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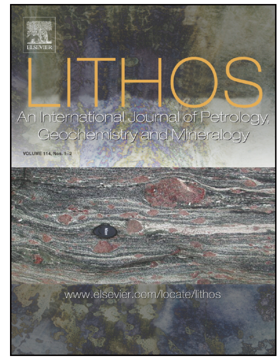

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Portrait of a Giant Deep-Seated Magmatic Conduit System: The Seiland Igneous Province

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ABSTRACT

The **Seiland Igneous Province** (SIP), Northern Norway, contains >5000 km^2 of mafic, ultramafic intrusions with minor alkaline, carbonatite and felsic rocks that were intruded into the lower continental crust at a depth of 25 to as much as 35 km.

The SIP can be geochemically and temporally correlated to numerous dyke swarms throughout Scandinavia at 560-610 Ma, and is linked to magmatic provinces in W-Greenland and NE-America that are collectively known as the Central Iapetus Magmatic Province (CIMP).

Revised mapping show that the SIP exposes 85-90 % layered tholeiitic- alkaline- and syeno-gabbros, 8-10 % peridotitic complexes, 2-4 % carbonatite, syenite and diorite that formed within a narrow (<10 Ma) time frame in the Ediacaran (560-570 Ma). Large peridotite complexes were emplaced into the still hot and unconsolidated gabbro (no dating available) and are regarded as the main-conduit systems.

Gravimetric data implies an average thickness of igneous rocks of 4-5 km and also features six deep lithospheric roots of ultramafic rocks extending min 9 km into the crust. Together, the root structures represent the main volcanic conduits conveying thousands of km^3 of mafic-ultramafic melts from the asthenosphere to the lithosphere.

The ultramafic complexes were predominantly emplaced into the layered gabbros at four major igneous centres, respectively, Nordre Brumandsfjord, Melkvann, Kvalfjord and Reinfjord. All complexes are situated in a right-way-up position and are steep sided forming large plugs. A marginal hybrid zone forms at the contact with country-rock and transitions gradually from olivine-mela-gabbro over pyroxenites that grades in to an olivine-clinopyroxenite zone, which is followed by a wehrlite zone and, finally, the centre of the complexes comprises pure dunite. From pyroxenite to dunite, olivine change from Fo_{72} to Fo_{85} and clinopyroxene from Di_{80} to Di_{92} i.e. the complexes observe a reverse fractional crystallisation sequence with time.

Parental melt compositions modelled from early dykes indicate komatiitic to picritic melts with 16-22 wt% MgO, Cr of 1594 ppm and Ni of 611 ppm, which were emplaced at 1450-

1500 ^{o}C. Melt compositions calculated from clinopyroxene compositions from Reinfjord are OIB-like with LREE enriched over HREE.

The high abundance of carbonatites and lamproites demonstrates the volatile-rich nature of the mantle source region and is further corroborated by the unusually high abundance of magmatic sulphides (0.5-1 %) and carbonated and hydrous assemblages (c. 1 %) throughout the region. In Reinfjord, they are also closely associated with PGE-Cu-Ni reef deposits.

Essentially, the ultramafic complexes in the SIP comprises deep-seated transient magma chambers that facilitated mixing and homogenisation of a rich diversity of fertile asthenospheric melts en route to the upper parts of the continental crust.

Keywords: Central Iapetus Magmatic Province, plume magmatism, mantle volatiles, AFC-processes

1. Ediacaran magmatism and the seiland igneous province

The Ediacaran (Ma 630-542) terminates the Precambrian and precedes the Cambrian explosion with the sudden appearance of most animal phyla we know of today. It is also characterised by massive outpouring of juvenile melts and volatiles along thousands of km of intercontinental rift zones formed prior to the opening of the Iapetus Ocean between 610 and 550 (Ernst and Bell, 2010). During the same period, the Earth experienced a sharp temperature increase of c. 10 ^{o}C that ended eons of frequent planetary glaciations (Snowball Earth) and low temperatures (Scotese, 2002). Over a few million years, Ediacaran magmatism formed numerous dyke swarms throughout Scandinavia, across N. America and

W. Greenland and is associated with several large igneous provinces (LIP's) collectively known as the Central Iapetus Magmatic Province (CIMP), which mostly formed at 575-560 Ma (e.g. Higgins and van Bremen, 1998) with some magmatism tapering into the Early Cambrian. The CIMP includes both the giant Sept Iles Layered Complex (Quebec) and the equally impressive but poorly known Seiland Igneous Province (SIP). In Canada, Greenland and most of Scandinavia we can only observe the upper crustal segments of the CIMP episode, whereas, in the SIP (Fig. 1) we have the only deep crustal exposure of the CIMP. Therefore, if we seek new knowledge about the deep-seated segments of a transformative LIP event, SIP may indeed be a locality worth studying.

Large igneous provinces (LIPs) are defined as "magmatic provinces with areal extents of >0.1 Mkm^2, igneous volumes > 0.1 Mkm^3 and maximum lifespans of ~50 Myr. They mostly have intra-plate tectonic settings and/or geochemical affinities, and are characterised by igneous production of short duration (~1-5 Myr) (e.g. Ernst, 2014). To produce such large volumes of magma within a narrow time frame, the presence of anomalously hot upwelling mantle, i.e. a mantle plume, is commonly inferred. LIPs are associated with giant magmatic feeder-systems transferring hot mantle-derived magmas to the cratonic crust. The feeder systems involve dykes that may transect the crust and intermittent magma chambers throughout the crust (e.g. Yu et al., 2015). The emplacement process profoundly modifies the lithosphere, impacts global climate and biology (e.g. Ernst and Youbi, 2017) and results in the formation of some of the world's largest ore-deposits (e.g. Arndt, 2013; Ernst and Jowitt, 2013, Ernst et al., 2005). Most of the well-studied LIP's only expose the upper few kilometres of igneous rocks, primarily the extrusive flood basalts (e.g. Yu et al., 2015) and sub-volcanic layered gabbros that are distant derivatives of the parent melt reservoirs in the deep lithosphere-upper asthenosphere. Essentially, most of the shallow intrusions and erupted lavas represent the end products in the igneous evolution of mantle-generated melts and our knowledge of the preceding igneous processes at great depths is limited due to the scarcity of deep exposures of these systems. High seismic velocities in the lower crust beneath flood basalt provinces (Farnetani et al., 1996; Ridley and Richards, 2010) and the compositional discrepancy between erupted basalts and likely picritic mantle melts suggest that magma chambers within the lower crust are an essential constituent of LIPs. To gain significant new knowledge about the early evolution of these magmatic systems and their ore-deposits we must approach the deep-seated parent reservoirs where the magmas first enter the lithosphere before they become modified as they ascend to shallower depths.

With formation pressures equivalent to 25-35 km depth, the SIP presents a rare glimpse into the lower segments of a giant magmatic plumbing system that conveyed large quantities of juvenile melts from the asthenosphere to the lower continental crust and further upwards in a short duration of time. Here, at 70^{o} N in northern Norway (Fig. 1), we have an unparalleled opportunity to study magmatic and tectonic processes facilitating the upward transport of thousands of km^3 of dense mafic-ultramafic igneous melts. Most studies (Robins and Gardner 1975; Bennett et al., 1986; Griffin et al., 2013) suggest that massive magmatic upwelling was sparked into motion by an Ediacaran mantle plume (Ma 580-560) impinging the Rodinian lithosphere under the emplacement of a rich diversity of mantle-derived melts during continental rifting (Andréasson et al., 1998; Daly et al., 1991; Elvevold et al., 1994; Krill and Zwaan, 1987; Roberts et al., 2006, 2010, Grant et al., 2016) and associated with the CIMP event. We cannot be sure that the SIP actually fed a LIP system in the upper crust, but it is indisputable that tens of thousands of km^3 of dense mafic and ultramafic magma passed through the SIP en route to higher levels of the continental lithosphere (Bennett et al. 1986; Griffin et al., 2013; Grant et al., 2016). Accordingly, we hypothesise that the 5000 km^2 Seiland Igneous Province (Fig. 1) may provide transformative new knowledge on:

- Emplacement of dense, juvenile ultramafic melts and the evolution and composition of the continental crust
- Role of large lower crustal magma-reservoirs in the differentiation, modification and homogenisation of mantle-derived magmas.
- Magma chamber processes and lithosphere - asthenosphere interaction processes
- Transfer and fate of volatile components (S, C, H) and economic metals from the deep Earth to the crust
- Formation of fertile magmatic ore-deposits

State of the art at SIP addressing these topics is described and discussed in this synthesis article and is integrated with our current knowledge of giant magmatic systems.

Here we show that the SIP comprises a rich diversity of mantle derived igneous products of the mafic, ultramafic and alkaline suites. Layered gabbro is widespread throughout the province, whereas most of the ultramafic rocks occur in three major intrusive centres on Seiland, Stjernøya and the westernmost parts of the Øksfjord Peninsula. Larger alkaline complexes occur on Sørøya in the far west and Stjernøya in the centre of the SIP.

Recent U-Pb zircon dating of gabbros and alkaline rocks imply that > 90 % of the igneous rocks were emplaced in only 4 Ma in the Ediacaran between 560 and 570 Ma (Roberts et al., 2006), although SIP magmatism began 574 ±5 (Robert et al., 2010) and terminated in the Cambrian at 523 ±2 Ma (Pedersen et al., 1989).

The backbone in our synthesis is that four major ultramafic intrusive centres embody the de facto conduit systems. These accommodated the transfer of primitive melts from the asthenosphere to the continental lithosphere. They also enabled mixing and homogenisation of diverse melt types in these transient ultramafic magma chambers.

Although the SIP shows a general igneous evolution from alkaline to tholeiitic to komatiitic/picritric and back to tholeiitic then finally alkaline products, we also observe that the entire spectrum of melts emerges along the same conduit systems in rapid succession or even *simultaneously*. Adding to this complexity is the fact that volatile-rich alkaline melts, today preserved as clots of carbonate-rich mineral assemblages, are omnipresent in the most primitive rocks where they comprise 1-2% of fresh unaltered peridotitic cumulates.

In fact, volatile fluxing from the asthenosphere to the lithosphere is vividly demonstrated at the SIP, particularly in the ultramafic complexes. Sulphides with mantle S-isotope signatures are a minor but conspicuous feature throughout the ultramafic rocks, and clots of hydrous and carbonate rich assemblages within unaltered peridotite samples, as well as hornblendite and amphibole-rich ultramafic assemblages (Larsen et al., 2016), also attest to the presence of high amounts of volatiles entering the system together with primary ultramafic melts. The carbonatites and alkaline rocks have O, C (Wulff-Pedersen, 1992), Nd and Hf (Roberts et al., 2010) isotopic signatures that include the most juvenile mantle values recorded in SIP, indicating their primary origin and that the mantle source region was volatile-rich. Compared with the relative sparse database of isotopic data from the Central Iapetus Magmatic Province, the SIP is in fact the CIMP-locality that provides the most juvenile Nd, Hf values we know of throughout the North Atlantic region (ε_{Hf} at +8 and ε_{Nd} at +4; Roberts, 2010).

Sub-economic grades of Cu-Ni sulphide deposits (±PGE) are formed and like any other lithology at the ultramafic centres, they are modified, remobilised and sometimes refined by later igneous events entering the conduit systems. A curiosity is remobilisations of PGE, Au and Cu in the Reinfjord Complex by the aqueous-carbonic alkaline melts when they infiltrated existing PGE-Cu-Ni reefs. This event produced an exotic parageneses of orthopyroxene and dolomite that is stable at only P >11 kbar (see section on P-T conditions) hence confirming the deep-seated properties of the SIP (Sørensen et al. 2015).

Satisfactory interpretations of the high diversity of igneous SIP-melt cohorts, as well as volatile fluxing and ore formation, are fragmentary in our current state of knowledge. Including our few publications there are around 40 peer reviewed journal publication covering a timespan of 70 years that address the geological setting of this incredibly diverse geological formation. Based on these publications, our own data, PhD and MSc theses, reports and field notes spanning 65 years of research, we suggest a working model sketching the genesis of the Seiland Igneous Province. Hopefully, this preliminary model of the SIP may contribute to a more profound appreciation of the deep-seated parts of giant magmatic systems and their importance for the lithospheric evolution of the Earth and, not least, may amplify more important areas of future research.

