Serpentine minerals constitute about 70% of the whole sample. Most serpentine shows mesh texture wrapping around olivine and rare pyroxene relicts (but not spinel).

The section contains about 5 - 7% of black spinel, with size ranging from 10 µm - 1 mm. The section is cross cut by a pyroxenite vein, which is up to 2 mm thick and constitutes about 7% of the sample. The vein is composed of orthopyroxene crystals up to 1.5 mm in size. These locally show undulatory extinction and bent crystals, which is evidence for deformation. There are also some evidences for shearing; serpentine minerals show foliation (perpendicular to the main fracture). Late fine-grained carbonate fills veins (up to 150 µm thick), which are associated with the pyroxenite vein. They are oriented perpendicular to the pyroxenite.

The section is of a rather unusual part of the rock and not a typical piece of harzburgite. It shows much more extensive serpentinisation than ET25 (the reason for selection) but the XRD will be more representative of the bulk composition

MODAL ANALYSIS - MINERAL PROPORTIONS

	Cpx	Ol	Opx	Srp	Fe o/ oho
% modal	1	20	10	70	<1



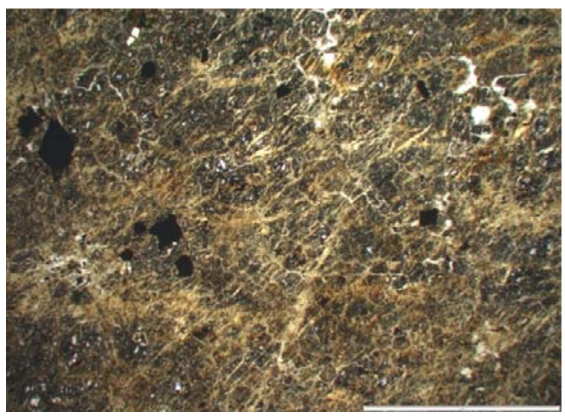


Figure 68. Scanned polished thin section image (3 cm longer edge) pyroxenite veinlet and optical photomicrograph showing crystals of spinel in a matrix of olivine and serpentine .

A.3.6.4 **Sample ET 27**

Lithology:	Locality:	Grid Reference:
OLIVINE CLINOPYROXENITE	UAE	()

A.3.6.4.1 SAMPLING

Approximately 5 kg of sample of olivine-clinopyroxenite from the ophiolite in the UAE was sourced from the BGS rock collection.

A.3.6.4.2 PETROGRAPHY AND MINERALOGY

Sample ET27 is an olivine clinopyroxenite. The rock is fresh and predominantly composed of clinopyroxene that constitutes approx. 80% of the sample. The crystals are coarse and range in size from 500 µm to 3mm with scarce scattered crystals up to 15mm with a poikilitic texture.

Olivine is largely fresh in this sample and constitutes approximately 10%. The crystals are characteristically fractured, displaying incipient mesh texture. The crystal edges and zones adjacent to fractures are altered to Fe oxide/oxyhydroxide (<1%), serpentine minerals (<2%) and locally iddingsite (2%) and talc (1%).

Plagioclase crystals are scarce, making up only 4% of the sample. The crystals are usually <15mm in size, they are mostly fresh, only locally displaying minor evidence for alteration to finely crystalline clay mineral phases.

Both olivine and plagioclase fill the interstices between clinopyroxene crystals.

The rock is crosscut by randomly oriented microfractures (<100 µm wide) along which the alteration of the original minerals is enhanced. In places, carbonate and very finely crystalline phase, probably quartz, were introduced into the system. The fracture-related alteration products are variable depending on the minerals reacting with the commonest being talc, chlorite (<2%) and serpentine.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Cpx	Ol	Plg	Srp	Chl	Idd	Fe o/ oho	Amph	Epd	Tlc	Qtz
% modal	74	10	5	<2	<2	2	<1	1	0.5	2	1

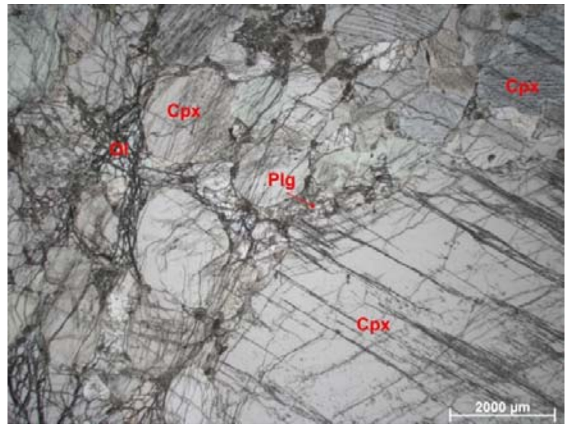


Figure 69. Scanned polished thin section image and optical microscopy photomicrograph showing large crystals of pyroxene in association with plagioclase and olivine .

A.3.6.5 **Sample ET 28**

Lithology:	Locality:	Grid Reference:
AMPHIBOLE-RICH ROCK	UAE	

A.3.6.5.1 SAMPLING

Approximately 5 kg of sample of amphibole rock, formed by the alteration of clinopyroxenite from the UAE, was sourceded from the BGS rock collection.

A.3.6.5.2 PETROGRAPHY AND MINERALOGY

Sample ET28 is an amphibole-rich rock containing approximately 70% of amphibole.

The rock analysed displays complex textural features. The original textures have been largely overwritten by newly formed finely crystalline amphibole. In places relict poikilotopic plagioclase (4%) and large crystals of clinopyroxene (1%) were still observed, however these phases display a significant degree of alteration; plagioclase being largely replaced by prehnite and clay mineral and clinopyroxene by amphibole. Relicts of large amphibole crystals are also apparent. In addition the amphibole-rich rock is cross cut by a few randomly oriented fractures that acted as fluid paths and served further fracture-related alteration. The fractures and adjacent rock predominantly consist of Fe oxide/hydroxide (2%), carbonate (2%), chlorite (1%) and other unidentified clay mineral phases - dominantly alteration product of plagioclase. Clinozoisite/epidote is present in both the veins and the body of the rock.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Amp	Plg	Cpx	FeO/OH	Crb	Chl	Prhn	Ep	Clay min
% modal	70	4	0.5	2	2	1	15	5	0.5

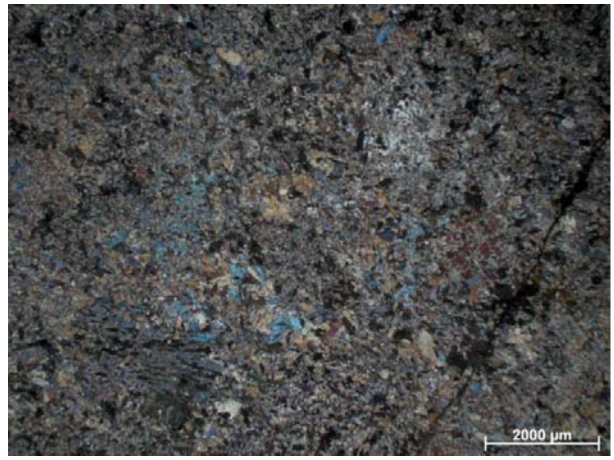


Figure 70.Scanned polished thin section image and optical microscopy photomicrograph showing the amphibole-prehnite-rich rock .

