Residential Excursion
to
Norway

Day 1

Saturday 22nd June – Subducting Baltica & Eclogite Extravaganza!

Reporter K. Braun

The day began with an introduction to the local geology at Selje Church Car Park.

Bergen to Trondheim is essentially one big lump of gneiss that is referred to in geological literature as the Western Gneiss Complex, WGC (also referred to as the Western Gneiss Region, WGR). The Western Gneiss Complex exposes the roots of the Scandinavian Caledonian mountain belt. Rock types include large ultramafic to mafic and acid intrusive bodies that have been modified to orthogneisses with bands and lenses of paragneisses including high-pressure (HP) and ultra-high-pressure (UHP) rocks such as eclogites, garnet pyroxenites and garnet peridotites.

Locality 1 – Shoreline @ Selje Church

The Norwegian gneiss is exposed at this locality, which consists of about 50% plagioclase feldspar, 10 to 30% quartz plus biotite and muscovite micas. The Norwegian gneiss is foliated with mica poor and mica rich layering. Most of these gneissose rocks were once igneous granites that have later been subject to flattening and/or shearing. The effect of buoyancy, vertical flattening, shearing and thrusting has caused the rocks to flatten and thin and the alignment of minerals that are platy or rod shaped. In some instances, these rocks have partially melted, indicating temperatures of 700 Celsius or more. The combination of melting and shearing, led to the formation of anisotropic layering into mica rich layers and mica poor layers. Pink pods are present, which are evidence of an augen gneiss. The presence of augen gneiss about the strain pattern in the rocks. The ‘Augen’ can either be rod shaped or blade shaped. Where the augen are rod like, they have been stretched in one dimension. Where two-way stretching occurs, the augen are flattened and stretched simultaneously to form blades (pancakes!). The augen in this region are strongly rodded indicating stretching in one dimension. The protolithic age of these gneissose rocks is thought to be 1700 to 900 Ma.

These rocks must have been involved with at least three phases of orogenesis; firstly during their initial formation as granites, secondly during a period migmatisation and flattening and thirdly, a period of exhumation and uplift to the present day ground surface. It is thought that the original granodiorite/granitic body formed during a major crust forming event and was subsequently overlain by Neoproterozoic sediments, before becoming entwined in the Silurian Caledonian orogeny about 420 Ma when they were converted to gneiss.

Meta basic amphibolite pods are also common and are wrapped within the body of the gneiss. It has been shown that these pods were once eclogites prior to conversion to amphibolite during exhumation. The wrapping of the gneissose material around the metabasalt material suggest that the metabasalt material is harder and less prone to melting compared with the surrounding granitic material; hence the more ductile gneissose material was effectively squashed around the harder metabasaltic material. Other metabasic pods are often found nearby either up or down the foliation to form lines of metabasic pods. These pods were once part of the same metabasic body that has been boudinaged. .See plate 1

Plate 1 Boudin Pod

Plate 2 En echelon

En echelon fracture sets are commonly visible in the gneissose material as well. These occur where stiffer bands of material fail by brittle failure when subject to stretching as opposed to rather than ductile deformation. .See plate 2

Locality 2 – Grytting

The rock at Grytting is a severely altered eclogite. The eclogites at this locality are designated as a national treasure. The name 'eclogite' comes from greek and means 'choice', which is interesting, as eclogitse choose not to have any plagioclase minerals within it! Eclogites mainly consist of omphacite and garnet.

In 1984, Smith discovered relict coesite in a clinopyroxene grain and noted poly crystalline quartz pseudomorphs after coesite, as inclusions within clinopyroxenes and garnets. Coesite is a high density variety of silica, which is denser than the earth's mantle and forms at mantle depths of at least twice the thickness of continental crust. The presence of coesite is therefore an indicator of "ultrahigh" pressures (UHP) in the region of 35 kbar or more, i.e. depths of 200km or deeper! Interestingly, Smith did not observe any evidence of UHP metamorphism in the adjacent gneisses. The mineral assemblage of these rocks is indicative of continental crust of amphibolite facies; thus 10 to 20 kbar pressures and 60 to 70 degrees Celcius. Smith therefore interpreted the gneissose rocks as a product of low grade metamorphism.