2. Assembly of sip

2.1 Revised Geological Map

A revised geological map was compiled using local area maps for Kvalfjord, Lokkarfjord and Melkvann (Yeo, 1984; Bennett et al., 1986; and Svensen, 1990), Breivikbotn, Rognsund and Tappeluft (Roberts, 2006), Hasvik (Tegner et al., 1999), Reinfjord (Grant et al., 2016, Grannes, 2016), Lillebukt (Cadow, 1993), Øksfjordbotn (Elvevold and Andersen, 1993) and Nordre Brumandsfjord (Griffin et al., 2013), with the other areas from the maps of Bennett et al. (1986) and Tegner et al. (1999). Gabbroic rocks include olivine gabbro, pyroxene gabbro, syeno gabbro, pegmatitic gabbro and metamorphosed gabbro and these are included as one unit in this map. The central parts of the Øksfjord peninsula are covered by the large Øksfjordjøkkelen glacier and have therefore never been mapped in detail. Recalculations of the proportions of different rock types by exposed area reveal that the gabbros make up 85% of the igneous rocks in the SIP with 8-10 % ultramafic and around 2-4 % carbonatite, alkaline and other rock types (such as diorite). These estimates are markedly different to those given previously (50% gabbro, 35% ultramafic, 15% alkaline and felsic) by Roberts et al. (2006). A further observation is that hornblendites appear to be concentrated around southern Stjernøya and the opposite northern coastline of the Øksfjord peninsula.

Figure 1 (Revised Geological Map)

It is also clear that the main body of ultramafic complexes features a dense cluster covering E. Stjernøya and SW-Seiland including 3 of the 4 major complexes described later in the text.

With the exception of a few gabbro bodies, the layered gabbros as well as the ultramafic complexes are situated in a “Right-way-up” orientation with the igneous layering dipping O^{o} - 20^{o} in varying directions.

2.2 Chronology of Igneous Events

Early isotopic data produced a wide range of dates from 829 ± 18 Ma for metagabbro and monzonite from Øksfjord (Krogh and Elvevold, 1990) to 501 ± 21 Ma (Sturt et al.1978), and other in between (Daly et al., 1991; Cadow, 1993). Many of these studies used Sm-Nd or Rb-Sr whole-rock geochronometers. This led to the interpretation of a long and protracted magmatic history for the SIP. Roberts et al. (2006) noted that these are likely to give spurious results as these systems can be reset by later alteration or have isotopic disequilibrium. More recent dating using U-Pb produced a more consistent and reliable data set for the spread of ages within the SIP (Pedersen et al., 1989; Roberts et al., 2006; Roberts et al., 2010) and are summarised below.

The oldest ages within the SIP are from alkaline and carbonatite rocks from Breivikbotn at 580-560 Ma with a more concentrated spread towards 580 Ma (Roberts et al., 2010). Mafic plutons show a very narrow range typically between 570-560 Ma (Roberts et al., 2006). It is important to note that the undeformed and heavily deformed gabbros give the same ages (Roberts et al., 2006). Neither the ultramafic rocks, nor the dykes have been accurately dated only relative ages by cross-cutting and field relations are recorded thus far. The gabbros are shortly followed by the formation of the ultramafic intrusions. This is deduced from large scale partial melting and assimilation of wall rock gabbro, implying that they were still close to their solidus at the time of the intrusion of the ultramafic melts (Yeo, 1985; Emblin, 1986; Svensen, 1990; Bennett et al., 1986; Griffin et al., 2013; Grant et al., 2016). Picrite-ankaramite and lamprophyre dykes cross cut and have chilled margins against the mafic-ultramafic associations and therefore post-date both by long enough for them to have cooled significantly. The youngest ages of 531-523 Ma are of nepheline-syenite pegmatites dykes from Stjernøya and Seiland (Pedersen et al., 1989). It therefore appears that smaller volumes of more alkaline and carbonatitic melts book-end the most voluminous mafic and ultramafic events in the SIP. The tighter spread of ages in more recent data from robust isotopic systems indicates that the vast majority of intrusions formed within a rather narrow time span of max. 10 Ma and this data is used to support the theory that the SIP formed through intercontinental rifting (Roberts et al., 2006; Roberts et al., 2010), consistent with some earlier interpretations (Krill and Zwaan, 1987; Daly et al., 1991).

3. Geometry and deep structures of the sip

The most prominent gravity anomaly on land in northern Scandinavia is related to the Seiland province. This gravity anomaly (Fig. 2a) has a maximum on the island of Sørøya, and is confined on its eastern side by a NW – SE trend, mostly on Seiland. Two additional prominent, but smaller positive anomalies are located on the islands of Seiland and Stjernøya. In both locations outcrops of ultramafic rocks are exposed. However, the largest gravity anomaly on Sørøya lacks direct correlation with exposed ultramafic rocks; therefore, the origin of the gravity anomaly must be located at greater depth.

The deep structure of the SIP was previously interpreted by 2D gravity modelling by Brooks (1970) and Olesen et al., (1990). Both interpreted the anomaly to be due to a massive sheet of mafic and ultramafic rocks, reaching a depth of 7-8 km (Olesen et al., 1990) and minimum 6 km (Brooks, 1970).

Recently Pastore et al., (2016) used 3D (IGMAS+; Schmidt et al., 2007) forward modelling of the gravity data to generate a density model of the deep structure of the SIP. This model is composed of bodies of different densities that are defined on vertical cross sections (Fig. 2). Adjacent cross sections are linked by triangulated surfaces. The gravity field of the model is calculated based on the algorithm of Götze & Lahmeyer (1988) and then compared with the observed data.

The modelled gravity data by Pastore et al., (2016) is from a gravity database comprising both land and marine gravity measurements (Gellein, 2003). In addition, this database was integrated with satellite-based gravity data in the poorly covered offshore areas in order to improve the analysis and constrain the shape of the gravity anomaly. The selected satellite compilation is the TRIDENT Global (Fairhead, 2015) compilation, which is based on three independently derived solutions of free air gravity from satellite altimeter data.

The comparison between the free air satellite (TRIDENT satellite) based gravity anomaly and the interpolated free air gravity anomaly obtained from solely land and marine measurements showed a considerable difference of 20 mGal in the offshore area between Sørøya and Stjernøya. This difference has an impact on the model structure, and specifically it limits the extent of the Sørøya gravity anomaly southward and controls the thickness of the intrusive complexes.

This new compilation of the gravity database was used to calculate the Bouguer gravity anomaly map shown in Figure 2 A. The Bouguer gravity map shows a local minimum at the offshore area between Sørøya and Stjernøya, which according to the gravity model reflects a local thinning of the SIP intrusions at that location. The gridding and map display was performed using Oasis Montaj (GEOSOFT).

Figure 2: (Bouguer anomalies)

The petrophysical database of the Geological Survey of Norway (NGU) (Olesen et al., 2010) was used to constrain the model. Density values of 300 samples were grouped into three main lithological units: metasediments (146 samples), gabbros (110 samples) and ultramafic/peridotite rocks (54 samples). Statistical analysis showed that densities of metasediments and gabbros have a nearly normal distribution, whereas the ultramafic/peridotite rocks show a more complex distribution. The ultramafic/peridotite rocks samples with low densities and a wide range of magnetic susceptibilities indicate that these samples were likely affected by weathering and/or alteration processes including serpentinisation. The mean density and standard deviation are: 2752 ±94 kg/m^3 for metasediments, 3042 ±126 kg/m^3 for gabbros, and 3112 ±188 kg/m^3 for ultramafic/peridotite rocks. For the modelling, a density of 2700 kg/m^3 for the metasediments was selected, which is the modal value. This value slightly deviates from the mean, which is believed to be shifted to higher values by higher metamorphic grade of samples nearer to the intrusion resulting from contact metamorphism.

For the intrusive rocks of the SIP, including both gabbros and ultramafic rocks, two density values were selected and used for modelling the intrusions: a value of 3100 kg/m^3, which is the mean density of both gabbros and ultramafic rocks and results in a density contrast with the host meta-gneisses of 400 kg/m^3; and a higher density value of 3300 kg/m^3 which is representative of some ultramafic rocks in the NGU database as well as fresh peridotite rocks in the southern Seiland Province at the Reinfjord Complex, measured between 3100 and 3300 kg/m^3 (Ter Maat et al., 2015). That the deeper part of the SIP may have a higher density would agree with a predominance of ultramafic cumulates in the deeper parts of layered gabbros.. The use of a density value of 3300 kg/m^3 for the intrusion, creates a higher density contrast to the host complex of 600 kg/m^3 and therefore better constrains the minimum depth and thickness of the intrusive complex.

The corresponding model, shown in Figure 2 is of a complex structure. There are two prominent roots for the intrusive complex which extend to a minimum depth of 9 km. The uncertainty on the depth of these roots is related to the density contrast between the intrusive and the host-rock. However, it is expected that the roots are composed of ultramafic rocks, which are denser than the gabbros, therefore the selected density of 3300 kg/m^3 is regarded as representative of the modelled intrusive structure. Furthermore, the inherent ambiguity in gravity modelling at large depths would not be able to resolve deeper small-scale structures. Therefore, it is possible that structures, such as a minor feeder dykes continuing deeper cannot be excluded.

Figure 2 B shows a map of the base of the mafic/ultramafic body of the SIP derived from the 3D gravity model. Contour lines at 4.5 km and deeper define several funnel shaped roots which occur in an annular pattern. This is highlighted by the dashed envelope (black) following the outer part of the 4.5 km contour line (Fig. 2b). The saucer-shaped mafic intrusion is suggested to be fed from below along the ultramafic funnel-shaped roots. The annular pattern of the ultramafic roots outlines a circular mega structure being c. 40 kilometres in diameter.

4. Layered gabbros

Robins and Gardner (1974) were the first to recognise that the gabbroic rocks formed from intrusion and crystallisation of basaltic magma and thus laid the foundations for subsequent research. Previous workers interpreted the locally strongly foliated and deformed gabbros as a result of metamorphic and anatectic transformation of amphibolite and meta-sedimentary assemblages during regional metamorphism. Robins and Gardner (1974), however, demonstrated that the gabbros often are undeformed and here display rhythmic modal layering, cumulate textures, and stratigraphic sections showing systematic mineralogical changes (phase layering) and changes in mineral compositions (cryptic layering) similar to anorogenic layered intrusions. The relationship between emplacement of the SIP intrusions and regional deformation is contested. Robins and Gardner (1974) and several subsequent workers viewed the intrusions as being synorogenic with the least deformed intrusions being emplaced at a late stage and the more deformed intrusions being emplaced at an earlier stage of the orogeny. Moreover, it was debated whether there were multiple orogenic events (Sturt et al., 1978), although this proposition is no longer tenable (Corfu et al., 2011). The recent U-Pb chronology of the gabbroic rocks and their evolved differentiates has demonstrated that the age of deformed and undeformed intrusions are identical within error (i.e. 560-570 Ma, Roberts et al., 2006). We therefore concur with Roberts et al. (2006) that the intrusions were variably deformed during emplacement of the Kalak nappe in the main Scandian phase (425-400 Ma) of the Caledonian Orogeny. This is supported by metamorphic cooling ages of the SIP constrained by Ar/Ar dating of hornblende from nepheline syenite on Stjernøya (c. 425 Ma, Dallmeyer, 1998) and U-Pb in apatite of the Hasvik Layered Intrusion (425-23 Ma, Wohlgemuth-Ueberwasser et al., 2017).

4.1 Three types of gabbros

Robins and Gardner (1974) identified three types of gabbros based on mineralogy: tholeiitic gabbro; syenogabbro and alkaline gabbros. The tholeiitic gabbros display a crystallisation sequence typical of tholeiitic magma (e.g. the up-section disappearance of olivine and the associated appearance of orthopyroxene); the Hasvik Layered Intrusion and Lille Kufjord Intrusion are the best-studied examples. Moreover, the chilled margin of the Hasvik Layered Intrusion is a tholeiitic basalt with c. 8 wt% MgO (Robins and Takla, 1979; Gardner, 1980; Tegner et al., 1999). The alkaline gabbros are characterised by the absence of cumulus orthopyroxene and normative nepheline, suggesting the parent magma was an alkaline olivine basalt (Robins and Gardner, 1974). The most-studied alkaline gabbro is the Rognsund Intrusion that also displays fine-grained nepheline-normative chilled facies of the intrusion (Robins, 1982). The syenogabbros are somewhat transitional between the tholeiitic and alkaline gabbros. The lower part of syenogabbros display a tholeiitic crystallisation sequence with olivine-orthopyroxene reaction and two pyroxenes, whereas the more evolved rocks of the upper portions display cumulus alkali feldspar, albitic plagioclase and two iron-rich pyroxenes. Robins and Gardner (1974) briefly described the SIP syenogabbro as a large sheet up to 2 km thick outcropping as a large ring structure with a diameter of c. 20 km, now forming a broad synclinal fold structure. The differentiation of the syenogabbros towards a syenitic residual is indicated by leucosyenite dykes interpreted as offshoots from the Seiland syenogabbro into the surrounding country rocks (Robins and Gardner, 1974).