A.3.6.6 **Sample ET 29**

A.3.6.6.1 SAMPLING

The 50 gm sample of antigorite serpentinite was originally collected by BGS staff from Liguria, northern Italy, was sourced from the BGS rock collection.

A.3.6.6.2 PETROGRAPHY AND MINERALOGY

Sample ET29 is a serpentinite. The rock is significantly deformed displaying distinctive one-directional cleavage and the presence of augen texture. It is predominantly composed of serpentine minerals that collectively form approximately 90% of the rock. The serpentine minerals display a wide textural range and occur as bastite, pseudomorphosed clinopyroxene and olivine, all scattered within a sheared groundmass of commonly recrystallised mesh serpentine. The rock is cross cut by late veins of coarse, massive to bladed serpentine and locally half spherical, radial aggregates that resemble polygonal serpentine. Fe oxide/oxyhydroxide makes up to 2% of the sample and occurs and finely intergrown mass within the serpentine minerals. It also occurs in association with chromite, surrounding the crystals and infilling the micro-fractures. The rock analysed contains scattered pseudomorphs of clinopyroxene that contain relicts of the original mineral, occurring as cleavage stripes or dispersed granular crystals. These pseudomorphs are characteristically brown stained and probably contain finely-crystalline clay mineral (2%) intergrown with serpentine.

Chlorite is moderately abundant in this sample, making up to 4%. It occurs and <200 µm bladed crystals that are intergrown with the serpentine groundmass, together forming a tight mosaic.

Chromite is rare in this sample (ca. 2%). The crystals (<800 µm) are dark-red brown, blocky and usually fractured and altered on the crystals boundary.

MODAL ANALYSIS - MINERAL PROPORTIONS

	Srp	Cpx	FeO/OH	Chl	Chr	Clay mineral phases
% modal	90	2	2	4	2	2

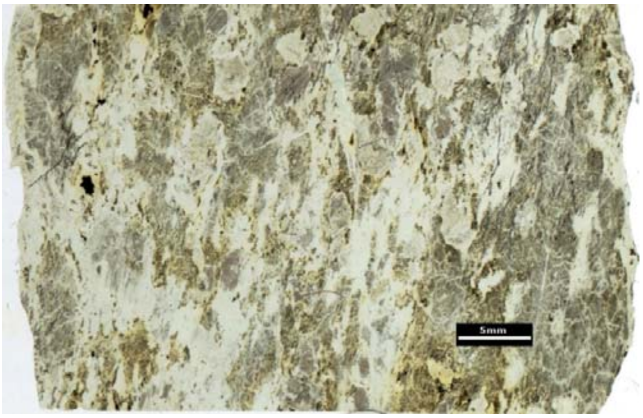


Figure 71. Scanned polished thin section image and optical microscopy photomicrograph showing sheared and locally recrystallised serpentinite

A.3.6.7 Sample ET 30

A.3.6.7.1 FIELD SAMPLING

The 50 gm sample was supplied by Nottingham University as an antigorite serpentinite from Cedar Hills Pennsylvania, USA that has been circulated by ARC as a standard material for testing.

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A.3.6.7.2 PETROGRAPHY AND MINERALOGY

Sample ET30 consists of four rock fragments roughly 1 cm in diameter, three are serpentinites and one is a microgabbro (Figure 72 a). The microgabbro consists dominantly of plagioclase feldspar with lesser clinopyroxene and a brown alteration product after the pyroxene.

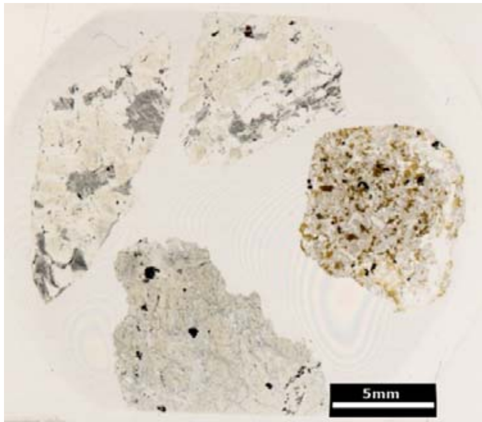
The serpentinite grains vary in composition. One is largely antigorite with pseudomorphas after orthopyroxene and a few % of relics of olivine Figure 72 b. The other two are a totally serpentinised but are a mixture of lizardite and serpentinite. One has relic areas of lizardite that are enclosed by antigorite while the other has antigorite in more discrete veins.

Chromite is present in the serpentinite samples (ca. 2%). The crystals (<800 µm) are dark-red brown, blocky and usually fractured and altered on the crystals boundary.

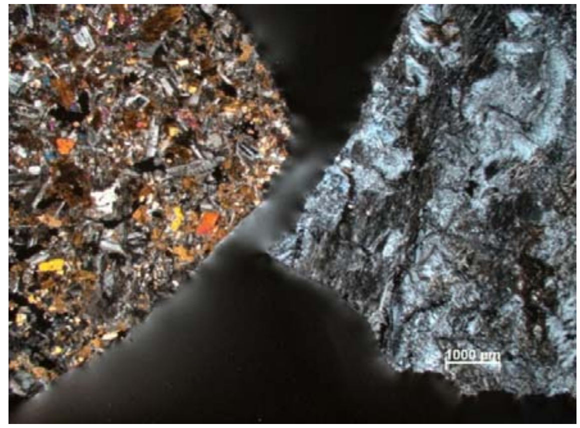
MODAL ANALYSIS - MINERAL PROPORTIONS Serpentinite

