



**3D MAPPING THE OPHIOLITE COMPLEX IN THE POLTESCO BEACH TO
KENNACK SANDS AREA OF THE LIZARD**

*Submitted by Caglar Aslan (Student ID: 680049081) to the University of
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Supervisor: Dr Jens Andersen

I certify that all material in this dissertation which is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

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1. ABSTRACT

In the study area, there is a highly deformed and metamorphosed assemblage of ophiolitic complex which consists of peridotite, gabbro and sheeted dykes. All lithologies of the ophiolitic sequence cannot be seen in the study area because it is a limited area from a geological perspective. All lithologies of ophiolitic sequence can be seen in the Lizard Ophiolite Complex. Besides the ophiolitic complex, there are also other rock types. This study attempts to explain the relationship between the Lizard Ophiolite and non-ophiolitic sequence units which consist of granite, basalt and hornblende schists. All lithologies have special features in this area. Therefore, age and stratigraphic relations are also significant for the understanding of tectonic and magmatic events. According to the field, geochronological, microstructural and previous studies, Ordovician basement and Devonian rocks of the Lizard Ophiolite Complex exist in rocks dug up on the Lizard peninsula. Identified from the rocks of the Lizard Ophiolite Complex, evidence shows three tectonic-magmatic events that took place between the Early and Late Devonian periods. Stratigraphically, the oldest lithology is peridotites (393-386Ma). They were formed at the thrust emplacement (396-376 Ma). This period included the stage of peridotites occurrence and the creation of the Kennack Gneiss. The Kennack Gneiss was emplaced in the area via an unknown magma resource. The Kennack Gneiss is a commingling of the basalt and granitic magma assemblage. According to previous age analysis, granitic magma intruded (376 ± 1.7 Ma) with basaltic magma at the same stage in the study area. Kennack Gneiss' granite magma resource is different from the other South Cornwall granites. This granite magma resource is relatively older. The following stage was metamorphic events and emplacement of the gabbro and basalt dykes. The study area has a number of altered units which are affected by the physical and chemical processes. These can be seen in the thin sections and serpentinite evolution can explain all the processes in the study area. The last step was the serpentinisation process at the late-post emplacement (370 Ma). However, serpentinisation processes were also continuing during the Variscan orogeny (Late Carboniferous- Early Permo Triassic). The study suggests that the Poltesco Beach area was affected by the basal thrust fault. However, in the Kennack Sands area, the Kennack Gneiss should also have been affected by the basal thrust.

According to the thin sections, the Kennack Gneiss' protolith is composed of igneous rocks. The Kennack Gneiss' granite section is I-type granite. Moreover, there are two indications of metasomatism in the study area. These can be seen in the contact points as a rodingitisation and chrysotile alteration.

The final step includes 3D modelling of the ophiolites and granite sections which are providing different perspectives on the study area. This study carries out this 3D modelling of the Kennack Sands to Poltesco Beach cliff area using photogrammetry software.

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2. INTRODUCTION

The study area is located between the Kennack Sands and Poltesco Beach, focusing on the coastal area. The combination of lithologies between Kennack Sands and Poltesco Beach are quite controversial because this location contains Kennack Gneiss (the mixture of mafic and felsic magmatic rock) and part of the ophiolite sequence together. With constant changes in contact points and coastlines within the study area, dominant rocks such as the granite and ophiolite sequence need to be mapped and analysed for their origin. The granite and ophiolite sequence need to be mapped as they are the dominant rocks in the field area. Thin sections should be prepared because of the analysis of the origin.

This study aims to explain the origin of the Kennack Gneiss, considering whether this lithology is genuine metamorphic rocks and how it became emplaced in the field area. However, Kennack Gneiss can also be classified as metamorphic in some sections of the study area. It is lamination and magma commingling that determine the difference between genuine metamorphic rock and igneous magma mixing rock. Specifically, the Kennack Gneiss is a genuine metamorphic rock in the Poltesco Beach area associated with the hornblende schist. Both these lithologies were affected by the structural events.

It also considers how the other lithologies, hornblende schist, gabbro and basalt dykes, can be related to the ophiolitic sequence and which lithologies were emplaced by tectonics or magmatic intrusion in the study area. The project gives us a detailed insight into the relationship between the Kennack Gneiss (the mixture of granite and basalt), the host serpentinite and the dykes in the area between Poltesco Beach and Kennack Sands. Initially, this study aims to explain the lithologies' existing mechanism and the relation between granite and ophiolite sequences.

The main studies include petrography and field studies. According to field observations how lithologies came to be located in the area. Additionally, it can be found how ophiolitic rocks and non-ophiolitic rocks can appear together. Tectonism and magma intrusion facilities are significant to understand the whole

geology of the study area. Besides the field observations, petrography can provide some fundamental information. Thin sections will be researched using the optic mineralogy and SEM (Scanning Electron Microscope) mineralogy. Mineralogy can give information about the circumstances of the lithology environment. Rocks' deformation and chemical changes can provide information about the situation during the formation of the lithology. Determining the ophiolite type determines a number of features about the environment. For example, the Lizard Ophiolite Complex has a small amount of chrome mineral. This can show that the Lizard Ophiolite Complex is related to an oceanic rift tectonic setting and it has MORB style magmatic activity. Mostly, chromite-rich ophiolites are related to a supra-subduction zone tectonic setting.

The project involves the collection of a detailed survey along the coast using a handheld camera and Pix4D Software. Images collected during this survey were then processed to generate a detailed topographical model of the coast. This provides a new visual perspective. Additionally, magmatic emplacement and tectonic events can be seen easily with a 3D model because fault lines and magma contact points can be seen as a natural observation. The 2D effect of paper cannot reflect the actual situation in nature.

This study is based on the Lizard Ophiolite complex and involves handheld photogrammetry mapping. This study is a detailed geological mapping project on this part of the Lizard Complex. As the study is based on the Lizard Ophiolite complex, mapping by handheld photogrammetry provides a detailed account of the Lizard Complex by the use of a camera and Epic Pro V (Capture Remarkable Panoramic Image). The other methods include the collection of different rock types for microscopic characterisation and analysis and 3D geological mapping.

Primarily, field observations and petrographic studies can provide some information about the evolution of the environment in this study area. Tectonic and magmatic evolutions are a significant part of the whole picture of the Lizard Ophiolitic sequence. At the same time, ophiolitic and non-ophiolitic lithologies can be important for the economic occurrences of some deposits. For example, some Cornwall granite bodies contain economic tin mineralisation. However, the

Kennack Gneiss' granitic magma is different from the other Cornwall granite bodies. Ophiolite members, one of them being serpentinite, can be used as sculpture and hobby materials. However, economic geology is not a topic in this study because the study area is a National Trust reserve.

3. GEOLOGICAL BACKGROUND

3.1. General Geology

3.1.1. Ophiolite

Ophiolite is an igneous rock complex which includes deep-sea sediments, basalt, gabbro and peridotites. Ophiolite sequence has a typical stratigraphy (figure 3:1). In this complex, gabbro and basalt are generally altered to irregular green rocks, and peridotites altered to blackish green, greasy serpentinite (Ishiwatari, 1999).

There are two types of ophiolites which are formed at divergent plate boundaries. These divergent plate boundaries are mid-oceanic ridges (MOR) and supra-subduction zones (SSZ). The type of ophiolites can be identified by the chemical composition of the rocks and minerals (Ishiwatari, 1999).

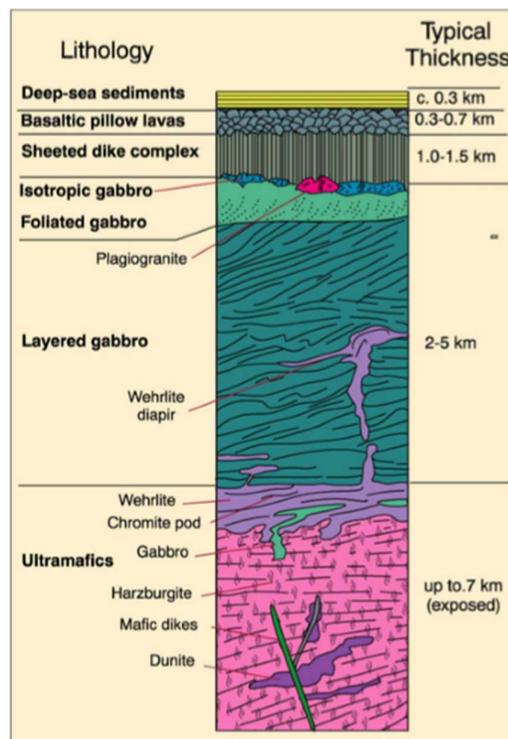


Figure 3:1 Stratigraphic Column of a Typical Ophiolitic Sequence (Nicolas, 1989)

Harzburgite and Lherzolite rocks are distinguished by contents of clinopyroxene. However, harzburgite may contain little clinopyroxene. It depends on clinopyroxene- poor (or -free) harzburgite rocks' melting degree. Peridotite and mineral occurrences of olivine, orthopyroxene and clinopyroxene can be seen in figure 3:2. Ishiwatari (1999) stated that mid-oceanic ridges mostly contain lherzolite, whereas supra-subduction zones mostly contain harzburgite.

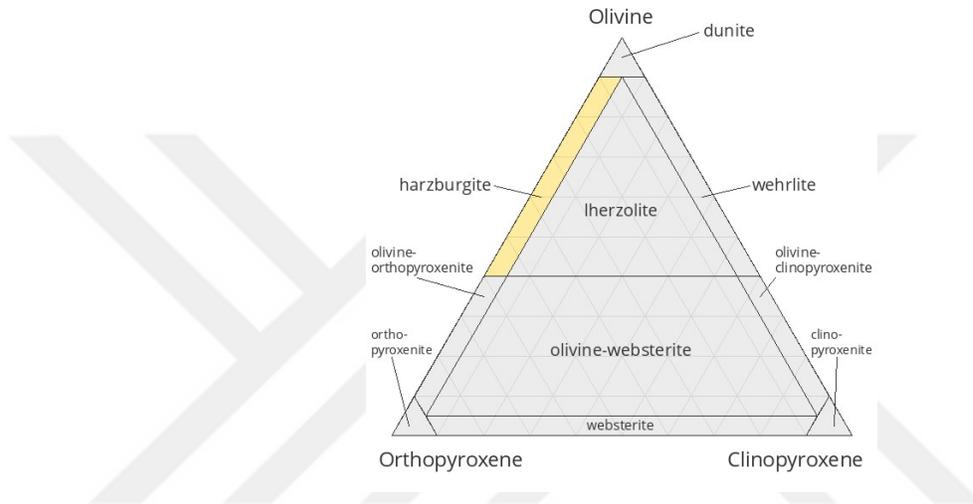


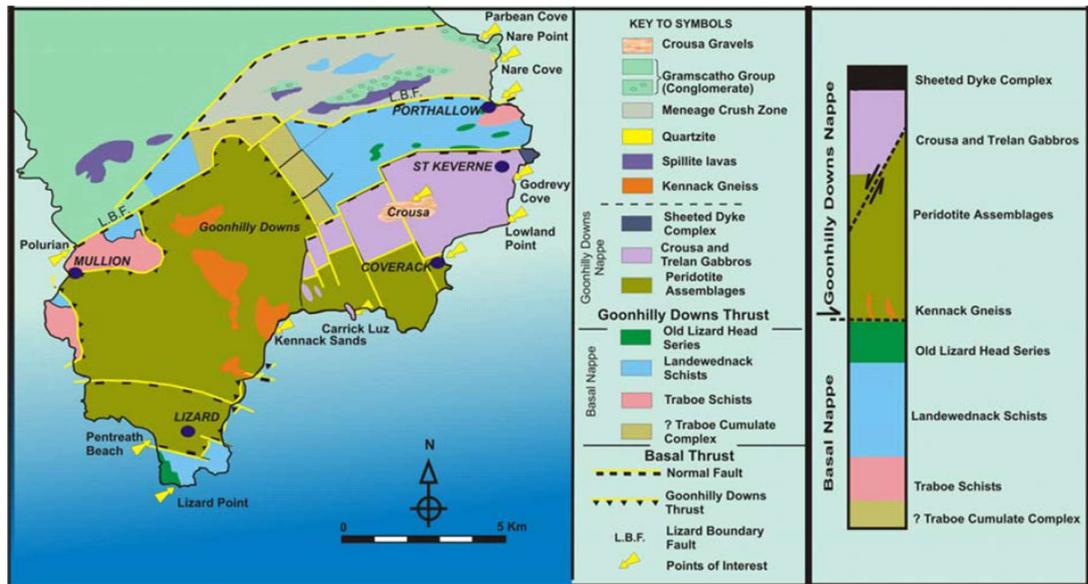
Figure 3:2. Modal classification of ultramafic rocks (after Streckeisen, 1973)

3.1.1.1 Lizard Ophiolite

The Lizard has the best examples of the ophiolites in Britain because this ophiolite complex contains surface sediments, below sediments, pillow lavas, sheeted dykes, gabbro and ultrabasic rocks which are peridotites. The Lizard area is entirely distinct geologically, all lithologies have contributed to its unique character. For example, there is granite lithology, which is granite, but unlike the origin of grey granite spread from Bodmin Moor to Scilly. This granite is reddish and forms only a small low-lying area in Kennack. Moreover, the ages are different from each other (Barton, 1965).

Even though the rocks are altered chemically and physically, most of the rocks are originally crystalline rocks. The Lizard is separated by a large fault (along from Polurrian to Porthallow) as can be seen in figure 3:3. This area not only has ultramafic rocks, but it also has granite rock. The most widespread rocks are dark green and red serpentine in the Lizard. Besides the granites and serpentine,

there is another lithology, gabbro, which is younger than serpentine. Gabbro is also younger than the reddish Lizard granite, which is generally located in Poltesco and Kennack (Barton, 1965).



Modified from Power M. 1997

Figure 3:3 Simplified Geological Map of Lizard Area and Section (Exeter Project, 2019)

The Old Lizard Head Series includes mica-schists, granulites and green schists. Schists are originated from brownish or red-brown marine shales and muds that contain muscovite and biotite. Weathered parts of these series generally contain chlorite and talc. These series have feldspar as a very common mineral, and greenschist with fluxional amounts of chlorite and hornblende (Barton, 1969).

Typical ophiolite sequence occurs from deep-sea sediments, basaltic pillow lavas, sheeted dyke complex, isotropic, foliated and layered gabbro and peridotites. The Lizard ophiolite sequence is different than other ophiolites because of the Kennack Gneiss units, which are not metamorphic gneiss. It is a mixture of two igneous rocks which are granite (felsic) and basalt (mafic). The Lizard ophiolite sequence can be seen in figure 3:4 (Power, et al., 1996).

There are three type peridotites in the Lizard area, which are hydrated harzburgites, lherzolites and dunites (Fleet, 1946; Green 1964). All of the peridotites are partly or fully serpentinised in the Lizard. Moreover, there are three different types of peridotite based on mineral assemblage: Aluminium rich enstatite, chrome rich clinopyroxene and olive-green aluminous spinel (Green,

1964). These mineral occurrences are anhedral texture and contain large orthopyroxene porphyroclasts. Another mineral assemblage is similar, which is anhydrous peridotite. Anhydrous peridotite contains plagioclase and low aluminium pyroxenes caused by the replacement of clinopyroxene by hornblende (Green, 1964).

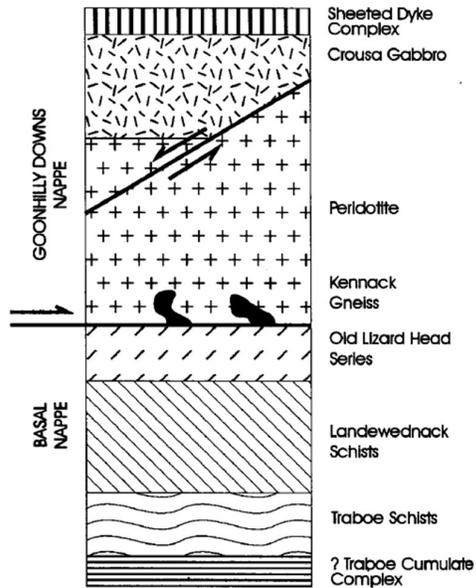


Figure 3:4 Tectonic Stratigraphy of Lizard Ophiolite (Power, et al., 1996)

The equigranular texture observed in granites is defined in the porphyroclasts of orthopyroxene and spinel. The recrystallised hydrous assemblage consists of olivine, pargasite and chrome spinel. As a result of recrystallisation, minerals' grains are gradually small (<1mm) (Green, 1964). The main difference of these assemblages is gradational (Rothstein,1981; Floyd *et al.*, 1993). This difference can be explained with the degree of recrystallisation and hydration of retrograde P-T environment related to diapir emplacement (Green, 1964a; Styles and Kirby, 1980), or vicinity of a major thrust fault (Power *et al.*, 1996).

3.1.2. Serpentinite

Peridotites, gabbros and basalts are highly altered due to Variscan orogeny. They were generated by Devonian rifting and obducted at the Variscan convergence Bromley,1979; Kirby, 1979; Floyd *et al.*, 1993).

Serpentinisation is widespread in the Lizard peridotite. There are two serpentine minerals namely lizardite and chrysotile that indicate hydration of the ferromagnesian phase (Midgley, 1951; Green, 1964b). Additionally, there is antigorite mineral, but this mineral is uncommon (Green 1964a, b; Power *et al.*, 1996). Moreover, lizardite was first explored in the Lizard (Midgley, 1951).

Flett (1946) claimed that the serpentinisation process is still progressing because of the weathering process. Floyd *et al.* (1993) partly accepted this situation but proposed a higher temperature (400-500 °C) and obduction condition. Hall (1979) added that rodingite alteration is affected by the Kennack Gneiss. The Kennack Gneiss is a mixing of basic and acidic magmas intrusion along the Goonhilly Downs Thrust in the initial stages of obduction (Sandeman, 1998). According to Hall (1979), rodingite alteration is not possible before the onset of obduction (Power *et al.*, 1997b).

There are two stages for the serpentinisation. The first is a pervasive serpentinisation episode which has lizardite, chrysotile and magnetite minerals. The second stage is not widespread evident in laterally persistent veins and associated minerals such as lizardite and chrysotile (vein serpentinite) (Power *et al.* 1997b).

Power *et al.* (1997b) claimed that the main core of pervasive serpentinisation is located at southern Kennack Sands. These serpentine characterise with white veins. These veins are serpentinised peridotite, and they contain orthopyroxene crystals and magnetite. Rodingite mineral associated with the orthopyroxene crystals and Fe-rich are found in the vicinity of Kennack Gneiss. Kennack Gneiss was affected by the rodingite alteration (Hall, 1979), which is related to the initial stages of obduction (Sandeman, 1988). According to radiometric dating (RbSr isochrone) of the Kennack Gneiss, serpentinisation occurred within the continental realm (post 369 Ma) (Styles and Rundle, 1984).

Primary serpentinisation occurred at relatively low temperature (250 °C) in the mineral assemblage of lizardite-chrysotile (O'Hanley 1996). However, Floyd *et al.* (1993) claimed that this might show recrystallisation in retrograde pressure. Other serpentinisation stages were occurred at relatively high temperature (250-400 °C) in the mineral assemblage of antigorite. This relatively high temperature

serpentinisation happened during the early period of obduction. Moreover, magnetite veins indicate recrystallisation of serpentine (O'Hanley 1996). The Lizardite- chrysotile minerals indicate serpentine's formation temperature was lower than 250 °C (Power et. al,1997).

Vein talc is present in the peridotite veins. This mineral accumulation is a pale green to white. Basic dykes within the peridotite contain the talc (Kennack Gneiss (Granite intrusion part) contact location with peridotite), the saponite mineral can crystallise. Massive talc may result from the product of the Si metamorphism of peridotite vicinity of acidic rocks (granite part of Kennack Gneiss). The xenoliths are covered with the mafic fractions of the Kennack Gneiss, there is a small vein of actinolite, chlorite and talc minerals, which are typical alteration results of rodingite mineral (Coleman, 1977).

The south part of the Lizard Peninsula is occupied by the enstatite or bastite serpentine. These rock types represent the latest phase of the continuous intrusion of the peridotites. The crystals are quite big enough for observation with the naked eye. The coarsely crystalline contents indicate that it cooled slowly. The most distinctive feature is the contents of bronze-like lustre, set in a blackish green serpentinite (Barton, 1965).

3.1.3. Gabbro

Gabbro series are randomly oriented in the Lizard area, and also gabbro sheets intrude the peridotite lithology. These rocks have steep dips in some areas. The steep dips indicate that dykes have developed rapidly from magma chambers (Roberts et al.,1993). The gabbro sheets are altered, with amphibole and sericite replacing clinopyroxene and plagioclase. These gabbro sheets contain rounded and pseudomorphs serpentinised olivine grains. Olivine minerals occur as an interstitial phase crystallising after clinopyroxene and plagioclase (Andrews, 1998).

According to Alexander and Shail (1996), fracture-hosted mineralisation between the gabbros and peridotites is difficult because of the wall rock composition in vein mineralogy and the absence of suitable contact of gabbro and peridotite. The chemical composition of gabbro and peridotite can provide some information about the correlation with each other. For example, prehnite ($\text{Ca}_2 \text{Al} [\text{AlSi}_3 \text{O}_{10}]$

(OH)₂) in the gabbro and talc (Mg₃ Si₄ O₁₀ (OH)₂) in the peridotite can be compared with each other. Additionally, calcite content from gabbro can be used for the correlation. Structural features (vein orientation, kinematics and morphology) also indicate the synchronous mineralisation events (Alexander and Shail, 1996).

The peridotite and gabbro contacts are a transition zone, which is approximately one km wide. The gabbro content changes from olivine-rich troctolite to feldspathoid olivine-rich composition. This situation indicates extremely variable grain size and partly was affected by the ductile shear zones which can be understood by elongated plagioclase and pyroxene grains. The shear zones dip at moderate to low angles. Moreover, stretching lineation plunges towards the northeast. Kinematic indicators show that displacement was from top to the east (Gibbons & Thompson, 1991; Roberts et al., 1993). There are crosscuts by basic dykes which indicate Mid-Ocean Ridge Basalt (MORB) characteristics (Roberts et al., 1993). This is a suggestion of their generation placement near the former oceanic ridge axis before obduction (Andrews, 1998).

The gabbros in the study area consist of mainly plagioclase and augite, with small amounts of ilmenite and magnetite (Bromley, 1979). Moreover, the southern gabbros contain olivine. Above the intrusive body of the gabbros, the section has indications of the progressive fractionation. In that direction, magnesium and iron contents are decreasing, and titanium and phosphorus contents are increasing (Kirby, 1979a).

Ridge-axis tectonics initiated oceanic spreading. Sheeted dykes, gabbro and peridotite lithologies were faulted as listric faults. The evolution of this tectonism can be seen in figure 3:5. Fe-Ti rich and Si poor magma migrated along the shear zones. Additionally, this magma produced oxide-rich gabbro (Hopkinson & Roberts 1995).

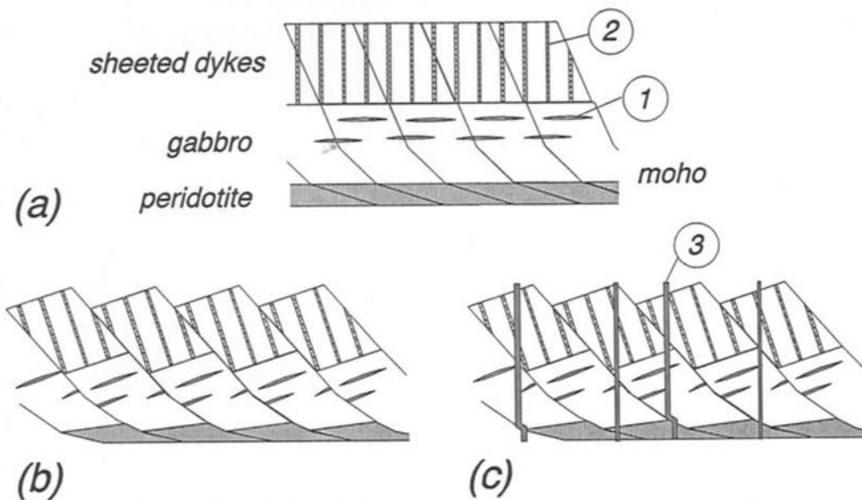


Figure 3:5. Evolution of tectonism in the east coast section of the Lizard ophiolite a) flat stratigraphy (set 1) cross-cut by plagioclase phyric dykes (set 2) b) during the low magma production, extensional structures were activated by seafloor spreading c) magmatic activity was repeated and aphyric dolerite dykes injected (Andrews, 1999).

Gabbro dykes are also associated with plagiogranites. Schematic depiction of the setting for plagiogranite formation is related to gabbro dykes in the spreading centres (figure3:6).

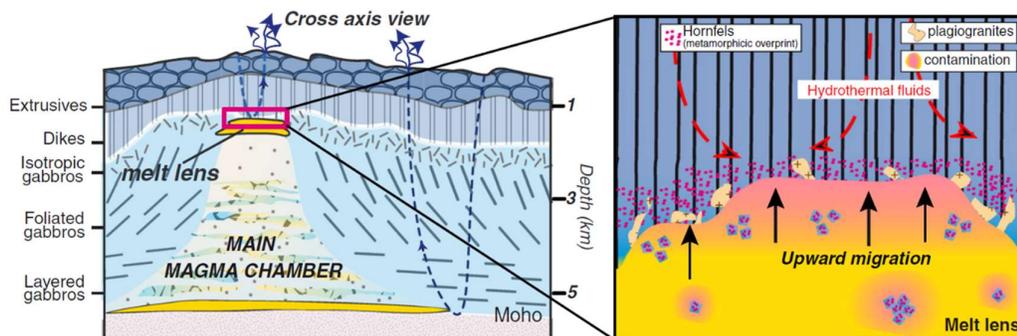


Figure 3:6 Oceanic crust forming during extension, emplacement of dykes overlying crust and vertical migration of the hydrothermally altered dykes which contain plagiogranite (Modified after Gillis and Coogan, 2002; France et al., 2009)

3.1.4 Dykes

The study area has a number of basic dykes which are NNW to SSW trending and their thickness in some parts reaches up to one-meter thickness. According

to field relations and geochemical classification, there are three types of dykes in the Lizard area (Roberts et al., 1993).

The first dykes are thin compared to than the other dykes, which are a few centimetres wide. These dykes' trends are towards the northeast. This set of dykes is composed of plagioclase, green amphibole (after clinopyroxene) and many opaque minerals. Intrusive gabbro lithology is related to this type of dykes. These lithology's form features indicate this part occurred after the gabbroic host had crystallised. Based on the geochemistry results, they represent fractionated residual melts segregated from the occurrence of gabbro rich magma chamber. These dykes were created by the effect of the ductile shear zones extensionally offset (Andrews, 1998).

The second type of dykes consists of plagioclase. These are metadolerite dykes and mainly observed towards Porthoustock as sheeted dykes which are ten centimetres to two meters thick with the trend running NNW-SSE, dip moderately to steeply east-northeast. However, these dykes are much more irregular than the first dykes' southwards. Petrographically, plagioclases are developed with brown amphibole (after clinopyroxene) and also it has olivine in the joints. Geochemically, these dykes are tholeiites with Mid Ocean Rich Basalt (MORB) characteristics (Andrews, 1998).

Andrews (1998) stated that the third type of dykes runs NNW-SSE, and they crosscut the peridotites, gabbro, plagioclase-phyric dykes and NE-SW trending shear zones. These dykes' thickness varies between ten centimetres to one and half meters. Moreover, alteration is changed because of the metamorphism effect, which is seen in the twinned plagioclase and clinopyroxene in sub-ophitic textures associated with olivine phenocrysts. These dykes have characteristics of primitive MORB (with tholeiites) features.

3.1.5 Hornblende Schists

Flett and Hill (1912) identified that hornblende schists are two different types in the Lizard area. These are Landewednack type and Traboe type. The Traboe type is generally derived from serpentine, and it has a steep foliation. In addition to these features, Traboe type hornblende schists are often coarser grade, and the mineralogical character is variable. The Landewednack type is generally

associated with basalt lavas and sills and also intrusion of gabbro (Floyd, et al., 1993).

Bromley (1979) claimed that Traboe type hornblende is derived from metamorphosed gabbros and basic dykes. However, Bromley (1979) denied the effects of metamorphism causes the intrusion of peridotite. According to field observations and chemical analysis, Kirby (1979b) stated that Traboe type hornblende schists had a much wider range and also this lithology is not associated with the Landwednack type. Moreover, he thought this lithology was derived from metagabbros. Styles and Kirby (1980) claim that there are two types of Traboe Hornblende Schist; generally, it consists of metagabbros, but it also contains a small proportion of basal thrust of the peridotite (along the south-east coast near Cadgwith) which was originated from contact with metamorphism of Landwednack type (Floyd, et al., 1993).

3.1.6 Granite

Intrusive, felsic lithology is mostly associated with the basic dykes. These granites commonly associated with sheeted dykes. Plagiogranites are widespread at the top of the gabbro lithology. The gabbro magma chamber is differentiated from plagiogranites. Moreover, plagiogranite veins also form in the gabbros, and they are cut by basic dykes (Andrews, 1998).