Question - how did coesite bearing eclogite that formed at pressures of 35kbar come to be juxtaposed against gneiss bodies signifying much shallower depths and considerably lower pressures of 10-20 kbar? Smith believed a 'foreign origin hypothesis'; where the eclogite and gneiss bodies were brought to juxtaposition by tectonic forces. The problem with this theory, is that does not explain how the denser eclogite bodies that are known to form at greater mantle depths than the gneiss, were brought together and mixed with the less dense gneiss that was thought to have formed at shallower mantle depths. An alternative hypothesis is that the eclogites formed in-situ from ordinary basalt or gabbro bodies that had been emplaced within the crust and that this crust was later plunged into the mantle at great depths and later uplifted to existing levels with evidence of higher grade metamorphism overprinted during uplift within the gneissose material but not the eclogites. This alternative hypothesis is referred to as the 'in-situ origin hypothesis'. When these theories were being debated, it was believed that only oceanic crust could be subducted…

Since 1984, relict coesites within garnet, omphacite and kyanite micro-inclusions and poly-crystalline quartz pseudomorphs after coesite have been identified across a number of other eclogite localities in the WGC, further supporting the idea that these eclogites have been subject to UHP and HP metamorphism. Further evidence for UHP metamorphism has recently been provided by the discovery of micro-diamonds in a garnet websterite lens within a small outcrop of peridotite at Bardane on Fjortoft island, well to the north of Selje.

Coesite has since been found in the gneissose material as well – providing evidence that the eclogites and gneissose material were metamorphosed together. As the gneissose material is a crustal protolith, it has been interpreted that continental crust was actually subducted to great mantle depths!

The most spectacular rock-type at this locality is the "pegmatitic orthopyroxene eclogite", originally described by the great Finnish petrologist Pentti Eskola (founder of the metamorphic facies principle). The rock is more correctly called a garnet websterite, and is similar to the coarse websterites of the Glenelg area in northwest Scotland. However the Selje rock has extremely coarse pale brown enstatite, pinkish red gemmy garnet and bright green diopside along with flakes of coppery-brown phlogopite mica and magnesite. Grains are up to 3cm long and rather randomly orientated, which is why the usually igneous term "pegmatite" has been used. Some recent research has led to the idea that this rock was originally a peridotite, but fluids rich in silica, potassium and carbonate have impregnated the rock and converted it into a websterite. Similar rocks are found among the "nodules" erupted in kimberlite pipes, and another outcrop of identical rock to the north of Selje near Molde contains metamorphic diamond! Back in 1921 Eskola deduced that such rocks were formed at very high pressures, and he would have been delighted to have been so well justified.

Locality 3 – Vetrhuset (Nordpollen)

The rock cutting along the road consists of gneiss with a pegmatite band. There is a high muscovite content, suggesting a sedimentary origin rather than igneous origin. Eclogite pods are visible in the road cutting, which are fine grained. The gneissose material appears to wrap around the eclogite pods. See plate 3

Pate 3 eclogite pod

Plate 4 meta-sed rock

At the shoreline, the gneissose material includes garnets, quartz and kyanite suggesting this rock pre-metamorphism was a silty mudstone that was converted to a mica schist.(Plate 4) White micas are present, which are a special type of muscovite that has a low aluminium high silica content with some magnesium and iron. This type of muscovite mica has a higher density due to a tighter packed atomic mass and is called phengite. Phengites form at low temperatures and/or high pressures. The presence of eclogites within the rock mass here is also an indicator of high pressures. Phengites are stable at significant mantle depths providing temperatures remain low. The bedrock at this locality is therefore not an ordinary mica schist but a high pressure variety. The garnets are calcium rich, which is further evidence of high pressures when present alongside kyanite and quartz. A close look at samples taken from the meta-sedimentary material revealed the presence of coesite inside garnet rims with quartz inclusions in the cores. The presence of coesite in the garnet rims indicates that the continental crust was also subject to UHP metamorphism. This site therefore suggests that the eclogite pods and surrounding country rock were subducted into the mantle and metamorphosed together; hence the eclogites were formed in-situ and are not of foreign origin.