	Srp	Ol	FeO/OH	Chr
% modal	90	2	5	2

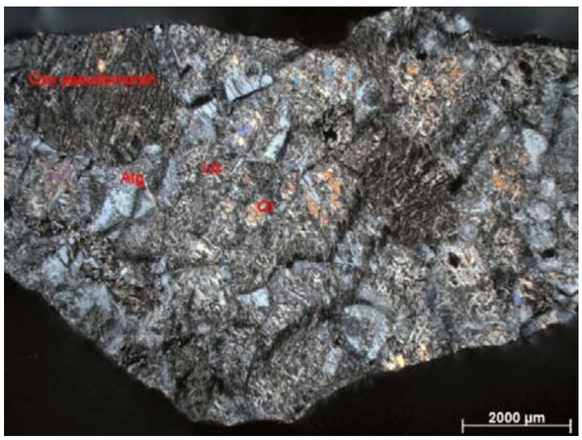
a



a



b



c

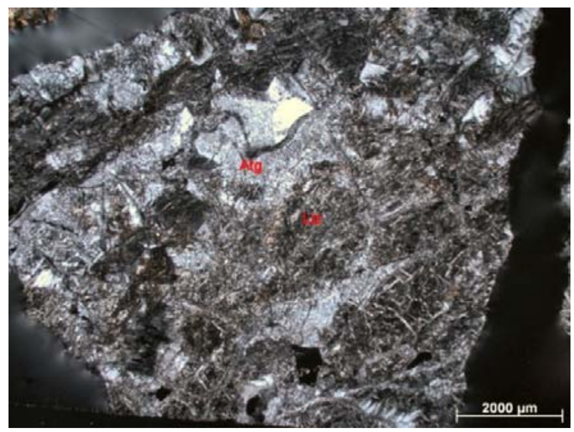


Figure 72. Scanned polished thin section image. Optical microscopy photomicrographs showing b) microgabbro fragment (left side) c) relics of olivine d) co-existing lizardite and antigorite .

Table 17. Optical petrography summary table .

			MODAL ANALYSIS DATA BASED ON OPTICAL MICROSCOPY ESTIMATION (%)												
ETI SAM. NO	Serpentine minerals	Olivine	Clino - pyroxene	Orthopy roxene	Plagio -clase	Chromite	Chlorite	Amphibole	Feo / oho*	Undifferen tiated Carbonate	Talc	Clay Min. Phases	Epidote(e)/ Prehnite(p)	Quartz	Sulphides and native metals
ET 1	92	-	-	-	-	-	1	-	2	-	-	5	-	-	-
ET 2	95	-	-	-	-	2	0.5	-	2	-	-	-	-	0.5	-
ET 5	95	-	-	-	-	2	1	-	1	-	1	-	-	-	-
ET 6	95	-	-	-	-	1	0.5	-	3	0.5	-	-	-	-	-
ET 7	62	7	13	-	1	2	4	3	2	-	<0.5	5	-	-	1
ET 8	44	10	10	10	3	-	1	1	3	-	-	27	-	-	1
ET 10	65	-	-	-	-	8	25	-	2	-	-	-	-	-	-
ET 11	80	-	-	-	-	3	15	-	2	-	-	-	-	-	-
ET 12	65	-	-	-	-	3	9	-	5	-	5	13*	-	-	-
ET 13	76	-	-	-	-	2	18	-	3	1	-	-	-	-	-
ET 14	85	-	-	-	-	4	7	-	4	-	-	-	-	-	-
ET 15	90	-	-	-	-	2	3	-	5	-	-	-	-	<1	-
ET 16	86	-	-	-	-	1	5	5	2	-	0.5	0.5	-	-	-
ET 17	90	-	<0.5	-	-	4	-	1	3	2	-	-		-	-
ET 18													-		
ET 19	60*	-	-	-	-	5	-	-	5	30	-	-	-	-	-
ET 20	75*	7	-	-	-	2	2	-	7	7	-	-	-	-	-
ET 21	80	-	-	-	-	10	5	-	3	-	-	-	-	-	2
ET 22	40*	-	-	-	-	10	2	-	3	45	-	-		-	-
ET 23	5	83	3	1	-	1	3	0.5	1	2	0.5	-	-	-	-
ET 25	30	40	1	20											
ET 26	70	20	9												
ET 27	2	10	74	-	5	-	2	1	1	-	2	2	<0.5e	1	-
ET 28	-	-	0.5	-	4	-	1	70	2	2	-	0.5	15p 5ep	-	-
ET 29	90	-	2	-	-	2	4	-	2	-	-	2	-	-	-
ET 30															

Notes:
Feo/oho - Fe oxides and oxyhydroxides
ET 12 * unidentified very finely crystalline Mg, Fe silicate, probably hydrated. This phase is likely to be an alteration product of chlorite
ET 19* Serpentine minerals are antigorite predominantly
ET 20* Serpentine minerals are: 47% of antigorite, 28% of lizardite
ET 22* Serpentine minerals are antigorite predominantly

A.4 Planning policies

This section contains the supporting data for Section 2 of the WP 1 Phase 2b report — *Detailed assessments of obstacles to mineral accessibility and availability*. It lists the detail for the basis of various types of designation and gives an example of the detail of how these are applied in one are only. To demonstrate this, the Lizard in Cornwall was chosen as it has the largest number of designated areas.

A.4.1 PROTECTED SITES DESIGNATIONS DIRECTORY

This information is copied from the Joint Nature Conservation Committee website (http://jncc.defra.gov.uk/page-1527).

JNCC collates information on protected sites in the UK and Overseas Territories designated under international Conventions and European Directives – principally Ramsar Sites, SACs, and SPAs. However, a range of other international and national nature conservation and landscape designations exist in the UK.

This directory covers the main designations, which exist in the UK, split into those that confer some form of statutory protection, and other designations. For each designation there is a short description outlining its purpose and the level of protection afforded to it, along with details of who is responsible for establishing the sites, and further sources of information.

Site designations that protect the UK's natural heritage through statute

Areas of Outstanding Natural Beauty (AONBs)

(in England, Wales, and Northern Ireland)
The primary purpose of the AONB designation is to conserve natural beauty – which by statute includes wildlife, physiographic features and cultural heritage as well as the more conventional concepts of landscape and scenery. Account is taken of the need to safeguard agriculture, forestry, and other rural industries and the economic and social needs of local communities. AONBs have equivalent status to National Parks as far as conservation is concerned.