Jones (1997) stated that D4 is a syn-metamorphic deformation which is related to the shear zone in the footwall to the Goonhilly Downs Unit. This metamorphic system is associated with granite and basalt (Kennack Gneiss) in the Lizard. The granitic sheets' emplacement is associated with the Kennack Gneiss. Basal thrust, granitic sheets and commingling both which is the Kennack Gneiss are syn-kinematic. They are cross-cutting S4 and carrying later S4 fabrics. Kennack Gneiss are folded by the isoclinal Cadgwith Antiform (figures 3:5a,b, 3:6c) (Jones, 1997).

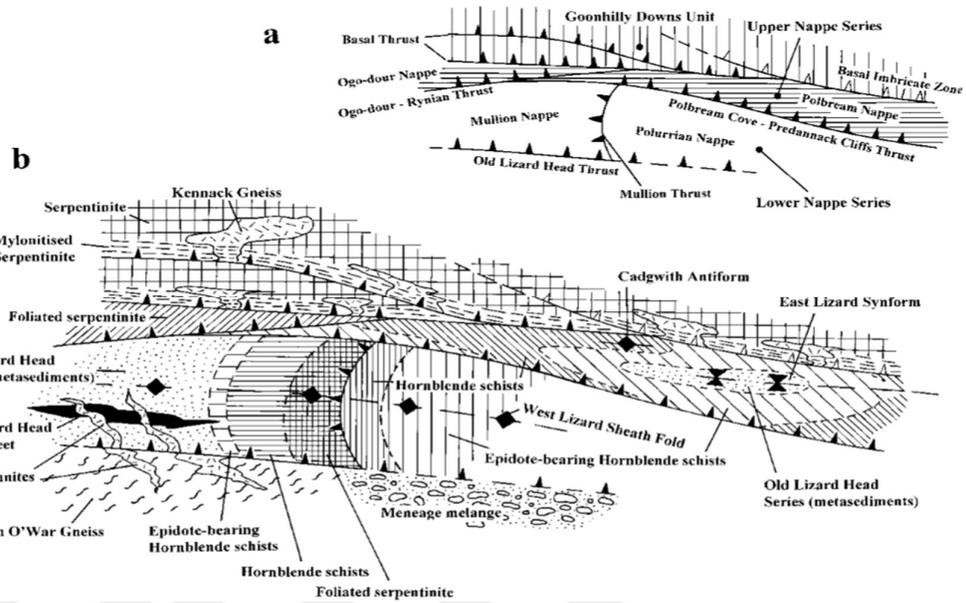


Figure 3.5. Goonhilly Downs Unit's lowermost part and Basal Unit's tectonic stratigraphy a) Major tectonic units and thrust b) Structure and internal tectonic units (Jones, 1997)

The Basal Thrust is also significant for the Kennack Gneiss because it is a mixing of basic and acidic lithologies. The lowest part of the Goonhilly Unit and Basal Thrust was reformed. Basal Thrust was imbricated, and double thrust contact is observed (Figure 3.6b). The lower part of the thrust leads to shearing and recrystallisation. They are due to serpentinitised peridotites. In the eastern coastal sections from Cadgwith the Church Cove, Basal thrust cuts most of lithologies which are serpentinite, hornblende schist and Kennack Gneiss (figure 3:6a) (Jones, 1997).

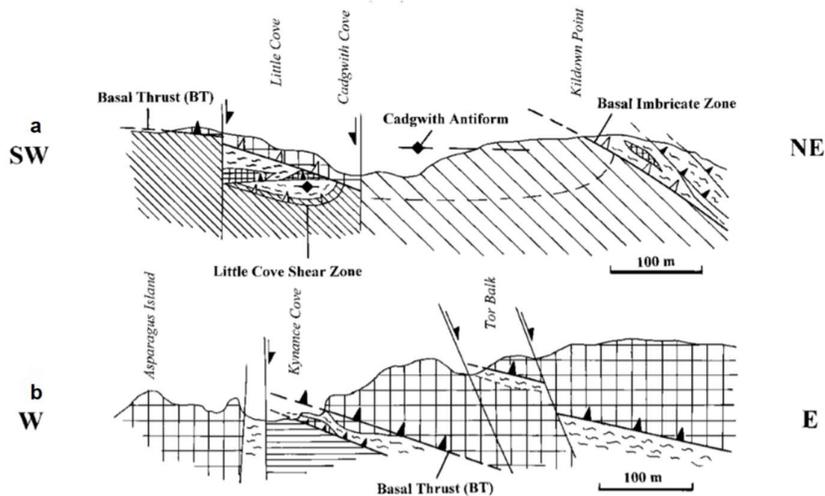


Figure 3.6. Simplified cross-sections of a) Devil's Frying Pan to Kildown Point and b) Kynance Cove (Jones, 1997)

age. Therefore, firstly the ophiolitic sequence was occurred and then granite and basalt were occurred due to the Variscan orogeny. In the study area, Lizard ophiolite has dominated the serpentinite according to field observations. The serpentinite units took place during the obduction. However, serpentinisation was completed by the Carboniferous to early Permian (Power et al., 1997). Moreover, there is gabbro lithology in the study area, which occurred as a Devonian oceanic crust overlaying mantle peridotite (Ealy & James, 2011). The Lizard Complex movement was in a period of the late Variscan (late Carboniferous – early Permo-Triassic) as extensional faulting (Shail, 1999).

Leake and Styles (1984) claimed that peridotites are one of the earliest rock types in the Lizard complex and also peridotites are highly deformed by the external forces. Hornblende schists are intrusive into the peridotites. Hornblende schists were weathered during the Tertiary (Ealy & James, 2011). Moreover, the peridotites were intruded by the gabbro, MORB-type basaltic dykes and the Kennack Gneiss.

Oceanic rocks from the Lizard Ophiolite is associated with the upper mantle peridotites. This relation can provide some information about its geological history. Some features of structural evidence provide knowledge of the fabric and external forces. For example, steeply dipping initial emplacement fabrics indicate the high temperature (900- 1100°C). Moreover, mantle peridotites were drifting towards to NE-SW in a pull-apart basin in the Early Devonian (c. 400–390 Ma). Following this, amphibolite schists were added to the ophiolitic sequence which is steeply dipping and was occurred at the Middle Devonian (c. 390–375 Ma). Both lithologies happened from the newly exhumed mantle, and they were juxtaposed during the NE-SW rifting. Peridotite's and amphibolite's (hornblende schist's) mineral assemblages indicate retrograde fabrics. These mineral assemblages are green amphibole, titanite and colourless magnesio-hornblende, which indicates a progressive temperature decrease during the thrust event (Cook, et al., 2002).

Basal peridotites and amphibolites are emplacement related structures, and they dip at low to moderate angles NW. These down dip lineations and kinematic indicators are evidence of shear. Syn- emplacement magmatism is can be seen

between Kennack Gneiss intrusion and serpentine filled faults. Finally, the peridotites and hornblende schists reach lower temperature (<250°C) stages of emplacement (c. 370 Ma) (Cook, et al., 2002).

In the study area, all units were disrupted by the NNW thrusts formed during the main phase of Variscan orogenesis. Moreover, these structures are crosscut by the post- Variscan normal faults (Power et al. 1996; Shail & Alexander, 1997).

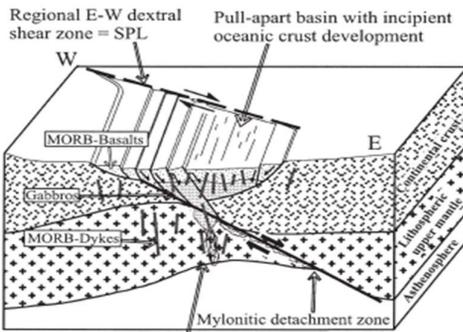
The Lizard ophiolite has three different groups of igneous rocks (Fig. 1; Flett & Hill, 1912; Green, 1964c; Floyd, Exley & Styles, 1993): the mantle units (Lizard peridotites: Cook, Holdsworth & Styles, 1998; Cook et al. 2000), the crustal units (Traboe Cumulate Complex, Crousa Gabbro, MORB-type dykes, Porthoustock amphibolites and Landewednack amphibolites: Leake & Styles, 1984; Roberts et al. 1993; Floyd, Exley & Styles, 1993). Moreover, thrust emplacement is associated with intrusions which contact between Lizard peridotites and the underlying metamorphic basement (Kennack Gneiss: Green, 1964c; Sandeman et al. 1995; Jones, 1997). Nutman et al. (2001) claim that Lizard Ophiolite lithologies were formed and juxtaposed between 400 to 375 Ma according to U/Pb zircon isotopic ages of intrusion and metamorphic events.

There are three stages for the emplacement of the rocks in the Lizard. These are pre-emplacment (c., 400-390 Ma), hot emplacement (c., 390-375 Ma), and cold emplacement (c., 365 Ma) (Figure 3:7 and 3:8).

Peridotites and Landewednack amphibolites were closely associated with each other Cook *et al.* (2000). Initially, upper mantle equilibration of spinel lherzolite happened with high pressure and high temperature (c. 16 kbar and 1120 °C) and then progressive re-equilibration with other rock types which are plagioclase lherzolite (c. 11 kbar, 1070 °C) transitional assemblage peridotite (c. 7.5 kbar, 1020 °C), mylonitic plagioclase- bearing peridotite (c. 7.5 kbar, 1010 °C) and mylonitic amphibole-bearing peridotite (c. 7.5 kbar, 990 °C) Cook (unpub. PhD thesis, Univ. Durham, 1999). This metamorphism is indicated by brown amphibole and plagioclase in the Landewednack amphiboles which were replaced at 550-700 °C and 2-6 kbar (table 3:2) (Cook, et al., 2002). U-Pb isotropic ages of c. 393 Ma and 386 Ma for metamorphic zircons in Landewednack amphibolites which happen c. 390 Ma have been identified.

PRE-EMPLACEMENT (c. 400-390 Ma)

[NOT TO SCALE]



Melting of asthenosphere
Infiltration of volatile-rich melts
= Possible magma source of gabbros, basalts
& MORB-type dykes

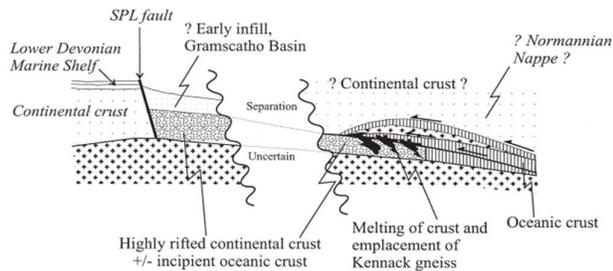
MORB-Basalts = Landwednack amphibolites
Gabbros = Crousa Gabbro, Traboe cumulates
Lithospheric upper mantle = Coarse-grained lherzolite
Detachment zone = Mylonitic peridotites
Continental crust = OLHS & MOWG

Figure 3:7 Pre-Emplacement of Lizard Ophiolite (Cook, et al., 2002)

Moreover, the Landwednack amphibolites are contacted with peridotites when the displacement runs to a low angle and dipping the extensional shear zone (Nutman *et al.* 2001).

a) "HOT" EMPLACEMENT (c. 390-375 Ma)

NNW [NOT TO SCALE] SSE



b) "COLD" EMPLACEMENT (c. 365 Ma)

NNW [NOT TO SCALE] SSE

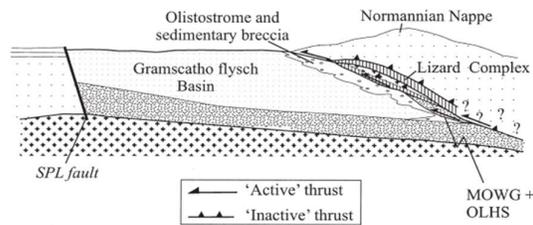


Figure 3:8 Hot and Cold Emplacement Stages in Lizard Ophiolite Complex (Cook, et al., 2002)

Pre-emplacment, thrust emplacement, and late to post emplacement are can be understood with fabrics, mineral assemblage and P-T conditions (table 3:2).

Table 3.2. Structural and metamorphic history of the peridotites and Lizard ophiolite Complex (Cook, et al., 2002)

Lithology (age)	Fabrics and shear sense	Mineral assemblage	<i>P-T</i> conditions# and other comments
Pre-emplacment (c. 393–386 Ma*)			
<i>Peridotites</i>	Sn: steeply dipping to sub-vertical Ln: plunge down-dip NE-SW extension in pull-apart setting??	<i>Spinel lherzolite</i> – Ol + Opx + Cpx + spinel‡ <i>Mylonitic amphibole-bearing peridotite</i> – Ol + Pargasitic Hb + Opx ± Cpx ± Plag ± spinel‡	<i>Spinel lherzolite</i> – 1120°C, 16 kbar <i>Mylonitic amphibole-bearing peridotite</i> – 990°C, 7.5 kbar Presumed to be in shear zone footwall
<i>Amphibolites</i>	Sn: steeply dipping to sub-vertical Ln: plunge down-dip NE-SW extension in pull-apart setting??	Brown amphibole+ Plag+Cpx	Preserved within shear augen; 550–700°C, 2–6 kbar Presumed to be in shear zone hanging wall
Thrust emplacements (c. 396–376 Ma**)			
<i>Peridotites</i> Basal peridotite Mylonitic shear zones	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting	Colourless Hb + chl + serpentine	Anastomosing shear zones in basal regions of hanging wall peridotites. Cross-cut early steep fabrics; 500–800°C
<i>Amphibolites</i> (1) Mylonitic shear zones	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting	Green amphib + Plag + Cpx + titanite	Dominant assemblage in footwall amphibolites; green amphiboles often preserve brown cores; 500–650°C, 3–5.5 kbar
(2) Mylonitic shear zones	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting	Colourless Hb + saussurite	Found in shear zones nearest to contacts with overlying peridotites
<i>Migmatism</i> Kennack Gneiss: mixed felsic and mafic magmas	Sn: low to moderate NW dip Ln: plunge down-dip Top-to-NW thrusting		Always cross-cuts pre-emplacment fabrics, locally cross-cuts emplacement-related fabrics: syntectonic
Late- to post-emplacment (c. 370 Ma) <i>Serpentine-filled faults</i>	Dip NW Top-to-NW thrusting and low-angle extn?	Lizardite-chrysotile	More than one movement/generation present; 20–250°C

Sn = foliation; Ln = mineral lineation; Ol = olivine; Opx = orthopyroxene; Cpx = clinopyroxene; Hb = hornblende; Plag = plagioclase; chl = chlorite; amphib = amphibole.

* Based on U–Pb zircon ages thought to date metamorphism of Landewednack amphibolites (Nutman *et al.* 2001).

** Based on U–Pb ages thought to date intrusion of Kennack Gneiss (Sandeman *et al.* 2000; Nutman *et al.* 2001).

3.3 U-Pb Geochronology

According to zircon analysis, Kennack Gneiss' age is around 376 ± 1.7 Ma, which was the time of the most important thermal activity (Sandeman, et al., 2000). Moreover, another radiometric age analysis indicates the same geological period, which is Devonian. K-Ar and Rb-Sr age analysis on the biotite and hornblende from the Kennack Gneiss show that these units age is between 355 to 422 Ma (Dodson; 1961; Miller & Green 1961). Styles & Rundle (1984) analysed whole rock with the Rb-Sr radiometric age method the results showing that isochrone age is 369 ± 12 Ma. Additionally, Sandeman et al. (1995) analysed hornblende from Kennack Sands with ^{40}Ar - ^{39}Ar . According to this analysis, this unit age is 366 ± 4 Ma and 366 ± 5 Ma. This age analyses carried out based on primary crystallisation of two units (mafic and felsic) in the Kennack Gneiss. When the displacement from the oceanic setting took place at approximately 500 Celsius degree, Kennack Gneiss units (felsic and mafic) were cooling and interlayered

with each other. Kennack Gneiss crystallised at 376 Ma and then cooled rapidly the result of the hornblende age results (Sandeman et al., 2019).

4. METHODOLOGY

This study includes field geology, photogrammetry, optical microscopy and scanning electron microscopy (SEM) studies. This chapter aims to how can carry out these works. Considering the ophiolite sequences, rock properties are significant to understand petrological features. Therefore, thin sections were used for understanding to petrological features. Photogrammetry was used for the 3D model, whereby its result of the 3D model, point clouds and meshes are used with a geological map. Finally, the 3D model and 3D geological map were carried out.

4.1 Field Geology

The studied field is located in Kennack Sands, Poltesco Beach and Gwendreath region. This study mainly focusses on coastline cliffs. In this region a number of contact point which is in contact with metamorphically (faulted) or intrusion. Difference between metamorphically and igneous chamber can be understood with field observations and thin sections' analyses. Notably, a number of samples were collected from the contact points. During the fieldwork, the Fieldmove Clino software was used with the mobile phone. Additionally, foliation' and faults' strike and dip measurements were carried out with compass and the software together. After the field works these measurements were saved as excel files and also .kmz file for the Google Earth service.

4.2 Photogrammetry

In order to carry out 3D mapping for cliffs, a number of pictures were taken by a handheld photo camera. Three thousand pictures were taken in the coastal area at the Kennack Sands and Poltesco Beach. These photos were taken with 70% overlapped because of the combination of the photos with 3D modelling software. There are a number of 3D modelling programme. In this study, modelling software

namely Agisoft PhotoScan and Pix4d were used. These softwares generally use with a drone. However, it cannot be used in this study because of the restrictions of the airfield permissions. The following stage is of the images in the Leapfrog software for the 3D cliffing model in the study area. During the use of Leapfrog software, cliff geological features and 3D model can be shown together, and some specific volume and high values can be calculated.

4.2.1 Agisoft PhotoScan

This software is quite enough to carry out 3D modelling of the cliff. There are some tricks of the using this software. Initially, photos features are important in using 3D modelling. Sky, clouds, boulders are a challenge for this program. Therefore, there are special features which are the magic wand, intelligent scissors. Both features were used to eliminate the undesirable things such as sky and boulders part on the pictures. Moreover, place marker features provide the focus on some key point in the pictures. Place marker provides to identify some points which can be chosen much easier to align photos features (figure 4:1).



Figure 4:1 Point Marker Process for the Easy Alignment of Photos

4.2.2 Pix4D Software

Approximately three thousand cliff's pictures were taken in the area. Due to the long duration of alignment, the software is used partly in this process. Once

photos are used in the software, features of rock structures and face features align with the coordinate system. There are many options for the 3D model in this software. Thus, the best option should choose for the geological 3D model (figure 4:2). This option is important because geological structures have much more detail and shape are not smooth. For instance, rocks' edges are not sharp.

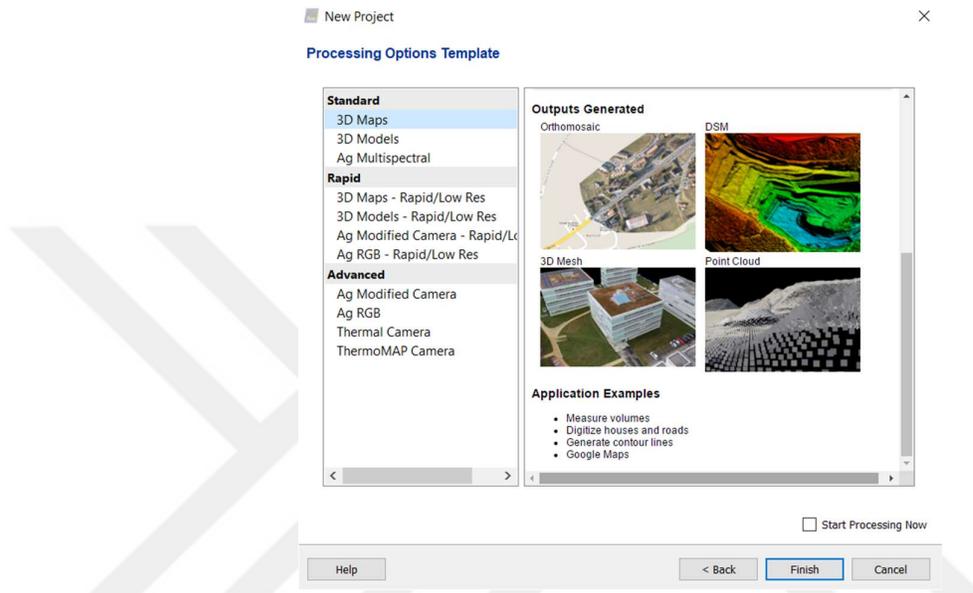


Figure 4:2 3D Maps option is Convenient for the Geological Map

Moreover, processing options should choose before the process (figure 4:3). Using high-resolution photos and generating 3D mesh is significant. Otherwise, point cloud is not quality enough and mesh is necessary for the fill the blanks. Both features provide high visual 3D model. Another feature is initial processing for the quality of 3D model. When the finish initial processing the software is giving brief report about the model, this report includes appearance of model and convenient for the mapping. If this model has a number of issues, it could be cancelled, and photos can choose again for the much more appropriate model.

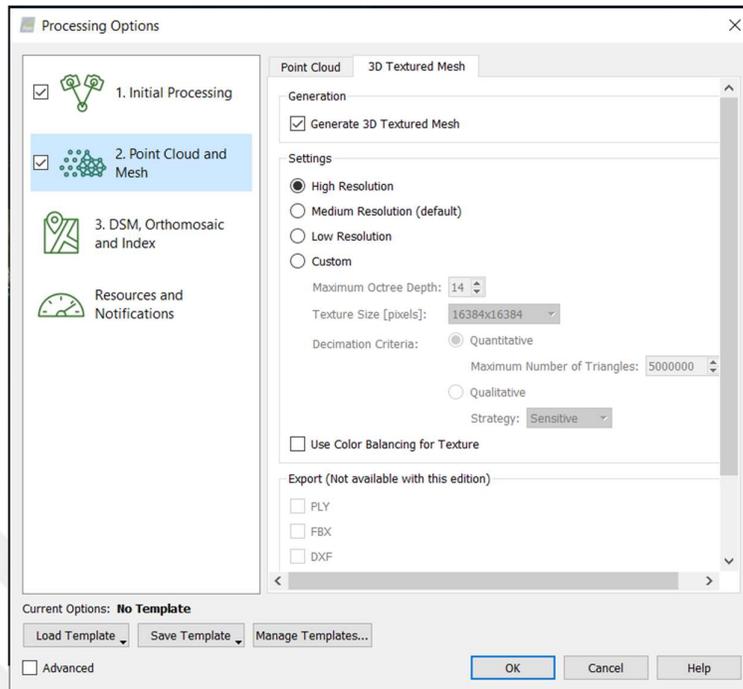


Figure 4:3 Processing Options in Pix4D Software

There are three main parts in the Pix4D for the modelling. The first is initial processing which is necessary for quality control. The second is producing point cloud and mesh which are using for the actual 3D model. The third is DSM (Digital Surface Modelling), orthomosaic and index properties which are additional information about photos.

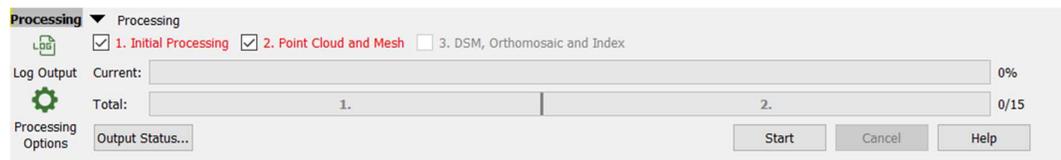


Figure 4:4 Initial Processing and Point Cloud and Mesh

4.2.3 Cloud Compare

After the production of the point cloud and mesh in the Pix4D software, these are stitched with Cloud Compare software. The Cloud Compare software can stitch PLY files to each other and form a point cloud or mesh. Triangle meshes provide missing parts of point cloud; caused by these missing parts occur because of shadow and sharp change of rock body. Point clouds represent real rock colours, however, meshes do not. Therefore, meshes colour should be adjusted to match

the rock colours. Mainly, this software was used for the stitch separate 3D models.

4.2.4 Leapfrog Software

Leapfrog Software can be used to stitch 3D models at the end of the cloud softwares data. Topography data can be to the software for the 3D analysis. Topography data obtained from Digimap Lidar map which is put into Leapfrog software with the same coordinate system. A different coordinate system causes stitching error. When the carried map, the British coordinate system was used. However, the software is convenient for the WGS 84 coordinate system. To overcome this, the coordinate system can be changed manually using georeferenced data (figure 4:5 and 4:6). There are two options for the settled 3D geological map data. The first option is a plot three points for the model, this method much more reliable than the other one because these models have three dimensions, and these have specific area (figure 4:5). To identify this area, it should be done at least three points can choose. The second option is choosing two points of vertical photos (figure 4:6).

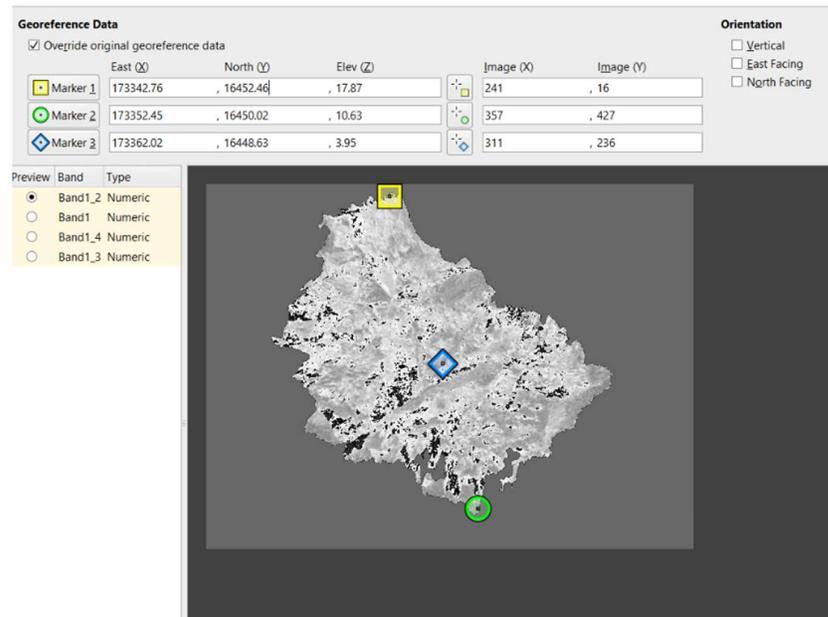


Figure 4:5 Georeference Data can be Entered Manually as Plot Three Points

The leapfrog software provides 3D visualisation of the geological map. Therefore, topography (DTM - Digital Terrain Model) was downloaded. The following stage was stitch with geological map (figure 4:7).