At the end of the shoreline outcrop, the quart grains exhibit a rod lineation that can be traced into garnet granular textures. The quartz lineation is thought to have once been a coesite lineation that has subsequently degraded to quartz. Conversion of quartz to coesite will increase the density of the country rock since coesite is a higher density variety of quartz. This densification could therefore aid subduction of continental crust!!!

Locality 4 – Flatraket Quarry, Nordpollen

The rock in the quarry is a quartz syenite that has arbicular structure with massive, round plagioclase feldspar minerals that are purplish-brown in colour. This rock is barely deformed with a matrix consisting of hornblende, plagioclase, quartz and augite. The rock formed 1600 Ma as a coarse grained quartz syenite that was later metamorphosed 1100 to 1000 Ma to a high temperature and moderate pressure within the range of the granulite facies. When this rock was metamorphosed, ductile deformation did not occur. Insteadthe rock dried out and shrunk leading to brittle failure and fracture formation. If the rock had been wet, ductile deformation would have occurred.

Plate 5 -Flatracket Quarry

Locality 5 – Outcrop of The Day – Verpeneset

This gorgeous rock is one of the most perfectly preserved eclogites known.

Plate 6 Gorgeous Eclogite

It was formerly a gabbro that has been subducted and converted to eclogite. The eclogite at this locality has zones rich in garnet and grass-green omphacite, or sugary zoisite, kyanite, phengite and quartz (formely coesite). The garnets are speckled internally and have a dark red or even black, almandine-rich cores and a lighter red rims richer in the pyrope variety. Amphibole is trapped within the garnet cores, along with other low-pressure minerals like epidote, plagioclase and chlorite, and these give the cores their dark, speckly appearance. The omphacite rods are aligned and streaking is also evident at this location. This rock is therefore a L-S tectonite that has formed in response to being stretched and flattened. The zonation in the garnets shows that they grew during increasing pressure and temperature along a trend typical of subduction zones, but in this case the crust being subducted was continental, and the eclogite was probably an intrusion of gabbro within it.

Norway Report (Bremanger)
Day 2 Sun 23/6/13

Reporter: *Maggie Donnelly (with **lots** of help from Dr Simon Cuthbert!!)*

At 9.00 am on a lovely morning, and forewarned by our leader – “Don’t miss the ferry!!” – we sailed from MålØy out into Nordfjord bound for Bremangerland – ‘the land of glaciers’. It was fabulous – the views were spectacular looking back at the town, the bridge linking the island of VågsØy to the mainland, the mountains and the islands.

The land we had left, to the north and far to the east, was part of the Western Gneiss Complex (WGC) of ‘Caledonized’ Baltic Basement, most of whose original crystalline rocks were formed during Proterozoic orogenies. They underwent recrystallization and deformation during the Scandian orogeny, with the degree of “Caledonization” increasing systematically from minimal in the southeast to diamond-grade eclogite facies in the northwest. On top of this is an orogenic wedge consisting of four allochthons (thrust sheet assemblages) that were thrust E/SE over the autochthonous Baltic Shield when the Iapetus Ocean closed and Baltica subducted beneath Laurentia during the 430–385 Ma Scandian orogeny. These are the Lower Allochthon (pre-Scandian arenaceous sediments), the Lower and Middle Allochthon (crystalline slices and their sedimentary cover derived from the Baltica margin), the Upper Allochthon (oceanic terranes derived from Iapetus and its margins) and the Uppermost Allochthon (stranded Laurentian upper plate which does not occur in this southern area of Norway). Today we would make a traverse through these allochthons.