AONBs are designated under the National Parks and Access to the Countryside Act 1949, amended in the Environment Act 1995. The Countryside and Rights of Way Act 2000 clarifies the procedure and purpose of designating AONBs.

Originally designated in Northern Ireland under the Amenity Lands Act (Northern Ireland) 1965, AONBs are now designated under the Nature Conservation and Amenity Lands Order (Northern Ireland) 1985.

In Scotland, National Scenic Areas are broadly equivalent to AONBs.

Countryside Council for Wales
Northern Ireland Environment Agency

See:
National Association of AONBs
Northern Ireland Environment Agency
UK National Park links

Areas of Special Protection (AoSP) (in England, Scotland and Wales) and Wildlife Refuges (in Northern Ireland)

Sanctuary Areas, originally designated under the Protection of Birds Acts 1954, were amended to AoSPs under the Wildlife and Countryside Act 1981. Designation aims to prevent the disturbance and destruction of the birds for which the area was identified, by making it unlawful to damage or destroy either the birds or their nests and in some cases by prohibiting or restricting access to the site.

Wildlife Refuges are equivalent to Areas of Special Protection in Northern Ireland. The statutory provision of an area as a 'Wildlife Refuge' is a protection mechanism under the Wildlife (Northern Ireland) Order 1985. It was intended that this provision would replace that of Bird Sanctuary, established under the Wild Birds Protection Act 1931. There are several coastal Bird Sanctuaries in Northern Ireland but as yet no Wildlife Refuges have been established.

UK Government

Country Parks

Country Parks are statutorily declared and managed by local authorities in England and Wales under the Countryside Act 1968 and in Scotland under the Countryside (Scotland) Act 1967 (in Northern Ireland Country Parks exist as a non-statutory designation). They are primarily intended for recreation and leisure opportunities close to population centres and do not necessarily have any nature conservation importance. Nevertheless, many are in areas of semi-natural habitat and so form a valuable network of locations at which informal recreation and the natural environment coexist.

Local authorities

See:
Northern Ireland Environment Agency

Historic Gardens and Designed Landscapes

Significant historic gardens and designed landscapes identified by Scottish Natural Heritage and Historic Scotland for their natural heritage and cultural importance. Inclusion in the Inventory confers a measure of statutory planning control in relation to the sites concerned and their setting through the Town and Country Planning (General Development Procedure) (Scotland) Order 1992 (GDPO) and SDD Circular No 6/1992.

Statutory country nature conservation agencies

See:
English Heritage
Countryside Council for Wales

Limestone Pavement Orders

Limestone Pavement Orders afford statutory protection for limestone pavements under the Wildlife and Countryside Act 1981. An Order, created by the relevant local government authority, prohibits the removal or damage of limestone within the designated area, after notification of its importance by English Nature, the Countryside Agency, and the Countryside Council for Wales or Scottish Natural Heritage. Limestone pavements are identified as a priority habitat in Annex I of the EC Habitats Directive.

Local authorities

See:
Limestone Pavement Action Group

Local Nature Reserves (LNRs) (in England, Scotland and Wales)/ Local Authority Nature Reserves (LANRs) (in Northern Ireland)

Under the National Parks and Access to the Countryside Act 1949 LNRs may be declared by local authorities after consultation with the relevant statutory nature conservation agency. LNRs are declared and managed for nature conservation, and provide opportunities for research and education, or simply enjoying and having contact with nature.

Local authorities

See:
Natural England (formally English Nature)
Scottish Natural Heritage
Countryside Council for Wales

Marine Conservation Zones (MCZs)

Marine Conservation Zones can be established to protect nationally important marine wildlife, habitats, geology, and geomorphology and can be designated anywhere in English and Welsh inshore and UK offshore waters. They are established under the Marine and Coastal Access Act (2009). Marine Conservation Zones will be one of six designations contributing to our ecologically coherent network of Marine Protected Areas.
See:
Marine Conservation Zones
Marine Protected Area Network

Marine Nature Reserves (MNRs)

The purpose of MNRs is to conserve marine flora and fauna and geological features of special interest, while providing opportunities for study of marine systems. They are a mechanism for the protection of nationally important marine (including subtidal) areas. Their designation requires the agreement of statutory and voluntary bodies and interest groups. There were three designated MNRs: Lundy Island (in England), Skomer Island (in Wales) and Strangford Lough (in Northern Ireland). Following the introduction of the Marine and Coastal Access Act (2009) MNRs in England and Wales were replaced by Marine Conservation Zones. Therefore, Strangford Lough remains the only Marine Nature Reserve in UK waters. Elsewhere, a number of voluntary marine nature reserves (vMNRs) have been established by agreement between non-governmental organisations, stakeholders, and user groups. These have no statutory basis.

Statutory MNRs are established under the Wildlife and Countryside Act 1981 for England, Scotland, and Wales. In Northern Ireland they are designated under the Nature Conservation and Amenity Lands (Northern Ireland) Order 1985.

Statutory country nature conservation agencies

See:
Lundy Field Society
Countryside Council for Wales
Northern Ireland Environment Agency

National Nature Reserves (NNRs)

NNRs contain examples of some of the most important natural and semi-natural terrestrial and coastal ecosystems in Great Britain. They are managed to conserve their habitats or to provide special opportunities for scientific study of the habitats communities and species represented within them.

NNRs are declared by the statutory country conservation agencies under the National Parks and Access to the Countryside Act 1949 and the Wildlife and Countryside Act 1981. In Northern Ireland, Nature Reserves are designated under the Amenity Lands Act (Northern Ireland) 1965.

Statutory country nature conservation agencies
See:
via Natural England website (formally English Nature)
Scottish Natural Heritage

Countryside Council for Wales
Northern Ireland Environment Agency

National Parks

In England and Wales, the purpose of National Parks is to conserve and enhance landscapes within the countryside whilst promoting public enjoyment of them and having regard for the social and economic well being of those living within them.

The National Parks and Access to the Countryside Act 1949 established the National Park designation in England and Wales. In addition, the Environment Act 1995 requires relevant authorities to have regard for nature conservation. Special Acts of Parliament may be used to establish statutory authorities for their management (e.g. the Broads Authority was set up through the Norfolk and Suffolk Broads Act 1988).

The National Parks (Scotland) Act 2000 enabled the establishment of National Parks in Scotland. In addition to the two purposes described above, National Parks in Scotland are designated to promote the sustainable use of the natural resources of the area and the sustainable social and economic development of its communities. These purposes have equal weight and are to be pursued collectively unless conservation interests are threatened.