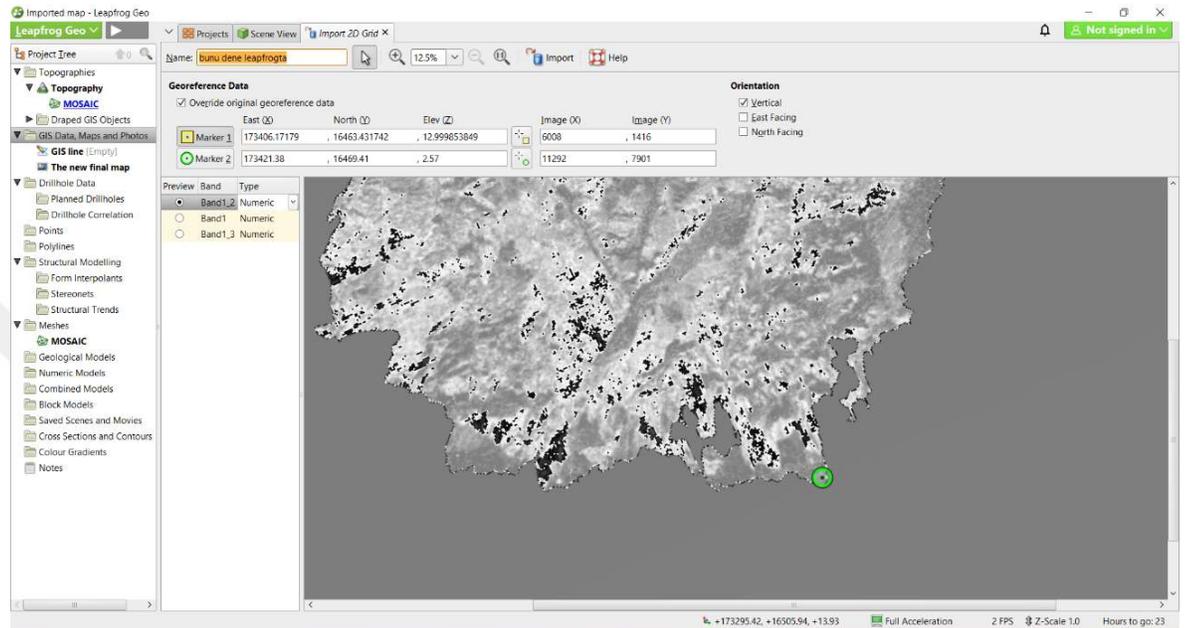


Figure 4:6 Georeference Data Input Manually as a Vertical Photo

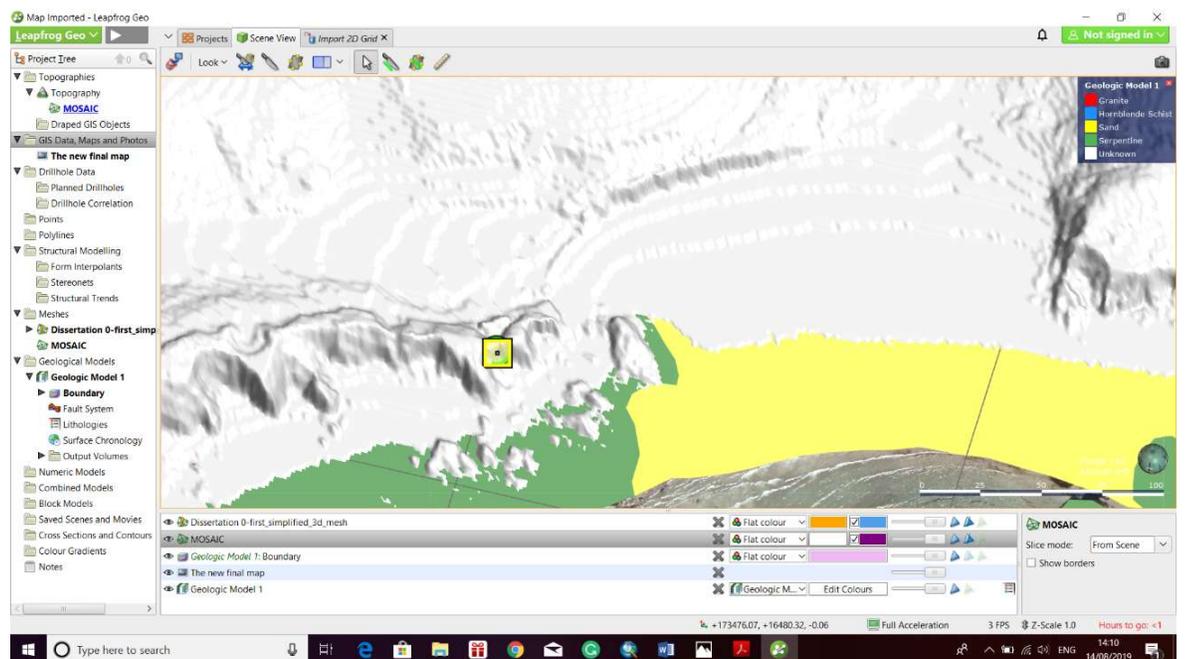


Figure 4:7 Geological Map and Topography Data Input the Leapfrog Software

4.3 Thin Section

4.3.1 Preparation

Rock samples are cut and attached to a glass slide with Canada balsam. Thin sections were prepared 30 μ (0.03mm) thickness of rock sample. This thickness feature is significant for the defining birefringence (Δn) using the Michel-Lévy interference colour chart. Rock samples are attached with a special epoxy, which is generally Canada balsam ($n > 1.54$) because refraction index (n) is important to define the Becke line test. These thin sections were using with optic microscope studies and scanning electron microscopy (SEM).

4.3.2 Interpretation

The thin sections were analysed with an optical microscope. These stages have three steps; plane polarised light, cross polarised light and conoscopic light. After these stages, identification of minerals are carried out, Plane polarised light which includes crystal shape, grain size, amount of the thin section, transparency (transparent or opaque), colour, pleochroism, cleavage, relief, Becke line test, refractive index and special features (inclusions, exsolutions, grain boundary reactions) optical properties. Cross polarised light includes anisotropic behaviour, maximum interference colour, birefringence, extinction and special features (optical zoning, twinning) optical properties. Conoscopic light includes optical properties such as uni-axial or bi-axial, optic sign and optic axial angle ($2V$). The last stage is comparing all the previous stages and concluding of the mineral type.

4.4 SEM (Scanning Electron Microscopes)

4.4.1 Preparation

Scanning electron microscopes include an electron gun which is a source of electrons and electron lenses to focus a beam on the sample. The figure of ED spectra of various minerals can be seen through SEM and recorded with a thin-window Si (Li) detector. A number of key parameters are significant to determine the mineral types. One of them is accelerating voltage, this study using 20 kV accelerating voltage. X-ray take-off angle is also important which is 30⁰ in this

study. The figures show only the major (α) peaks of the elements' label except C K peak from the carbon coating. Additionally, many minerals can present with various range of compositions. For this reason, general specific characteristics features should be considered in the determination of the mineral type (Reed, 2005).

Thin sections and carbon coating are necessary for the scanning electron microscope. Thin section preparation was explained in the previous section. Carbon coating is carried out with two carbon rods, one of them is short, and the other one is long, and the head section is sharpened. These are using with coater machine (Emitech K950). These rods contact each other with tension; however, at the same time, they should not break. After the rods are set in the machine, it should be covered with special equipment and then the pump button is pressed, and after approximately 5 minutes the light becomes 100%. A further step is the outgas section, after pressing the outgas button and then the ampere dial (6 amps approximately) is turned up approximately for 30 seconds then turned off. During the process, flaming can be seen in the head of the carbon rods. The final step is pressing the evaporate button approximately three seconds and at least three times. During this process, extremely bright light is exposed. It should not be observed because of the risk of eye damage. Then stop button is pressed, the thin sections are ready to be set in the SEM section.

4.4.2 Interpretation of SEM Results

Thin sections are using with scanning electron microscopy. In thin sections has a number of minerals and elements. They have specific energy dispersive (ED) spectra. Therefore, the result of this spectra shows that minerals characteristics based on the element's spectra. In this study, the Oxford Instruments were carried out for the spectrum reports. This report includes some elements spectra and containing elements ratio (Wt.%) (see figure 4:8). For example, this spectrum refers to monazite mineral. It can be reached spectra lists from Electron Microprobe Analysis and Scanning Electron Microscopy in Geology book (Reed, 2005). Moreover, Wt.% values can use for the determine the mineral type. Both of them provide the result of the mineral type and specific character. For instance,

there are eleven types of pyroxene based on Reed's book spectrum; study area contains mainly augite (pyroxene) mineral.

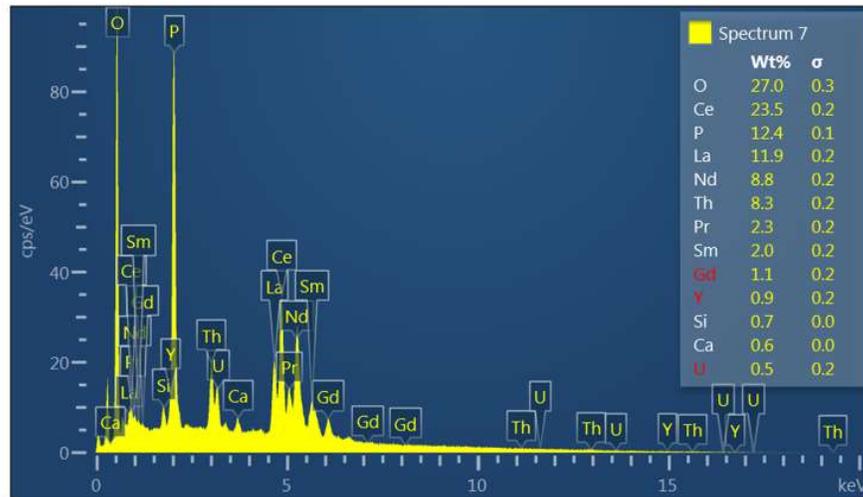


Figure 4:8 Monazite Minerals' Spectra

4.5. LIMITATIONS

Normally 3D mapping is carried out with drones. However, in this study a handheld camera was used as photographs were necessary for 3D model softwares. Therefore, modelling of the whole area is not represented in one single file. There are a number of separate 3D models which have been attempted to be stitched together at the end of the study because even if using a supercomputer, these processes take a long time (couple of weeks) which was not available. Processing 3D models takes a long time, depending on the number of photos and their quality often taking 6-12 hours for each section. For this reason, it should be carried out with drones, which was not possible in this study because the study area is close to an airfield and legal restrictions prevent using these drones. Even though six thousand pictures were taken in the study area, they were not stitched properly. However, the drones softwares applications provide convenient photos for the main program.

The Lizard is a National Trust area which means every part of the study area is protected by the government. Therefore, the samples were collected without using a hammer.

5) FIELD RELATIONS

Age differences are important in the analyses of the evolution of these units and their contacts with each other. There are three main stages in the study area. The first is the occurrence of the ophiolite sequences which is occurred 400 Ma years ago. The following step was emplacement of hornblende schist lithology which settled in 390 Ma years ago. Finally, Kennack Gneiss replaced at the 376 +/- 1.7 Ma years ago. The other lithologies: gabbro and basalt dykes intruded later. Finally, the last step was serpentine and serpentine filled fault system occurred. This area highly altered with physical and chemically, there are lots of fault and antiform in this area and sea effect is can be seen in serpentinites especially in the washed serpentinites. Alteration prevents the identification minerals in the thin sections especially in basalt and gabbro lithology. Therefore, these lithologies' occurrence mechanism cannot be easily understood. However, contact points, fault lines and other structural deformations such as antiform, synform in the study area can explain some mechanisms of tectonism and metasomatism. Additionally, rodingitisation and chrysotile alteration show metasomatism effect on the serpentinised ultramafic bodies. Rodingite is a metasomatic rock which is mainly composed of calcic pyroxene and grossular-andradite garnet.

5.1. Kennack Sands

Kennack gneiss has sands from peridotites. The sand area contains red grain serpentinite pebbles. Moreover, this area contains peridotite, granite, basalt dykes and Kennack Gneiss. Kennack Gneiss contains basalt (basic) and granite (felsic) dykes together, and these parts are highly deformed with cracks and contacts. Asbestos can be seen in this area because of the structural deformation. Additionally, asbestos can be seen in the contact points. These contact points are between the serpentinite rocks and the Kennack Gneiss or gabbro (see figure 5:1).



Figure 5:1 Contact Points and Asbestos

The south of the Kennack Sands coastline region has a number of granite and serpentinite contact points and also basalt dykes. Mostly they contact with a fault system. One point which found in the south of Kennack Sand is different to the other contact points as it has magma chamber replacement. The following section, which is thin section samples shows that this lithology is gabbro. Gabbro lithology is highly altered. Therefore, there is not enough fresh content for the primary mineral occurrences. Based on the first observations gabbro is reddish-grey and some parts are greenish (see figure 5:1).

In Kennack Sand peridotite has a shiny mineral (see figure 5:2). Therefore, it could bastite serpentinite. However; there is not slickenside face and this lithology not highly altered. The final decision is this lithology metamorphosed from lherzolite or harzburgite and not highly metamorphosed. According to clinopyroxene ratio, it can define at the petrography section again.



Figure 5:2 Bastite Peridotite

Kennack Gneiss lithology can divide three parts because some parts have layered basalt and granite rocks as a laminated (see 5:3). However, especially in the cliff section granite ratio is higher than basalt ratio and mostly basalt dykes cut this lithology and also some parts have gabbro lithology. The gabbro lithology associated with the Kennack Gneiss. Gabbro settled in as dykes with the migration of hydrothermal fluids. For this reason, gabbro section was inserted as a dyke in the map.



5:3 Laminated The Kennack Gneiss in Kennack Sands North Section

In the Kennack Gneiss foliations run from NE to SW. Structural deformations are perpendicular to foliations and they are strike NW to SE (see figure 5:4). Moreover, basalt dykes settled in similar fault zones (NW-SE) because basalt formation replaces at the structural gaps (figure 5:5).

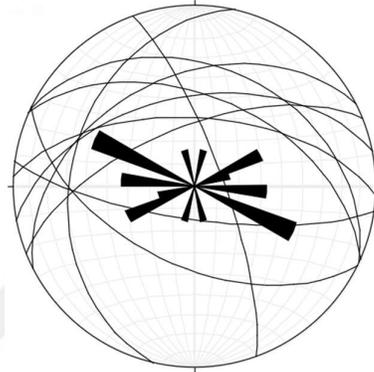


Figure 5:4 Major Faults' Stereonet and Rose Diagram

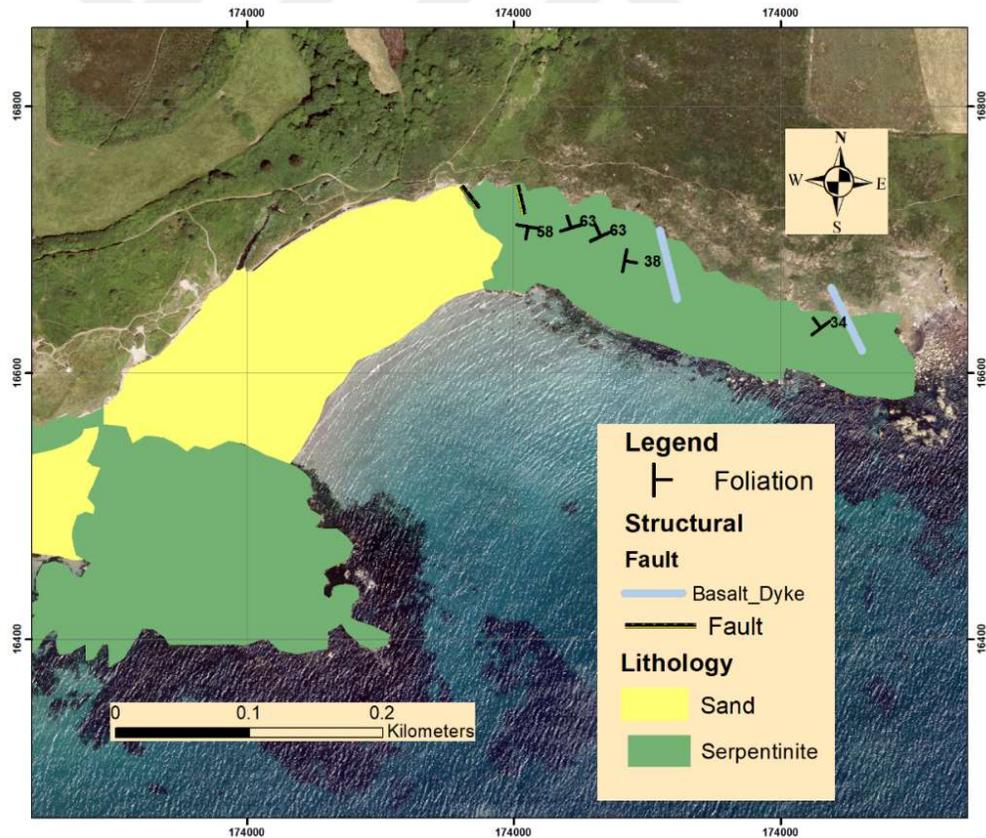


Figure 5:5 North Section of Kennack Sands

The north of Kennack sand has bastite serpentinite and sand which are occurred from peridotites. Sand lithology has also containing red-green pebbles which contain shiny mineral as same as bastite serpentinite.

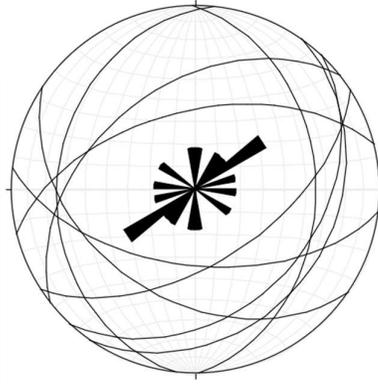


Figure 5:6. Kennack Gneiss' Stereonet and Rose Diagram

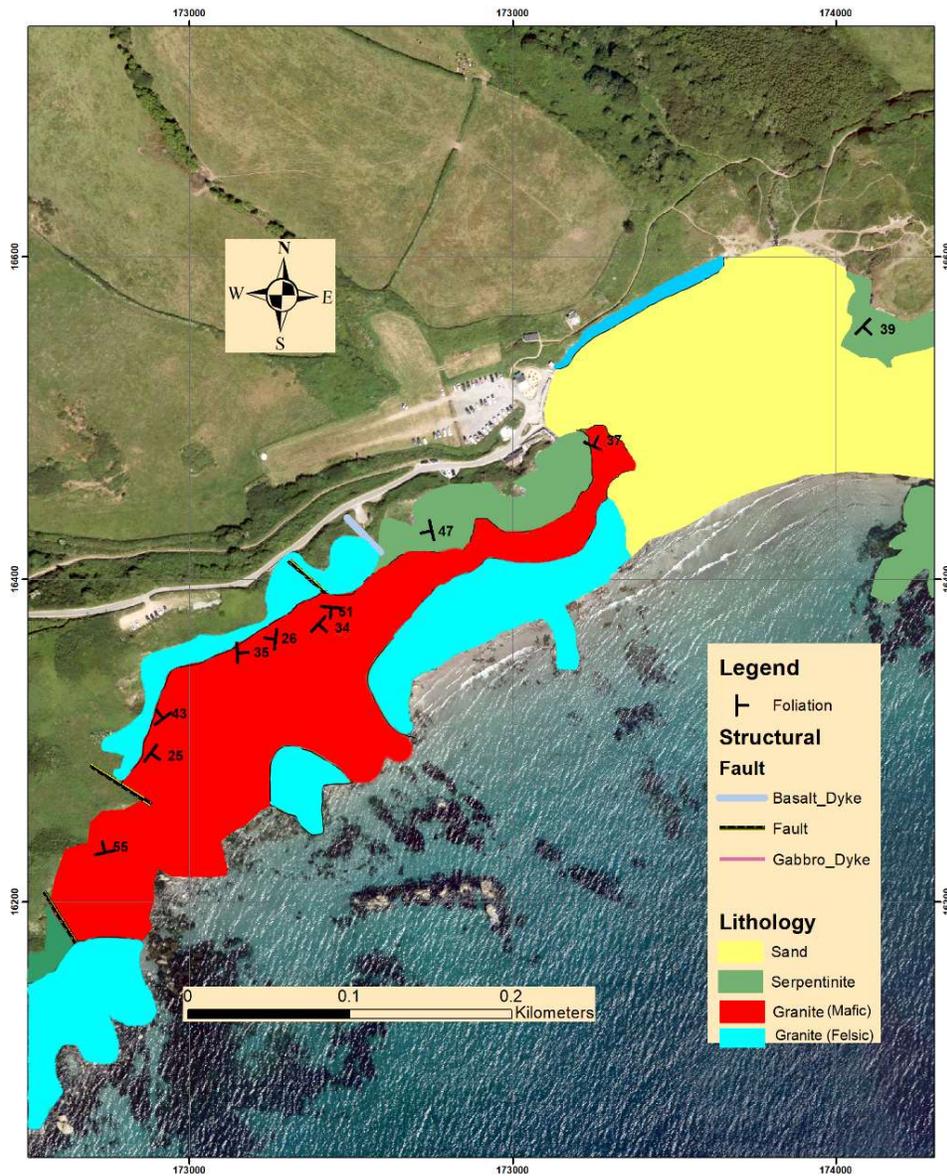


Figure 5:7 Middle Section of Kennack Sands

The middle section of Kennack Sands has contact between serpentinite and granite lithology. There are no faults in this contact area. Therefore, this contact is intrusive. The age differences support this conclusion because Kennack gneiss (basalt + granite) is younger than peridotites and serpentinite was metamorphosed from peridotite. The serpentinite and Kennack Sands have a number of basalt (mafic) dykes. The gabbro dykes have contact points with serpentinite rocks. These gabbro dykes' intrusion towards the North-West (see 5:8). Based on the age relation, the gabbro magmatic intrusion was replaced from the South East. Metasomatism can be seen in this region as a calcium rich alteration which is rodingitisation (see 5:9).



5:8 Gabbro Intrusion Towards SE to NW



5:9 Rodingitisation in the Study Area

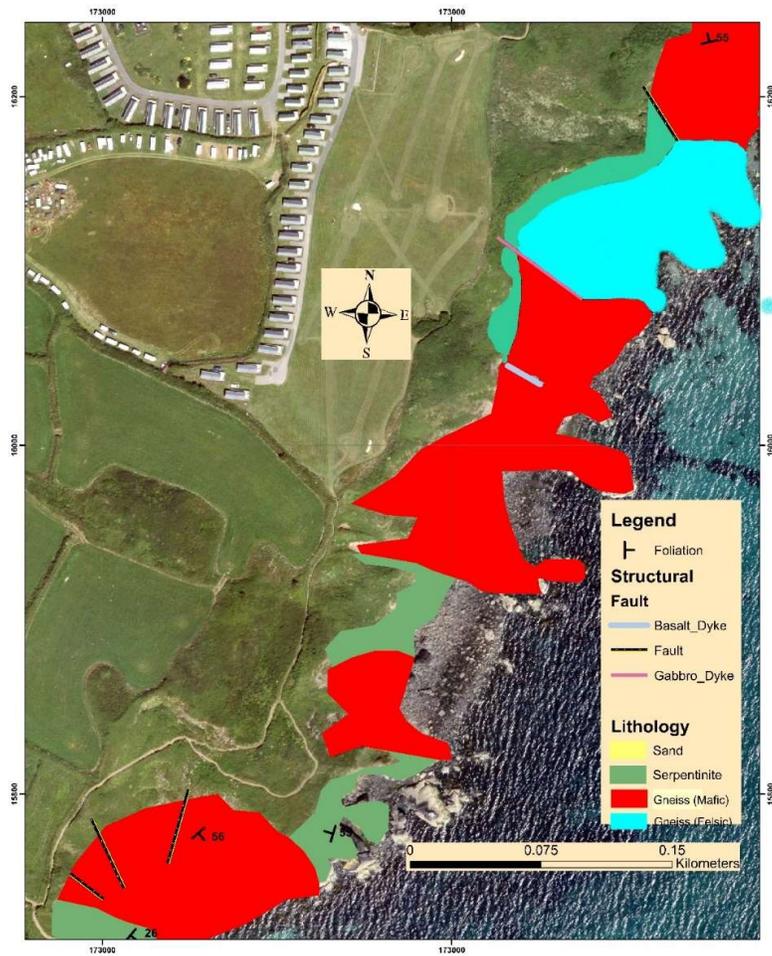


Figure 5:10 The South Section of Kennack Sands

5.1.1. Kennack Gneiss

The Kennack Gneiss is composed of two main rock types, basalt and granite. They are much more widespread in the study area separately. Especially, Kennack Gneiss cannot be seen in the cliff part but can be seen in large boulders in the coastline. Kennack Gneiss is composed of thin layers of basalt and granite, which are two to ten centimetres width (see in figure 5:11).



Figure 5:11 Kennack Gneiss- white parts granite, black parts are basalt

Kennack Sands not only has layered intersects of basalt and granite, but it also appears with the vast felsic body (granite) and small interlayers of mafic (basalt) section (figure 5:12). For this reason, it can be separated into felsic rich Kennack Gneiss and mafic rich Kennack Gneiss. Therefore, the Kennack Gneiss lithology was divided two different type in the study area map. These are Gneiss (Felsic) and Gneiss (Mafic).

Kennack Gneiss can sometimes be identified as a metamorphic gneiss in the study area especially, when the foliations are parallel to layering. The metamorphic texture could have been formed by strongly tectonic activity. This tectonic activity could have caused shearing. Also, the basalt and granite magma were affected by the same tectonic activity.



Figure 5:12 Two different Kennack Gneiss (Left side is mafic (basalt) rich-right side is felsic (Granite) rich

Moreover, there is a non-metamorphic Kennack Gneiss in the study area. This non-metamorphic Kennack Gneiss is commingling of basalt and granite magmas, and they are successive intrusions. Therefore, interfingering texture can be seen in some places in the study area (see figure 5:13). Interfingering suggests that perhaps this is not metamorphic rock. Mixing low viscosity basaltic melts leads to a quite chaotic melt. This process is related to the magma mixing process.



5:13 Example of Non-Metamorphic Kennack Gneiss

5.2. Gwendreath Region

There is a vast outcrop to the northeast of Gwendreath town. This outcrop is three hundred meters from the town. The formation consists largely of serpentinite but contains basalt dykes. Serpentinite has a number of joints, the joint interval varying between 5 to 30 centimetres. The serpentinite's foliation strikes northwest, and their interval varies between one to two meters.

The serpentinite's colour is mostly dark green, and some parts are shiny green. These parts represent the slip plane. Some parts of the serpentinite lithology are reddish, this part is similar to bastite serpentinite, but there is no mica content. The reddish parts are generally not fresh; the iron content leads to the red colour. The second rock type is basalt, which is approximately 10 meters in thickness.

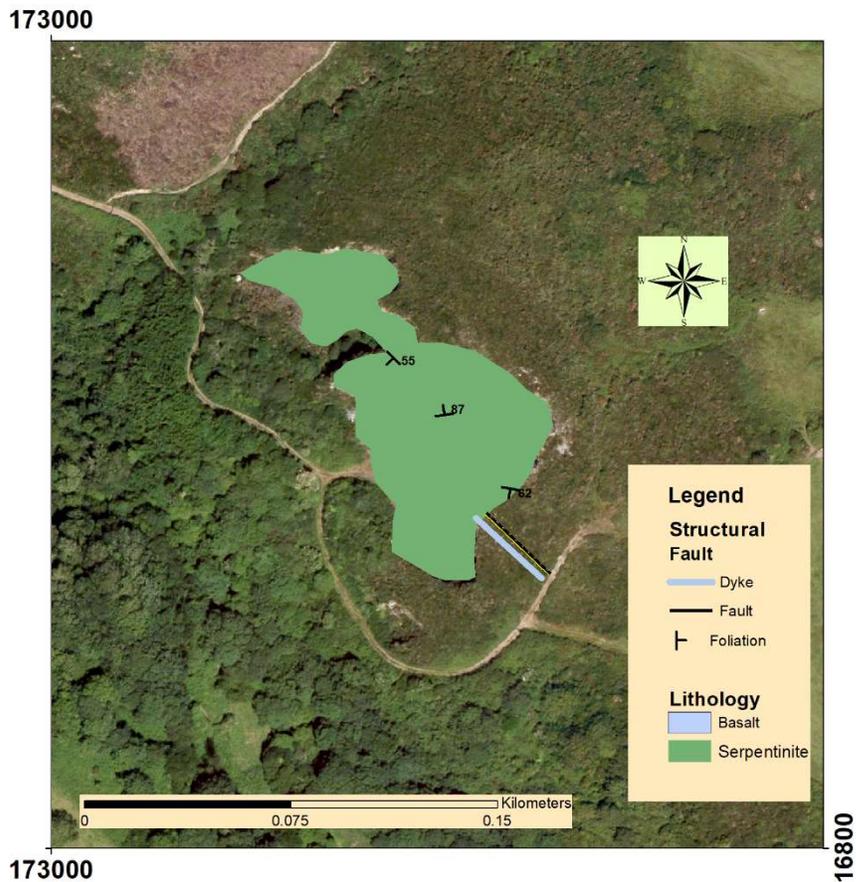


Figure 5:14 Gwendreath Map

This location is the north of Kennack Sands and approximately 500 meters near. Fault and basalt dyke's orientation is similar in both areas. However, serpentinite features are different. Gwendreath serpentinite (figure 5:15) has much more slickenside. Even though near to the Kennack Sands, this serpentinite type is different from Kennack Sands' serpentinite. Kennack Sands' serpentinite has a bastite mineral and it does not have slickenside faces. Gwendreath's serpentinite has a number of slickensides faces and a much more a greasy to silky lustre. Gwendreath's serpentinite features are similar to the south of Poltesco Beach serpentinite.



Figure 5:15 Gwendreath Serpentinite

5.3 Poltesco Beach

Poltesco Beach includes peridotites, serpentinites, granite and hornblende schists lithology. This location had formed with tectonism. Especially, hornblende schist area three fault. Moreover, alteration is high in this place. Some alterations can be seen in the cliff area, which is due to structural deformation. Most of this alteration form is asbestos, which can be seen in figure 5:18. This area was very active as can be seen from joints, faults and anticline structures. Serpentine blocks foliations are towards to NW to SE (figure 5:16).

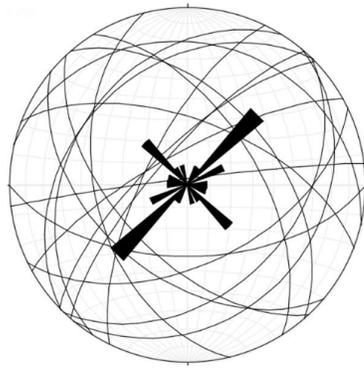


Figure 5:16 Serpentinites' Foliation Stereonet and Rose Diagram

These blocks have a number of joints which have the same direction as the foliation plane; however, they have an asbestos infilling (approximately ten centimetres). Moreover, this unit was cut by a reverse fault. This unit contacts with a granite lithology which runs towards to NE to SE. Unlike the contact between the granite and serpentinite, serpentinite - hornblende schist contact is fault contact.