We arrived at Odleide on Bremanger, just beside the terminal, where there was a huge black cliff. We were now in the structurally highest part of the WGC, and very close to the edge of the Hornelen Basin, a large mass of Middle Devonian redbeds that extends over 40 kilometres inland towards the east. The islands we had sailed past were composed of augen gneiss units with layers of quartzite and meta-anorthosite (a plagioclase rich meta-igneous rock) enclosing small bodies of eclogite and serpentinite. Similar coesite-bearing eclogites on the north side of Nordfjord such as at Verpeneset (which we saw yesterday) have been metamorphosed at a maximum pressure of 27 kbars and 670^0C corresponding to a depth of about 90 km. It was remarkable to think that rocks of such deep origin were now found so close to almost unmetamorphosed sedimentary rocks which have never been deeper than a few kilometres from the surface. The rocks of the great cliff overlooking the ferry pier were flaggy, layered with small isoclinal folds and with a platy character, an extremely fine-grained grey gneiss with little bits of K-feldspar augen. We were now in a 5 km thick zone of mylonite with a consistent south-dipping foliation, extending a minimum of 40 km eastwards from the mouth of the Nordfjord. It is a ductile shear zone formed at 500 – 600^0C and 8 – 10 kbar in the Lower to Middle Crust. Lapworth coined the term ‘mylonite’, which means ‘milled rock’; however**,** *these* rocks were not formed by milling or crushing, but by intense ductile shearing in which the rocks behave almost like plasticine – the grain size reduction was brought about by ‘hot-working’. On the other hand, about 1 km south and up the structural section along the road towards the tunnel through the mountain, the mylonite behaves in a more brittle way – as an **ultra**cataclasite (a cohesive or welded tectonic breccia).

We made our way down to the shore where weathering had picked out the structure and grain size reduction in the rocks; they contained paper-thin layering and small deformed pegmatites.

Paper thin layering and asymmetric augen

They had originally been granites and diorites and had *en-echelon* veins – arrays of quartz-filled fractures which formed during shearing when the rock was coming up to the surface. As it did so, the pressure was released and fluid entered. There were asymmetric augen and mineral lineations that indicated top to the *west* shearing. This thick package of mylonites lies within the Vetvika Shear Zone (one of the world's biggest ductile shear zones) which caps the WGC and is part of the enormous Nordfjord-Sogn Detachment Zone that runs along the coast from MålØy to Bergen. Its top-west shear sense is consistently opposite to the direction of the main thrusts along which the overlying Caledonian allochthons had been moved hundreds of kilometres to the east. It is also younger than those thrust faults and often coincides with, and overprints them, showing that the motion on these major Caledonian thrusts has been reversed, apparently carrying the allochthons back to the west over the WGC (the Baltic cratonic margin) from where they had come, a process that was, when first discovered in the 1980's, called "orogenic collapse". It is almost identical to the geometry of the South Tibetan Detachment System in the High Himalaya of Nepal and the Tibetan Plateau.

The process is now thought to have occurred in a manner something like this: the cratonic margin of Baltica had collided with Laurentia and had followed the oceanic lithosphere down the subduction zone for a couple of hundred km – continental subduction! During this subduction the eclogites formed within the Baltica rocks, at around 425Ma. However, the oceanic lithosphere broke off from the continental leading edge and sank away from it into the deeper mantle. The buoyant continental material was now free to rise back up the subduction zone, and it slid up along the underside of the allochthons. So, although it looks as though the allochthons had slid back down to the west, in fact the WGC had slid back up to the east underneath them. Here it's better to think of the *upthrow* of the fault rather than the downthrow! It was a simple shear system, like a pair of scissors, in which the *footwall* of gneiss moved *upwards* and to the *east*. This had happened after eclogite facies metamorphism at 425 Ma – the WGC experienced very rapid decompression associated with early slip on extensional detachment horizons. It was exhumed rapidly with little loss in temperature, and then cooled quickly at this depth. (It was jokingly suggested that the process ***could*** be described as Ultra **Low** Pressure Metamorphism – ULPM..........although in fact it isn't!!) During this time the eclogites, and especially the gneisses, experienced retrogressive metamorphism such that most of the high pressure minerals were obliterated, with only some of the rare eclogites now surviving to show what had happened.