Countryside Council for Wales
Scottish Executive

See:
Association of National Park Authorities
Countryside Council for Wales
Scottish Natural Heritage
UK National Park links

Natura 2000

Natura 2000 is the name of the European Union-wide network of nature conservation sites established under the EC Habitats and Birds Directives. This network will comprise Special Areas of Conservation (SACs) and Special Protection Areas (SPAs). Marine Natura 2000 sites contribute to our ecologically coherent network of Marine Protected Areas.

European Commission

See:
EUROPA - The European Union on-line
Marine Protected Area Network

Natural Heritage Areas (in Scotland)

Natural Heritage Areas are intended to be special large discrete areas of the countryside of outstanding natural heritage value containing a wide range of nature conservation and landscape interests where integrated management will be encouraged taking account of recreational use and wider socio-economic activities. Powers to designate NHAs are set out in the Natural Heritage (Scotland) Act 1991. None have been designated.

Scottish Ministers

Ramsar sites

Ramsar sites are designated under the Convention on Wetlands of International Importance, agreed in Ramsar, Iran, in 1971. Originally intended to protect sites of importance especially as waterfowl habitat, the Convention has broadened its scope over the years to cover all aspects of wetland conservation and wise use, recognizing wetlands as ecosystems that are extremely important for biodiversity conservation in general and for the well being of human communities. The Convention adopts a broad definition of wetland, namely "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". Wetlands "may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands." Ramsar sites will be one of six designations contributing to our ecologically coherent network of Marine Protected Areas.

The UK's ratification of the Convention extends to its Overseas Territories and Crown Dependencies.

UK Government / Governments of Overseas Territories / Crown Dependencies

See:
Protected Sites (Ramsar)
Marine Protected Area Network

Regional Parks (in Scotland)

Regional Parks are extensive areas of the countryside where existing land uses continue but are managed by agreement with the landowners to also allow for public access and informal recreation and to protect local landscapes. Local Authority proposals for the establishment of Regional Parks are designated upon the confirmation by Scottish Ministers under the Wildlife and Countryside (Scotland) Act 1981.

Scottish Ministers

Sites of Special Scientific Interest (SSSI) (England, Scotland and Wales) and Areas of Special Scientific Interest (ASSI) (Northern Ireland)

The SSSI/ASSI series has developed since 1949 as the national suite of sites providing statutory protection for the best examples of the UK's flora, fauna, or geological or physiographical features. These sites are also used to underpin other national and international nature conservation designations. Most SSSIs are privately owned or managed; others are owned or managed by public bodies or non-government organisations. The SSSIs/ASSI designation may extend into intertidal areas out to the jurisdictional limit of local authorities, generally Mean Low Water in England and Northern Ireland; Mean Low Water of Spring tides in Scotland. In Wales, the limit is Mean Low Water for SSSIs notified before 2002, and, for more recent notifications, the limit of Lowest Astronomical Tides, where the features of interest extend down to LAT. There is no provision for marine SSSIs/ASSIs beyond low water mark, although boundaries sometimes extend more widely within estuaries and other enclosed waters. Under the Marine and Coastal Access Act 2009 there is the ability to de-designate an area of a SSSI in England or Wales that is below the low water mark if it would be more appropriately managed as a Marine Conservation Zone. SSSIs will be one of six designations contributing to our ecologically coherent network of Marine Protected Areas.

Originally notified under the National Parks and Access to the Countryside Act 1949, SSSIs have been renotified under the Wildlife and Countryside Act 1981. Improved provisions for the protection and management of SSSIs were introduced by the Countryside and Rights of Way Act 2000 (in England and Wales) and the Nature Conservation (Scotland) Act 2004.

ASSIs are notified under the Nature Conservation and Amenity Lands (Northern Ireland) 1985. Measures to improve ASSI protection and management are contained in the Environment (Northern Ireland) Order 2002.

Statutory country nature conservation agencies

See:
via Natual England website (formally English Nature)
Scottish Natural Heritage
Countryside Council for Wales
Northern Ireland Environment Agency
Sites of Special Scientific Interest and Marine Conservation Zones (Guidance Note 4)
Marine Protected Area Network

Sites of Special Interest (SSI) (Jersey) and Proposed Sites of Special Interest (SSI) (Jersey)

SSI are sites of local and national importance containing important botanical and/or zoological populations. Sites are diverse in nature, ranging from dune to woodland and maritime heathland. These SSIs are protected under Island Planning (Jersey) Law 1964 (as amended). Sites with protected species are protected under the Conservation of Wildlife (Jersey) Law 2000 (as amended).

Proposed SSIs are currently owned by various organisations and are protected under the Conservation of Wildlife (Jersey) Law 2000 but are not protected by Island Planning Law (Jersey) 1964 (as amended).

Sites administered and managed by the Island (Jersey) Government, National Trust for Jersey and private landowners.

See:
Jersey Government, Environmental Services Unit

Special Areas of Conservation (SAC) and Sites of Community Importance (SCI)

SACs are designated under the EC Habitats Directive. The Directive applies to the UK and the overseas territory of Gibraltar. SACs are areas that have been identified as best representing the range and variety within the European Union of habitats and (non-bird) species listed on Annexes I and II to the Directive. SACs in terrestrial areas and territorial marine waters out to 12 nautical miles are designated under the Conservation (Natural Habitats, &c.) Regulations 1994 (as amended). and beyond 12 nautical miles are designated under the Offshore Marine Conservation (Natural Habitats &c.) Regulations 2007 (as amended). SACs will be one of six designations contributing to our ecologically coherent network of Marine Protected Areas.

Sites that have been submitted to the European Commission by Government, but not yet formally adopted by the Commission, are referred to as candidate Special Areas of Conservation (cSACs). Sites that have been adopted by the EC, but not yet formally designated by governments of Member States are known as Sites of Community Importance (SCIs). In the UK, designation of SACs is devolved to the relevant administration within each country. In UK offshore waters JNCC is responsible for identification and recommendation to Government of SACs.

SACs, together with SPAs, form the Natura 2000 network

UK Government; Defra; Devolved administrations; Government of Gibraltar

See:
Protected Sites (SAC)
SACs with marine components
Marine Protected Area Network

Special Protection Areas (SPA)

SPAs are classified by the UK Government under the EC Birds Directive. The Directive applies to the UK and the overseas territory of Gibraltar. SPAs are areas of the most important habitat for rare (listed on Annex I to the Directive) and migratory birds within the European Union. SPAs in terrestrial areas and territorial marine waters out to 12 nautical miles are classified under the Wildlife and Countryside Act 1981 and beyond 12 nautical miles are designated under the Offshore Marine Conservation (Natural Habitats &c.) Regulations 2007 (as amended). SPAs will be one of six designations contributing to our ecologically coherent network of Marine Protected Areas.