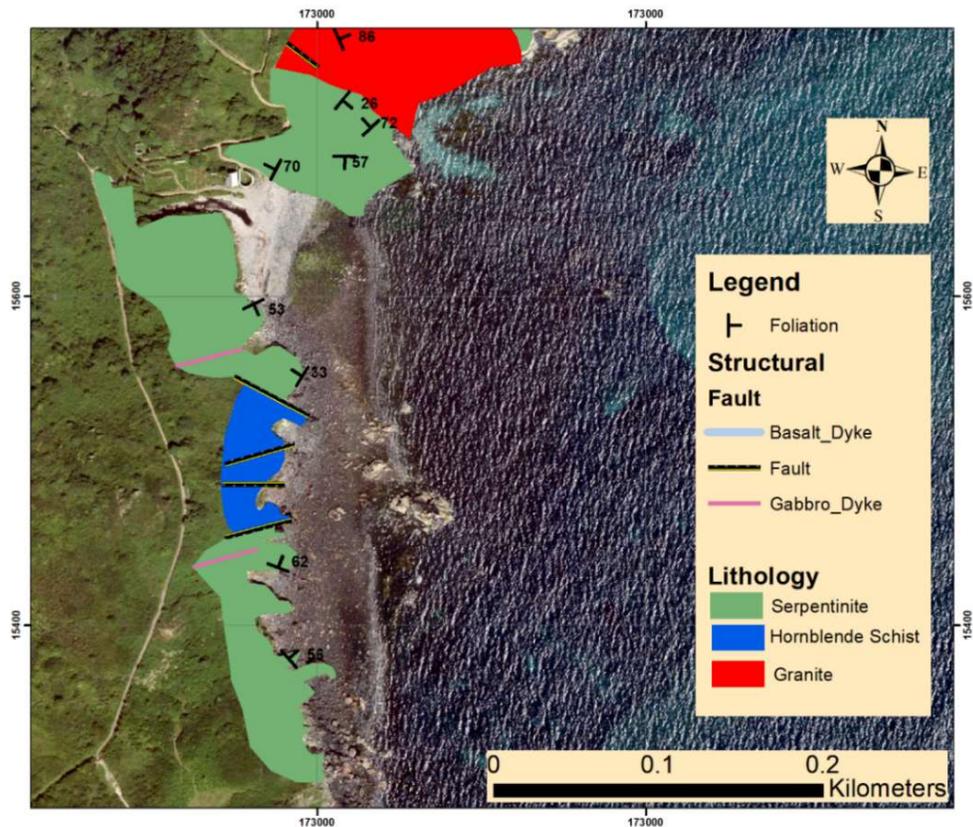


Figure 5:17 Poltesco Beach Geological Map

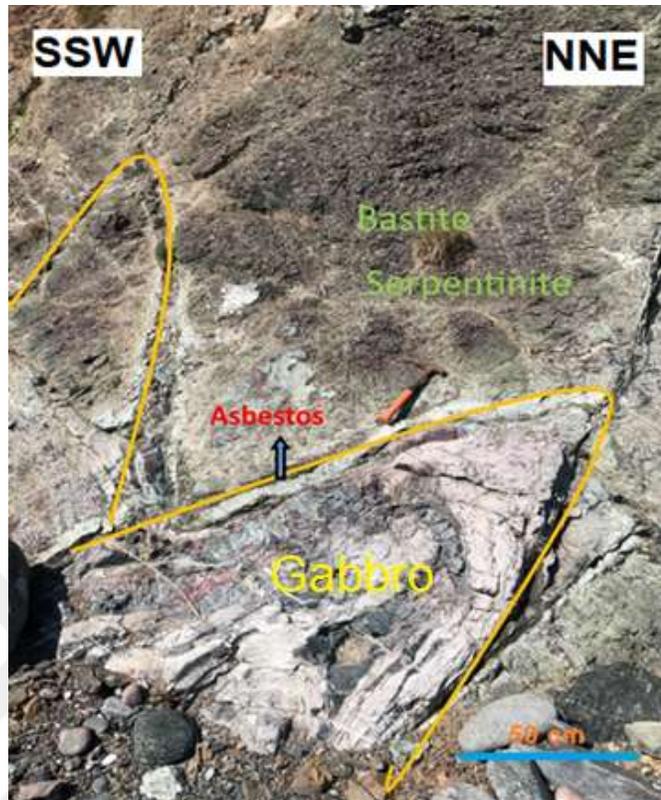


Figure 5:18 Anti-form structure in the Poltesco Beach

In the Poltesco town pathways has a number of small outcrops. These are serpentinite and along to coastline there continuous until the main entrance of the beachside. In this region peridotites have gabbro dykes. These dykes are parallel to fault lines. Some fault lines infilled filled serpentine and asbestos (see 5:18). The north section of Poltesco beach, near of the granite contact there is a reverse fault, orientation is east to west (figure 5:19). This reverse fault has a dip of 26 degrees. Therefore, it can be classified as a thrust fault. The Poltesco Beach section is a highly tectonic area. There are a number of low dip degree minor faults, antiform and synform structures. These antiform and synform structures can be identified as an anticline and syncline because the fold centre has younger units. Mostly, out of core is serpentinite and the fold lines are filled with asbestos or clay. There are hornblende dykes in the vicinity of these areas.

The south of Poltesco Beach's serpentinite is different from other serpentinites. Some parts contain rodingite (see figure 5.20). Rodingite has high calcium content and indicates metasomatic alteration. This situation is evidence of

hydrothermal fluids released from the veins. This location's serpentinite features differ from Kennack Sands' serpentinite.



Figure 5:19 Serpentine filled fault and joints

Poltesco Beach serpentinite has a greasy to silky lustre like Gwendreath region serpentinites. Moreover, this serpentinite contains rodingite and antigorite minerals (figure 5:20).



Figure 5:20 Rodingite (white calcium-rich part) in Poltesco Beach Serpentinite

In the south of the study area, the serpentinite type is different than bastite peridotite and washed serpentinite.



Figure 5.21 Asbestos Filled Fault Gabbro from Poltesco Beach Area

6. PETROGRAPHY

6.1. Serpentinite

Serpentine lithology is widespread in the Poltesco Beach and Gwendreath locations. It is also spread in the north of the Kennack Sands location. Notably, Poltesco Beach and Gwendreath serpentinite's has slickenside faces, and these faces are shiny. These features can be seen in the orientation of some serpentinite minerals. Thin sections olivine grains' shape is subhedral and there is a mesh structure (figure 6:1 and 6:2).

Some mineral shapes were affected by the alteration. The Fibre shape is a production of serpentinite minerals. Serpentinite samples contain abundant olivine, much pyroxene, and rare pentlandite. The thin sections also contain opaque minerals, magnetite and magnesium chromite. Moreover, some trace elements are significant to determine what kind of metamorphism occurred in the area. For instance, negative anomalies of Europium (Eu) element indicate the formation of the lower crust plagioclase crystallisation (Appendix 1).

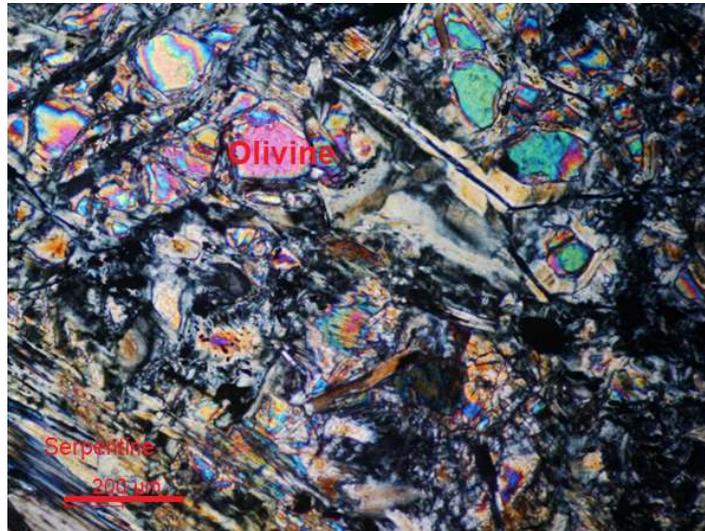


Figure 6:1 Serpentinite Thin Section (Cross Polarised Light)

The other elements are lithophile which indicates a hydrothermal system. These elements are cobalt, copper, and nickel in the serpentinite samples. The other trace elements are vanadium, bromine and chlorine. Additionally, calcium is enriched in the minerals. Especially calcium element is rimmed with iron oxide and occurred in titanite minerals in the serpentinite samples.



Figure 6:2 Serpentinite Thin Section (Plane Polarised Light)

According to SEM analyses, this lithology contains pentlandite $(\text{Fe, Ni})_9\text{S}_8$ and magnesio-chromite MgCr_2O_4 minerals (Figure 6:4 and 6:6). This situation shows sulphur and oxide minerals can occur in the serpentine in the Lizard. This area has indications of hydrothermal activities.

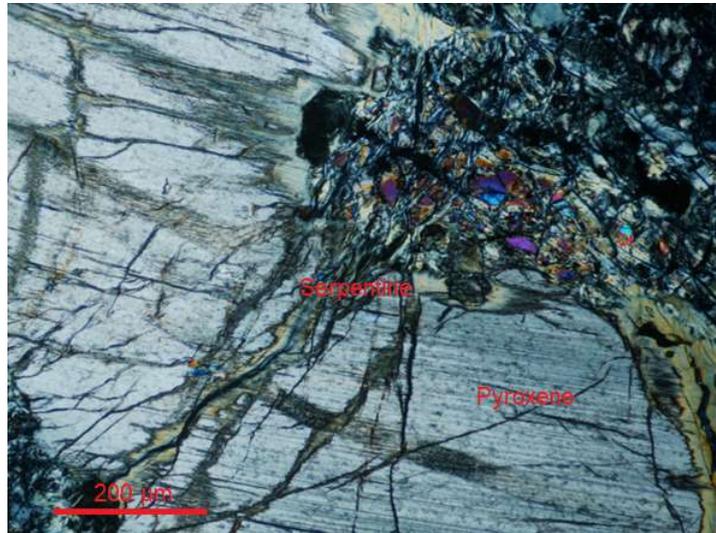


Figure 6:3 Serpentine Thin Section containing Pyroxene mineral (Cross Polarised Light)

Based on the field observations and the mineralogy content, these serpentinites were created by the metasomatism of lherzolite or free clinopyroxene harzburgite because the samples contain chrome, clinopyroxene (augite), enstatite as the orthopyroxene (see figure 6:4 and 6:6). Clinopyroxene ratio is very low, therefore, this rock is probably free clinopyroxene harzburgite.

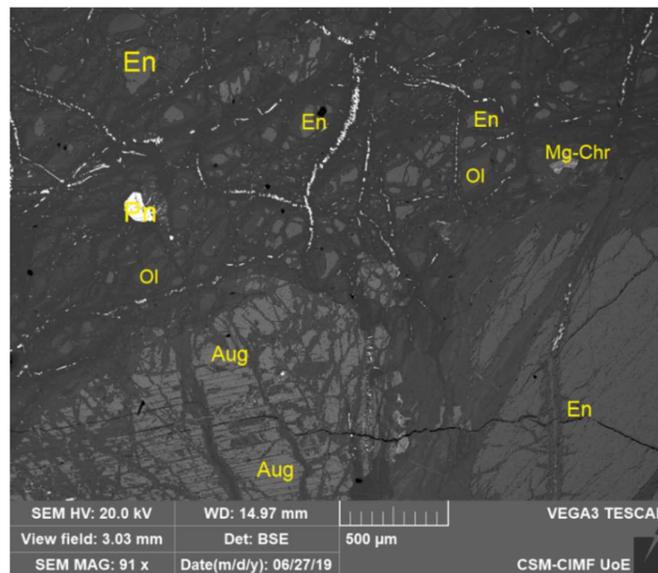


Figure 6:4 Enstatite (En), Magnesiochromite (Mg-Chr), Augite (Aug), Pentlandite (Pn), and Olivine

Bastite serpentinite was described in the field relations section. On the basis of the SEM results, these bastite minerals are represented as an enstatite mineral because bastite minerals are a pseudomorph mineral from enstatite minerals.

There are three types of serpentinite mineral in this study area: washed, bastite, and slickenside common serpentinite. Their mineralogical content is nearly identical. However, the bastite serpentinite has enstatite minerals together with olivine minerals (see 6:4). The other differences are physical features which are basically colour: bastite serpentinite's colour is dark red and dark green, washed and slickenside common serpentinite is dark green. The red colour probably comes from the bastite mineral. Additionally, some thin sections are more deformed by external forces. These deformations can be seen as asbestos and talc minerals. The other form of serpentinite mineral is antigorite which is layered hydrated magnesium silicate and indicates hydrothermal alteration (figure 6:5).

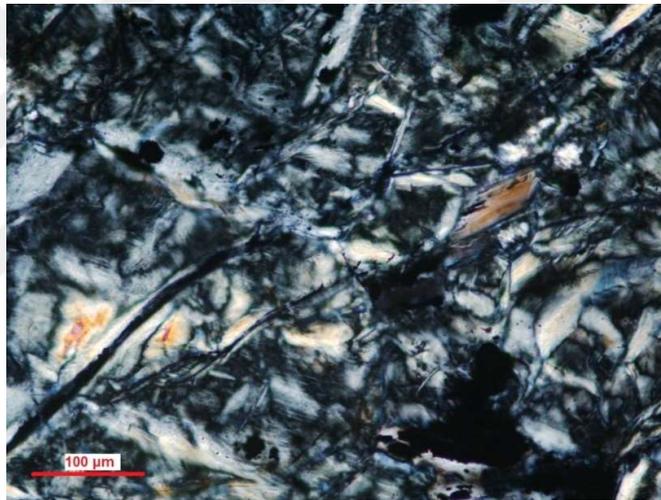


Figure 6:5 Antigorite in the Serpentinite Thin Section

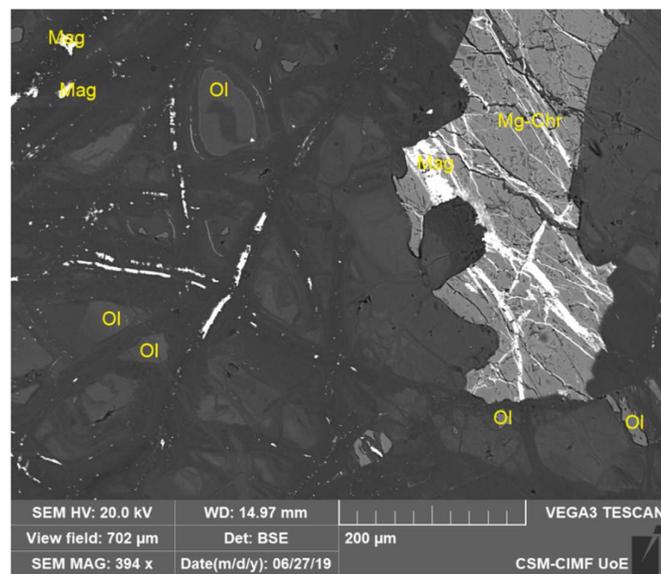


Figure 6:6 Magnetite (Mag), Magnesiochromite (Mg-Chr), and Olivine

6.2 Hornblende Schist

Hornblende schists are mainly located in Poltesco Beach in this study area. This lithology is metamorphic, and the location is highly faulted. In the chemical composition of the hornblende schist are calcium and enriched iron. Additionally, the titanium and potassium elements are rich. There are hornblende, titanite, apatite and mica minerals in the samples (see figure 6:8 and 6:9). Other amphibole schists contain plagioclase. However, these samples do not contain any plagioclase mineral. According to the mineralogical assemblage and colour of the amphibole (green - figure 6:7), this lithology occurred with mylonitic shear zones at the thrust emplacement (396-376 Ma).



Figure 6:7 Hornblende Schist Thin Section (Plane Polarised Light)

Hornblende schists are located in the highly metamorphic locations in the study area and these are enriched with calcium, and titanium element content which can be seen as a titanite mineral in the samples.

Some trace elements are seen in the samples. These are vanadium (V), zircon (Zr), tungsten (W), gallium (Ga), and holmium (Ho) which probably come from the granite contact with the magma. Another contact is serpentinite and chrome (Cr), nickel (Ni), and cobalt (Co) minerals which possibly come from this unit. These elements are transition elements and characterised by relatively small

ionic radius. Compatible elements (Ni, Cr, Co) are strongly crystallised during the early stage of magmatic evolution. Yttrium anomalies are significant evidence for this lithology related to hydrothermal activities (Appendix 2).



Figure 6:8 Amphiboles, Biotite and Felsic Minerals in the Hornblende Schist

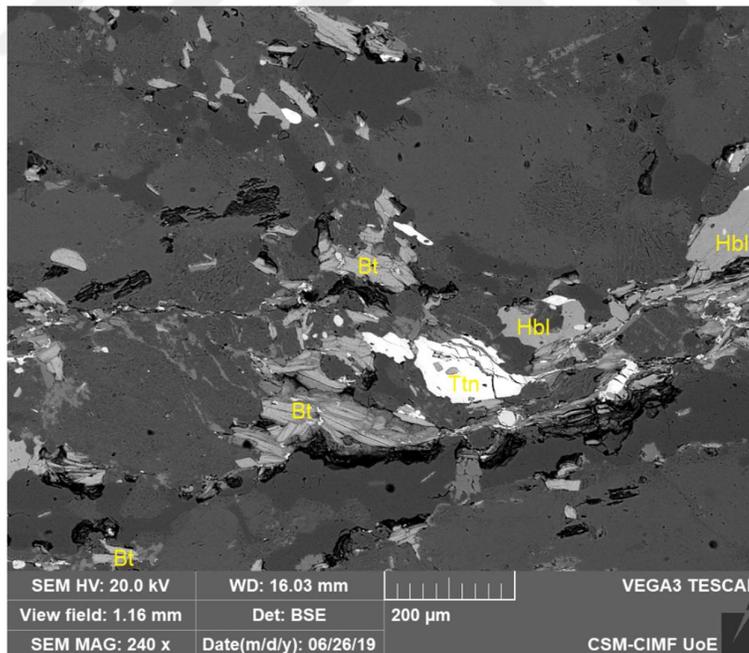


Figure 6:9 Amphibole- Hornblende(Hbl), Titanite (Ttn), and Biotite (Bt)

6.3 Gabbro

Gabbro dykes are common in the study area. Mostly, they are highly altered. Therefore, primary minerals are not common (figure 6:10). Brown and white minerals are common. Gabbro chemistry provides information about the

geological environment. Plagioclase type indicates the magma types which are tholeiitic or alkaline in the study area.

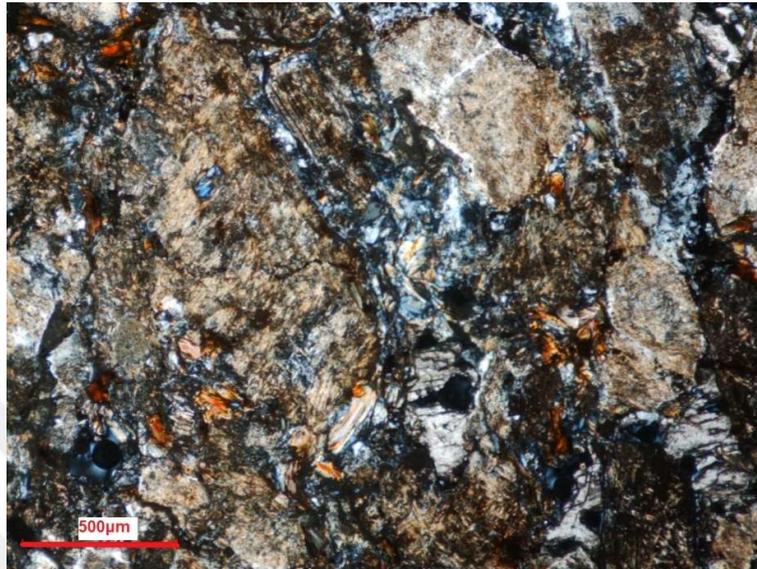


Figure 6:10 Gabbro Thin Section (Cross Polarised Light)

Samples consist of apatite (flour), plagioclase, oligoclase, pyroxene (augite), and amphibole minerals. The plagioclase minerals are occasionally altered by sericite (Figure 6:11).

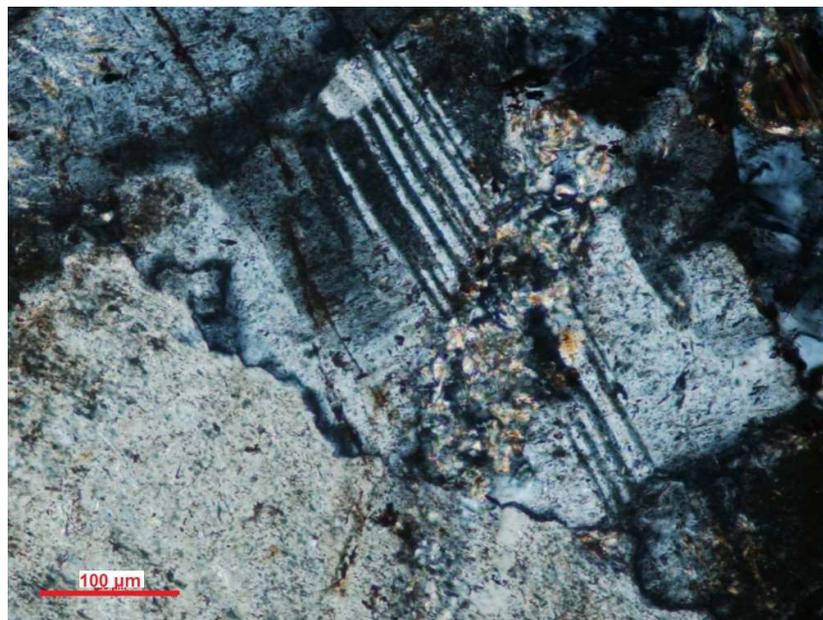


Figure 6.11 Plagioclase (Twinning) altered by sericite

Moreover, this sample has high iron, calcium and potassium contents. Plagioclase chemistry is mainly anorthoclase and orthoclase. Both contain sodium (Na) elements (see appendix 3). Therefore, it is close to the albite area in the albite- orthoclase- anorthite trigram. The gabbro thin sections have abundant calcite, plagioclase and biotite minerals (Figure 6:12 and 6:13).

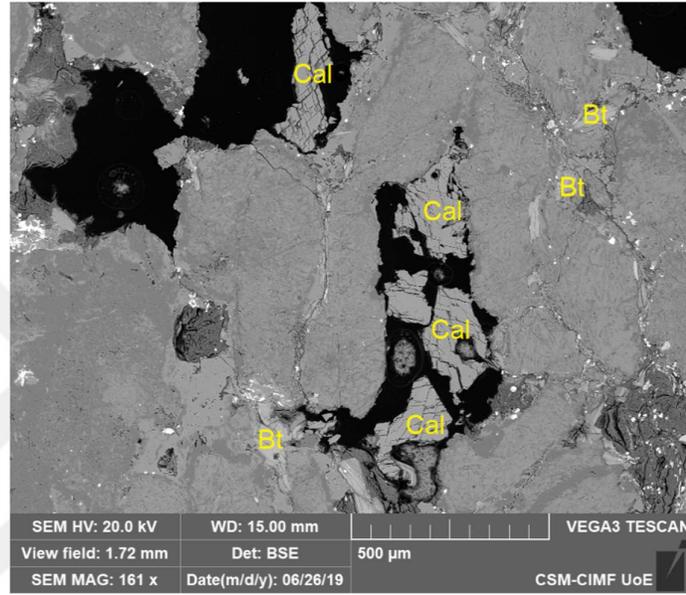


Figure 6:12 Calcite (Cal) and Biotite (Bt) Minerals in Gabbro Thin Section

The characteristic features of the mid-ocean ridge are low potassium content and depleted of rare earth elements. The gabbro samples do not have any rare earth elements. There is potassium content. However, the potassium content is not enough to classify the area as an alkaline environment. Furthermore, the potassium content is secondary in the gabbro because of the alteration.

Gabbro is seen as dykes in the study area and mostly contact with Kennack Gneiss and serpentinite lithologies. Thus, some minerals come from contact units. Moreover, basalt lithology associated with gabbro lithology because of the contact of the Kennack Sands. This situation can give some information about the characteristics of mid-ocean ridge formation. Calcium content is high and also potassium content is partly high. In the result of chemical properties, this system can include in the tholeiitic system. The other component of the MORB (mid ocean ridge basalt) environment is N-MORB or P-MORB which are difference between ratio of titanium oxide and potassium oxide content.

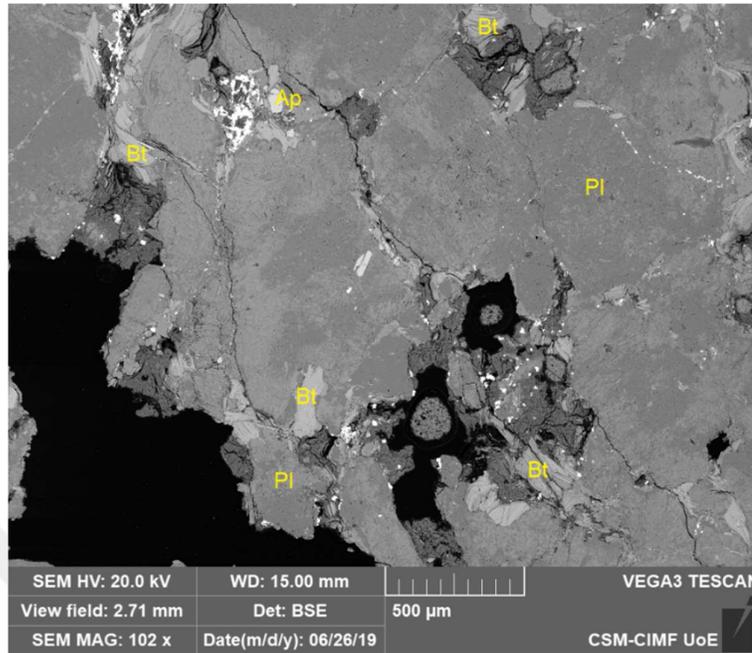


Figure 6:13 Biotite (Bt), Plagioclase (Pl) and Apatite (Ap) minerals in the Gabbro Thin Section

6.4 Granite

Granite is in contact with the basalt unit in the study area. The Kennack gneiss is a component of basalt and granite lithologies. Different sections of the Kennack Gneiss show different mineralogical features. There are a number of granite samples from the study area. Some of them contain plagioclase mineral, therefore, this granite could be identified as plagiogranite. However, other thin sections also contain potassium feldspar (K-feldspar). Therefore, this granite is not plagiogranite. This indicates this rock is granite and the other features confirm features of a typical granite.

The granite samples are different from each other because of the mafic content. When the mafic content is high, the titanite and iron content is also higher. Some samples contain chalcophile elements (pyrite and chalcopyrite) and other samples contain lithophile elements.

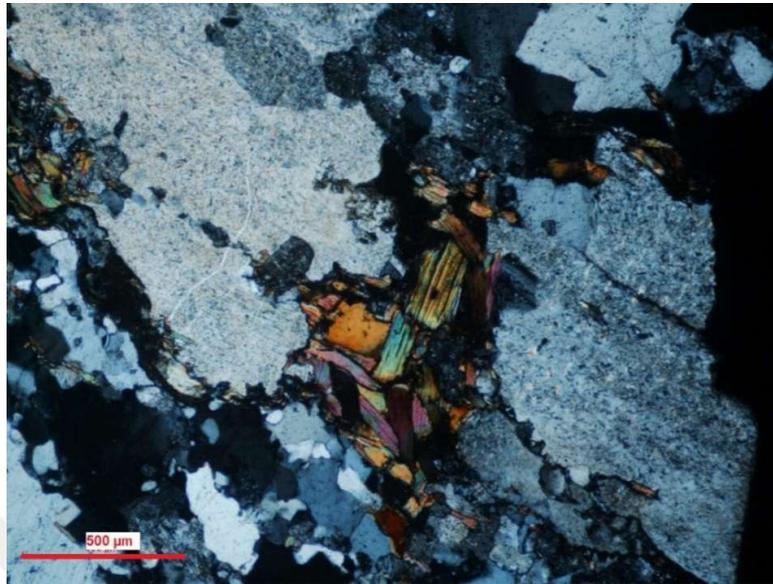


Figure 6:14 Biotite, Muscovite and Quartz minerals in the Granite Sample
 In some parts have sericite which indicates alteration and also tin, copper and pentlandite ores in the samples result from the hydrothermal alteration.

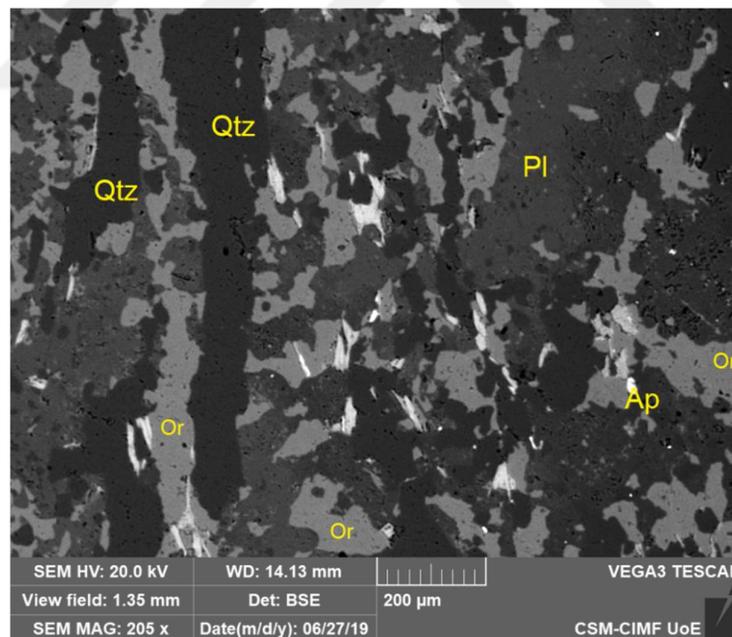


Figure 6:15 Quartz (Qtz), Apatite (Ap), Orthoclase (Or) and Plagioclase minerals
 Moreover, there are monazite minerals in the granite lithology. They have rare earth elements which are thorium (Th), cerium (Ce), lanthanum (La), tantalum (Ta), tungsten (W), samarium (Sm), holmium (Ho), hafnium (Hf), dysprosium (Dy), praseodymium (Pr), gadolinium (Gd), yttrium (Y), vanadium (V), neodymium (Nd) and osmium (Os) (Appendices 4, 5, 6 and 7).