Viewpoint over the Nordfjord

We drove up the hairpin road towards the south to a viewpoint over the Nordfjord, from where MålØy could be seen in the distance. Passing through a tunnel we crossed over the uppermost mylonites and, in a tunnel through a high ridge passed a thin belt of ultracataclasite (cohesive, welded fault breccia) and fault gouge. Here was a major tectonic break where we would leave the WGC and its cap of mylonites and enter the overlying allochthons. In the next part of the excursion, traversing the island of Bremanger, we would pass over the Middle and Upper Allochthons. The Middle Allochthon is a basement-cover thrust sheet complex similar to Assynt, with Baltic gneisses and their psammitic cover. This is equivalent to the giant Jotun Nappe Complex in the Jotunheim mountains far to our southeast. The Upper Allochthon comprises slices of the Solund-Stavfjord Ophiolite Complex and formed ~ 440 Ma, just offshore from Laurentia as Baltica approached, in a manner similar to, but later than, Dalradian events in Scotland. When collision occurred, this ophiolite, the youngest in the Caledonides, was thrust up and over the Baltica crust. However, there would be no sheeted dykes or pillow lavas in our visit today; instead the supra-ophiolitic Kalvåg Melange is found, intruded by an island arc granodiorite at about 440Ma, with accompanying contact metamorphism producing sillimanite and cordierite. This was overprinted by low-grade regional metamorphism, probably around 425 Ma associated with obduction of the ophiolite and collision with Laurentia.

Continuing up structural section southwards into the classic U-shaped glacial valley of Kongsdalen and then swinging west along strike, we arrived at Dalsbotn. The Bremanger Gneiss basement of the Middle Allochthon lay in the hills to the north, and unconformably overlying it in the valley side to our south was a bedded and folded quartzofeldspathic meta-psammite of a type commonly known in Norway as “Sparagmite”. This basement-cover pair is repeated several times in a thrust duplex, and here we were able to examine the psammite in one of these thrust slices, with occasional cross-beds showing younging away from the basement. There is a history of major sandstone deposition events on the northern continent from around 1000 to 600 Ma, suggesting erosion of the old Grenville, Sveconorwegian and Valhalla orogens. Examples include the Moine, Torridonian and Grampian Group in Scotland. It has been proposed that there was a Scandinavian shallow sea ~ 600 -700 Ma, whose sediments now form part of the Lower and Middle Allochthons. Turning to face south, the steep valley wall exposes greenstones of the ophiolitic upper allochthon that lie structurally above the Middle Allochthon; so exposed in this one valley is a cross section through a large part of the Scandian nappe pile, containing rocks which represent the tectonically telescoped Baltica continental margin through into the Iapetus Ocean that lay outboard of Laurentia. Not bad for a single viewpoint! The valley itself is cut along the trace of the parallel Dalsvatn and Kongsdalen normal faults that sole down into the Vetvika Shear Zone and are probably syn-sedimentary faults related to the nearby Hornelen Basin. The Old Red Sandstone fill of this basin unconformably overlies all the rock units in our field of view on the flanks of the spectacular peak of Hornelen just out of sight to our east.

We continued to the southeast, and then cut south up section into the upper allochthon ophiolitic rocks at Bremanger village, before driving round to the south shore of the Bremanagerpollen fjord, in deformed variants of the Kalvåg Melange, to arrive at Loviknes by a lovely bay. Our leader pointed out the thrusts/detachments in the surrounding mountains as well as the different allochthons, before taking us into a quarry of quartzite with abundant graphite. This was the cover over the green schist volcanics of the Upper Allochthon, and was laid down originally as organic rich muds with silica – radiolarian chert – on a deep ocean bed. The chert had changed to quartzite, and then to quartz schist because of the layers of graphite and mica. There was chlorite and sericite (a mica) but no feldspar. Some distance to the south were greywacke turbidites, as well as enormous turbidite blocks and volcanic rock, the latter associated with the nearby Solund-Stavfjord ophiolite complex, which formed at 443 ± 3 Ma. These are interbedded in a mud matrix with chert beds. Folding occurred as the whole mass in great slabs slid down the submarine slope creating olisthostromes – a melange of continental- and oceanic-derived materials. The setting for this could well have been an island arc; the clastic sediment was deposited in a back-arc basin rather than open ocean, and was probably derived from the adjacent arc. There was an enormous boulder at the entrance to the quarry and we were able to examine it and identify many of its clasts…… huge, large, small and tiny.