4.2 Interaction with metasediments

All three gabbro types frequently include blocks of the country rock metasediments that were metamorphosed and folded into banded and sometimes migmatitic rocks prior to magma emplacement (Fig. 3) (Roberts 1974; Robins and Gardner, 1974). Their typical mineral assemblage contains quartz, K-feldspar, plagioclase, garnet, biotite and sillimanite and mainly representing pelitic, arkosic and quartzitic sandstone belonging to the Klubben Fm. (Roberts 1974). The inclusions in the gabbros vary from cm-sized recrystallised blebs to blocks of folded metasediment that may be tens of metres across. The xenoliths are generally abundant close to the margins of the intrusions, but they are also present far from the margins where they are engulfed in the layered rocks (Robins and Gardner, 1974; Robins et al., 1991; Tegner et al., 1999). The xenoliths are typically extensively assimilated and recrystallised to pyroxene hornfels and/or corundum-hercynite spinel anorthosite with Ca-rich plagioclase (Robins and Gardner, 1974; Robins et al., 1991; Tegner et al., 1999; 2005). The abundance of xenoliths throughout the gabbroic intrusions was interpreted to be a consequence of lateral expansion of the mafic magma chambers spalling off country rocks stoped from the roof, possibly followed by sinking of xenoliths into the magma chamber due to their increased density following metamorphic reactions (Robins and Gardner, 1974; Tegner et al., 1999).

Figure 3: Field evidence of layering and blocks of meta-sediment xenoliths

4.3 Lille Kufjord Intrusion

The Lille Kufjord Intrusion is a small layered intrusion (c. 5x1 km) that crops out on the southwestern shore of Seiland (Robins and Gardner 1974; Robins et al., 1991) (Fig. 1). The intrusion has near-vertical outer contacts, and is oval in map view, largely undeformed and appears to retain its original intrusive form. The intrusion is composed of a max. 100 m thick marginal Zone, a c. 1400 m thick Layered Series. An unexposed Hidden Zone is inferred. The Marginal Series is dominated by gabbronorite and olivine gabbronorite showing modal and textural layering roughly parallel to the steep contact, including colloform layering as described in the Marginal Border Series of the Skaergaard Intrusion (Wager and Brown, 1967). Gabbronorite pegmatites are also common in the Marginal Zone where they mingle with granitic rocks that were interpreted as partial melts of country rock xenoliths (Robins et al., 1991). The Layered Series is subdivided into Lower Zone a (c. 380 m), Lower Zone b (c. 750 m), and Upper Zone (c. 270 m). Lower Zone “a” is spectacularly layered and contains about 40 macrorhythmic units; the ideal unit is composed of a basal olivine cumulate followed upwards by a diopside-olivine cumulate and finally by a plagioclase-diopside-olivine cumulate. In Lower Zone a, olivine varies between Fo_{82} and Fo_{66} and detailed studies of macrorhythmic units show that the highest values occur in the basal olivine cumulate layers and generally decreases upwards. The macrorhythmic units were explained as the result of periodic recharge of olivine-saturated liquids resulting in horizontal liquid stratification at the bottom of the chamber and crystallisation mainly from the diffusive boundary at the top of the basal liquid layer (Robins et al., 1991). The base of the plagioclase-diopside-olivine layers is commonly undulated with olivine or olivine-diopside finger structures (dm-sized) protruding upwards and explained as a consequence of reactions with olivine-saturated liquids expulsed from the underlying layer by compaction (Robins, 1982). The overlying Lower Zone b is composed of modally-layered olivine (Fo_{82-71})

whereas the Upper Zone is composed of more evolved gabbronorite. The first appearance of cumulus Ca-poor pyroxene in the Upper Zone, and the disappearance of cumulus olivine, is interpreted as the result of olivine-melt reactions typical of fractionation of tholeiitic magma (Robins et al., 1991). The presence of numerous centimetre-sized xenoliths suggests the magma was also altered by contamination. This is confirmed by Sr and Nd isotopes of Upper Zone rocks and modelling of coupled assimilation and fractional crystallisation (AFC), suggesting a modest rate of mass assimilated to rate of mass crystallised (<0.08; Aitcheson and Forrest, 1994)

4.4 Hasvik Layered Intrusion

The Hasvik layered intrusion occupies 12 km^2 and is located at the southwestern tip of Sørøya (Fig. 1) (Robins and Gardner, 1974; Tegner et al., 1999; Tegner et al., 2005). A pronounced aeromagnetic anomaly, however, suggests that the intrusion likely is larger and extending below the sea to the South. The Hasvik intrusion was emplaced into metasedimentary country rocks at 5-7 kbar. The stratigraphic section is c. 1600 m thick composed of a ~1500 m thick Layered Series overlying a thin Basal Zone and underlying a thin Upper Border Series (Fig. 4). The Basal Zone interdigitates with the contact-metamorphic aureole and is composed of gabbronorite and includes numerous centimetre-sized xenoliths of highly recrystallised metasediment. The Upper Border Series is only preserved as a c. 60 m thick layer that caps the Layered Series at the top of a small mountain and is composed of massive oxide gabbronorite with large amphibole oikocrysts. The Layered Series is divided into a Lower Zone (c. 335 m thick) composed of olivine gabbro, a Middle Zone a (c. 410 m) composed of gabbronorite, a Middle Zone b (c. 540 m) composed of oxide gabbronorite with olivine re-appearing in the uppermost c. 100 metres, and an Upper Zone (c. 190 m) of oxide-apatite-ferronorites. The most primitive cumulates contain olivine (Fo_{78}), augite and plagioclase (An_{72}) and occur in the upper part of the Lower Zone. Below this level the plagioclase An% (An_{63-72}) and mg# of Ca-rich pyroxene (Di_{71-77}) increases up section. Above, plagioclase (An_{62-53}) and Ca-rich pyroxene (Di_{77-40}) decrease up section. These mineralogical and compositional variations were interpreted as the result of a basal magma recharge and mixing in the Lower Zone followed by continuous fractional crystallisation through the Middle and Upper Zones (Tegner et al., 1999). The intrusion contains innumerable recrystallised country-rock xenoliths increasing in abundance up section through the Middle and Upper Zones. A study of Sr and Nd isotopes demonstrated a remarkably steady increase in initial $^{87}Sr/^{86}Sr$ from near mantle values in the upper part of the Lower Zone (0.7038) to more crustal values at the top of the Upper Zone (0.7089), and negatively correlated ε_{Nd} values (Fig. 4). The anti-correlated plagioclase An% and initial $^{87}Sr/^{86}Sr$ values was explained by coupled assimilation of the country rock and fractional crystallisation (Fig. 4) (Tegner et al., 1999). Modelling suggests the rate of mass assimilated to rate of mass crystallised was near-constant at 0.27, consistent with a steady-state AFC process that was controlled by the heat from cooling and crystallisation of the magma. The high rate of mass assimilated to rate of mass crystallised fraction and its constancy through the Middle and Upper Zones reflects the ready availability of fusible xenoliths (Tegner et al., 1999; Tegner et al., 2005). This makes the Hasvik Intrusion one of the most contaminated layered intrusions known, and Robins and Gardner (1974) and Tegner et al. (1999) argued that the incorporation of innumerable metasedimentary slabs and flakes into the magma chamber promoted contamination.

Figure 4: Plagioclase and Sr-isotope variations up section

4.5 Rognsund Intrusion

The Rognsund intrusion is exposed on the southeastern coast of Stjernøya and across the sound (Rognsund) on the south-western coast of Seiland (Fig. 1), occupying an area of ~50 km^2, and was first described by Robins (1982). The layered rocks of the intrusion are generally metamorphosed and define a synclinal structure with an axis running parallel to the sound. An up to 250 m thick contact-metamorphic aureole is developed in the host metasediments and includes hornfels, and closer to the intrusion margin, rheomorphic breccias produced by contact anatexis. In the Hakkstabben area of Seiland, Robins (1982) mapped a c. 900 m thick sequence of layered mafic rocks. The outermost marginal zone is up to 200 m thick and contains abundant, small (typically cm-sized) meta-sedimentary xenoliths that have recrystallised to Ca-rich plagioclase, hercynitic spinel, and corundum. A fine-grained rock close to the contact has been interpreted as a chilled margin with the composition of an alkali olivine basalt. Otherwise the marginal zone is composed mainly of noritic cumulates that generally have a strong metamorphic overprint. The presence of primary (cumulus) orthopyroxene rather than olivine, together with the abundant meta-sedimentary xenoliths, is interpreted as a consequence of crustal contamination an is referred to as the contaminated zone (Robins, 1982). In contrast, the >700 m thick layered series is dominated by cumulus plagioclase (An_{85-65}), Ca-rich pyroxene, olivine (Fo_{74-65}), and Fe-Ti oxides appearing at an early stage of fractionation. The lack of primary orthopyroxene and normative nepheline testify to the alkali olivine basaltic character of the parental magma. Robins (1982) describes the spectacular layering displayed in the intrusion including size- and modally-graded layers, and crescumulate layers with elongate and skeletal olivines (and clinopyroxene) up to one metre in length. In several places the layering is disrupted in slump structures and load structures. Systematic up section decreases in the An% of plagioclase and Fo% of olivine was interpreted as a result of fractional crystallisation uninterrupted by magma recharge.

5. Ultramafic intrusions

In this section, the main features of each of the four main ultramafic complexes in the SIP are summarised. For more detailed descriptions of each intrusions the reader is referred to earlier works; Melkvann (Yeo 1984), Nordre Brumandsfjord (Sturt et al., 1978; Griffin et al., 2013), Kvalfjord (Svensen 1990) and Reinfjord (Emblin 1985; Grant et al., 2016) as well as an earlier review of all four intrusions (Bennett et al., 1986).

5.1 Melkvann

The Melkvann ultramafic complex covers an area of c. 100 km^2 on the island of Seiland, to the east of the Nordre Brumandsfjord complex (Fig. 1). It consists of two lobes, one to the South and one to the North-East (Bennett et al., 1986). The complex is intruded into both gabbroic and metasedimentary country rocks. The contacts between the ultramafic complex and the country rocks are discordant either, sub-vertical or steeply inward dipping (Bennett et al., 1986).

5.1.1 Country rocks: The metasediments are psammitic, pelitic and semi-pelitic lithologies, calc-silicates and metaquartzites, all parts of the Klubben Fm. (Yeo, 1984). The regional amphibolite facies (almandine-sillimanite-orthoclase) metamorphism of the sediments is overprinted by a contact aureole of pyroxene-granulite facies metamorphism and rheomorphic breccias. The contact aureole formed through the combined effects of the intrusions of mafic, and then ultramafic melts in the complex. Yeo (1984) separated the gabbro into two types, an earlier metamorphosed two-pyroxene gabbro dyke complex with intrusive breccias and a later olivine gabbro that mostly occur as giant rafts in the ultramafic complex (Fig. 7). The two-pyroxene gabbro has tholeiitic affinities with olivine, clinopyroxene, plagioclase, orthopyroxene, magnetite and alkali-feldspar. Locally the gabbro grades into syenitic compositions (Yeo, 1984). The olivine gabbro is characterised by having alternating laminae of olivine leucogabbro and olivine gabbro. Orthopyroxene is intercumulus in the olivine leucogabbro and clinopyroxene contains spinel rather than orthopyroxene exsolution. Both features indicate that the magma that formed the olivine gabbro was critically undersaturated in SiO_2.

Figure 5: Field-evidence, emplacement features

Figure 6: Field-evidence, contact features, recharge, replacive dunites, dykes

5.1.2 Marginal and roof zones: In some places the contacts are transitional and are composed of multiple generations of sheeted dyke complexes. These zones are up to 300 m wide. Many of these dykes and sheets contain xenoliths of the gabbro host rocks (Bennett et al., 1986). Dykes and sheets include apophyses that appear to be more replacive (reaction and assimilation) than dilational. These often have saw-toothed edges, with complex internal mineralogical variations, e.g. olivine-rich margins next to anorthositic, bleached gabbro (Yeo, 1984).