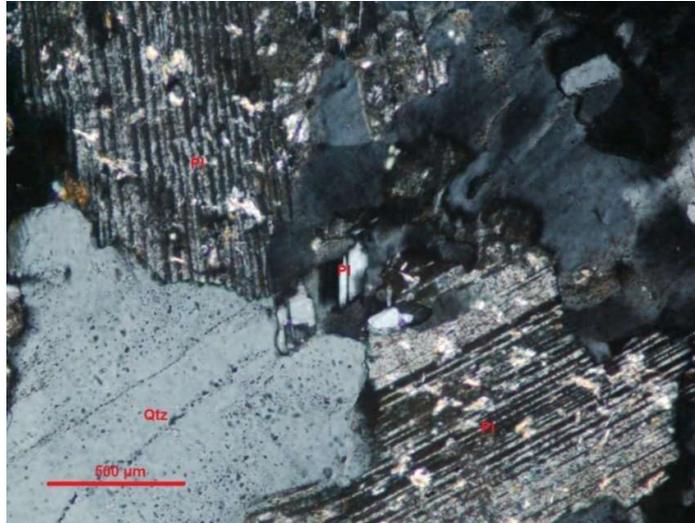


Figure 6:16 Plagioclase (Pl) and Quartz (Qtz) minerals in the Granite Samples

In addition to rare earth elements there are apatite and zirconium minerals. Europium (Eu) anomalies show plagioclase recrystallisation at the magma chamber's top sequence. This sequence associated with gabbro dykes. High silica melt cannot move directly because of the gabbro melt viscosity is higher than silica melt. Therefore, gabbro can move with granite as dykes.



Figure 6:17 Biotite, Plagioclase, and Quartz Minerals in the Kennack Gneiss Sample

Monazite is can be seen in the granite lithology which contains a number of rare earth elements (figure 6:18).

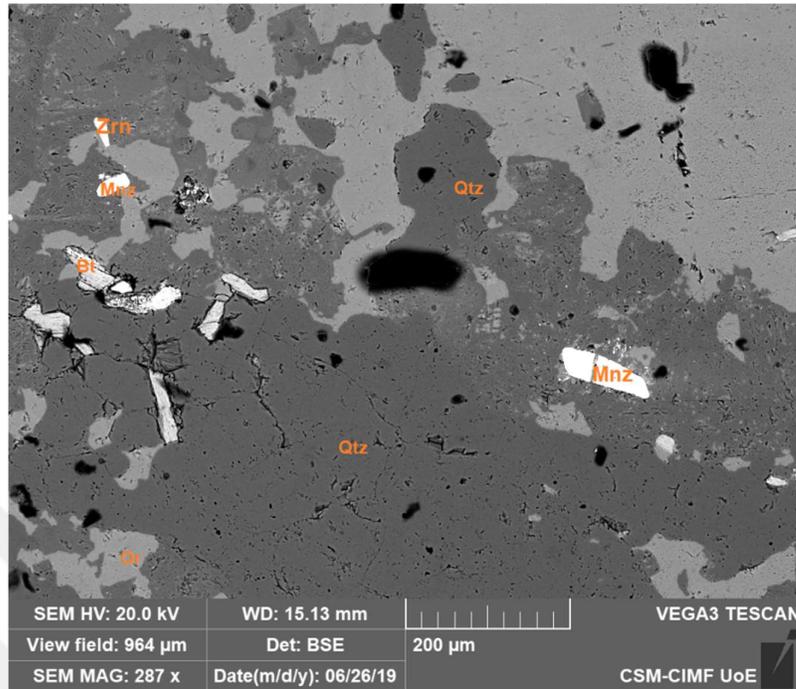


Figure 6:18 Monazite (Mnz), Zircon (Zrn), Biotite (Bt), Orthoclase (Or), and Quartz Minerals

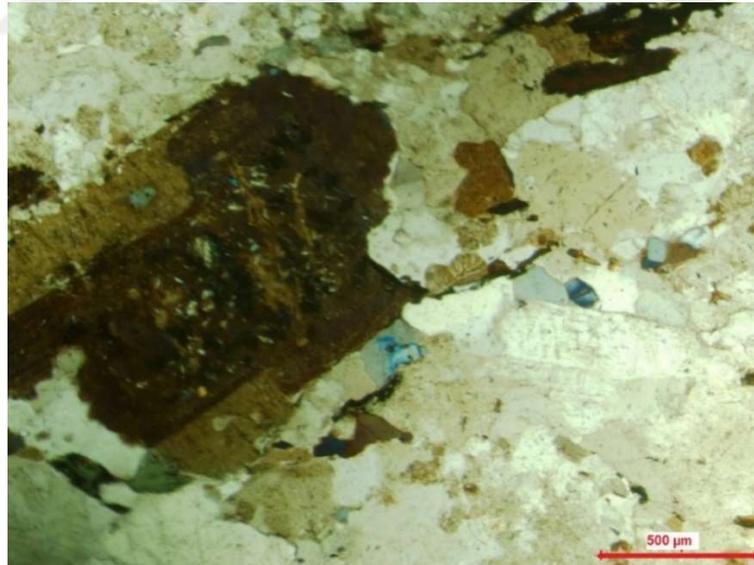


Figure 6:19 Plagioclase and tiny hexagonal blue minerals

Kennack Gneiss has lithophile (i.e. REE, Ti, Zr, Hf) chalcophile (i.e. Cu, Mo, Ba) and siderophile (Ni, Co, Fe) elements. Thus, Kennack Gneiss has a mixing of a number of element combination. This situation causes the hydrothermal fluids, mixing of mafic and felsic component and also magma chamber's chemical composition.

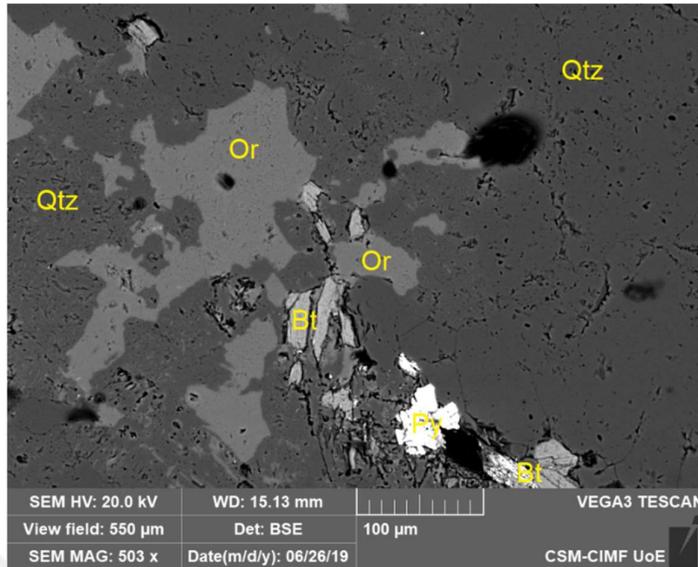


Figure 6:20 Pyrite (Py), Quartz, Orthoclase (Or), and Biotite (Bt) Minerals in the Granite

Some part of Kennack Gneiss enriches titanium content. There are titanite and rutile minerals in the samples.

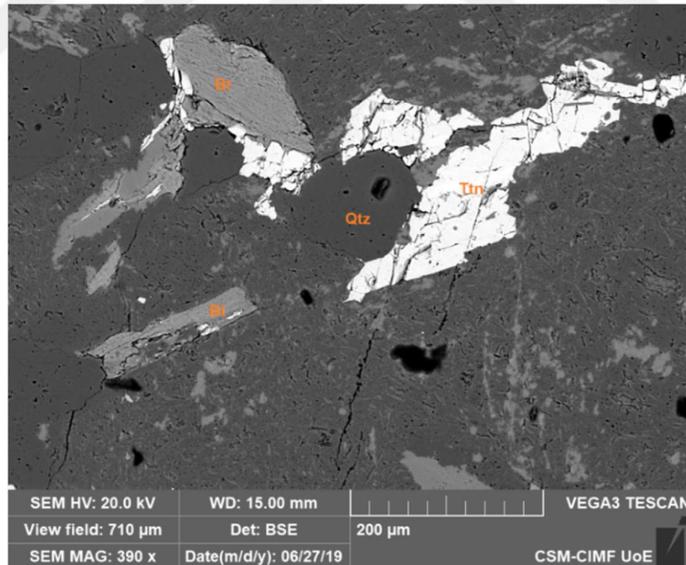


Figure 6:21 Biotite (Bt), Quartz (Qtz), and Titanite (Ttn) minerals in the Granite Sample

6.5 Basalt

The study area basalt formed two different types. The first is basalt dyke, the second is the Kennack Gneiss component. All units are highly altered in the study area and basalt too. This situation can be understood in mineralogical feature in thin sections. For example, there is chlorite in the thin section figure 6:22.

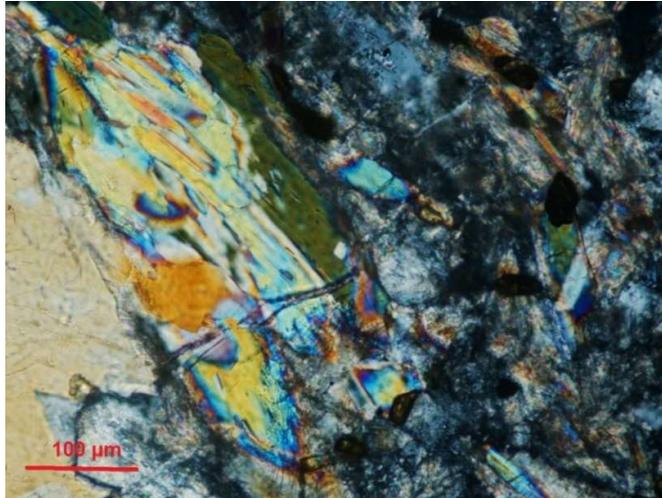


Figure 6:22 Chlorite Mineral in the Basalt Sample

According to SEM results, these samples contain augite, ilmenite and rutile minerals (figure 6:23). Some samples contain potassium (K) due to granite contact (appendix 8). Potassium is referring to alkaline basalt. However, potassium is not the primary elements in the basalt samples in the study area. This potassium content comes from Kennack Gneiss' plagioclase associated with the gabbro and sheeted dykes. For this reason, this basalt can be classified as a tholeiitic basalt because calcium content is high and also it has potassium content.

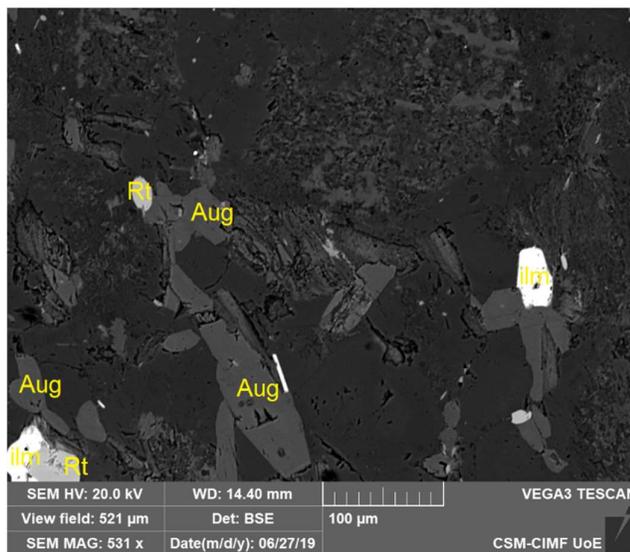


Figure 6:23 Clinopyroxene Augite (Aug), Rutile (Rt) and Ilmenite (ilm) Minerals

Olivine is uncommon in the basalt thin sections. Generally, basalt has tholeiitic basalt properties except alkaline (K) content.

7. PHOTOGRAMMETRY

Photogrammetry provides a 3D creation model based on 2D images. The technique stimulates the human ability to use overlapping 2D images for the perception of depth. Humans use both eyes for depth perception; therefore, photogrammetry imitates this method. A number of pictures should overlap each other by at least 50%, and also these pictures should include GPS data (Global Positioning System) for the stitch onto other localities. The principle of photogrammetry for 3D mapping can be seen in figure 7:1 (Shaanan & Charles, 2012-2013).

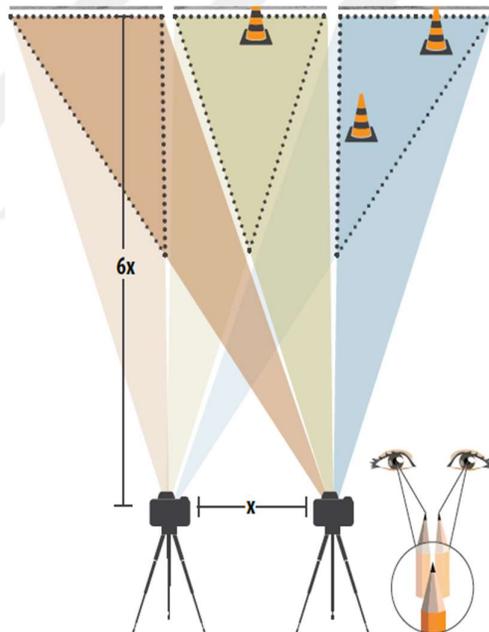


Figure 7:1 Illustration of Photogrammetry Principle

7.1 Agisoft PhotoScan

The Agisoft PhotoScan software is convenient for 3D modelling with drones and handheld photos. This study used handheld photos because of some legal restrictions. Initially, the 3D model was carried out in the Kennack Sands location. The first model included bastite peridotite lithology and a cutting fault with

associated asbestos section. The result of the 3D model of the lithology, some features can be seen in the cloud such as foliations, faults, and lineations. Thus, it can be used for structural determination and also it can calculate the volume and area of the lithologies separately. An example of 3D modelling can be seen in figure 7:2. Lithology differences can be identified with the colour change and foliations can be seen with depth.

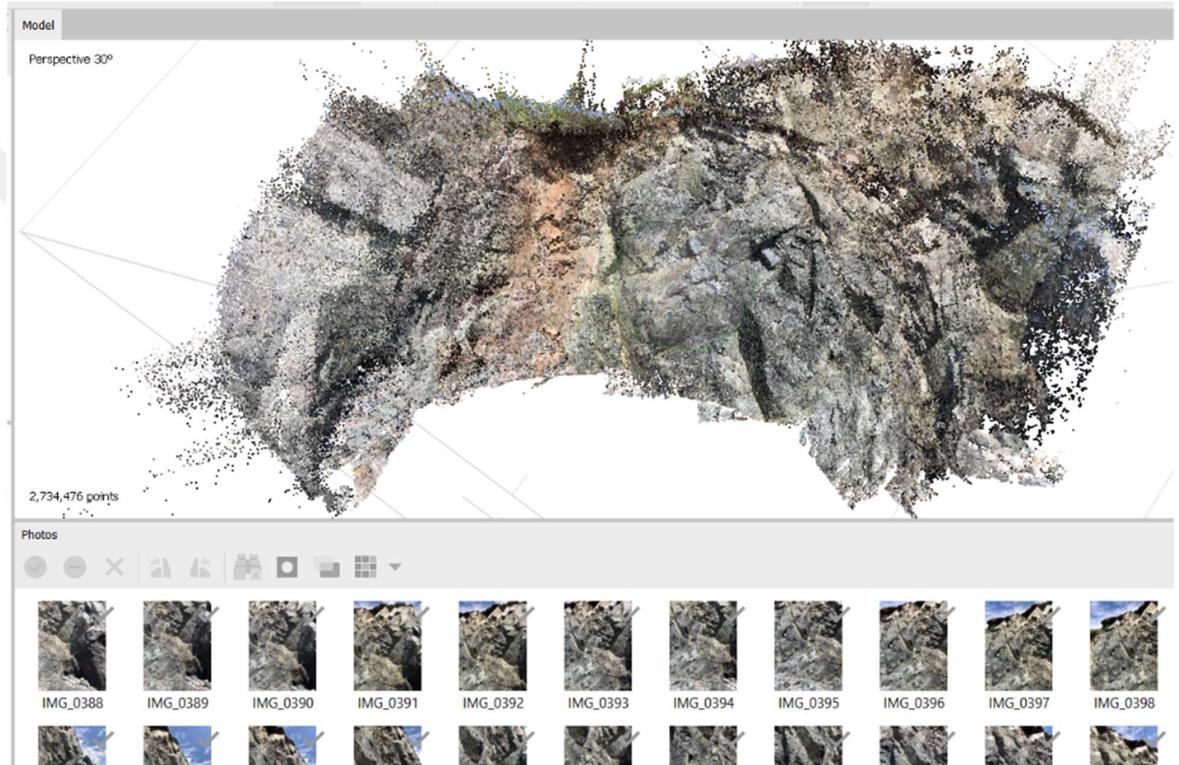


Figure 7:2 3D Model of Middle Section in the Kennack Sands with the Agisoft PhotoScan Software

Depth is important to calculate the volume. Moreover, altitude and length can be measured without a tape measure. The quality of the cloud can be understood with tie points in the cameras. In the first section, sixty-five cameras were used, and 2,734,476 points were stitched together. The following step is filling some blanks in the model, which can be created with the mesh features. The most important feature is calculating volume and input in the other software because of the mining plan or other geological based projects. Otherwise, the same visualisation can be seen with photos, however, the importance of 3D modelling

is it can be used with some calculations. The same location can be seen in figure 7:3. However, it does not have any height, length and volume values.



Figure 7:3 Same Location as 3D Model

In the photo foliations, gabbro dykes and lithology differences can be seen. However, there is no information about calculating or analysing the volume or area of the location.

7.2 Pix4D Software

Initially, the Agisoft PhotoScan software was used for 3D modelling. However, the other results were not satisfactory because of the angle of photos direction and also it mainly works with drone photos. Therefore, this project moved on to Pix4D Software. This software has a number of additional features such as an initial report about 3D point cloud and 3D mesh.

Pix4D uses the WGS 84 coordinate system. A geological map in the ArcMap has been carried out using the British Coordinate system. For this reason, it needed to be changed for the Leapfrog Software. However, thanks to the coordinated photos, the locations of the photos can be seen in the satellite map automatically in the Pix4D Software (figure 7:4).

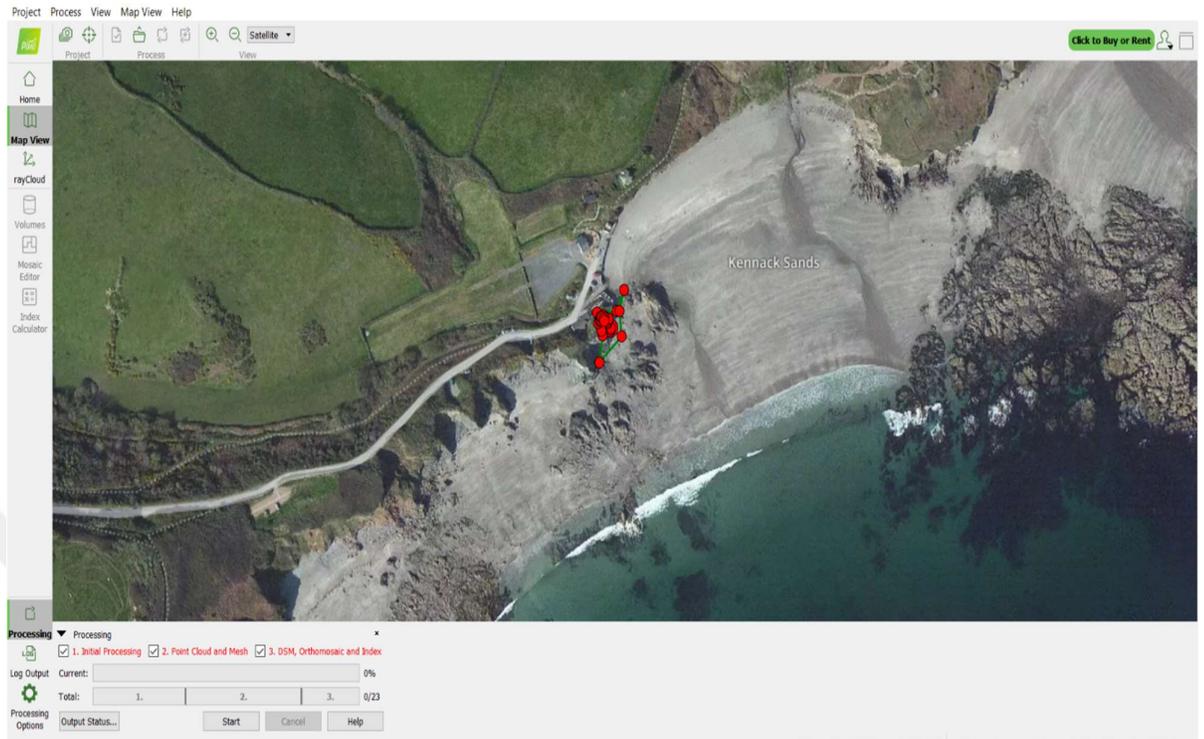


Figure 7:4 Photographs' locations in the Pix4D software

The processing results are point clouds and meshes which can be seen in figure 7:5. Foliation and cracks can be seen easily. Meshes provide filling the blanks and it provides a more complete representation.

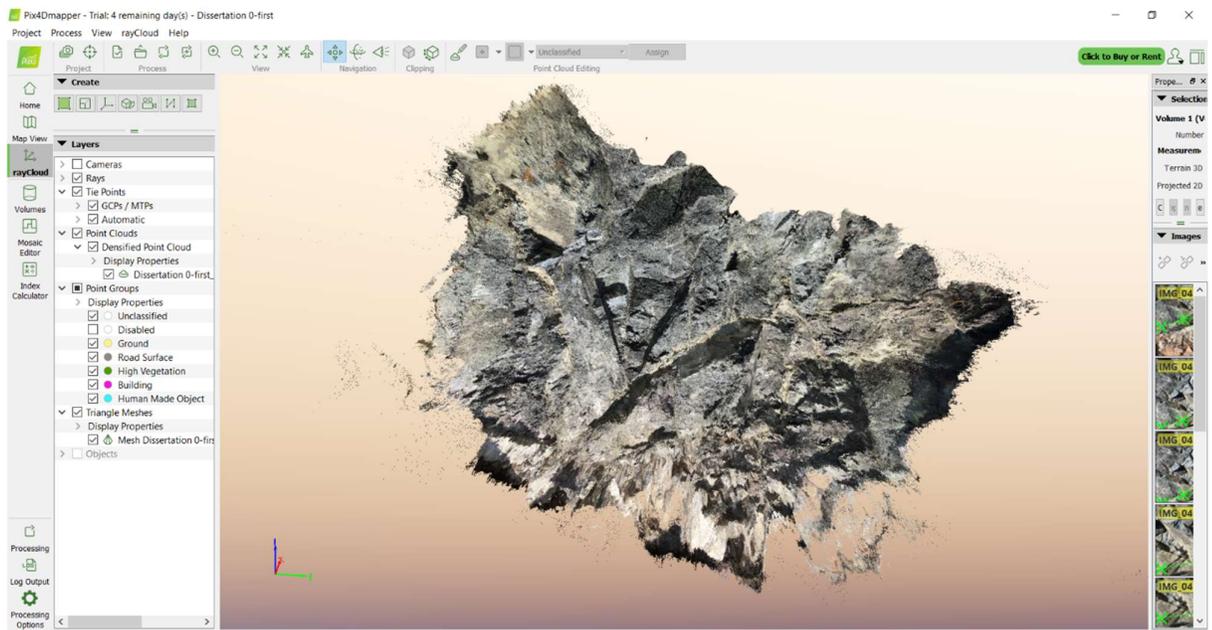


Figure 7:5 Mesh Studies in the Pix4D software

7.2.1 Quality Report of 3D Mapping Points Cloud and Mesh

The quality of point clouds and mesh are relative to some features. Therefore, during the photography and during the selection of subdivided photos some quality features should be considered. For this reason, the initial quality report should be confirmed. Features of the quality report can be seen in figure 7:6 - 7:7 – 7:8.

Quality Check

Images	median of 76041 keypoints per image	✓
Dataset	100 out of 100 images calibrated (100%), all images enabled	✓
Camera Optimization	3.94% relative difference between initial and optimized internal camera parameters	✓
Matching	median of 46970.5 matches per calibrated image	✓
Georeferencing	yes, no 3D GCP	⚠

Preview

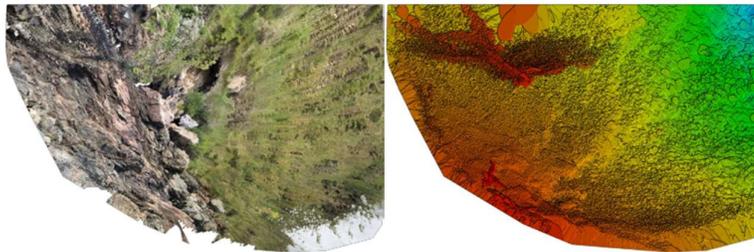


Figure 1: Orthomosaic and the corresponding sparse Digital Surface Model (DSM) before densification.

Figure 7:6 Some Information about 3D Model

Overlap

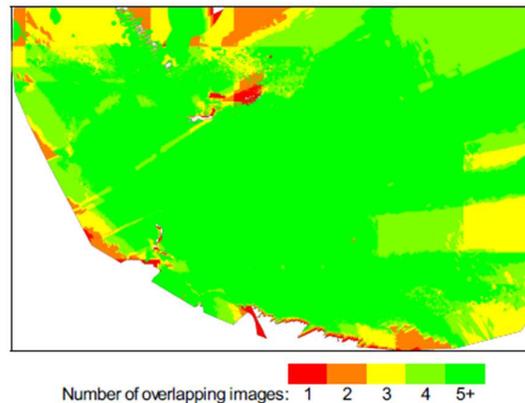


Figure 4: Number of overlapping images computed for each pixel of the orthomosaic. Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Figure 7:7 Overlapping Quality about Cliff Section

Results



Number of Generated Tiles	1
Number of 3D Densified Points	1130715
Average Density (per m ³)	284589

Figure 7:8 Information about 3D Model

There are thirty-five separate 3D models of the Kennack Sands and Poltesco Beach area. Their longitudes range between ten meters to a hundred meters and their altitudes change according to cliffs' heights. Some models are highly detailed, and they reflect the whole structural and geological features. Some of them are not highly detailed and also they contained some blanks even if produced using the meshes structure. Therefore, they are not useful to calculate area or volume and also they are not suitable for structural or geological observations. The best 3D models have a range of colour, lineations, foliations and fault lines. One example of a 3D model can be seen in figures 7:9; 7:10 and 7:11 from different perspectives. Other 3D models can be seen in appendices.