From here we drove up into the hills for lunch in an intriguing valley bowl containing the lake Rylandsvatn. We sat on greywacke and could see paler diagonal sheets of granodiorite cutting across the darker rocks, and also in the distance, the igneous contact of the granodiorite, a pluton extending some 20 km and cutting across units in the Upper Allochthon. The greywacke had been hornfelsed by the granodiorite in contact metamorphism, and was now tough with little veinlets; it did not have a coherent stratigraphy but was badly disrupted – giant blocks in a granodiorite matrix. Thermal shock had fractured the greywacke into sheets that foundered into the granodiorite magma at temperatures of up to 900 -1000^{0}C in a process known as stoping. The granodiorite was an arc related magma, which had invaded the ophiolitic melange in the Iapetus Ocean. Ophiolite obduction had occurred at ~ 425 Ma (Wenlock) – at almost the same time as the WGC eclogite formation. All this had taken place just off Laurentia, with Baltica on the horizon. We walked over the greywacke, examining the granodiorite veins, dykes and stoping, and found hornfels with striking crystals of cordierite in the muddier beds.

Returning to the bus, we then drove further to the southwest end of the Bremangerlandet and parked just before the Bridge to the island of FrØya. Here at the side of the road, where some large blocks of the granodiorite lay, was the Kalvåg Melange type locality and again the hornfelsed contact. Cordierite had weathered out of the pelite bed and there was sillimanite indicating that the metagreywacke had experienced a very high temperature (850^{0}C) but low pressure (4 kb, 12 km depth). Across the bridge to the island was the 440 Ma FrØya gabbro, while across the sound of Frøysjøen, in the bare mountains and islands to the southeast lay the Middle Devonian sandstones of the central Hornelen Basin.

We headed back the way we had come but instead of returning through the tunnel to Odleide we continued eastwards on the road along the north of Bremanger and then through a sub-sea tunnel to the island of Rugsundøya. We had a comfort stop beside a small fjord, and in the 860 m high cliff face of Hornelen mountain across the water (the highest sea-cliff in Europe) we could see the unconformity of Devonian conglomerates and sandstones on top of augen gneiss and quartzite. Legend claims that Olav Trygvasson (Norwegian king 995 -1000) climbed this face, and the viking raider fleets used to rendezvous below it. Our leader produced an amazing diagram of the Hornelen Basin geology, showing the proportion of different clasts he had found in the conglomerates, in the early days of his geological career. The whole basin had been formed by a huge listric fault, and the sediments had been sourced from the same Middle and Upper Allochthon rocks as we had seen on Bremanger. The setting was very similar to the fans of Death Valley, with alluvial fans at the sides and axial sandstones down the middle. A huge quantity of sediment had been deposited – up to 100 m thick units of clay, fine and coarse sandstone, with diagonal syn-sedimentary faulting. However………..the basin was now today's mountain range……………erosion had reversed the topography.

We drove on eastwards, crossing by a bridge to the mainland and then through the brand new 6 km Vingen Tunnel below the 750 m conglomerate arête of Vingen, then to the southwest, surrounded by high mountains and ice caps, to an old quarry in a gorge near the ferrosilicon smelter plant at Svelgen, where we could examine these massive Devonian sandstones with huge cross bedding. The sand had been transported from east to west in the basin, the coarsening up sequences fingered into each other and this was repeated for a stratigraphic thickness of 25 km, with all the beds dipping at about 25^{o} to the west. They had been originally red but were now green as a result of weathering, and mild metamorphism had formed chlorite, preserved in the lower slopes of the quarry face because these had been covered by glacial till. Over to the west was shale, sand and conglomerate from debris flow fans, and lacustrine deposits occupied the middle of the basin. There were regular cycles of sedimentation, the reasons for which are currently debated. They could be a result of regular fault movements on the basin which then filled up, **or,** as our leader favoured, of 100,000 year Milankovitch-type climatic cycles. There was, of course, no evidence for ice having been here in the Devonian.