The roof zone is primarily exposed in the western and central parts of the complex around Steinfjell and Tverrfjell (Fig. 7). It is a hybrid zone containing anorthosite, troctolite, olivine leucogabbro, olivine melagabbro, olivine pyroxenite, wehrlite and dunite (Yeo, 1984). Remnants of layered olivine gabbro are exposed on the high ground of Tverrfjell as large enclaves that were intruded by ultramafic dykes and sheets. On Steinfjell, layered olivine gabbro is also found as dissected screens and irregular enclaves. Olivine gabbro (Fo_{72-78}) is also observed on the crests of ridges (at elevations above 400 m) extending up to 3 km inland from the western contact south of Steinfjell (Bennett et al., 1986). Layering within the enclaves and the invading sheets of ultramafic material suggests that the enclaves are *in situ* relics of a larger olivine gabbro body, i.e. the roof of the ultramafic complex (Fig. 7) (Yeo, 1984; Bennett et al., 1986). The size and intensity of dykes and sheets increase away from the gabbro, whereas rafts and xenoliths of gabbro decrease in size and concentration away from the gabbro contact. The field relationships indicate the following sequence of events: passive replacement of olivine gabbro by mafic and ultramafic melts forming olivine melagabbro, development of olivine clinopyroxenite dykes and associated rheomorphism of olivine gabbro and emplacement of gabbro pegmatite dykes and intrusion breccias, emplacement of irregular and dilation UM dykes and finally late dykes that postdate the main phases of intrusion of the UM complex (Bennett et al., 1986). The roof zones are thought to have formed through a protracted process of dykes and sheet emplacement, mechanical disruption, partial melting, remobilisation and assimilation of the olivine gabbro envelope (Bennett et al., 1986).

5.1.3 Ultramafic rocks: The dominant rock type in the Melkvann Complex is olivine clinopyroxenite. Locally it grades into wehrlite through a modal increase in olivine, and to feldspathic olivine-hornblende clinopyroxenite through increases in amphibole and plagioclase. The latter is more characteristic of the marginal zones along with blocks derived from the olivine gabbro envelope and rarer olivine-rich ultramafic xenoliths (Bennett et al., 1986). Olivine typically has compositions of around Fo_{77} (Yeo, 1984).

Dykes and irregular bodies of wehrlite and dunite up to 200 m across are emplaced into olivine clinopyroxenite (Fig. 7). Here, the clinopyroxene is oikocrystic and dunite locally grades into poikilitic wehrlite that encloses blocks of coarse-grained olivine clinopyroxenite (Bennett et al., 1986). Variations in olivine and spinel give small scale layering in one dunite body, but otherwise layering is absent. The intrusive relationships between dunite and olivine clinopyroxenite indicate that the dunites are replacive of the host olivine clinopyroxenite (Yeo, 1984; Bennett et al., 1986). Olivine in dunites are between Fo_{80-82} and decrease from dunite-wehrlite to replacive dunite (Yeo, 1984).

5.1.4 Late dykes and alkaline intrusions: Later intrusive events are dominated by ultramafic dykes. In some areas the dykes constitute more than 50% of the total outcrop volume (Bennett et al., 1986). Amphibole-bearing dykes within the central zone have E-W orientations. Late picrite dykes have N-S and E-W trends with chilled margins against ultramafic and mafic rocks (Yeo, 1984). The eastern area of the complex is strongly fenitised. The fenitisation is associated with the emplacement of late magnetite-apatite-hornblendite clinopyroxenites, which also occur elsewhere in the complex and envelope where they produce en echelon swarms of SW-NE dykes and small plugs of syenite and nepheline syenite pegmatite (Bennett et al., 1986). These are then postdated by a suite of highly alkaline nepheline-syenite pegmatites (E-W orientations) (Fig. 7) with accessory corundum, biotite, magnetite, apatite and calcite (Robins, 1971) that yielded concordant U-Pb zircon ages of 531 ±2 Ma (Pedersen et al., 1989).

5.2 Nordre Brumandsfjord

The Nordre Brumandsfjord Complex covers an area of ca. 50 km^2 and is exposed on a plateau at approximately 1000 m elevation (Fig. 1). The complex is separated from Melkvann by a narrow 3 km body of steeply dipping and strongly deformed country rocks gabbro. It is intruded into the western limb of a synform structure that developed around the Melkvann complex (Bennett et al., 1986). Griffin et al. (2013) estimate that the majority (60-70 %) of the ultramafic rocks represent contaminated ultramafic rocks and gabbro rafts, formed by partial melting and assimilation processes. Therefore, much of the work on the Nordre Brumandsfjord intrusion has focused on the intrusion mechanisms observed at the marginal and roof zones where partial melting and assimilation of the country rocks has led to hybrid rock types. Nordre Brumandsfjord is not mapped in detail and therefore is not included in Figure 7.

5.2.1 Country rocks: The majority of ultramafic rocks in Nordre Brumandsfjord have contacts with the gabbroic country rocks except for the southern margin that intrude directly into metasediments which include quartzites, calc-silicate gneisses and psammitic granulites. Xenoliths of the metasediments features high degrees of anataxis. Veins and dykes of dioritic material intruded the ultramafic rocks (Sturt, 1980; Griffin et al., 2013). A 3-km contact aureole has developed in the metasediments that features pyroxene-hornfels facies metamorphism along with rheomorphic breccias (Sturt, 1980). The country rocks are fine- to medium-grained layered alkaline gabbro, with cumulate structures, graded bedding and even rare examples of current-bedded structures (Griffin et al. 2013). The gabbro also contains abundant rafts of metasediment (Bennett et al., 1986).

Marginal and roof zones: The country rock gabbro is intruded by ultramafic rocks at the N, W, and E. In the eastern margin, the gabbro is intensely sheared (Griffin et al., 2013). The marginal zones are characterised by dense dyke swarms of varying orientations (Sturt et al., 1980). To the north, the roof of the pluton dips moderately (ca. 40°) under the marginal layered gabbros (Griffin et al., 2013). The gabbros here are cut by sheets and dykes of ultramafic rocks, which lead to the detachment of roof pendants and large xenoliths. The dykes indicate dilational emplacement of ultramafic rocks during a block-stopping process (Griffin et al., 2013). Dyke compositions encompasses feldspathic olivine clinopyroxenite, dunite, feldspathic lherzolite, wehrlite, pyroxene-hornblende peridotite and olivine gabbro (Bennett et al., 1986). The thinnest dykes are millimetre to centimetre thick and are often dunites (Griffin et al., 2013). None of the dykes have chilled margins against the host rocks (Griffin et al., 2013). Dykes often have saw-toothed contacts and have irregular zones of dunite or wehrlite along their walls. Adjacent to the dykes, the gabbro shows bleaching where the abundance of clinopyroxene decreases along with an increase in plagioclase and olivine. The dykes include xenoliths and xenocrysts that originate from the wall rock gabbros (Bennett et al., 1986). Rafts and large xenoliths of layered gabbro within the ultramafic pluton near the margins show signs of thermal, and probably mechanical stresses that have led to disaggregation. The ultramafic magma was then able to penetrate the xenoliths as thin veins and along grain boundaries. The gabbro xenoliths commonly contain significantly less pyroxene than the gabbro host rocks, and in extreme cases they become anorthositic or leave behind 'ghost xenoliths' within the ultramafic rocks. This is a sign of melt extraction and recrystallisation of the original gabbro. Plagioclase-bearing lherzolites are interpreted to have formed through mixing of the primary ultramafic melts and fusion melts from melting of the gabbro (Griffin et al., 2013).

The roof zone is well exposed in the centre of the intrusion where ultramafic rocks contain numerous large rafts of the host gabbros (Griffin et al., 2013). Below the roof zone, many of the gabbro rafts lack clearly defined layering, they have leucocratic neosomes and local pegmatitic patches that intersect the layering, i.e. features implying anataxis of the gabbro rafts (Griffin et al., 2013). Veins of neosomes and gabbro pegmatites proceed from the xenoliths and into the ultramafic rocks (Griffin et al., 2013). Back-veins may extend for several meters into the ultramafic rocks but they usually taper out into dunitic material.

5.2.2 Ultramafic rocks: The ultramafic rocks include dunite, lherzolite, feldspar lherzolite and olivine-bearing pyroxenites/wehrlites. It is hypothesised that this range of compositions represents progressive contamination by partial melting of the host gabbros of an intrusive dunitic melt (Griffin et al., 2013). Ultramafic rocks along the northern contact with the gabbro are observed as complex networks of dykes, sills and sheets varying in size from several meters to 1 mm. The ultramafic rocks range from dunite to feldspathic lherzolite, where the thinnest veins are typically dunite. Most of the dunitic rocks in Nordre Brumandsfjord contain ‘xenocrysts’ of plagioclase or clinopyroxene derived from the gabbros. Xenocryst-free dunites are almost purely composed of olivine, with minor to trace amounts of clinopyroxene, orthopyroxene, ilmenite, spinel and sulphides. In some samples clinopyroxene appears to be replaced by hornblende and / or biotite (Griffin et al., 2013). Ultramafic rocks with higher modal contents of clinopyroxene with or without orthopyroxene were grouped as peridotites. Plagioclase within the peridotites is mostly xenocrystic, but clinopyroxenes occur as primocrysts, xenocrysts or in reaction rims formed between olivine and plagioclase. Peridotites are the most abundant ultramafic rocks in the Nordre Brumandsfjord Complex, and they contain high modal proportions of clinopyroxene and orthopyroxene; olivine is Fo_{76-79} (Griffin et al., 2013). The main rock type is feldspathic plagioclase-bearing olivine clinopyroxenite (or plagioclase-bearing peridotite), which locally grades into wehrlite and dunite by a modal increase in olivine, or to olivine melagabbro by a modal increase in plagioclase (Bennett et al., 1986).

5.2.3 Late dykes and alkaline intrusions: Late dykes and pegmatitic veins cut the complex. These include wehrlite, feldspathic pyroxene hornblende peridotite, gabbro, hornblende gabbro and blosteroporphyritic amphibolite (picrite and ankaramite) (Bennett et al., 1986). The dykes have NW-SE orientations and may occur in dense swarms that occupy up to 40% of the outcrop area (Sturt et al., 1980).

Figure 7: Geological maps of the Melkvann, Kvalfjord and Reinfjord ultramafic complexes

5.3 Kvalfjord

The 35 km^2 Kvalfjord Ultramafic Complex occurs in two steep-sided, near coalescent intrusive centres that were emplaced into tectonised and modally layered olivine gabbro (Fig. 7). The contacts cut the layering of the host gabbro discordantly and are clearly intrusive (Bennett et al., 1986). The main rock type within the ultramafic complex is olivine clinopyroxenite, with subordinate wehrlite, dunite, and olivine melagabbro.

5.3.1 Country rocks: The Kvalfjord Ultramafic Complex is exclusively intruded into modally layered olivine gabbro. The olivine gabbro is emplaced into quartz-feldspathic paragneiss and developed a broad zone of rheomorphic breccias in the paragneisses (Fig. 7). Towards the ultramafic complex, the host-gabbro becomes progressively more tectonised containing an igneous layering parallel foliation (Svensen, 1990). Distal igneous layering of the olivine gabbro is sub-horizontal but becomes progressively more steeply dipping towards the ultramafic complex under the formation of a southwards plunging synform accommodating the Kvalfjord Complex (Svensen, 1990) much like the synform hosting the Melkvann Complex. The layered gabbros are composed of 4 - 8 km's of cumulates. Cumulate structures are common in the gabbro. Towards the Kvalfjord Complex, the cumulate structures in the gabbro are overprinted and highly modified by a penetrative high-temperature deformation and recrystallisation event associated with the emplacement of ultramafic rocks. The gabbro mostly consists of modally layered olivine gabbro but in the contact zone, leucogabbro and anorthosite is common (Svensen, 1990).