Figure 7:9 3D Model of Serpentinite and Gabbro Contact

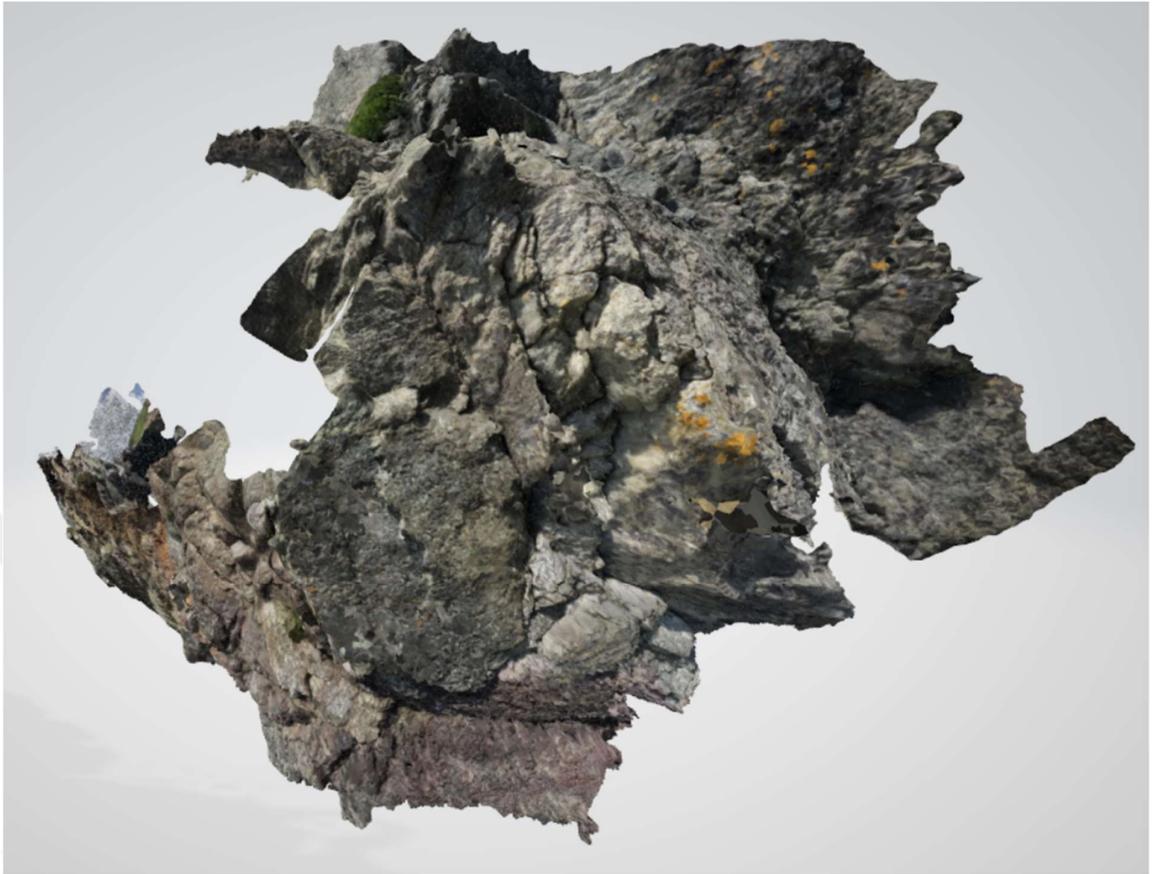


Figure 7:10 Other Perspective of Same 3D Model of Kennack Sands Area's Part



Figure 7:11 Other Perspective of Same 3D Model of Kennack Sands Area's Part

The same 3D models can be exported as different document types such as 3D pdf, PLY and LAS. The 3D pdf version can be seen in Figure 7:12. However, these model's appearances are not the same as the main files. Thus, they cannot be used for the geological interpretation.

Dissertation 0-second_simplified_3d_mesh



Figure 7:12 Same 3D Model in the Kennack Sands

7.3 The Leapfrog Software

The Leapfrog software was used for 3D observation in the cliff area with the ArcMap Geological Map. Moreover, the topography can be seen easily and also the other map details such as car park and buildings can be seen in the Leapfrog software. The general view of the Leapfrog software results includes basalt and gabbro dykes, granite, hornblende schist, serpentinite lithologies and faults (figure 7:13 and 7:14). The other closest results and geological map are in the appendices section.

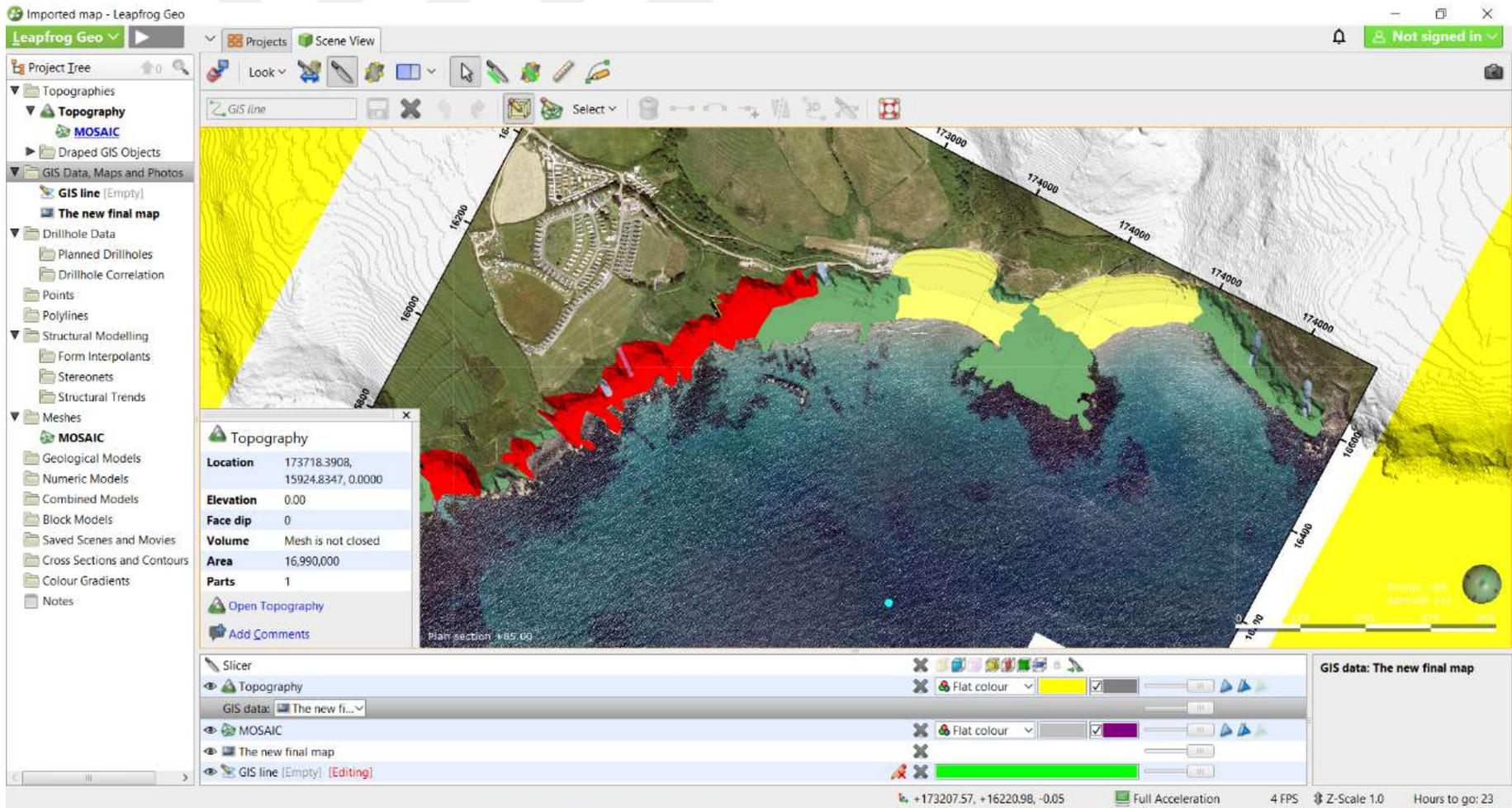


Figure 7:13 Imported Geological Map in the Leapfrog Software

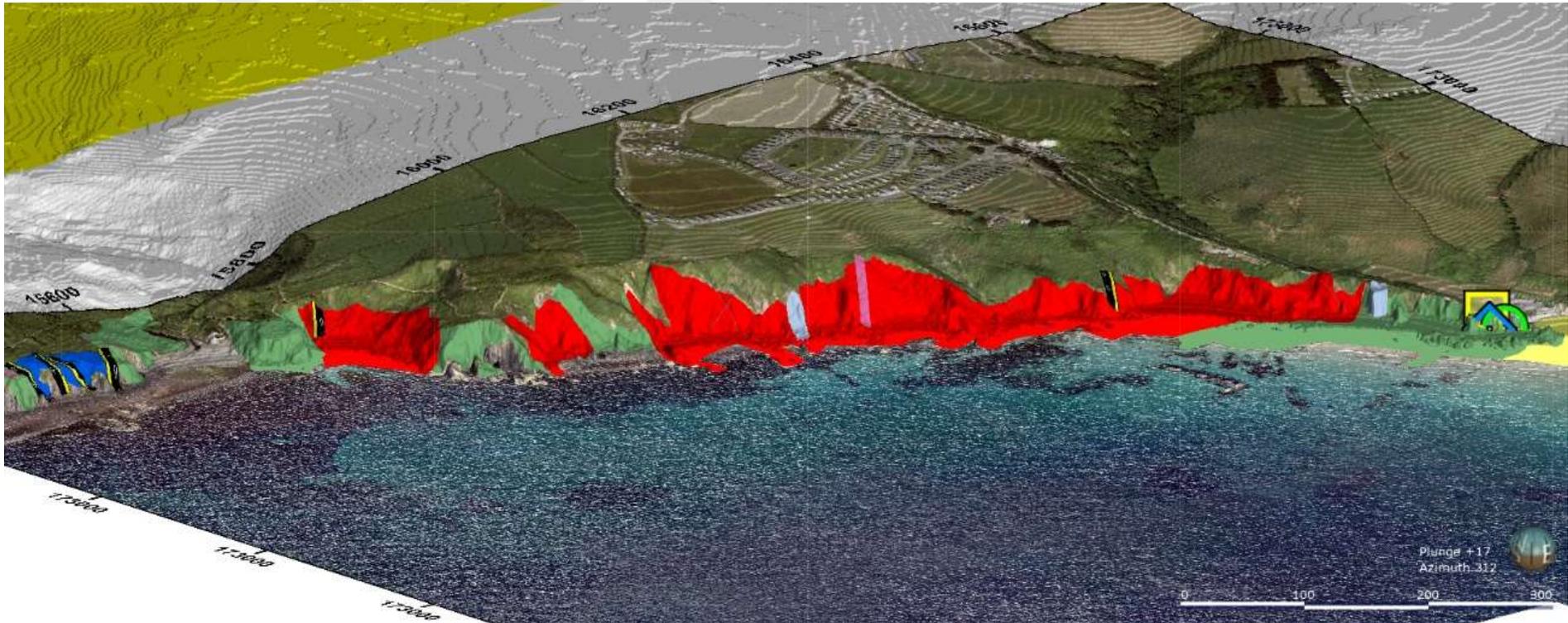


Figure 7:14 3D View of Study Area in the Leapfrog Software

8. DISCUSSION

8.1. Evolution of the Serpentinite

Serpentine minerals are widely found in the field as a result of external conditions. These external conditions are mainly created through the alteration of minerals by sea water. Although the current study area is located at the seaside, it is not known whether the sea water exists in the environment during the period when serpentinisation takes place. Therefore, it is not known whether serpentine minerals in the study area are altered by sea water. However, it is known that the region is deformed as a result of the Variscan tectonism. According to the age data in the literature, it is known that serpentinisation and Variscan tectonism occur simultaneously. In addition, rodingitisation and chrysotile mineral, which are rich in calcium, are observed in the areas where there is a contact between magmatic intrusions and peridotites. In terms of age, peridotites are the oldest rocks in the study area. Referring to this, the evolution of serpentinites occurs following the completion of tectonic evolution and magmatism. One of the most prominent characteristics of the serpentinisation in the field is that it is red and green due to the minerals it contains. Normally, the colour of serpentinites is mostly dark green, and they have slippery appearances. However, in this case, dark red additionally accompanies and the source of red colour is the bastite mineral in the peridotites.

This study area's peridotites were ultimately serpentinised. Therefore, there is no harzburgite, lherzolite or wehrlite peridotites. According to the thin sections, the main lithology was free clinopyroxene harzburgite or lherzolite because the thin sections have a number of clinopyroxenes (augite). Clinopyroxene ratio is very low, therefore, this rock is probably free clinopyroxene harzburgite.

Bastite peridotites mineral assemblage is enstatite, olivine, augite and magnesiochromite. Moreover, they contain plagioclase which are come from same magma content as the Kennack Gneiss which contain granite.

The serpentinite units took place during the obduction. However, serpentinisation was completed by the Carboniferous to early Permian (Power et al., 1997). Moreover, there is gabbro lithology in the study area, which occurred as a Devonian oceanic crust overlaying mantle peridotite (Ealy & James, 2011). The Lizard Complex movement was in a period of the late Variscan (late Carboniferous – early Permo-Triassic) as extensional faulting (Shail, 1999).

8.2. Protolith of the Kennack Gneiss and Emplacement and Evolution

As a result of the studies in the area, it was thought that the granite was plagiogranite, but the presence of potassium K-feldspar in the content showed that this was not possible. The possibility of granite to be a plagiogranite was considered because of the fact that plagiogranites were related to ophiolites and it was observed in the north-eastern part of the lizard ophiolite. However, it was turned out that the granite was just a normal granite considering thin sections.

Peridotites occurred in the study area and then hornblende schist was emplaced by structural events. The following emplacement was the metasomatism of Kennack Gneiss. The basalt and granite lithology were a resource from the magma chamber. The Cornubian batholith is quite near the study area. However, there is no relationship either petrographically or mineralogically. Therefore, it can be concluded that the Kennack Gneiss is completely different from other granite types in South West England. The Kennack Gneiss granite is pinkish, equigranular and contains plagioclase. For this reason, it can be identified as a typical granite. Additionally, gabbro is seen as dykes in the study area. The gabbro dykes' samples also have plagioclase in the study area because gabbro and granite are found together in the magma chamber. Gabbro's viscosity is higher than high silica content lithology which is granite. Therefore, it could be released much more easily at the uplifting stage.

The study area includes the ophiolitic sequence and also granite formation (Kennack Gneiss- a mixture of basalt and granite). Kennack Gneiss is not a genuine metamorphic rock. However, this name is useful because some parts of

the layered granite and basalt section look like a metamorphic unit. The origin of this granite resource differs from the other granites in south-west England. The difference between the Kennack Sands granite and other south-west England granites is the plagioclase content. Moreover, Cornubian batholite is younger than Kennack Gneiss granite.

According to the Kennack Gneiss' felsic part thin sections, granite has plagioclase which are primary minerals for the I-type granites. Moreover, hornblende and biotite can be seen in the granite thin sections. Biotite is the most common mineral in I-type granites. Hornblende mineral is can be seen in only I-type granite. Therefore, Kennack Gneiss protolith has an igneous source. Mantle plume formed Kennack Gneiss in the study area. This plume may have led to some metasomatism in the vicinity of the older rocks, however, there is no evidence of metasomatism every part of field. Some part of the Kennack Gneiss was affected by the tectonism. Furthermore, affected tectonic areas have been layered parallel to foliation. This part of Kennack Gneiss is metamorphic rock and not commingling of basalt and granite rocks.

It was mentioned in the study that Kennack Gneiss was not a metamorphic rock. The reason for this is that two rock types in it do not mix with each other during the magma crystallisation stage and, instead, they create a new stratified rock. However, the fact that foliations and compositional layering are generally parallel with each other indicates that this rock may be metamorphic. In addition, hornblende schists found in the study area were formed in a similar way with the effect of metamorphism and they are close in terms of age and their formation mechanism is similar to Kennack Gneiss'. Therefore, Kennack Gneiss could be evaluated as having a metamorphic nature as a result of tectonic events occurring at the same time, except that it is formed by a separate crystallisation in terms of formation. In conclusion, there is not only metamorphic Kennack Gneiss but also non-metamorphic one in the study area.

Sandeman (1988) claimed that Kennack Gneiss' mafic magma chemical characteristics of calc-alkaline basalt might be related to the volcanic arc. Even though these chemical properties suggest calc-alkaline basalt, this chemical

composition might result from the alteration effect. Mineral occurrences are not entirely distinct, and minerals can come from the other lithologies at contact points. These mineral assemblages were affected by the gabbro.

According to previous research, basalt lithology was moved by the thrust fault in the Kennack Gneiss. According to evidence from the Poltesco region, this fault runs east to west. However, there is not any observation of the fault north of the Kennack Sands. Therefore, possibly the south section of the study area has undergone much more active tectonism and the Kennack Sands area Gneiss (basalt and granite) could be both syn-kinetic and intrusive. Moreover, the Poltesco Beach area has hornblende schist lithology associated with the tectonism. It is possible that hornblende schist lithology was affected by the thrust fault.

Basalt classification (N-MORB)- tholeiitic and basalt samples contain titanite and ilmenite minerals. These are calcium and titanium enriched minerals. The granite (Kennack Gneiss part) has Ta, Nb, P, Eu and Ti anomalies. These minerals are high fields elements (HFSE) which are an indication of the N-MORB environment.

8.3. Tectonic and Structural Evolution

According to Nutman, et al. (2001), this area has a three-stage evolution of the environment: pre-emplacment (393-386 Ma), thrust emplacements (396-376 Ma) and late- to post- emplacements (370 Ma). The oldest unit in the study area is peridotites. Later amphibolites (hornblende schist), basalt and gabbro dykes, and basalt and granite as the Kennack Gneiss lithology syn-chronologically were emplaced in the area. This emplacements was intrusive in the study area and hornblende schists are probably associated with the tectonic events after the Kennack Gneiss replacement. The Variscan orogeny occurred later than the whole replacement (the post-Permian to the Triassic). Serpentinisation began late- to post the emplacements (370Ma) stage and this process was continuing with external forces such as weathering and tectonic events.

In the study area, serpentinites and granite lithologies are foliated and have lineations. This situation is a consequence of the orientation of mineral grains at

the pre-magmatism phase. Boudier and Coleman (1981) claimed that mineral grains accumulate and orientate underneath of the divergent plates mantle diapirs as in the Semail (Oman-MORB- type) ophiolite. These grains are formed by high-temperature plastic magma.

It is observed that peridotites are not lherzolite rocks but free clinopyroxene harzburgite and the majority of these are transformed into serpentinite rock due to the fact that it is clinopyroxene and it is not very common. Additionally, it was observed that there was no olivine-rich (olivine >90%) (dunite) rock.

Gabbro dykes have also been seen in this study area. Yellowish white rodingite (calcium-rich) minerals are an indication of metamorphosed gabbro dykes. Miyashiro (1973) suggested that ocean floor metamorphism causes the ocean water's movement in the cracks and fractures because of the heat of the magma.

Mid-ocean ridge oceanic crusts show N-MORB (normal mid-ocean ridge basalt) type geochemical features. These features are low potassium oxide ratio (<0.2) and tholeiitic components. There is no content of trace elements. Moreover, light rare earth elements (LREE) are more depleted compared to heavy rare earth elements (HREE) (Sarifakioglu and Dilek, 2016). N-MORB type rocks' fractional crystallization contains olivine, plagioclase and clinopyroxene. These rocks can be seen in serpentinite rocks and also granite lithology.

The dykes strike NNW-SSE because the tectonic extension is similar to this direction. This orientation is the same as the faulted and the cracks section. These spaces were filled with the basalt and gabbro dykes. Alexander and Shail (1996) claimed that later ENE-WSW extension caused the reactivation, and formation of the NNW striking faults, for instance, in the Kennack Sands vicinity.

Photogrammetry studies should be carried out using drones because it is important that camera points are defined for 3D softwares and also the number of pictures needed can be determined with the special program associated with the 3D softwares. These can easily be downloaded to tablets or smart phones.

Moreover, storages of these models require large capacity. For this reason, external storage should be used for the photos and exported documents.

9. CONCLUSION

It is concluded that Kennack Gneiss has a magmatic origin since Hornblende mineral is a typical I-type granite mineral. In addition, Kennack Gneiss is found in the study area both as a metamorphic form, which has an excellent lamination, as well as a non-metamorphic form, which occurs in the way of magma mixing as a result of separately crystallisation of magma. It is observed that metamorphic Kennack Gneiss is mostly concentrated in Poltesco region where metamorphism occurs in a more effective way. Besides, it is observed that felsic concentrated Kennack Gneiss, which is found in the north of Kennack Sand Coast, is also metamorphic.

In previous studies, it was mentioned that peridotite was lherzolite. However, it was observed that the rate of clinopyroxene was not very high and it was concluded that the rock was harzburgite. As a result of mineralogical study, it has been concluded that peridotites in the study area are harzburgites, which contain free clinopyroxene.

Another conclusion is that Gabbro, hornblende schist and serpentinisation co-occur with Variscan tectonism simultaneously and they have similar characteristics mineralogically in terms of content.

The Middle to Late Devonian period (~390-366Ma) is the time when emplacement of the Lizard Ophiolite Complex arose. The mantle and emplacement over deformed and metamorphosed oceanic crust started decoupling through top-to-the-NW thrusting. While emplacement was taking place, the intrusion of a mixed suite of felsic and mafic magmas that might have been concentrated over the detachment surface was present at widespread magmatism. Interpreted from the geochemical characteristics of this suite of intrusive rocks, a subduction zone environment might be a place where the Lizard Ophiolite Complex's initial emplacement might have occurred. The development

serpentine-filled fault zones were contained in extensive, seemingly extensional re-activation of thrust contacts.

A second generation of oceanic crust sequence that was revealed by gabbro and mafic dyke intrusion between the early and middle Devonian period (~ 375 Ma) had a later evolution that mainly contained magmatism. However, low-angle ductile shear zones might have largely had NE-SW directed extension of the oceanic crust and this might indicate a magma-starved slow-spreading ridge environment.

According to field, geochronological, microstructural and previous studies, Ordovician basement and Devonian rocks of the Lizard Ophiolite Complex exist in rocks dug up on the Lizard peninsula. Achieved from the rocks of the Lizard Ophiolite Complex, evidence shows three tectono-magmatic events that took place between Early and Late Devonian periods.

According to the field data, thrust fault in Poltesco Beach is an indication of a very strong tectonic action and the fact that magmatic rocks here have undergone more metamorphism. In addition, incidence density of alteration minerals, which are asbestos and rodingite in this case, has remarkably increased at the intersection points of gabbro dykes found here and serpentinites.

The reason behind the early tectonic evolution of the mantle section of the Lizard Ophiolite Complex might be tectonic exhumation of mantle at extensional lithosphere-scale mantle shear zones during the Early Devonian period or earlier (~397 Ma). This event is stated to have conceivably happened at the time of asymmetric extension that is related to oceanic rifting and continental breakup. Exhumation is the time when the high-T and high-P mineral accumulation (~1200°C & 15Kb) present at the Lizard peridotites balanced back to conditions of lower T and P (~919-1074°C & 5-6Kb) in a gradual manner. Bearing resemblance to deformation and metamorphism of early materialised oceanic crust in the hanging wall of the inferred shear zone, deformation that occurred at ultramafic and mafic Traboe cumulates due to high temperature (~900-1050°C) might have been situated at the base of the crustal sequence near the Moho.

All units are highly altered in the study area. In particular, the dykes have a number of alteration minerals. Serpentines are altered from the lherzolite or free-clinopyroxene harzburgite.

The Variscan orogeny was effective from the post-Permian to the Triassic age as observed as extensional faults. The Poltesco Beach section was underneath an area undergoing a greater number of metamorphism and tectonic events. The serpentinites were stressed by high temperature and pressure. Serpentinisation has occurred together with the Variscan tectonism and alteration minerals such as rodingite and asbestos have been formed as a result of metasomatism in the study area.

Due to the fact that the software currently available is designed for drone photos these are much more suitable for photogrammetry studies.

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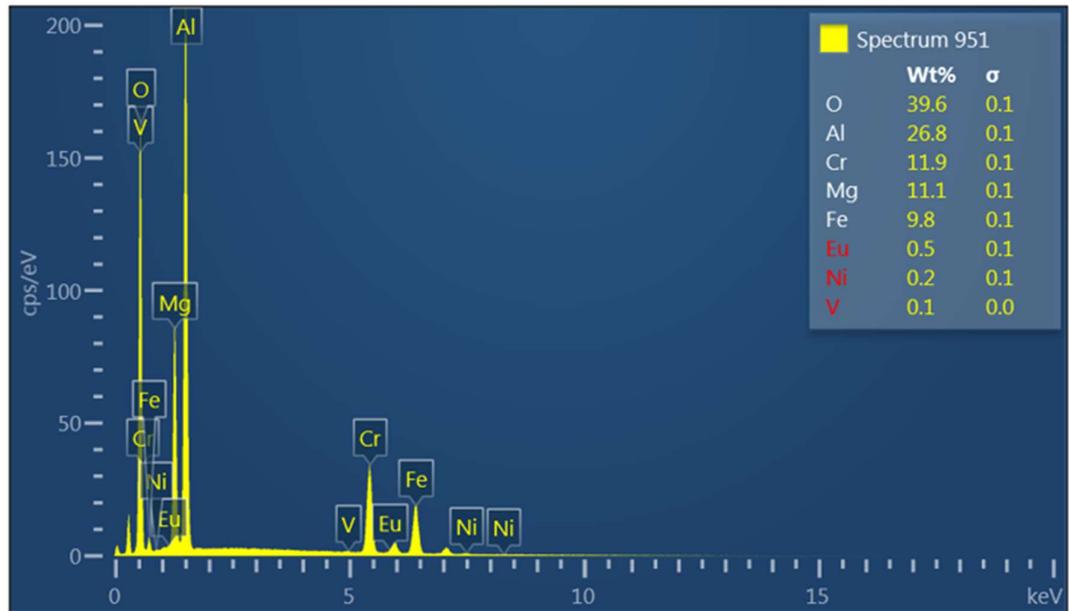
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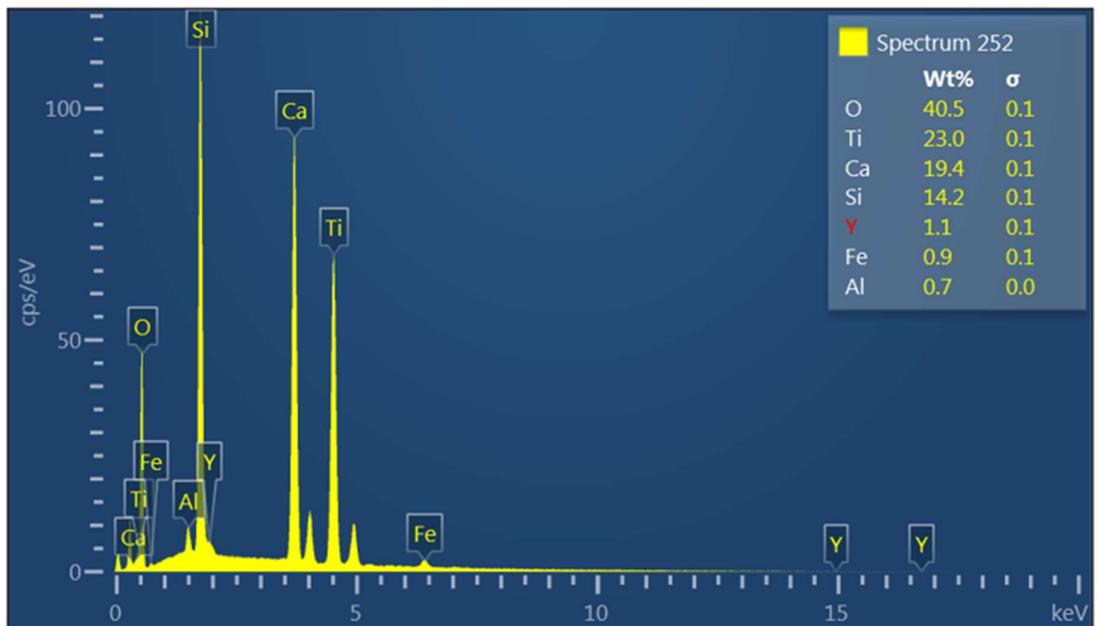
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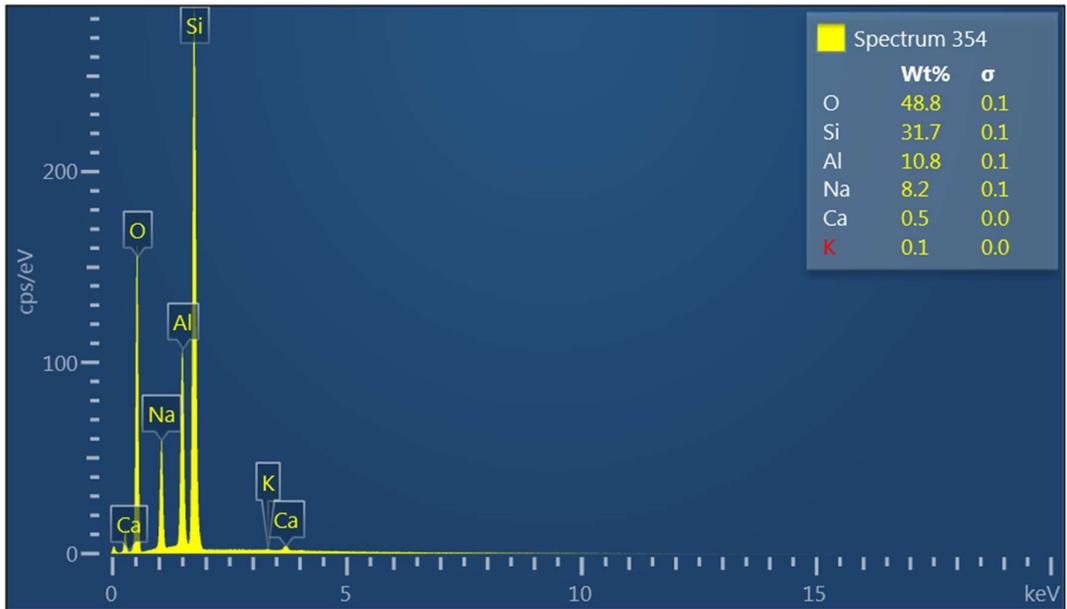
11. APPENDICES



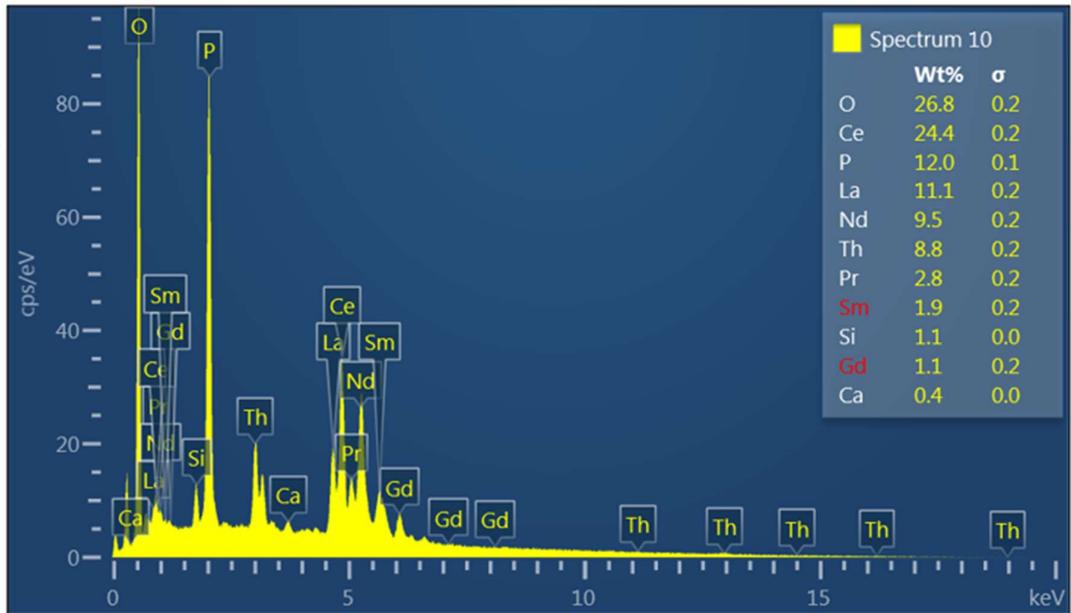
Appendix 1. Europium Elements in the Serpentinite Samples
 Negative anomalies of Europium (Eu) element indicate the formation of the lower crust plagioclase crystallisation.