We had a 'view stop' by the lake Dalsetevatnet to see the big picture – the basin fines interfingering with alluvial conglomerate, with mud at the base of each coarsening-upward cycle, was obvious. Simon has logged the clasts and they all derive from the Middle and Upper Allochthons. We continued west to a locality just before the Isane tunnel, to examine the Devonian conglomerate. It contained no WGC clasts of the High Pressure Zone; instead, sand and mud were eroding out. The basin is Middle Devonian (about 380 Ma) and so the Western Gneiss Complex, which has mica Ar-Ar ages also around 380 Ma had still lain at more than 30 km depth when these sediments formed at the surface. They must have emerged at the surface later, even as late as the Carboniferous – this would explain the lack of WGC clasts in the basin conglomerates.

We were now rushing for the ferry and another beautiful sail back north across Nordfjord towards home. Looking to the southeast from the ferry, the normal-sense low angle detachment fault between the mylonitic gneiss and the Devonian sediments was dramatic. Subducted Baltica crust with eclogites and entrained fragments of mantle peridotite (exposed in the mountains to the west) had risen up from the mantle to lie adjacent to the conglomerate, using the Nordfjord-Sogn Detachment shear zone, which had been the original subduction channel………this fault had a throw of over 100km!

We disembarked on the north shore and drove the considerable distance back west to MålØy, and to our 'very welcomed' dinner, after a fascinating and challenging day of geology.

Later, and suitably refreshed, as it was midsummer a number of us set off to Kråkenes fyr at the northernmost tip of VågsØy to see the midnight sun. We arrived at the lighthouse around 11.45 pm, in time to see the last of a bonfire set by some revellers. The local sheep were most unhappy to have their seclusion disturbed and were somewhat aggressive – I've never been accosted by a sheep before!! However, it was all worth the effort as we watched the sun sink down behind the clouds and then return in a very few minutes. We were a very merry band……. especially as someone had had the presence of mind to bring along some 'cheer'! And so, after a ***very*** long day, we got back to the hotel and so to bed.

References

1. Excursion Notes, Dr Simon Cuthbert (and lots of help).
2. W.J. Wilks, S.J. Cuthbert, 1994. The evolution of the Hornelen Basin detachment system, western Norway: implications for the style of late orogenic extension in the southern Scandinavian Caledonides, *Tectonophysics 238, 1-30.*
3. Hannes K. Brueckner and Simon J. Cuthbert, 2013. Extension, disruption, and translation of an orogenic wedge by exhumation of large ultrahigh-pressure terranes: Examples from the Norwegian Caledonides. *Lithosphere.*

Day 3, 24 June 2013.
Reporter: *Julian Overnell (with a lot of help from Dr Simon Cuthbert).*

The main theme for the day: a visit to large area of mantle dunite in Almklovdalen and to a dunite mine at Aheim.

Tectonic background. The area of mantle rock is approx 10 km^2 in the form of a vertical sheath fold with gneiss in the sheath core and surrounding the sheath. The rock is thought to be typical of mantle rocks and is similar to mantle xenoliths sometimes found in dykes. The bulk of the rock is high magnesium forsterite with a minor magnesiochromite spinel ($MgCr_2O_4$) and occasional flecks of phlogopite mica. Although the chromium content is less than 1%, this value is high compared with most crustal rocks. The emplacement is thought to be due to the subduction of Baltica deep into the mantle under Laurentia during the Scandian orogeny. The subduction presumably froze surrounding mantle, and when the continents subsequently pulled apart this piece of mantle was drawn up and is now at the present erosion level. Basalt, which forms the basis of most cratons, is the first melt of mantle rock, so the question arises: did this piece of mantle contribute to the formation of Baltica? Analyses of U-Pb ages in 4,000 to 5,000 detrital zircons in stream sediments from all over the Baltica craton have either mid proterozoic or Caledonian ages but no Archaean ages, except for streams draining this dunite mass which do show Archaean ages. Thus it seems that this mass was not responsible for any of the surrounding gneiss and is very much exotic. It probably lay beneath the margin of Laurentia immediately before the Caledonian orogeny.