SPAs, together with SACs, form the Natura 2000 network.

UK Government; Defra; Devolved administrations; Government of Gibraltar

See:Protected Sites (SPA)
SPAs with marine components
Marine Protected Area Network

World Heritage Sites

World Heritage Sites are designated to meet the UK's commitments under the World Heritage Convention. The UK's ratification of the Convention also extends to its Overseas Territories and Crown Dependencies. These sites are designated for their globally important cultural or natural interest and require appropriate management and protection measures. Natural properties may be terrestrial or marine areas.

UK Government / UNESCO World Heritage Committee

see:
Department for Culture, Media and Sport

Other natural heritage conservation designations in the UK

Areas of Great Landscape Value (AGLVs) in Scotland

The requirement to designate AGLVs is set out in SDD Circular 2/1962. They are defined by local authorities in development plans with a view to safeguarding areas of regional or local landscape importance from inappropriate developments. A number of other regional and local landscape designations are also used by local authorities in Scotland, including Regional Scenic Area.

Local authorities

Biogenetic Reserves Network

Biogenetic reserves act as 'living laboratories' and are representative examples of various types of natural environment in Europe. They can consist of natural or semi-natural habitats and their selection is based on their value for nature conservation and protected status based on four criteria: 'typical', 'unique', 'rare' and/or 'endangered' which can be applied to habitats or species. The protected status must be adequate to ensure the conservation or management of the sites in the long term in accordance with fixed objectives.

UK Government / Council of Europe

Biosphere Reserves

Biosphere Reserves are areas of terrestrial and coastal ecosystems promoting the conservation of biodiversity with sustainable use. Biosphere reserves serve to demonstrate integrated management of land, water, and biodiversity.

UK Government / UNESCO

European Diploma Site (Category A) and European Diploma Site (Category C)

The European Diploma is an award established by the Council of Europe under Regulation (65) 6 of the Committee of Ministers of the Council of Europe of 6 March 1965 for certain landscapes, reserves and protected national features, and Resolution (73) 4 of 19 January 1973 on the Regulations for the European Diploma (amended and revised by Resolution (88) 39 of 5 December 1988, (89) 12 of 19 June 1989 and (91) 16 of 17 June 1989).

By awarding the European Diploma, the Council of Europe recognises that the area is of particular European interest for natural-heritage and that the area is properly protected. The Diploma can be awarded to national parks, nature reserves or natural areas, sites or features. The award is for a five-year period. Annual reports are required for each area, and the renewal of the award at 5 years is only made after independent assessment of the site. The Diploma can be withdrawn at any time if the area comes under threat or suffers serious damage.

UK Government / Council of Europe

see:
EUROPA - The European Union On-line

Geological Conservation Review sites (England, Scotland, Wales) & Earth Science Conservation Review Sites (Northern Ireland)

Geological Conservation Review (GCR) and Earth Science Conservation Review (ESCR) sites are non-statutory sites identified by the statutory nature conservation agencies as having national or international importance for earth science conservation on the basis of their geology, palaeontology, mineralogy, or geomorphology. Although GCR/ESCR identification does not itself give any statutory protection, many GCR/ESCR sites have been notified as SSSIs/ASSIs.

Statutory country nature conservation agencies

see:
Earth heritage
Earth Science Conservation Review

Geoparks

Geoparks are internationally-recognised areas encompassing one or more sites of scientific importance in which the geological heritage is safeguarded and sustainably managed, with strong local involvement.

UK authorities / UNESCO

see:
International Network of Geoparks

Heritage Coasts (in England and Wales)

A Heritage Coast is a section of coast exceeding one mile in length that is of exceptionally fine scenic quality, substantially undeveloped, and containing features of special significance and interest. The designation is agreed between local authorities and (in England) the Countryside Agency or (in Wales) the Countryside Council for Wales, as an aid to local authorities in planning and managing their coastlines.

Local government authorities/ Countryside Agency/ Countryside Council for Wales.

see:
Countryside Council for Wales

Marine Consultation Areas (in Scotland)

Marine Consultation Areas are identified by Scottish Natural Heritage as deserving particular distinction in respect of the quality and sensitivity of the marine environment within them. Their selection encourages coastal communities and management bodies to be aware of marine conservation issues in the area.

Scottish Natural Heritage

National Scenic Areas (in Scotland)

National Scenic Areas (NSAs) are designated by Scottish Ministers as the best of Scotland's landscapes, deserving special protection in the nation's interest. Special development control measures for the 40 National Scenic Areas in Scotland were introduced by the Scottish Development Department through SDD Circular No 20/1980. National Planning policy for NSAs is set out in NPPG14 on Natural Heritage.

AONBs are broadly equivalent to National Scenic Areas in England, Scotland, and Wales.

Scottish Ministers

see:
Scottish Natural Heritage

National Trust / National Trust for Scotland properties

The National Trust (for England, Wales and Northern Ireland) and the National Trust for Scotland are independent charities that conserve the cultural, built and natural heritage of the UK. Both National Trusts own or have protective covenants over land of historic interest or natural beauty. Under the National Trust Act (1907) and the National Trust for Scotland Order Confirmation Acts 1935 and 1938 their holdings are inalienable and cannot be sold or mortgaged. The Trusts have powers to create bylaws relating to access and management of land.

Comparable independent bodies exist in a number of the UK's Crown Dependencies and Overseas Territories, for example the National Trust of Guernsey and the National Trust for Jersey.

The National Trust / The National Trust for Scotland

see:
National Trust
Natural Trust for Scotland

NGO properties

A variety of non-governmental organisations such as the John Muir Trust, Plantlife, the Royal Society for the Protection of Birds, Wildlife Trusts and Woodland Trust own or manage nature reserves or other areas of land that are important for biodiversity. These sites may be intended primarily for nature conservation, or for other purposes such as protection of landscape features or the provision public access to the countryside. These areas of themselves have no statutory basis, but a large number are also designated SSSIs / NNRs / SPAs / SACs / Ramsar sites, etc.