Appendix 2. Titanite Mineral and Yttrium Elements in the Hornblende Schist Lithology
 Yttrium anomalies are significant evidence for this lithology related to hydrothermal activities.

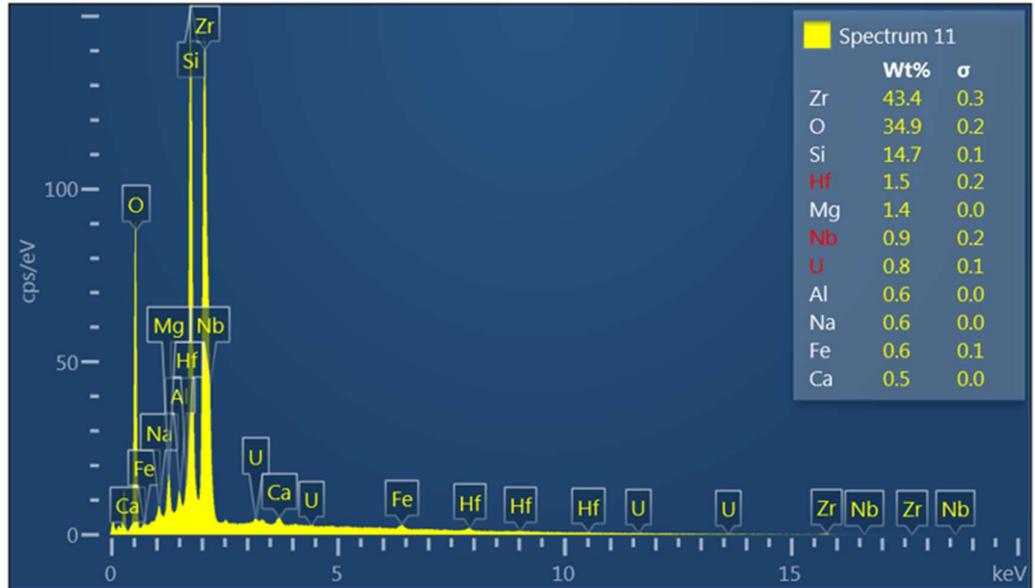


Appendix 3. Sodium Content in the Gabbro Thin Section (Plagioclase Mineral)

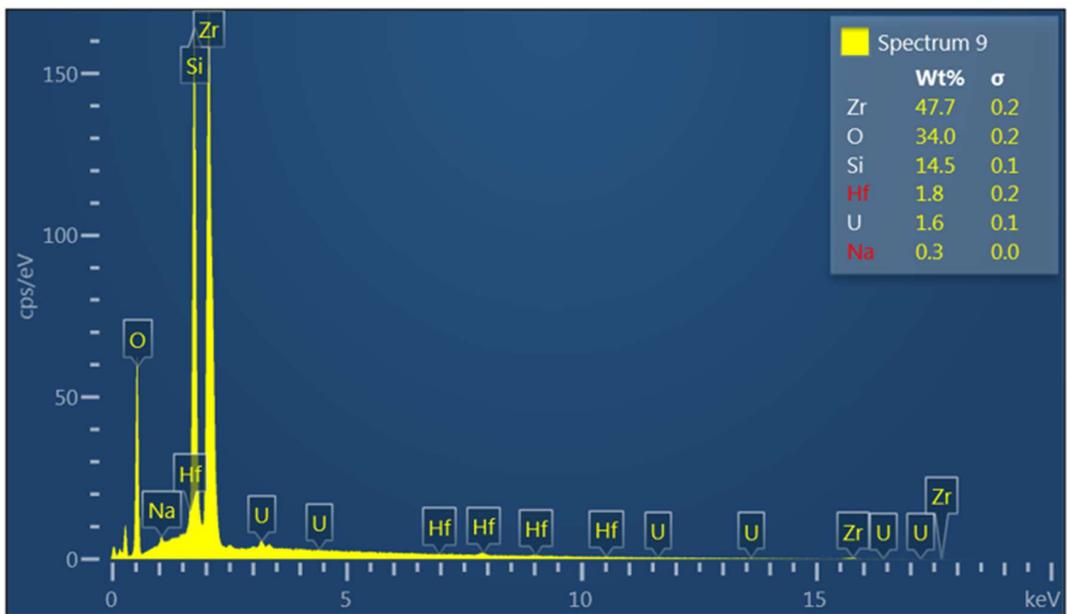


Appendix 4. Monazite mineral in the Kennack Gneiss which contain Rare Earth Elements

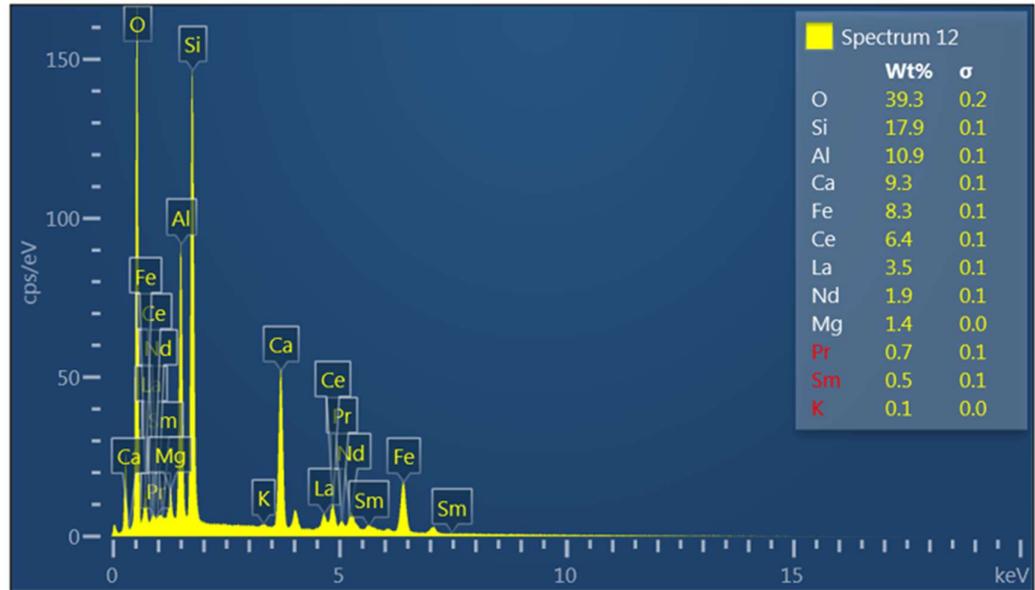
There are monazite minerals in the granite lithology. They have rare earth elements which are thorium (Th), cerium (Ce), lanthanum (La), tantalum (Ta), tungsten (W), samarium (Sm), holmium (Ho), hafnium (Hf), dysprosium (Dy), praseodymium (Pr), gadolinium (Gd), yttrium (Y), vanadium (V), neodymium (Nd) and osmium (Os).



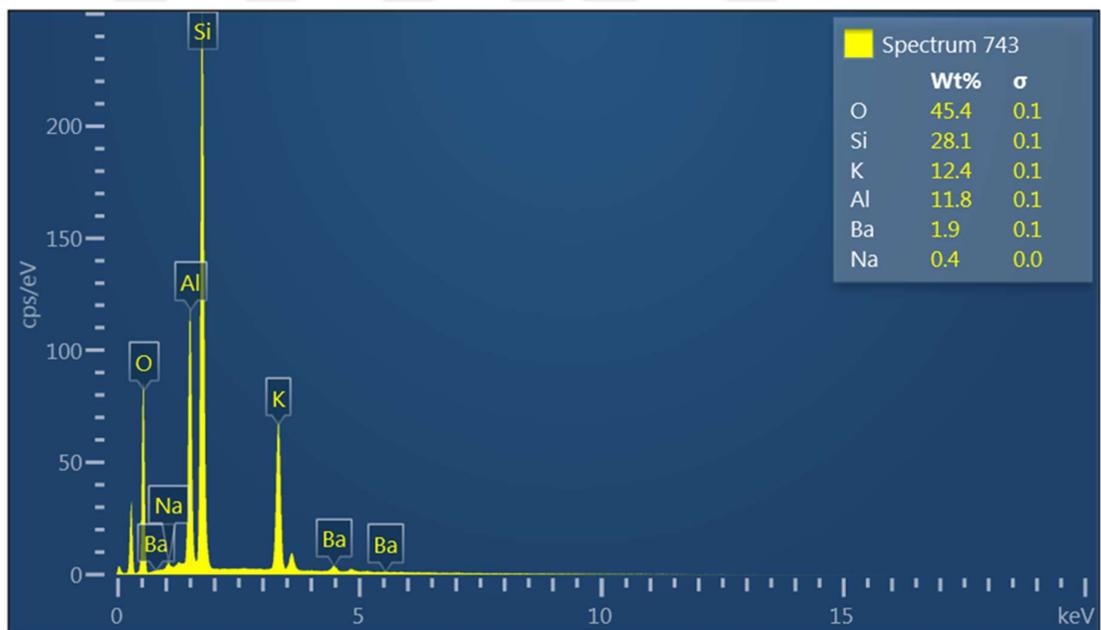
Appendix 5. Zircon Mineral, Hafnium (Hf), Niobium (Nb) and Uranium (U) elements in the Kennack Gneiss



Appendix 6. Zircon mineral in the Kennack Gneiss

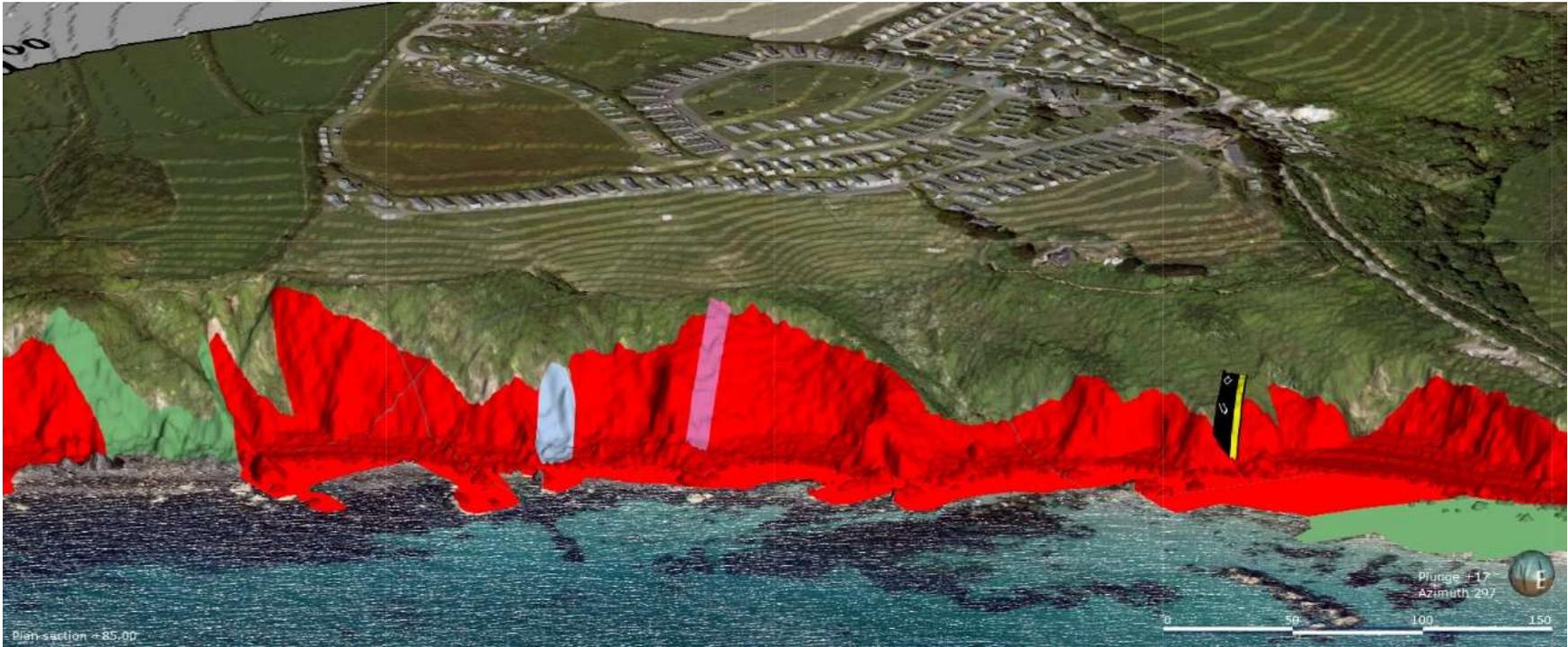


Appendix 7. Caesium (Ce), and Lanthanum(La) contains in the Kennack Gneiss

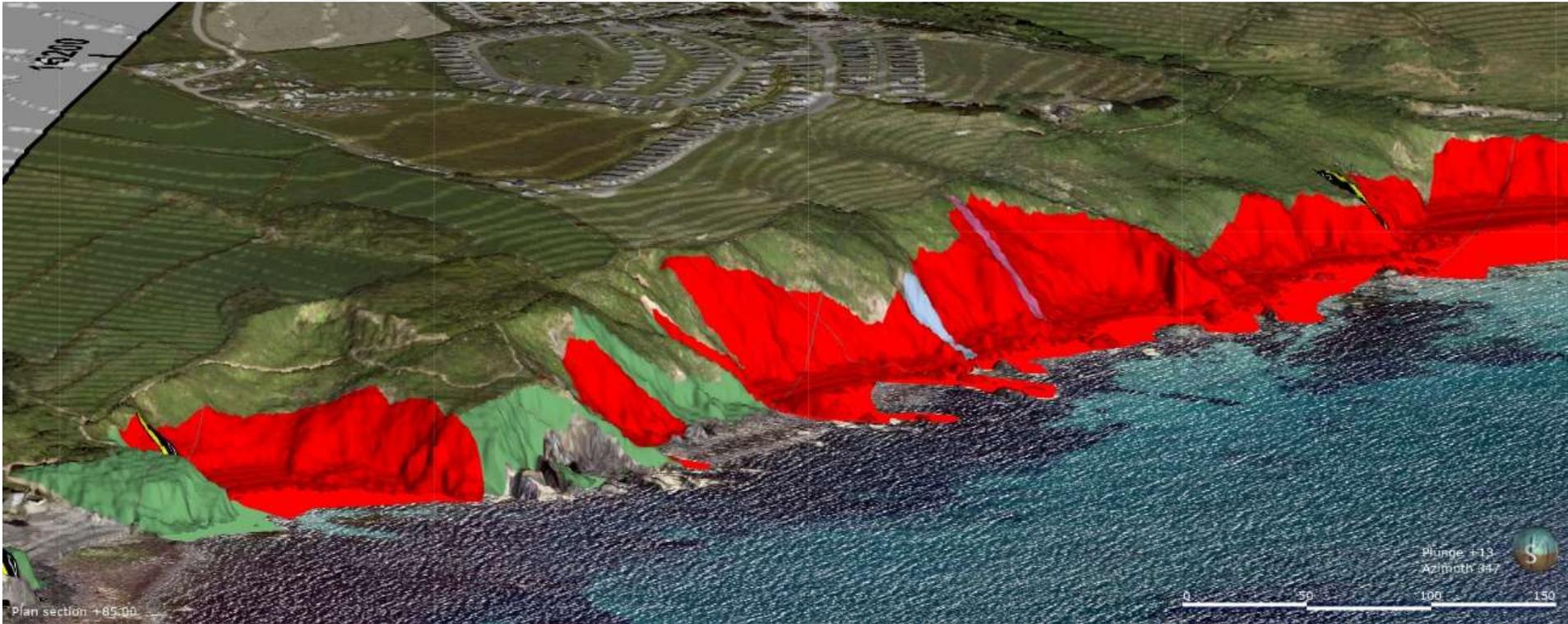


Appendix 8. Basalt thin section contain potassium (K) due to granite contact

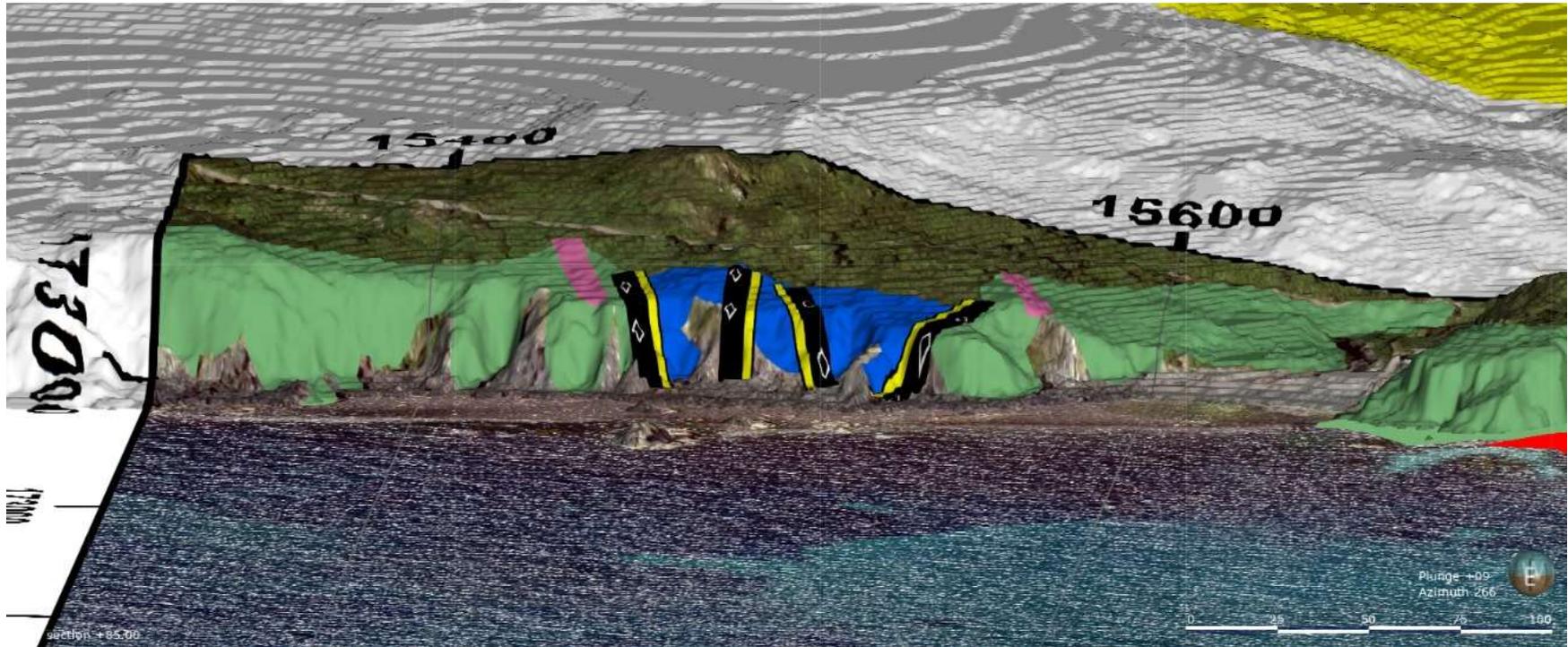
Potassium is referring to alkaline basalt. However, potassium is not the primary elements in the basalt samples in the study area. This potassium content comes from Kennack Gneiss' plagioclase associated with the gabbro and sheeted dykes. For this reason, this basalt can be classified as a tholeiitic basalt because calcium content is high and also it has potassium content.



Appendix 9. Cliff 3D View and Geological Map in the Leapfrog Software



Appendix 10. Cliff 3D View and Geological Map in the Leapfrog Software

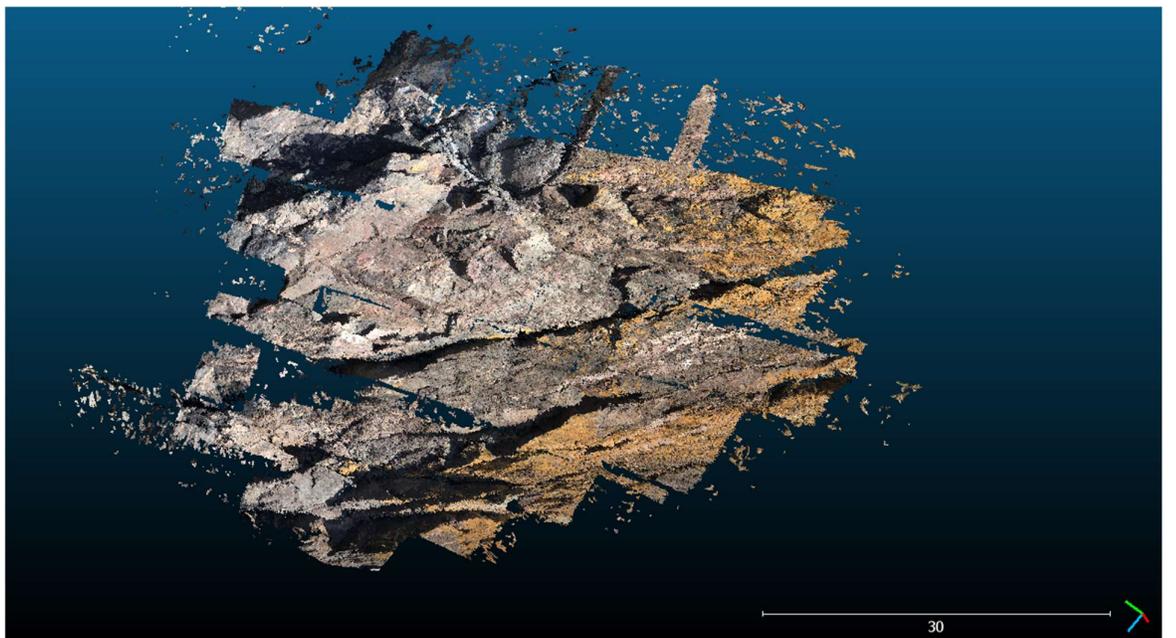


Appendix 11. Cliff 3D View and Geological Map in the Leapfrog Software

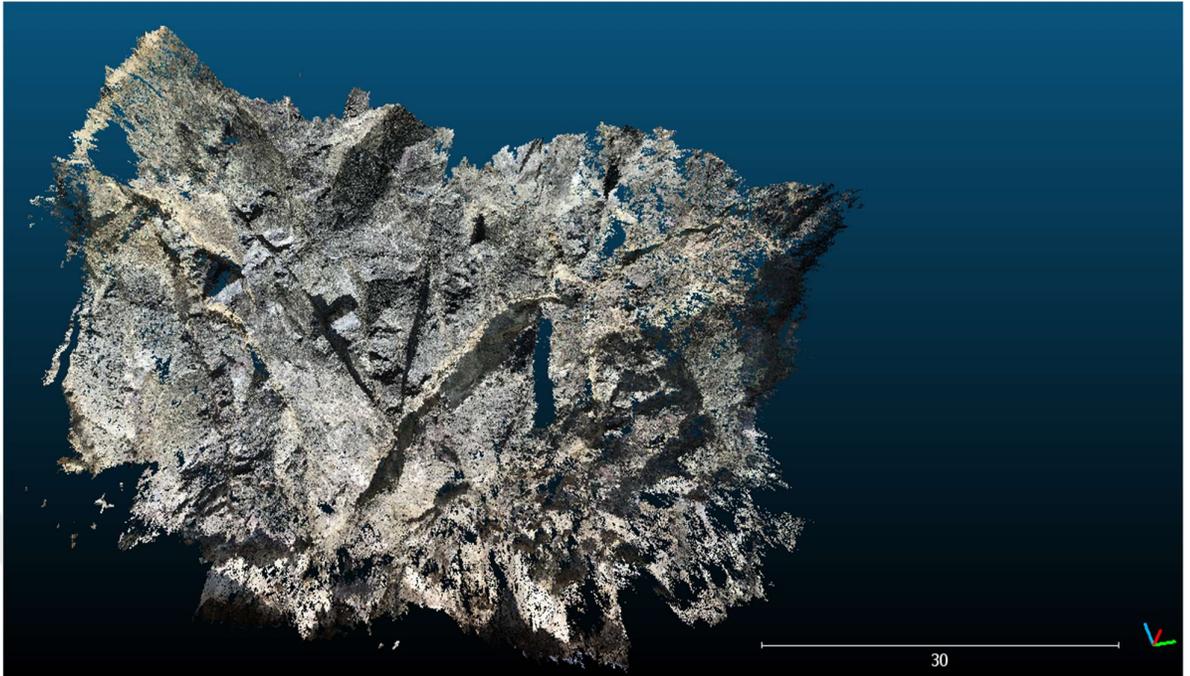
3D model's two-dimension photos come from the Cloud Compare software.
These are the result of .LAS documents in the software.