The Excursion. The party drove to Almklov, parked near Lien Farm (0323466,6879335) and walked up a track through the woods before striking off left across rough countryside of moss, heather and scrub to finish at the small summit of Helgehornvatnet (0322451,6879234). This is a protected site for the geology (and plants); no collecting allowed. Before protection, the site had previously been dynamited by rock collectors. This had the effect of exposing bright garnets and an interesting fold structure – for us to see and enjoy.

Fig. 1. Bright "cape ruby" garnets and chrome diopside with some yellow-weathering olivine and yellowish-grey enstatite in loose clasts of garnet-pyroxenite at Helgehornvatnet. Secondary amphibole replacing the diopside is found in darker green patches .

Fig. 2. View of mantle dunite with folds of garnet pyroxenite.

The corrugated internal cast of a fold on the left of the picture has been interpreted as a structure which arose from mixing of two ductile rocks of different viscosity; in this case the surrounding dunite was more ductile than the pyroxenite. The folded garnet pyroxenite just above and below the handle of the walking stick and which abuts the corrugations has been interpreted as due to intrusion as dykes deep within the convecting mantle and is unrelated to the Scandian subduction/exhumation event.

Fig. 3. The group standing on top of the mantle

Fig. 4.

Close-up view of garnet pyroxenite bands *in situ*.

These garnet pyroxenite layers (darker weathering) do not have a basaltic composition and are therefore not eclogites, but are a more ultramafic, picritic composition and are thought to be igneous dykes intruded at mantle depths. The colours of the garnets in these bands range from purplish-red "cape ruby" Cr-rich pyrope in the orangey peridotite layers to orange almandine in the websterite layers, especially near their centres. The more purple colour of the garnets towards the edges of the websterites and in the peridotite are due to metasomatic uptake of Cr from the pre-existing chromite-bearing dunite. Likewise, as seen in other exposures at Lien, the garnet and pyroxene content in the peridotite tends to decline away from the pyroxenite layers until it disappears and the rock becomes a pure dunite. It is thought that the chemical components of the pyroxenite magma diffused a short distance into the dunite, causing garnet and pyroxene to develop, a process known as "refertilisation". This is thought to have taken place during the mid-Proterozoic

Other fold structures in the mantle rock were visible at this location, in chlorite-amphibole peridotites, but the folding was again spectacular, as in Fig. 4. The chlorite is pale purple and chrome-rich as it formed by retrogressive metamorphic breakdown of chromite or chrome-pyrope after the peridotite was emplaced into the crust, probably during exhumation. The darker layers are hornblendite formed by retrogressive metamorphism of the garnet pyroxenites.

Fig 5 Spectacular folding of banding in mantle rock

Visit to Sibelco Grubse olivine quarry. The quarry produces forsterite sand. The main use of the sand is for slag "conditioning" in blast furnaces and basic oxygen furnaces in which role it is a suitable partial replacement for magnesite. It is also used for making refractory bricks for steel furnaces and casting sand for foundries.

The party was met at the gates by a production geologist Marte Kristin Tøgersen. After donning safety boots and hats and high visibility vests we were taken to see the crushing of the ore, then into the quarry where we witnessed one of the twice weekly blastings. The track followed the margin of the quarry where it had apparently been put through a band of eclogite or garnet pyroxenite which had undergone partial alteration to leave a selection of interesting-looking rocks in the roadway. "Cape ruby" garnets and green chrome-diopside/omphacite were visible in many rocks together with their contact alteration products including dark amphibole and purple chrome clinochore (kämmererite) having the appearance of mica. These were collected avidly.

Visit to Oppedal on the coast of Vågsøy near Måløy (0293978,6876946) to see the wave-sculptured gneissic rock formation called the "Kannesteinen".

After the visit to the quarry the party drove NW from Måløy to Oppedal and were suitably astonished by the rock, Fig. 5.which had been sculptured by waves and stones. Rhona Fraser and Hugh Leishman for scale.

Fig. 5. The Kannesteinen, with Hugh Leishman and Rhona Fraser.

Note. GPS positions are UTM segment 32V easting, northing.