5.3.2 Marginal and roof zones: The sub-vertical wall zones contain a 30-50 metres wide transition zone, which gradually changes from olivine-gabbro, over olivine-melagabbro to plagioclase-free olivine-clinopyroxenite (Svensen, 1990). According to earlier work (Bennett et al., 1986) the marginal zone should be a 1 km wide olivine-melagabbro but later re-mapping demonstrates that olivine-melagabbro is restricted to the roof zone in south and rarely exceeds c. 400 meters in thickness (Svensen, 1990). In rare places, the olivine-melagabbro contains anorthosite layers and relics of layering with the same orientation as the host olivine-gabbro. The transition towards both olivine-gabbro and olivine-clinopyroxenite is gradual and is interpreted as a hybrid zone where the hot ultramafic melts reacted with and partially assimilated the olivine-gabbros. Otherwise, both the wall and roof zones are characterised by decimetre to >100 metre size olivine-gabbro inclusions in various states of resorption by the ultramafic magmas (Svensen, 1990). The intensity and size of gabbro inclusions increases towards the roof of the intrusion and in the topographically highest area they form a "Block-Ocean" with metre-sized blocks of olivine-gabbro engulfed by olivine-clinopyroxenite dykes and sills clearly disengaging the olivine-gabbros in a stoping process (Fig. 7).

5.3.3 Ultramafic rocks: The ultramafic complex is dominated by olivine-clinopyroxenites (Fig. 7), with large irregular and dyke-like bodies of peridotite (Fig. 7) that are mostly wehrlite and dunite (Svensen, 1990). Contacts between olivine-clinopyroxenite and peridotite vary from sharp and well-defined to more gradual and chilling textures are absent. Both olivine-clinopyroxenites and peridotites are coarse-grained and only the olivine-clinopyroxenites show rare examples of modal layering. Wehrlites vary from homogenous olivine-clinopyroxene rocks to poikilitic with very coarse-grained clinopyroxene-oikocrysts (Svensen, 1990). Replacive dunites are common in the southern-parts of the complex where intrusive melts clearly assimilate clinopyroxene in both wehrlites and olivine-clinopyroxenites (Svensen, 1990). In places, the wehrlitic lithologies engulf decimetre-thick layers rich in pegmatitic clinopyroxene with individual crystals up to 15 cm. Olivine in the peridotites is bimodal with coarse-grained olivine-porphyries featuring deformation bands and undulose extinctions resting in a groundmass of fine- to medium-grained stress-free olivine. The two populations show overlapping compositions between Fo_{74} and Fo_{84} whereas the olivine-clinopyroxenites show a more narrow compositional range at $Fo_{77\text{-}81}$ (Svensen, 1990). The Ni content (785-1540 ppm) of olivine is less than half of that observed in the other ultramafic complexes and there is no correlation between Ni and Mg in olivine. Clinopyroxenes vary from Di_{85} in olivine-clinopyroxenite to Di_{88} in peridotite. Olivine and clinopyroxene comprises 90% of the ultramafic rocks with amphibole, Cr-spinel and hercynite as the dominant accessory phases.

5.3.4 Late dykes and alkaline intrusions: Late dykes include several generations of veins of coarse-grained pegmatitic olivine gabbro, which lack chilled margins. In some places these form dense dyke swarms. The dykes exhibit comb structures, may contain skeletal olivine crystals, and have cores of hornblende clinopyroxenite or wehrlite, and intersect both the central complex and the marginal zones. Dilational dykes of olivine-hornblende clinopyroxenite, olivine gabbro, hornblende gabbro and olivine leucogabbro also occur in the ultramafic complex. All these dykes are sub-vertical, and predominantly follow a NE-SW trend and they lack chilled margins. The lack of chilled margins indicates that they were emplaced while the host-rock was relatively hot (Bennett et al., 1986; Svensen, 1990). Later sub-vertical dykes with ankaramitic-picritic compositions (Robins 1975, Robins and Takla, 1979) feature a chilled margin. These dykes are further postdated by sub-horizontal nepheline syenite pegmatites (Fig. 7) intersecting both the Kvalfjord Ultramafic Complex and the envelope (Bennett et al., 1986). These dykes with 0.5 metre nepheline and biotite crystals terminate the igneous activity assembling the Seiland Igneous Province and were dated (zircon U/Pb) to Ma 523 ±2 (Pedersen et al., 1989).

5.4 Reinfjord

The Reinfjord Ultramafic Complex is a steep sided intrusion of ultramafic rocks that were emplaced into layered gabbro except at the NW and SW corners where meta-sediments predominates (Fig. 7). The complex differs from the other three complexes in that the ultramafic rocks have well-developed layering and there is a concentric distribution with the pyroxene-rich rocks in the marginal parts and olivine dominated rocks towards the centre. Similar to the other complexes, the ultramafic rocks show modal variations of increasing olivine and decreasing pyroxene and plagioclase from the gabbro contacts to the core of the complex and from early to late ultramafic rocks. The host gabbro has a sub-alkaline affinity (Bennett et al., 1986). The complex is concentrically zoned from olivine mela-gabbro at its margins (Grannes, 2016) to pyroxenites, olivine clinopyroxenites and wehrlites to dunites + wehrlites in the core of the complex.

5.4.1 Country rocks: Most of the ultramafic rocks are intruded into the Langstrand Gabbronorite. Intrusive contacts with the metasediments are only observed in the SW and NW (Fig. 7). The metasediments are psammitic to semi-pelitic garnet-bearing paragneiss. The intrusion of the Langstrand gabbronorite and the ultramafic rocks formed a contact aureole extending up to 2 km away from the contacts (Bennett, 1974). Rheomorphic breccias within granitic and granodioritic neosomes occur within 20-30 m of the Reinfjord-metasediment contacts, indicating higher degrees of metamorphism that lead to anataxis of the metasediments (Bennett et al., 1986; Grannes, 2016) and in places the formation of m-sized bodies of granitic pegmatite (Grannes, 2016). The Langstrand gabbronorite is a layered sub-alkaline (Bennett, 1974) intrusion containing plagioclase-clinopyroxene-olivine cumulates with accessory apatite, pyrrhotite, zircon, amphibole and biotite. Gabbro layering is sub-horizontal, also at the contact towards the Reinfjord Complex, i.e. the horizontal to vertical change in layering polarity observed at the Melkvann and Kvalfjord Complexes, is absent at Reinfjord.

5.4.2 Marginal and roof zones: Marginal zones are observed along the contacts towards the country rock gabbros and metasediments. These are typically <150 m thick and are hybrid zones containing coarse-grained websterites, plagioclase bearing ultramafic rocks, olivine-melagabbro, rheomorphic gabbro (Fig. 5b), gabbro pegmatite, and variably recrystallised xenoliths of gabbronorite and metasediments (Grant et al., 2016). Metre-thick apophyses of ultramafic rocks can extend for several hundred metres into the gabbronorite and are sub-parallel to the igneous layering of gabbro (Fig. 5a). Xenoliths of the gabbronorite are typically lensoid in shape and can be up to several hundred meters in length down to several meters and centimeters (Fig. 5e). The xenoliths of gabbronorite are variably recrystallised and foliated with neosomes of more plagioclase-rich leucogabbro. Xenoliths are draped in a websterite reaction rim when in contact with wehrlite and olivine-clinopyroxenites. Mafic dykes extend from the ultramafic complex and into the marginal zones and host gabbronorite and thin veins of plagioclase extend from the gabbronorite into the ultramafic rocks (Grant et al., 2016). Plagioclase is absent in the ultramafic rocks throughout the complex but becomes increasingly abundant towards the marginal zones (Emblin, 1985; Grant et al., 2016; Grannes, 2016). Recent field work discovered a gabbroic roof zone in the Reinfjord Ultramafic Complex, on an isolated cliff face to the North East partially below the glacier (Fig. 7). The roof zone contains a thin hybrid zone in direct contact with dunite but is poorly studied in the vertical cliff-sides (Fig. 7)

5.4.3 Ultramafic rocks: The complex is divided into three different series; the lower layered series (LLS), upper layered series (ULS) and central series (CS) (Emblin, 1985). The LLS is exposed in a steep cliff face at the SW corner of the intrusion in contact with metasediments (Fig. 7). A thin (50 m) gabbro screen above structurally separates the LLS from the ULS. The LLS is rhythmically and modally layered sequence with approximately 4 cyclic units of olivine- and pyroxene-dominated cumulates (Emblin, 1985; Bennett et al., 1986). The base of each unit is predominantly composed of olivine-rich lherzolites with large oikocrystic orthopyroxenes and poikilitic wehrlites. The subsequent layers are more clinopyroxene-rich wehrlites and olivine-clinopyroxenites that contain orthopyroxene oikocrysts (Bennett et al., 1986).

The ULS is spatially separated from the LLS, but it is unclear if it formed at the same time as the LLS or not. Like the LLS, the ULS is also modally layered and contains 7 cyclic units of olivine- and clinopyroxene-dominated cumulates (Emblin, 1985). The ULS outcrops along the eastern and western sides of a plateau region between 500-800 m above sea level. The base of each unit is predominantly composed of wehrlite and dunite, with increasing amounts of clinopyroxene in the upper layers where olivine-clinopyroxenite become increasingly dominant. Layering varies from meter to centimetre scales and excellent examples of cumulate features such as cross-bedding, slumping and load structures are observed throughout the ULS (Fig. 6). The intrusive contacts with the country rock gabbro are steep.

The CS, the most voluminous part of the complex, occupies the central region of the intrusion (Fig. 7) and is composed of cryptically layered dunite and wehrlite. The cryptic layering is observed as small variations in bulk rock chemistry and mineral chemistry (e.g. forsterite or Mn contents in olivine), however, the cryptic layering is chaotic with numerous small reversals in the Ol-chemistry (Grant et al., 2016). Dunitic dykes, irregular veins and structures intersects ULS and, in several places are rooted in the CS (Fig. 6e,f). The dunite dykes range from metres to centimetres in thickness and interstitial olivine around primocryst clinopyroxene is common (Grant et al., 2016). The dunite dykes appear to be replacive, where olivine saturated melts have infiltrated semi-consolidated pyroxene-rich cumulates (Emblin, 1985; Grant et al., 2016). Therefore, the magmas that formed the CS intruded after the ULS cumulates were formed. However, the time interval between the ULS and CS is likely to have been short since the ULS cumulates were unconsolidated and porous allowing the CS-forming melts to filter through the ULS (Fig. 6e, f). The CS also contains several reefs of sulphide hosted Ni-Cu-PGE deposits within the cryptic layering (see later section on ore-deposits). Another, characteristic feature is the common occurrence of mm- to cm-sized carbonate-rich clots (Fig. 9) and dykelets characterised by carbonates, opx, Fe-Ti oxides, amphibole, biotite and sulphides estimated to comprise 1-2 % of the ultramafic lithologies.

From contact to centre and with time the Reinfjord Ultramafic Complex evolved from mafic plagioclase-clinopyroxene-olivine cumulates to clinopyroxene-rich cumulates to olivine dominated cumulates. This sequence implies that the magmas and therefore cumulates, became more refractory, MgO-rich and olivine-rich with time, hence may be termed a ‘regressive fractionation sequence’. This sequence developed through repetitive recharge of progressively more primitive magmas into an open magma chamber system (Grant et al., 2016).

5.4.4 Late dykes and alkaline intrusions: Late dykes are abundant in the CS and in some areas, constitute c. 50 % of the outcrop volume (Fig. 6c). The dykes have several generations that can be determined using cross-cutting relationships all with approximately NE-SW orientations. The sequence is wehrlites — olivine clinopyroxenites — hornblende-bearing olivine clinopyroxenites — hornblende gabbros. Most dykes do not have chilled margins against the dunites and wehrlites that they intrude, except for the very late gabbroic dykes. In fact, some dykes have fuzzy contacts towards dunite and it is hard to define the actual contact (Fig. 6d). Alkaline dykes and thin veinlets are also present, although it is uncertain if these post-date the rest of the dyke generations. The alkaline dykes and veinlets contain abundant plagioclase along with hornblende, phlogopite, apatite, dolomite and Cu-Ni sulphides and are often accompanied by inclusion trails of dolomite, magnetite, orthopyroxene and CO_2 fluids. Several late dykes with chilled margins cross cutting all features, are also observed. However, they were not studied in detail.

6. Alkaline Complexes in the Seiland Igneous Province

Carbonatite-Syenite associations represent minor but conspicuous magmatic episodes comprising 2-3 % of the SIP at 7 localities.