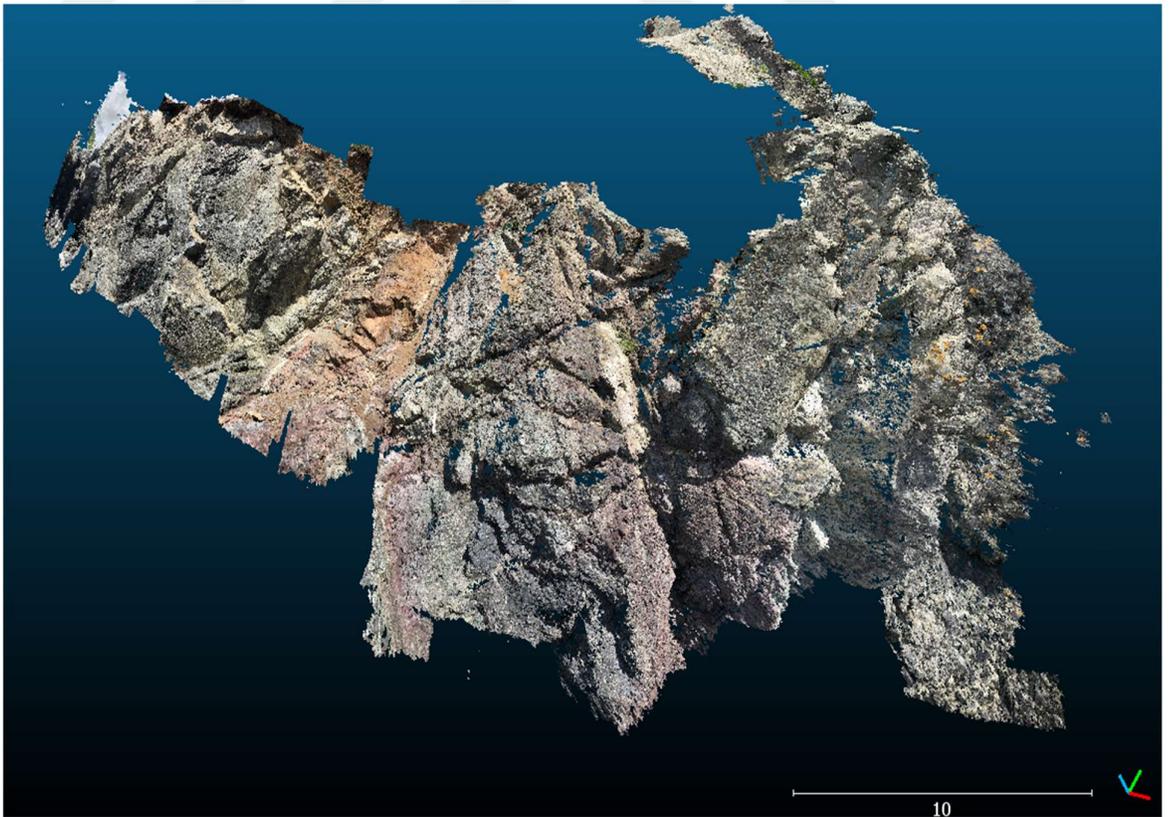
Appendix 12. Kennack Gneiss 3D Model



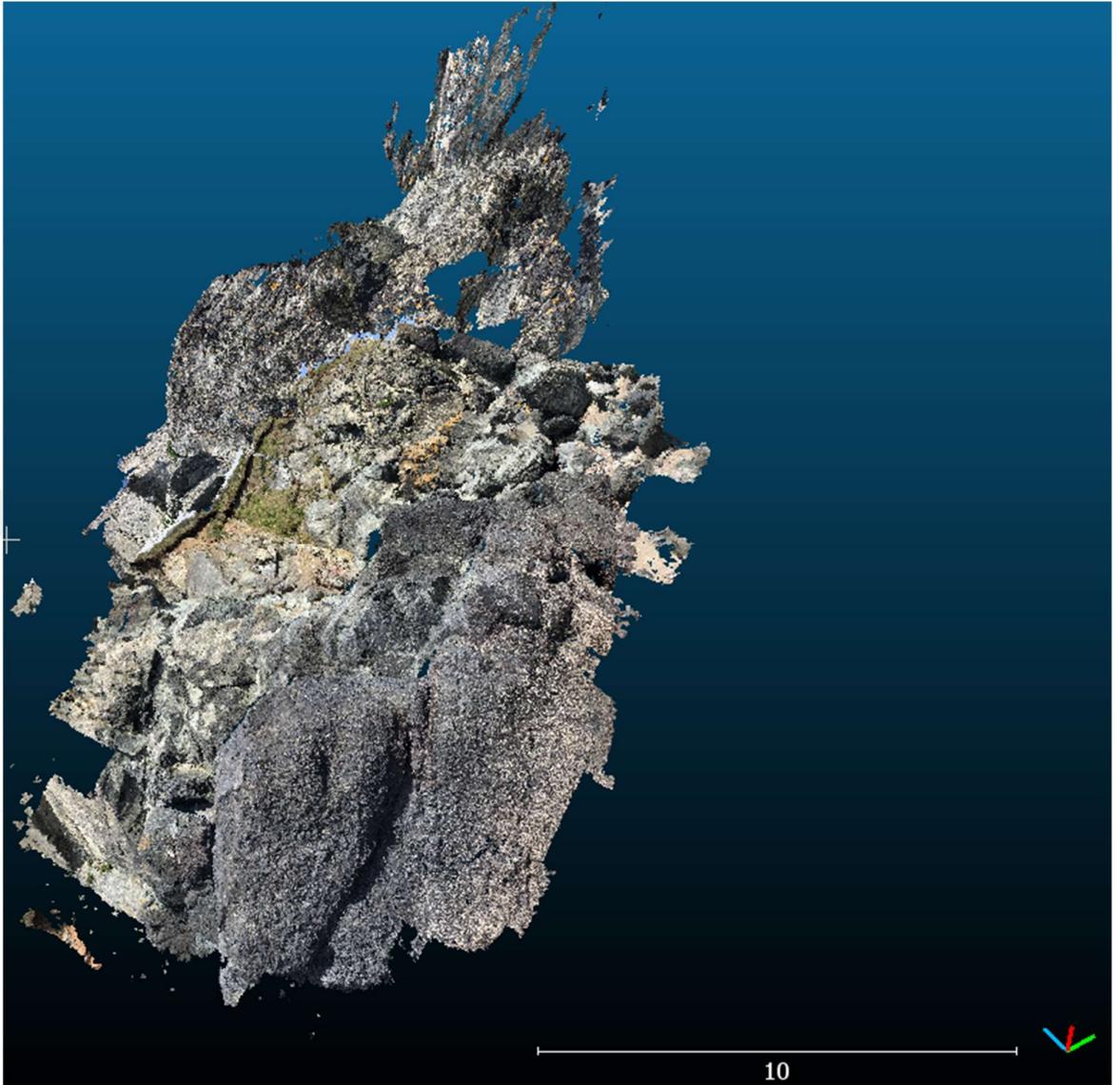
Appendix 13. 3D Model of Bastite Peridotite but not complete



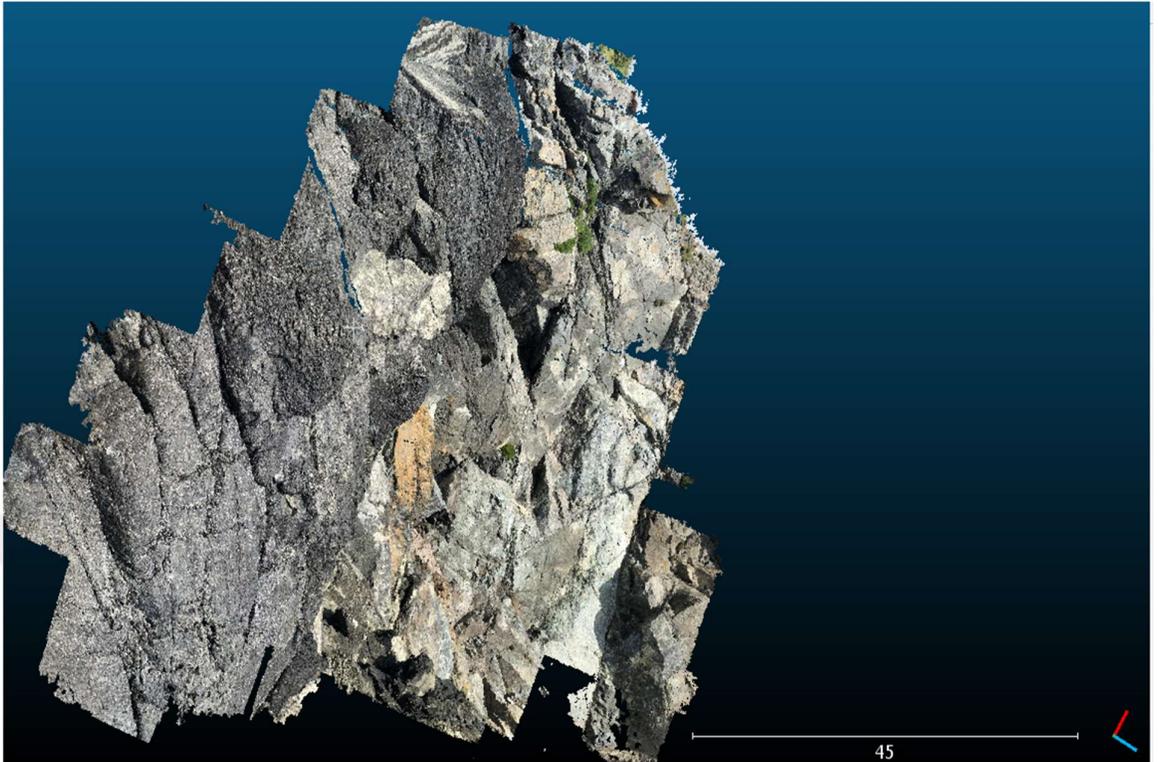
Appendix 14. 3D model of Peridotite which has cracks



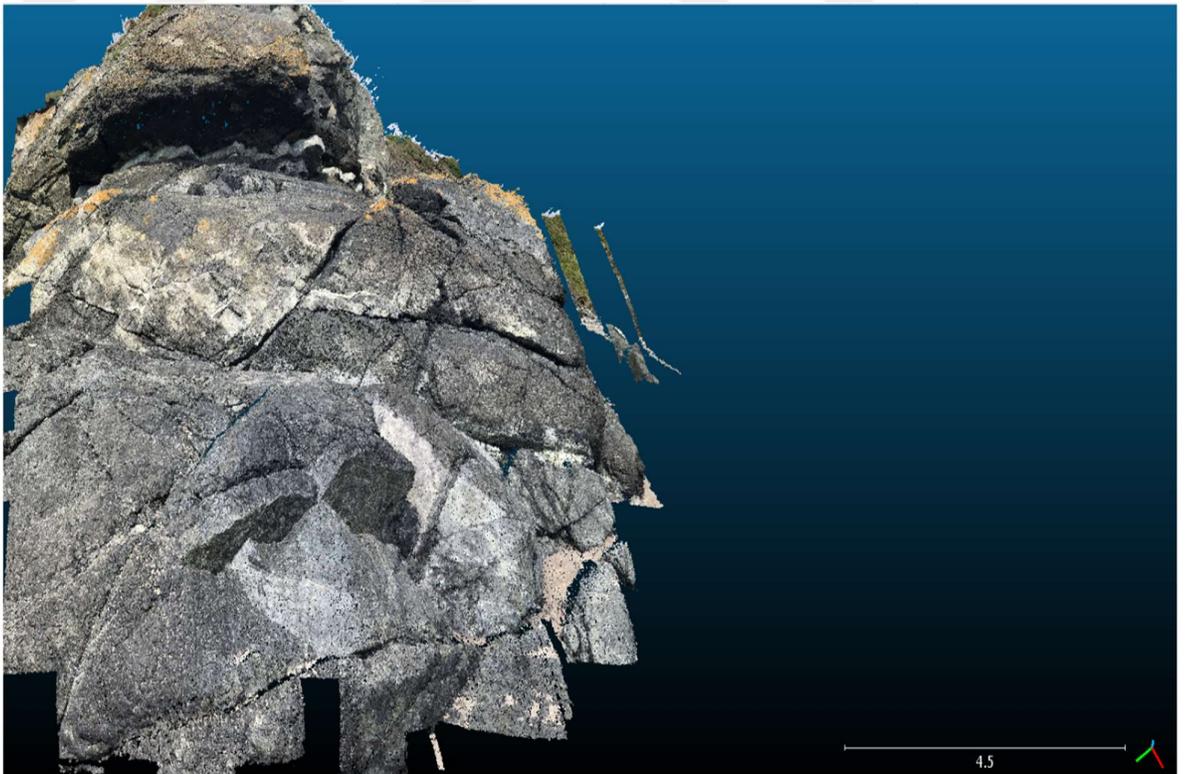
Appendix 15. 3D Model of Contact Between Peridotite and Gabbro Dyke



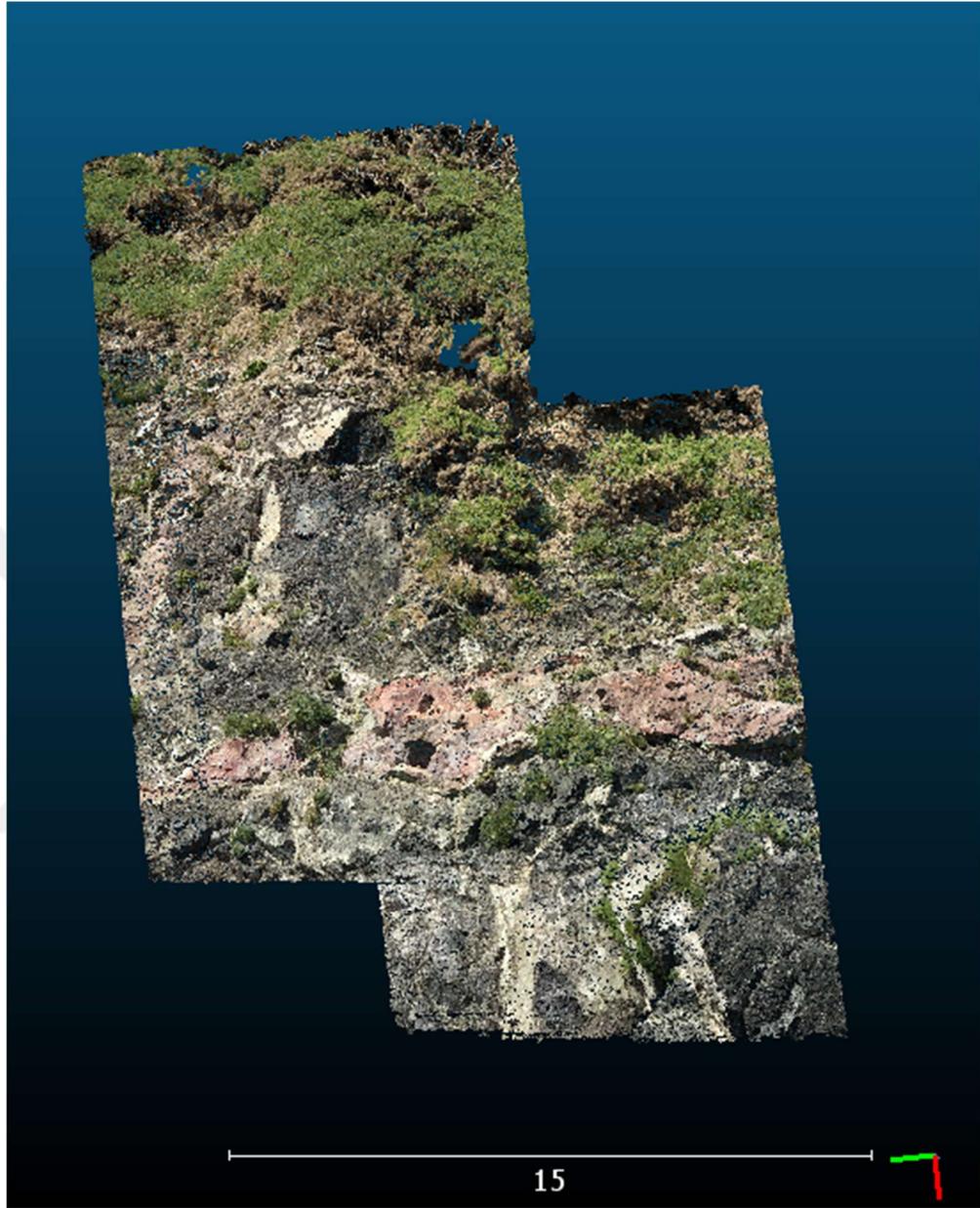
Appendix 16. 3D Model of Basalt - Kennack Gneiss and Grass Part



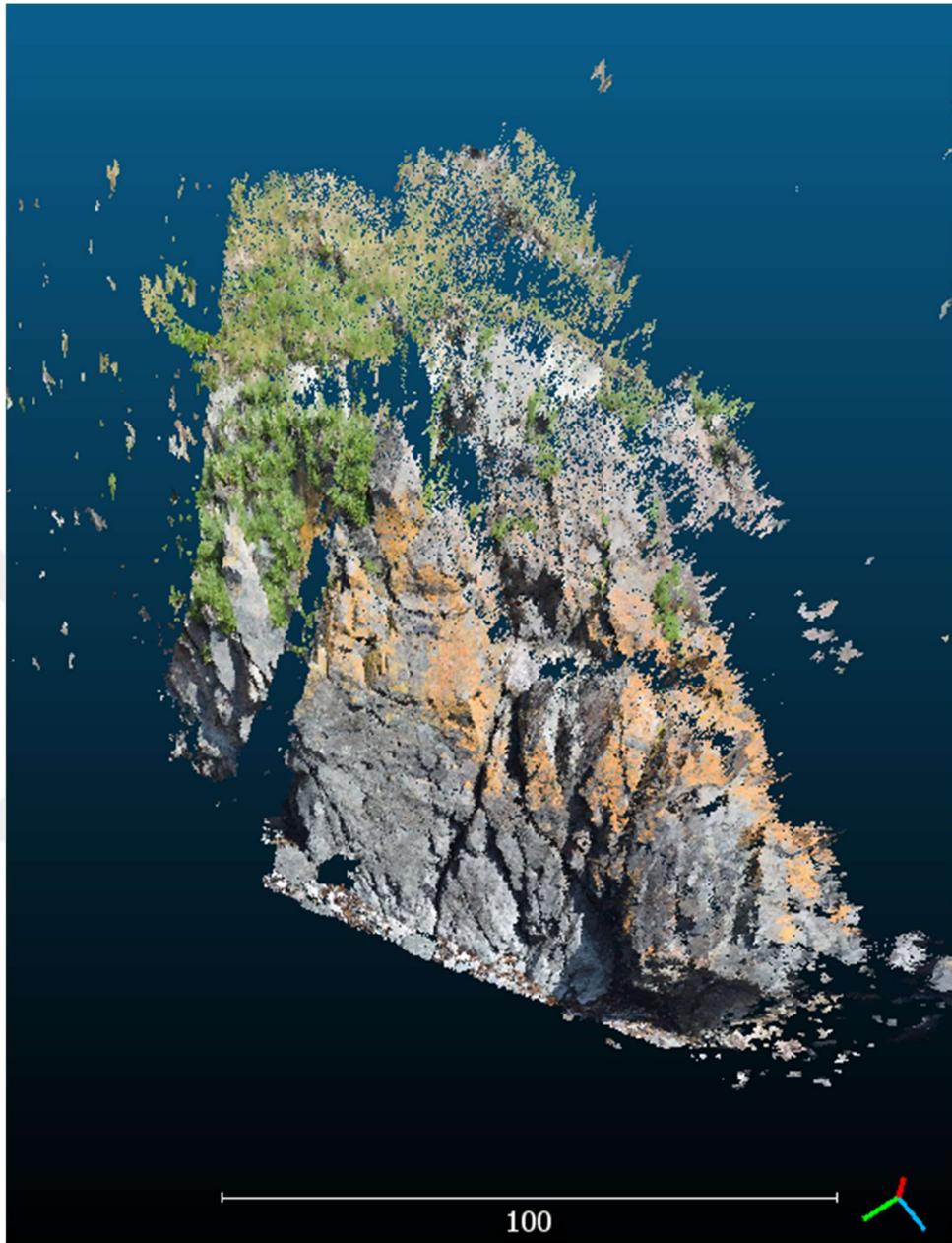
Appendix 17. 3D Model of Contact Points in Study Area



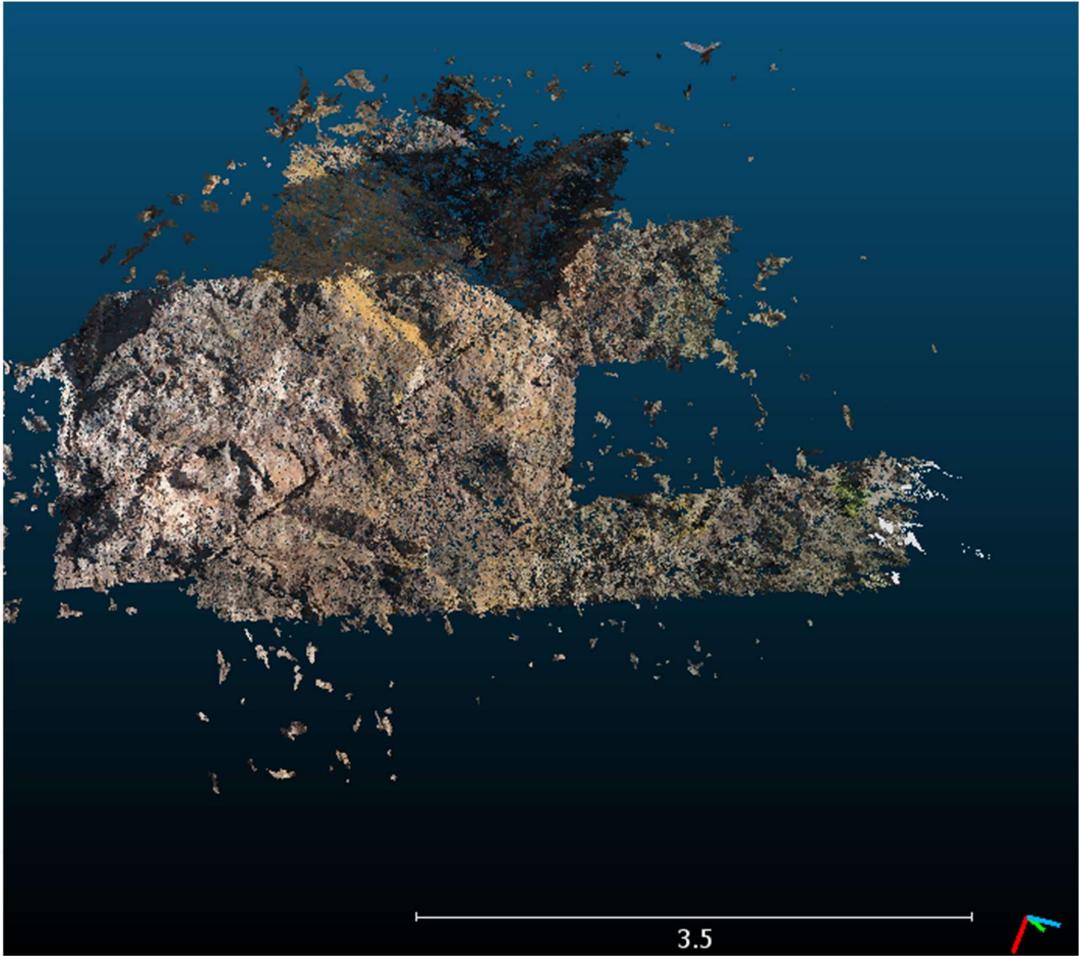
Appendix 18. 3D model of Kennack Gneiss (Mostly) Basalt Section



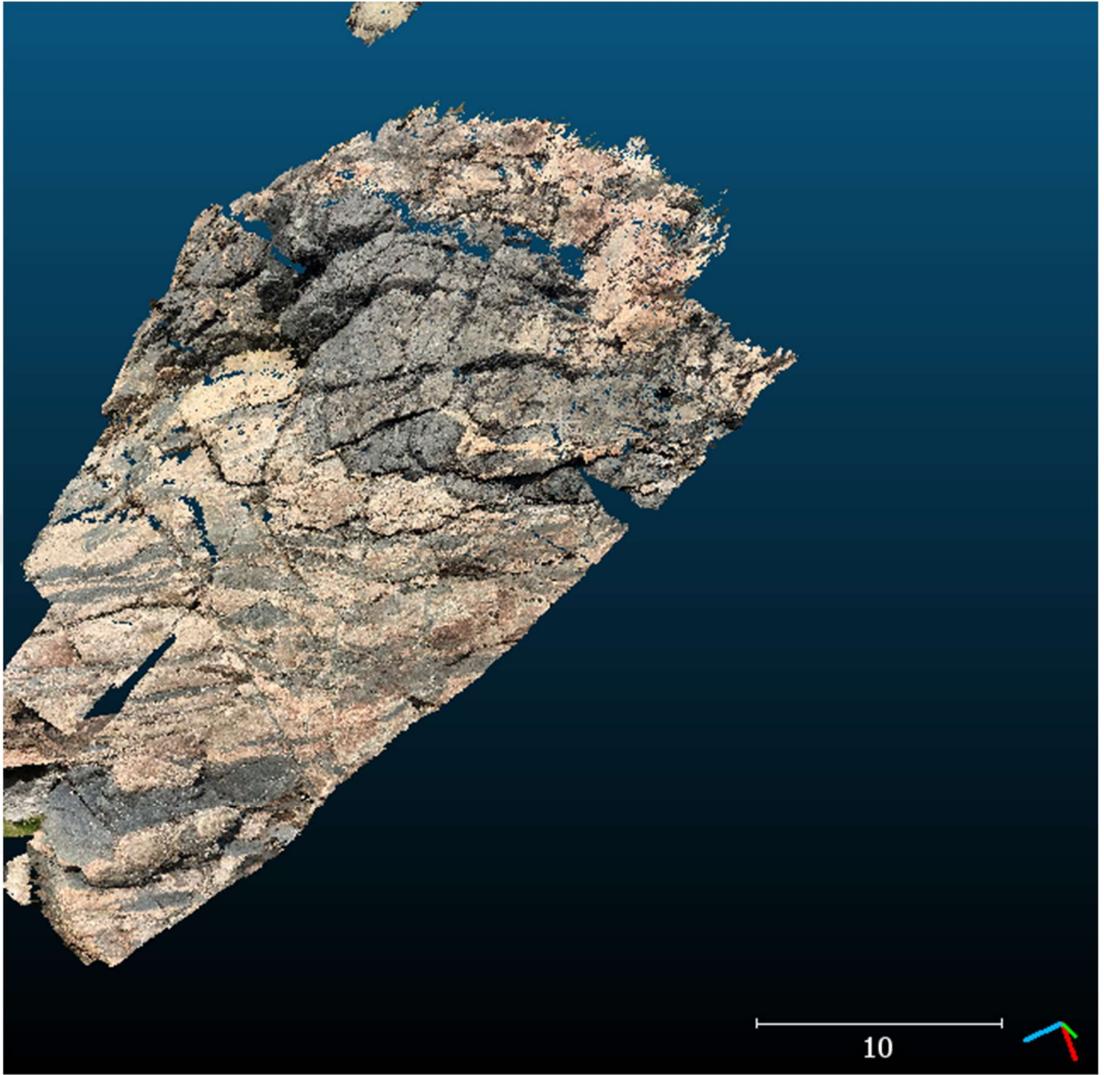
Appendix 19. Basalt Dyke 3D Model and Grass Part as much as Photo Quality



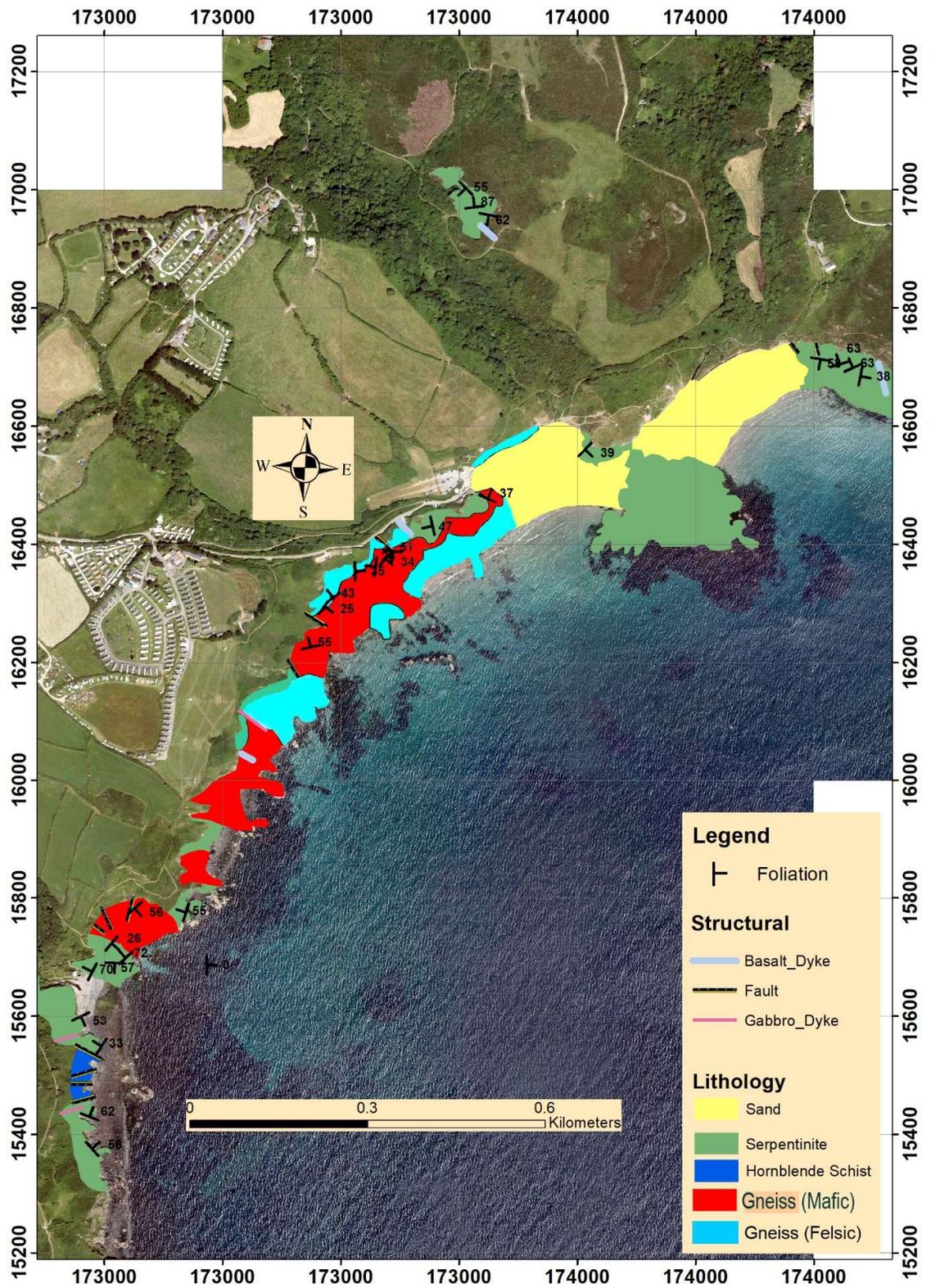
Appendix 20. 3D Model of Kennack Gneiss Mafic Part



Appendix 21. 3D Model of Bastite Serpentinite- Shadow and Grass Part Cause to Error



Appendix 22. Kennack Gneiss (mostly granite) 3D Model



Appendix 23. The Geological Map of Study Area