NGOs

Regionally Important Geological and Geomorphological Sites (RIGS)

Regionally Important Geological and Geomorphological Sites (RIGS) are the most important places for geology and geomorphology outside statutorily protected land such as Sites of Special Scientific Interest (SSSI). Sites are selected under locally-developed criteria, according to their value for education, scientific study, historical significance, or aesthetic qualities. Whilst not benefiting from statutory protection, RIGS are equivalent to local Wildlife Sites, and *"...consideration of their importance becomes integral to the planning process"'*.

Local government authorities

See: www.ukrigs.org.uk

Sensitive Marine Areas (in England)

Sensitive Marine Areas (SMAs) are non-statutory marine areas notable for their marine animal and plant communities or which provide ecological support to adjacent statutory sites. A further aim is to raise awareness and disseminate information to be taken into account in estuarine and coastal management planning. These areas rely on the co-operation of users and local communities for sustainable management.

Natural England (formally English Nature)

Wildlife Sites

Local authorities for any given area may designate certain areas as being of local conservation interest. The criteria for inclusion, and the level of protection provided, if any, may vary between areas. Most individual counties have a similar scheme, although they do vary.

These sites, which may be given various titles such as 'Listed Wildlife Sites' (LWS), 'Local Nature Conservation Sites' (LNCS), 'Sites of Importance for Nature Conservation' (SINCs), or Sites of Nature Conservation Importance' (SNCIs), together with statutory designations, are defined in local and structure plans under the Town and Country Planning system and are a material consideration when planning applications are being determined.

Local government authorities

Woodland Parks / Forest Parks

Woodland Parks are similar to Forest Parks but are smaller in scale and located near to centres of population. Forest Parks, Forest Nature Reserves, or Woodland Parks are identified and managed by the Forestry Commission primarily for recreation purposes.

Forestry Commission

see:
Forestry Commission

Northern Ireland Environment Agency

Source: http://jncc.defra.gov.uk/page-1527 Accessed 18/10/2011

A.4.2 ONLINE MAPPING TOOLS USED:

Nature on the Map - Natural England - provides spatial information on a variety of protected sites

http://www.natureonthemap.naturalengland.org.uk/

MAgiC – Multi-Agency Geographic Information for the Countryside – Interactive map providing information on environmental schemes and designations.

http://magic.defra.gov.uk/

SiteLink – provides spatial information on key Protected Areas across Scotland

http://gateway.snh.gov.uk/sitelink/index.jsp

Forestry Commission Scotland – Basic Land Information Search

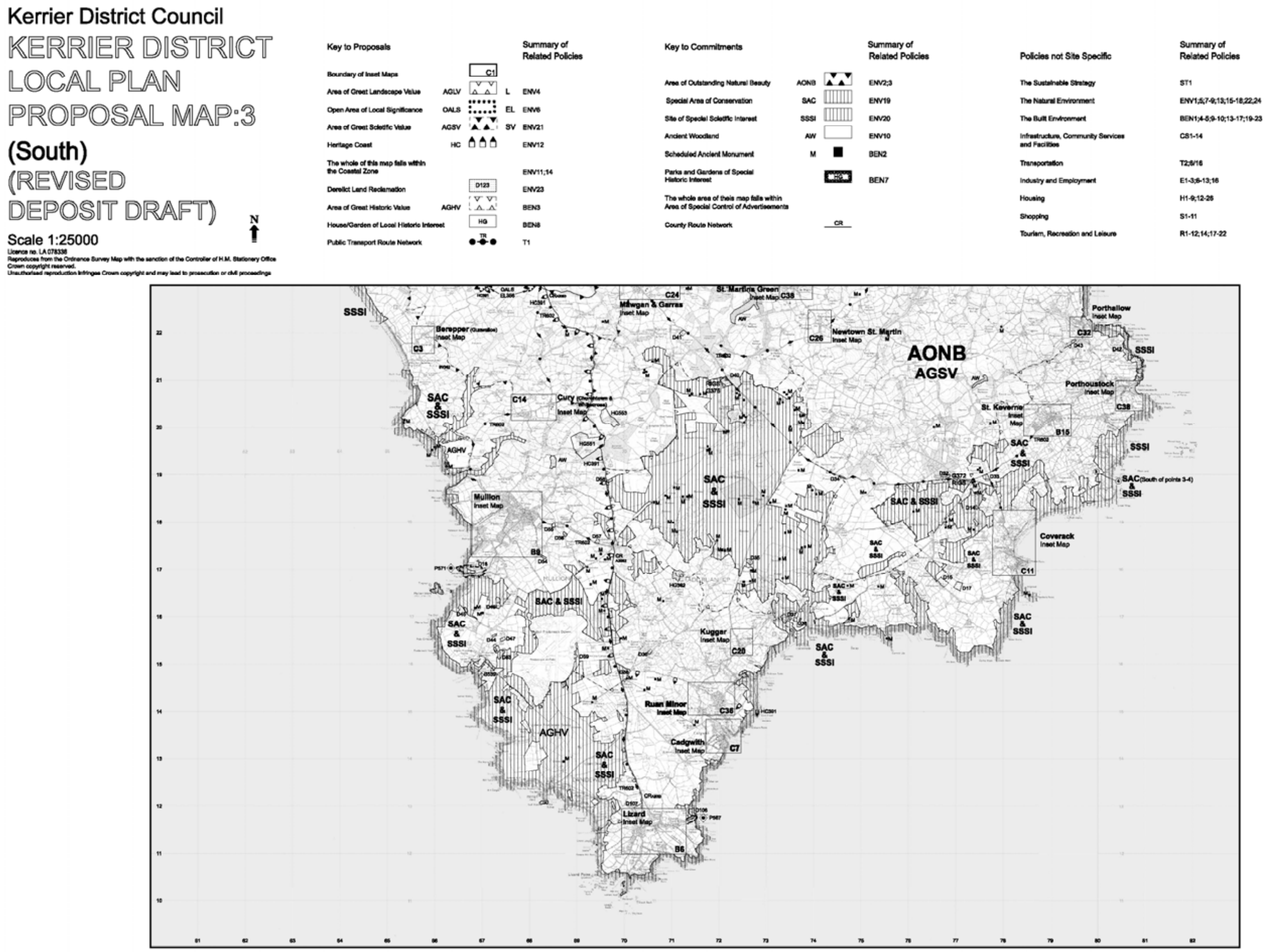
http://www.forestry.gov.uk/forestry/infd-62fg7f

A.4.3 LIZARD PENINSULA AS AN EXAMPLE OF LOCAL PLANNING POLICIES

The Lizard Peninsula: an example of the local planning policies that are likely to be applicable to a CCSM development proposal together with an example of a proposals map showing other policy concerns (For policy documents see **http://www.cornwall.gov.uk/Default.aspx?page=17398**; for proposals maps see **http://www.cornwall.gov.uk/Default.aspx?page=26319**) [Copyright BGS, NERC].