Larger complexes occur at W. Sørøya in the Breivikbukta and central south Stjernøya in the Lillebukta intrusive complexes and finally the somewhat smaller Pollen Carbonatite on NW Stjernøya (Fig. 1). Breivikbukta comprises two complexes, a large dyke 100-300 metres wide c. 7 km long, which is emplaced into the Klubben Fm. quartzitic meta-sediments in a ring like structure (Sturt et al., 1978). Another part of this complex appears 200-400 metres further to the East as a nepheline-syenite dyke complex emplaced into a gabbro-diorite complex (Sturt et al., 1978). Lillebukta comprises a sub-circular plutonic complex covering 4 km^2

(Robins, 1971) which is emplaced into hornblendite and layered gabbro, whereas the Pollen complex is a strongly deformed carbonatite covering 0.8 Km^2 in a c. 2 km long dyke.

The other 5 localities all comprises narrow pegmatitic nepheline-syenite dyke complexes centimetres to metres in width; one is located in the central E. parts of Stjernøya (Svensen, 1990) intersecting both the Kvaløya ultramafic complex and the gabbro envelope (Fig. 7) and the four other localities are on Seiland (Sturt et al., 1978; Robins, 1971)

The Sørøya alkaline complexes are the oldest rocks of SIP (579-570 Ma) (Roberts et al., 2010) and the youngest are Lillebukta and dykes on Stjernøya (523 Ma) and Seiland (531 Ma) (Pedersen et al., 1989) i.e., alkaline magmatism book-end the SIP-forming igneous events.

The Breivikbukta alkaline complexes comprises carbonatites, nepheline syenite and pyroxenite emplaced in a psammitic schist and is in places bordered by a metre thick fenitisation zone (Sturt and Ramsay, 1965; Roberts et al., 2010). The syenite complex to the East comprises numerous intersecting dykes and smaller intrusions ranging in composition from nepheline syenite and syenite emplaced into diorites, gabbros and pyroxenites (Sturt and Ramsay, 1965). The intrusive chronology of the Sørøya complex is shonkinitic malignites followed by nepheline syenites and finally silico carbonatites. All the rock types contain aegerine augite, hastingsitic amphibole and alkali feldspar. Accessory phases includes garnet, apatite, monazite xenotime and zircon. Recent age dating provides overlapping ages of syenites, malignites and carbonatites (Roberts et al., 2010). Interestingly, the alkaline rocks of Sørøya yields some of the most primitive isotopic data of any rock in SIP (and in CIMP) with E_{Nd} of +4 and E_{Hf} of +8 (Roberts et al., 2010).

The Lillebukta and Pollen carbonatites comprises calcite, biotite and apatite and are distinguishable from the Sørøya complex by much lower trace-element contents. The Pollen complex forms a 2 km dyke body and comprises strongly deformed gabbros and syenites. The 4 km^2 Lillebukta alkaline complex began with emplacement of an intense dyke swarm of nepheline syenite, syenite and alkalipyroxenitic rocks. This event was followed by emplacement of carbonatites and finally lichdfeldite and syenite pegmatites and mafic dykes. The carbonatites are dominated by calcite, biotite and c. 10% apatite and are associated with a zone of pervasive fenitisation 200-800 metres wide (Wulf-Pedersen, 1992).

Stable isotope analysis of the Breivikbukta and Lillebukta carbonatites yields typical mantle values with $D^{13}C$ at -6 to – 8 $^{o}/_{oo}$ and $D^{18}O$ at +6 to +8 $^{o}/_{oo}$.(Wulf-Pedersen, 1992).

7. Dykes

Dykes of picrite, ankaramite and lamprophyre composition are observed throughout Seiland, Stjernøya (Robins, 1975; Robins and Takla, 1979), Øksfjord peninsula (Reginiussen et al., 1995), and in association with Melkvann (Yeo, 1984; Leaver et al., 1989) and Reinfjord (Grant et al., 2016). The dykes intersect most mafic and ultramafic features, implying these were emplaced towards the end of magmatic activity in the SIP. Their lower age limit at 523 Ma is constrained in some areas by later cross-cutting alkaline rocks such as syenite pegmatites (Robins and Takla, 1979; Leaver et al., 1989). Some dykes have chilled margins against their host rocks, suggesting that the mafic and ultramafic intrusions had cooled significantly by the time of their emplacement. However, many dykes intersecting the ultramafic complexes features gradual sometimes hazy contacts and are medium- to coarse-grained throughout their centre and contact (Fig. 6d), i.e. they were emplaced in a hot partially unconsolidated host rock. Dykes occur as isolated bodies or in dense dyke-swarms in the central parts of the major ultramafic complexes. Here they occupy c. 40-50 vol% of the complex in dykes varying from cm's to half a metre in thickness (e.g., Grant et. al., 2016). Up to five different dyke generations were identified by Reginiussen et al., (1995) in the Øksfjord peninsula, the latest of which are lamprophyre dykes that are concentrated in the area around the Tappeluft intrusion. The vast majority of dykes typically have roughly N-S strikes although ENE-WSW strikes are described at Seiland (Leaver et al., 1989). All dykes have steep dips of 70-90°. They typically have Ne-normative compositions and the most primitive have MgO contents of up to 21 wt.%, xMg up to 71.4 and high Ni (642 ppm) and Cr (1596 ppm) contents, meaning that some may represent primary mantle melts. Most dykes display juvenile compositions. All dykes have steep rare earth element profiles (high LREE/HREE) that are similar to OIB and consistent with an intra-plate setting (Grant et al. 2016). Plagioclase, clinopyroxene and amphibole are common phenocryst phases in picrite dykes. Some picrite dykes contain mineral lamination and can be accompanied by modal and cyclic layering with mineral chemistries and crystallisation sequences that are similar to the ultramafic intrusions. It has therefore been suggested that the most primitive picrite dykes and ultramafic intrusions are cogenetic (Bennett et al., 1986). Similarities between the trace element compositions of primitive picrites and the calculated parent melts from the ultramafic rocks from Reinfjord further supports this hypothesis (Grant et al., in review). Lamprophyre dykes all have much more evolved compositions, with low xMg (0.2-0.3), Ni

(7-16 ppm), and Cr (24-85 ppm) and therefore must have undergone a significant amount of fractionation prior to emplacement. Modelling by Grant et al. (in review) suggests that they could be formed by 40-50% crystallisation of melts similar in composition to those that formed the ultramafic rocks at Reinfjord. Phenocrysts of amphibole, biotite, Fe-Ti oxides and apatite with interstitial plagioclase are observed in the lamprophyre dykes (Reginiussen et al., 1995).

8. Significance of PGE-Cu-Ni deposits

It was recently confirmed that SIP may have a significant ore-forming potential of Cu-Ni-PGE deposits (Schanche et al., 2012). Equally important for the formation of SIP, the ore-forming processes in the Reinfjord Complex document the importance of volatile fluxing of sulphur and carbon during emplacement of the ultramafic magmas (Nikolaisen, 2016; Larsen et al., 2016). Accordingly, minute but conspicuous assemblages of magmatic carbonate and sulphide are common throughout the Reinfjord Complex, particularly where Cu-Ni-PGE deposits occur.

Reinfjord features both *contact deposit* (Søyland-Hansen, 1971) and reef deposits, always hosted in the dunitic cumulates of the CS (Schanche et al., 2012; Larsen et al., 2016). Only the reef deposits are described here because of their significant contributions to understanding asthenosphere-lithosphere melt-transfer (see section 9).

8.1 Reef deposits

Reef deposits appear as a 5 Ohm conductor providing an excellent contrast to the 3000 Ohm Central Series dunitic cumulates (Schanche et al., 2012). Modelling implied a conformable saucer-shaped body at a depth of c. 100 m below the surface and exploratory drilling confirmed the presence of weakly disseminated reefs at 85 and 110 m below the surface with 1.6 and 1.2 wt% total sulphides, respectively. In drillhole RF-1, the upper reef comprises 5 metres of dunite with an average of 0.4 wt% sulphide-bound Ni, 0.14 wt% Cu and 70 ppb PGE+Au whereas the lower reef comprises 5 metres with 0.23 wt% Ni and 715 ppb PGE+Au. Importantly, most of the PGE+Au is confined to a 1 m dunite section with 1635 ppb PGE+Au including 750 ppb Pd, 430 ppb Pt, 220 ppb Au and, 235 ppb IPGE with an Os-peak at 140 ppb. The Ni peak actually occurs 7 metres higher up, hence the PGE-reef is clearly decoupled from the Ni-reef and the Ni-reef is decoupled from the Cu-reef. Mineralogically, c. 50 % of the sulphides are pentlandite and chalcopyrite, the remaining part being pyrrhotite. Detailed studies demonstrated that peak values are associated with dunitic cumulates belonging to the Central Series (Nikolaisen, 2016; Larsen et al., 2016).

Figure 8: Drill-Core chemistry and position of PGE-Cu-Ni reefs RF-4

The sulphide reefs were also discovered in two recent drill holes sampled c. 600 metres north of the RF-1 and RF-2 cores (Fig. 7). In RF-4 (Fig. 8) , the reefs occur from 40-80 metres below the surface in the Central Series dunites. Cu peaks with values of c. 0.1 wt % Cu in two 10 m thick reefs separated by 20 metres of dunite (Fig. 9). Finally, there is a deep-seated Cu-reef at 349 m with 0.1 wt% Cu occurring at the transition between Central Series dunites and Marginal Series pyroxenites. Like RF-1, the PGE reef, with 0.3 ppm PGE over 5 metres, is decoupled from the Cu-reefs in occurring at 64 metres between the two Cu-maxima. None of the Cu reefs are associated with significant Ni-sulphide anomalies. The highest Ni values occur 5 metres above the PGE-reef.

There are 4 more PGE reefs with c. 0.1 ppm PGE, but none of them are close to the Ni and/or Cu sulphide reefs (Fig. 8).

It is clear that the main PGE-reefs are decoupled from both Cu and Ni reefs, and that the Ni-reef, that occur 5 and 7 metres above the PGE-reefs, are Cu-poor. Furthermore, PGE reefs coincide with relatively Sulphur poor segments of the igneous stratigraphy (Fig. 8).

The Pt/Pd ratios at all anomalous horizons in the drill-cores are between 1:1 and 1:2 whereas, "barren" sections have an average of 2:1 (Fig. 8, Fig. 9). The PPGE/IPGE ratios are comparable to the Merensky Reef (S. Afr. Rep) with typical values of 2-10 (Iljina, 2012). Platinum Group Minerals (PGM) are dominated by tellurides mostly Moncheite ($(Pt, Pd)Te_2$) and Merenskyite ($(Pd, Pt)(Bi, Te)_2$) whereas Au varies from pure gold to electrum with 40 % Ag (Nikolaisen, 2016; Larsen et al., 2016).

Figure 9: textural setting of PGM and sulphides and dolomite

Most of the PGM's occur together with sulphides often intimately intergrown with pentlandite exsolution in pyrrhotite tenors (Fig. 9) whereas gold-rich phases show a close association with carbonate-sulphide assemblages (Nikolaisen 2016; Larsen et al., 2016).

In situ ion probe sulphur isotope analysis of sulphides yielded bulk $\delta^{34}S$ values around -2 to -2 $^{o}/_{oo}$ for reef deposits as well as for sulphides in barren parts of the dunites whereas the host gabbro and paragneisses gave average values of +4 $^{o}/_{oo}$ and +11 $^{o}/_{oo}$, respectively (Oen

2012; Larsen et al., 2016). Accordingly, the parental melts forming the ultramafic cumulates gained its sulphur from a distinctively different source region than both the paragneisses and also the gabbros; although, both gabbros and ultramafic cumulates displays $\delta^{34}S$ within the typical mantle range.

9. State of the art of SIP

In this section we describe some of the current issues related to the emplacement of SIP specifically, and more generally the deep-seated properties of high-yielding magmatic systems such as LIP-forming regions and hot-spots.

9.1 Approaching parental melt compositions

Two models for the parent melts of the ultramafic intrusions have been proposed. The dunite melt model was derived from observations from the Nordre Burmandsfjord Complex by Griffin et al., (2013) and Sturt et al., (1980), which led to the hypothesis that the range of ultramafic rocks formed through large-scale contamination of a dunitic parent magma and a contaminant derived by partial melting of the host gabbros. These authors suggest that the dunitic magma had MgO contents of up to 40 wt.%, temperatures of 1650-1700°C, was 'dry' and had an extremely REE-depleted composition. Melts of this kind would be some of the hottest and most magnesian ever reported, certainly for times as late as the Ediacaran. Griffin et al. (2013) also modelled the mantle melting conditions in which dunite melts could form and suggested that melting of extremely depleted harzburgite residue within an upwelling mantle plume could result in melts with these extreme characteristics.

The picrite melt model was developed through observations from the Reinfjord, Melkvann and Kvalfjord complexes and proposed that these intrusions predominantly formed by fractional crystallisation of picritic to komatiitic melts with only moderate to low amounts of contamination (Bennett et al., 1986; Grant et al., 2016). Early dykes found throughout SIP features picritic to komatiitic compositions, 16-21 wt% MgO, Cr of 1594 ppm and Ni of 611 ppm, indicating that they underwent little fractional crystallisation and would be in equilibrium with most of the more primitive olivine compositions in the ultramafic complexes of SIP (Fo_{80-85}). Melt compositions calculated from partition coefficients and trace element compositions in clinopyroxene from Reinfjord are OIB-like with LREE enriched over HREE (Thaarup, 2016; Grant et al., in prep). These calculated compositions are remarkably similar to the compositions of the picritic dykes.

As discussed throughout this work, from the high abundance of alkaline, carbonatite and other volatile enriched magmas, the REE-enriched composition of most intrusions and the presence of PGE-Cu-Ni reefs in Reinfjord, it does not appear that the SIP tapped a particularly 'dry' or ultra-depleted mantle source. It is possible that Nordre Brumandsfjord is a special case, yet this could be difficult to reconcile with its close proximity in space and time to Melkvann (Fig. 1 and 7). It is therefore clear that there needs to be considerably more work and data on the ultramafic intrusions to determine the types of melts that formed them.

9.2 Mantle-plume properties of melt-forming region

Information about the mantle sources beneath the SIP come from ultramafic nodules within dykes, inverse trace element modelling of parent melt compositions and isotopic studies.

Ultramafic nodules are observed in hydrous alkali basalt or basanite (Robins 1975; Leaver et al., 1989) and are separated into 3 different groups; Type I, Type II and cumulate. Type 1 xenoliths are the most common and are spinel lherzolites, harzburgites, dunites and wehrlites. Fabrics include laminated, disrupted, granoblastic and porphyroclastic. The latter is most common and contain kink-banded olivine in a matrix of neoblastic unstrained olivine and clinopyroxene (Leaver et al., 1989). Superficially they have many similar features to those of the most primitive rock types in some of the ultramafic intrusions (such as in Reinfjord) but with X_{Mg} of 85-90 and olivine of Fo_{87-91}, the ultramafic nodules are more primitive. Amphibole, phlogopite, plagioclase and carbonate (mostly dolomite) are present as accessory phases and suggest that the nodules were affected by metasomatism (Leaver et al., 1989). Type II nodules include olivine websterites, olivine clinopyroxenites, wehrlites and dunites. They are generally richer in Al and Ti than Type I, have igneous textures and often show signs of partial recrystallisation. Olivine compositions range from Fo_{74-81} and accessory phases include kaersutite ±phlogopite, orthopyroxene, magnetite, ilmenite and iron sulphides (Leaver et al., 1989). Composite nodules are very rare and contain veins of clinopyroxene, amphibole with minor spinel olivine and plagioclase, which cross cut Type 1 nodules (Leaver et al., 1989). In general, it appears that the nodules are from an upper lithospheric mantle which had undergone depletion and enrichment events on a relatively local scale before being entrained into the host magmas (Leaver et al., 1989).

Recalling that the SIP essentially represent a deep-rooted segment of the Central Iapetus Magmatic Province (CIMP), it is pertinent to include some of the few data on the inferred mantle properties from elsewhere in the CIMP. Data from CIMP kimberlites, and carbonatite dykes from SW Greenland and Labrador imply relatively juvenile values of E_{Hf} at +4 and E_{Nd}

at +3 on the average (Tappe et al., 2011). These data are corroborated by even more juvenile values from the SIP where carbonatites and nepheline syenite yielded average values of E_{Hf} at +8 and E_{Nd} at +4 (Roberts, 2010). A limited collection of stable isotope data also implies typical mantle carbonate values of $d^{18}O$ of +7 and $d^{13}C$ of -7 for SIP whereas SW Greenland/Labrador kimberlites are slightly heavier. In the SIP, we also have typical mantle values of bulk sulphide around 0 for the reef deposits and +4 for the layered gabbro. Accordingly, the source of mantle sulphur became lighter as melt extraction proceeded from the production of basaltic melts to form layered gabbros to picritic-komatiitic melts forming the ultramafic complexes. The isotopic data from the most pristine rocks and the high abundance of carbonated alkaline and ultramafic rocks throughout the CIMP is generally interpreted as a result of derivation from a carbonated fertile peridotite within the asthenosphere (Tappe et al., 2011; Grant et al., 2016). Tappe and co-workers (2011) even suggest that an asthenosphere-derived carbonate-silicate melt component at the athenosphere-lithosphere boundary was present throughout the craton base at 610-550 Ma underneath the CIMP. Certainly, in the SIP, the relatively high abundance of carbonatites, lamprophyre, hornblendite and volatile-rich alkaline rocks, together with the omnipresence of sulphides and carbonates in the ultramafic complexes, corroborates this hypothesis.

9.3 Paleogeographic location of the SIP in the Ediacaran

Neoproterozoic paleomagnetic reconstructions show that after breaking away from Rodinia, Gondwana was positioned at the southern hemisphere below 30^{o} North (Torsvik and Cocks, 2005). Ediacaran continental rifting commenced between the nascent continents of Laurentia & Baltica, Laurentia & Gondwana and Baltica & Siberia. It is generally agreed that the SIP was emplaced in the Ediacaran in a continental fragment, but it is debated if this micro-continent was positioned at the periphery of Baltica or closer to Avalonia/Amazonia and the Laurentian cratons (see summary in Corfu et al., 2007).

The debate centres around the Kalak Nappes Complex (KNC) which host SIP and traditionally is correlated with the Upper Allochton of the Caledonian tectonostratigraphy. Other than crystalline basement slices, pelites, paragneisses and limestones, KNC is by far dominated by the Klubben psammite Fm., that also is the principal host of the SIP intrusives and was deposited prior to 980 Ma (e.g. Corfu et al., 2007). KNC was intruded by orogenic granitic rocks at 980-960, 850 and 700 Ma.

Opposing a Baltic affinity of KNC, Corfu et al., (2007) argue that *orogenic* Neoproterozoic granites with analogue ages are absent in the western parts of the Baltic craton. Moreover, Cambrian and Ordovician meta-sediments forming at the Baltic shelf, and abundantly present in the Upper and Middle Allochtons of the Caledonides, are absent in KNC. Finally, chronological analogues to the klubben Fm. are not documented from any parts of the Baltic Craton. Geochronologically, the Klubben Fm. resembles sedimentary formations from the Laurentian Margin (Krummedal Fm., E. Greenland) and Avalonia (Moine Fm., Scotland). Late Proterozoic orogenic granites analogue in age to the KNC intrusions are common in the central Appalachians where we also see extensive mafic volcanism associated with the CIMP event at 570-560 Ma (Corfu et al., 2007).

In conclusion, it may be hypothesised that the SIP formed during CIMP magmatism in NE North America and SW-Greenland and was active throughout the opening of the South Iapetus Sea between Laurentia and Gondwana (i.e. paleo Amazonia and Avalonia). The timing of this opening is another controversy but is generally placed at 550 Ma (e.g. Cawood et al., 2001; Harz and Torsvik, 2002). Accordingly, only the late alkaline magmatism (531-520 Ma), including the Lillebukta alkaline complex and Stjernøya dykes, appear to postdate the opening of the Iapetus.

Later, the KNC terranes experienced left lateral transfer to the W. Baltica Craton (Corfu et al., 2007). Ar-Ar dating of Caledonian thrust (Dalmeyer, 1988) in KNC at 420-400 Ma, the fact that Silurian sedimentary lithologies lie unconformably above KNC and the absence of (reliable) early Caledonian metamorphic ages (Corfu et al., 2007), imply that KNC and SIP finally came to rest on the Baltic craton during the Scandian event (420-400) of the Caledonian orogeny (Corfu et al., 2007). Late Caledonian docking of SIP also explains why the magmatic fabric of SIP is so exceptionally well preserved.

9.4 Importance of assimilation

Mg vs Al: Bulk rock data from the four main ultramafic intrusions are summarised in Fig. 10. Compositional ranges for plagioclase, clinopyroxene and olivine were taken for each intrusion and tie lines were drawn between each mineral phase. The ‘contaminant component’ from Griffin et al. (2013) is also included. The ‘contaminant’ falls along the tie line between clinopyroxene and plagioclase and is similar in composition to a melt that would form by melting of gabbro along the cotectic between plagioclase and clinopyroxene in the Fo-Di-An ternary diagram at 10 kbar (Presnall et al., 1978). Melts that plot along a tie-line with this composition should therefore be indicative of contamination. It is clear that the cumulates from Reinfjord are essentially binary mixtures between olivine and clinopyroxene for the ultramafic rocks and clinopyroxene and plagioclase for gabbroic rocks, supporting previous data that showed limited signs of contamination (Grant et al., 2016). For Melkvann, Nordre Brumandsfjord and Kvalfjord, the ultramafic rocks all show considerable variation and are off the olivine-clinopyroxene tie line, containing some plagioclase, with trends plotting towards that of the 'contaminant'. Together with the field data and petrology this suggests that contamination of ultramafic rocks by partial melting of gabbro is more widespread in Melkvann, Nordre Brumandsfjord and Kvalfjord compared to Reinfjord.

Spinel compositions: Dunite, wehrlites and olivine clinopyroxenites from Reinfjord, particularly those that contain no plagioclase, contain spinel compositions that are high in Cr and Fe and low in Al. These fall into two groups; inclusions within olivine that are magnetite in composition, and interstitial Cr-Al spinels. The pristine gabbros themselves contain low amounts of Cr and no spinel, only ilmenite and or magnetite as the main oxides. Hybrid rocks in the marginal zones, including plagioclase bearing peridotites, pyroxenites /websterites and olivine and spinel bearing gabbros contain spinels that are significantly more Al-rich and Cr-poor than elsewhere. Spinel compositions from Nordre Brumandsfjord and Melkvann are mostly within the Al-rich field that crosses over with gabbroic rocks and marginal rock types. The observation of Al-rich spinels in plagioclase bearing peridotites, formed by mixing between primitive melts and anatectic melts of wall rock gabbros, has been noted in ophiolite sequences (Bédard, 1993; Bédard and Hébert, 1998). Plagioclase + spinel is not an equilibrium assemblage and their coexistence in hybrid peridotites was thought to be negated if the plagioclase grains were xenocrystic (Bédard and Hébert, 1998). The spinel compositions from the ultramafic rocks in the SIP may therefore be powerful recorders of this reaction process (Fig. 11) (see phase diagrams in these papers).

Figure 10. MgO vs Al2O3, whole rock.

Figure 11. Spinel compositions.

9.5 The apparent P loop of the SIP and emplacement of dense igneous melts

We have compiled the available estimates of pressure and temperature conditions reported from across the SIP (Appendix 1). The only estimate of the ambient P-T conditions of the metasediments before igneous activity (at 702 Ma) is 752°C ± 22.5 and 8.05 ± 1.75 kbar (Gasser et al., 2015). This is marked as point 1 on Fig. 12. Crystallisation and cooling conditions during emplacement are mostly estimated from two pyroxene thermobarometry studies (Griffin et al., 2013, Grant et al., 2016) and is marked at point A on Figure 12. Temperatures of crystallisation however could vary from <800°C for carbonatites to between 1400 and 1450°C (Bennett et al., 1986) or even 1700°C (Griffin et al., 2013) for ultramafic melts, however our observations support a picritic-komatiitic melt composition and we therefore mark the temperature at approximately 1450°C. The pressure is inferred from the pressure of two-pyroxene cooling conditions of 1050 ±35°C and 7.9 ±1.1 kb, marked with B on Fig. 12. The ultramafic rocks of the Reinfjord ultramafic complex are cut by numerous dykes ranging from wehrlite to gabbro in composition. Temperature estimates using the calculations of Ridolfi and Renzulli (2012) from amphiboles in ultramafic rocks from the CS, marginal zones, late wehrlite-gabbro dyke swarms and amphibole-bearing carbonate clots give ranges of 1180-940°C. Pressure estimates using single amphibole analyses are generally not reliable (Molina et al., 2015). Therefore, the plagioclase-amphibole barometer (Molina et al., 2015) was used for several of the dykes where possible. This gave pressure estimates of 11.6 to 15.46 kb. The dykes are cut by numerous thin shear zones, which by offset of dykes gives an extensional tectonic setting (Sørensen et al., in prep). Studies of the assemblages in the shear zones gives temperatures slightly lower than the crystallisation temperatures of the dykes at similar pressures (Fig. 13). The spatial and PT-proximity of dykes and shear zones makes the interpretation that the CO_2 from dykes relates to the reaction-driven strain softening likely. The indication of a pressure increase after crystallisation agrees well with the high PT-estimates of Caledonian uplift of 663°C ±13 and 8.5-10 kbar (Gasser et al., 2015), point 3 on Fig. 12 and also with other reports of P-increase after crystallisation. Other studies generally suggest that the P-increase is a result of Caledonian thrusting (Elvevold and Andersen 1993; Elvevold et al., 1994; Elvevold and Reginiussen et al., 1996; Gasser et al., 2015). The P-increase could also be associated with collapse of the lower continental crust upon emplacement of heavy mafic-ultramafic complexes as implied by synformal depressions hosting Kvalfjord and Melkvann (section 5.1 and 5.3) possible emplacement of kilometres of flood basalts associated with the Central Iapetus Magmatic Province – very similar to the 2 kb P-increase documented for the Skaergaard Intrusion (Larsen and Tegner, 2006) when overlain by 6-7 kilometres of flood basalts.