Location	Mineral Planning Authority	Local Plan and Adoption Date	Key Policies	Wording of policies
Lizard Peninsula, Cornwall	Cornwall Unitary Authority	Cornwall Minerals Local Plan, 1998	Policy C1	**Application will be considered having regard to the following:** Evidence of the presence of 'mineral'. Visual impact of the proposals on the landscape and countryside. The effects on agriculture. Effects on local amenity and communities – including visual intrusion, and the potential effects of dust, vibration, and fumes. The effects of noise. The impact of road traffic on local road systems. The impact on nature conservation and earth science. The impact on the historic environment. The impact upon groundwater, surface water, drainage, and flooding. The impact on recreational uses and rights of way. An indication of the completion date. Proposals for mitigation of detrimental effects.
			Policy C3	Minerals development, which may give rise to damage to either water resources or the water environment, will not be permitted unless this harm can be satisfactorily mitigated. In addition, the tipping of mineral waste will not be permitted in the flood plain unless any harm can be satisfactorily mitigated.
			Policy C4	When granting planning permission for minerals development, conditions will be imposed to minimise and mitigate emissions of dust, smoke, and fumes.
			Policy C5	When granting planning permission for minerals development, conditions will be imposed to reduce noise and vibration levels at sensitive properties and environments by: a) Employment of all best practicable means to prevent or minimise the creation of noise and vibration during the approved use of the site; b) Defining the permitted hours of working; c) Setting maximum noise limits at the site boundary and / or neighbouring noise sensitive locations; d) Requiring mechanical and landscaping measures to mitigate noise emissions; and e) Requiring the operator to monitor and keep records of noise, ground vibration, and air overpressure.
			Policy C6	Minerals development will not be permitted where the traffic generated from the site would a) Significantly jeopardise the interests of highway safety; or b) Cause significant congestion on the road network; or c) Cause significant nuisance to the environment, local amenity or communities; unless such detrimental effects can be successfully mitigated.

			Policy C7	In determining applications for mineral development and associated operations, the County Council will seek to ensure that an adequate buffer zone will exist between the mineral development and neighbouring incompatible non-mineral development and neighbouring incompatible non-mineral development or land uses…
			Policy C8	In granting planning permissions for minerals development, screening and landscaping will be required in order to improve the visual appearance of mineral workings. Landscaping schemes should reflect the local character and distinctiveness.
			Policy C9 (No mineral processing at site though)	The erection of ancillary mineral processing or manufacturing plant at mineral extraction sites will be permitted, except where it would give rise to significant detrimental effects on the environment, local amenity or communities which cannot be satisfactorily mitigated.
			Policy C11	Applications for the establishment of new wharves or the improvement of existing wharves, used for the loading, unloading, handling and distribution of minerals will be permitted except where there are significant detrimental effects on the environment, local amenity, or communities, which cannot be satisfactorily mitigated.
				Note: No restoration policies were 'saved' by the secretary of state.
		Structure Plan	Policy 5	Mineral resources should be conserved and managed to provide a steady supply of minerals to meet needs subject to environmental and social considerations and the need for high standards in restoration and aftercare. Development should ensure: • the conservation of the mineral resources; • a steady supply of minerals is available; • impacts on the environment are minimised and encouragement is given to the use of secondary or recycled aggregates; • an increased use in non road based transport; • the improvement of operational standards at all mineral workings; • that high standards of restoration and aftercare are secured on a progressive basis; • that adequate overall capacity for mineral wastes arising in Cornwall is provided for during the Plan period.


Kerrier District Council
KERRIER DISTRICT LOCAL PLAN PROPOSAL MAP:3
(South)
(REVISED DEPOSIT DRAFT)
N
Scale 1:25000
Licence no. LA 078336
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Crown copyright reserved.
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Key to Proposals
Summary of Related Policies
Boundary of Inset Maps C1
Area of Great Landscape Value AGLV L ENV4
Open Area of Local Significance OALS EL ENV6
Area of Great Scietific Value AGSV SV ENV21
Heritage Coast HC ENV12
The whole of this map falls within the Coastal Zone ENV11;14
Derelict Land Reclamation D123 ENV23
Area of Great Historic Value AGHV BEN3
House/Garden of Local Historic Interest HG BEN8
Public Transport Route Network TR T1
Key to Commitments
Summary of Related Policies
Area of Outstanding Natural Beauty AONB ENV2;3
Special Area of Conservation SAC ENV19
Site of Special Scietific Interest SSSI ENV20
Ancient Woodland AW ENV10
Scheduled Ancient Monument M BEN2
Parks and Gardens of Special Historic Interest BEN7
The whole area of theis map falls within Area of Special Control of Advertisements
County Route Network CR
Policies not Site Specific
Summary of Related Policies
The Sustainable Strategy ST1
The Natural Environment ENV1;5;7-9;13;15-18;22;24
The Built Environment BEN1;4-5;9-10;13-17;19-23
Infrastructure, Community Services and Facilities CS1-14
Transportation T2;6/16
Industry and Employment E1-3;6-13;16
Housing H1-9;12-26
Shopping S1-11
Tourism, Recreation and Leisure R1-12;14;17-22
AONB
AGSV
SAC & SSSI
SSSI
AGHV
Porthallow Inset Map
Porthoustock Inset Map
St. Keverne Inset Map
Coverack Inset Map
Newtown St. Martin Inset Map
Mullion Inset Map
Kugger Inset Map
Ruan Minor Inset Map
Cadgwith Inset Map
Lizard Inset Map
Berepper Inset Map

A.5 Glossary

Amph	*Amphibole*
Bst	*Bastite, serpentine pseudomorphs after orthopyroxene*
Cbr	*Carbonate*
Chl	*Chlorite*
Chl	*Chlorite*
Chr	*Chromite*
Cpx	*Clinopyroxene*
Ep	*Epidote*
Feo/oho	*Fe oxide/oxyhydroxide*
Mgt	*Magnetite*
Ol	*Olivine*
Opx	*Orthopyroxene*
Plg	*Plagioclase*
Prhn	*Prehnite*
Srp	*Serpentine*
Tlc	*Talc*
Qtz	*Quartz*

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