A common observation is that sulphides associates with carbonates near alkaline veins or shear zones related to dolomitisation of wehrlite and dunite in the Reinfjord UM-complex. The mineral assemblage has kimberlitic compositions (Nikolaisen, 2016) in Reinfjord comprising plagioclase, orthopyroxene, hornblende, phlogopite, ilmenite/rutile and copper minerals (chalcopyrite, bornite and minor chalcocite). These samples also have CO_2 fluid inclusions in plagioclase with carbonate solids. As discussed above, dykes and veins were followed by carbonation shear zones that offset the dykes in an extensional fashion. These shear zones host the reaction of cpx and ol to form dolomite and enstatite along subgrain boundaries, facilitating grain boundary sliding and promoting strain weakening (Sørensen et al., in prep). With pseudosections it is possible to stabilise this assemblage under a narrow PT and X_{CO2}-range (Fig. 13) at P>11 kbar. It is suggested the X_{CO2} was balanced by the remaining dolomite still preserved during aqueous fluid infiltration.

10. Synthesis

10.1 Assembly of the system

10.1.1 Early and late alkaline-carbonatites: Some of the earliest recorded ages are from the Breivikbotn carbonatite-alkaline complex. The carbonatite was dated at 574 ± 5 Ma and the alkaline gneisses and nepheline syenite dykes that intruded into the Breivikbotn Gabbro (clearly older) have ages between 580 and 570 Ma (Roberts et al., 2010). The youngest ages of 523 ±2 Ma and 531 ±2 (Pedersen et al 1989) in the SIP are from the syenite-pegmatites at Stjernøya and Seiland, respectively, and 540 ±39 Ma and 521 ±22 Ma for apatite-rich hornblende clinopyroxenite from the Lillebukt Alkaline Complex on Stjernøya (Cadow, 1993). Other late intrusive rocks are picrite dykes, lamprophyre dykes, fenitisation of ultramafic lithologies with magnetite-apatite-hornblendite clinopyroxenites and small plugs of syenite and nepheline syenite pegmatite in Melkvann (Bennett et al., 1986). The alkaline-carbonatite rocks from both Breivikbotn and Stjernøya all have mantle ε_{Nd} values of around +4 (Cadow, 1993; Roberts, 2010) and are therefore likely to be derived directly from the mantle. Small volume alkali-carbonatite complexes therefore appear to occur before and after large volumes of mafic and ultramafic volcanism in the SIP. This has also been observed in some other LIPs, such as the Deccan Traps (Basu et al., 1993) and Parana-Etendeka LIP (Gibson et al., 2006), where carbonatites and alkali rocks both precede and follow the main pulses of flood basalt magmatism (Ernst and Bell, 2010). These authors attribute the early alkali-carbonatites to low degree melts resulting from the impact of the mantle plume head on a metasomatised lithosphere (Gibson et al., 2006) and this agrees with plume melting models where carbonatites are formed either above or distally to the main plume head (Bell and Rukhlov, 2004).

10.1.2 Main phase of the SIP; mafic and ultramafic magmas: The alkaline rocks from Breivikbotn overlap ages recorded for the mafic rocks throughout the SIP, however the majority of the mafic rocks have ages between 570 and 560 Ma (Roberts et al., 2006). Olivine forsterite-content and bulk rock Mg-numbers, Cr and Ni contents of chilled margins suggest that many of the mafic rocks formed from magmas that are not in equilibrium with mantle olivine and had undergone some degree of fractional crystallisation prior to their emplacement (Tegner et al., 1999). The mafic magmas intruded directly into lower crustal metasediments, causing large km-sized contact aureoles where temperatures were raised from amphibolite to granulite facies temperatures. Contamination by the metasediments led to isotope values that range from depleted mantle, overlapping those of the alkaline rocks, towards highly crustally contaminated values (Tegner et al., 1999). However, the bulk rock REE profiles are similar to OIB and do not vary significantly even across large ranges in isotopic values (ε_{Nd} and ε_{Hf}) (Roberts, 2010). The trace elements may therefore reflect a primary mantle character of the magmas that formed the mafic intrusions, whilst the isotopic values are more dramatically affected by contamination by ancient crustal sediments.

The mafic phase of the SIP is shortly followed by the emplacement of ultramafic complexes. The only recorded dates for ultramafic rocks are 550 ±34 Ma (whole-rock Sm/Nd) for Tappeluft (Mørk and Stabel, 1990), however the ultramafic intrusions all cross-cut earlier formed gabbro intrusions (Bennett et al., 1986; Sturt et al., 1980; Griffin et al., 2013, Grant et al., 2015) and were therefore formed later than the episodes of mafic magmatism. The field relationships indicate that the ultramafic magmas were intruded when the mafic cumulates were still hot and close to their solidus, hence shortly after the mafic magmas (Bennett et al., 1986; Griffin et al., 2013). Thick marginal zones and roof zones are observed at the contacts between the mafic and ultramafic rocks, and these zones contain hybrid rock types that formed through contamination of ultramafic melts by partial melts derived from the wall rock gabbros. In Kvalfjord, Melkvann and Reinfjord there are abundant and clear examples of where clinopyroxene-dominated cumulates (e.g. olivine clinopyroxenite) are replaced by irregular and discordant bodies of dunite and wehrlite. The replacive dunites formed through a melt-rock reaction involving the dissolution of clinopyroxene in the cumulates and precipitation of olivine (Grant et al., 2015), and they reveal that the magma chamber formed initially through the formation of clinopyroxene-dominated and then by olivine-dominated cumulates. The sequence from gabbro to clinopyroxene-rich to olivine-rich cumulates is contrary to the expected fractional crystallisation sequence and follows a 'reverse fractionation sequence'. A reverse fractionation sequence can form through repetitive emplacement of magma and replacement of earlier formed cumulates (Grant et al., 2016). Similar processes are observed in other deep crustal ultramafic complexes such as

Kondyor (Burg et al., 2009), Chillas (Jagoutz et al., 2006; Jagoutz et al., 2007) and beneath LIPs (Yu et al., 2015). The ultramafic melts predominantly intrude into country rock gabbros that are both hotter and contain less crustal material than the colder crustal meta-sediments that the mafic rocks predominantly intruded. This ensures that the ultramafic melts can maintain higher temperatures and more primitive mantle compositions than those that formed the mafic intrusions. Therefore, the transition from mafic to ultramafic rock types simply may derive from a continual and sufficient flux of magmas into the conduit system (Grant et al., 2016). We highlight the importance of crustal level melt-rock reactions in developing the trends observed in the ultramafic complexes. We do not, however, rule out the possible contributions of mantle processes, such as depletion of the mantle source by prolonged episodes of melt extraction (Griffin et al., 2013), increasing mantle temperatures from plume head to plume tail or increasing degrees of melt production due to the removal of the lithospheric lid. Trace element data from clinopyroxenes and the calculated equilibrium melts indicate that the ultramafic melts from Reinfjord have relatively enriched REE compositions that are similar to OIB and the picrite-komatiite dykes in the SIP (Thaarup 2016, Grant et al. in review). Although significant amounts of critical trace elements and isotopic data are lacking in the SIP, the OIB-like and enriched REE compositions of the mafic, ultramafic and late picrite dykes as well as continuous production of volatile-rich alkaline magmas, may indicate that the mantle source did not become significantly depleted throughout the duration of the SIP. However, much more work is required to establish the mantle source of all of the rocks in the SIP using trace element and isotopic data. Earlier studies of the CIMP, the large Ediacaran magmatic event spanning Canada, Greenland, and Baltica, highlighted the high abundance of volatile-rich alkaline dykes and intrusive carbonatite complexes (e.g. Tappe et al., 2011), particularly in

SW-Greenland and Labrador, such that it was proposed if the parent melts might tap an enriched volatile-rich carbonated peridotite asthenosphere that formed prior to plume impingement. Indeed, looking at the high diversity and abundance of volatile-rich alkaline and ultramafic rocks in SIP, the presence of an anomalously volatile-rich upper mantle is supported.

Figure 14: Evolution of conduit system, assembly of ultramafic complexes

11. The Short Story of the SIP

Our and other studies of the SIP demonstrate that the deep crustal conduit systems, now fossilised as large ultramafic complexes, remained open and supported multiple recharge events maintaining primitive chemical compositions of the conduit magma chambers. Reverse fractionation from Ol-melagabbro to pyroxenite to olivine-clino-pyroxenite to wehrlite to dunite show the importance of thermal as well as chemical sealing of the conduit system and explain the reverse fractionation that commonly is observed in flood basalt provinces upwards in the volcanic stratigraphy (Chifeng, Emeishan, Deccan, Siberian). The SIP also demonstrates that conduit-magma-chambers accommodate a huge spectrum of melts of alkaline, tholeiitic, picritic and komatiitic affinities that overlap in time and space. However, the overall chronology, alkaline-tholeiitic-picritic/komatiitic-tholeiitic-alkaline transpires with alkaline igneous events initiating and terminating the entire magmatic evolution of the area.

Important elements of the assembly of the SIP may be summarised to the following events:

1. *Ediacaran mantle plume* coinciding with the CIMP event impinge the continental lithosphereand initiate partial melting of carbonated asthenospheric peridotite. The apparent paleogeographic location of SIP was between Paleo Gondwana and Laurentia close to NE North America and SW-Greenland that also saw significant CIMP activity similar to the SIP.

2. *Emplacement* of tholeiitic-, alkaline and syeno-gabbros heating the country rock meta-sediments from ambient amphibolite facies to granulite facies conditions in a 1-3 km thick contact aureole. Partial melting and assimilation of meta-sediments closest to the gabbros

3. *Assimilation*. Shortly after emplacement of alkaline complexes and gabbros, while they were still hot and partially unconsolidated; emplacement of picritic-komatiitic melts at T=1400-1450 ^{o}C. Partial melting and assimilation of cpx+opx in the gabbro. Formation of rheomorphic gabbros and para-gneisses.

4. *Thermo-Chemical insulation*. Formation of olivine-melagabbro grading into olivine-clinopyroxenite and insulation of the conduit-system leading to T-conservation of melts and cessation of gabbro/gneiss contamination. Here it should be stressed that most of the dilational dyke swarms concluding SIP-magmatism, developed in the ultramafic feeder system. Therefore, they also “enjoyed” chemical insulation and potentially could have progressed much higher up in the continental lithosphere avoiding contamination with older crustal lithologies.

5. *Magma-chamber growth*. Multiple recharge events on the 10-100 metres scale in the cumulus stratigraphy, but also transient closed system conditions. T-Increase and Wehrlitic cumulate formation.

6. *Replacive Dunite – Dunite cumulates*. Magma-chamber growth – multiple recharge events. Assimilation of wehrlitic pyroxene and formation of dunitic cumulates. Formation of dunite-hosted PGE-Cu-Ni Reefs in Reinfjord. Homogenisation of olivine compositions. Subsequently, pervasive infiltration of aqueous-carbonic alkaline melts. Partial remobilisation of PGE-Cu-Au.

7. *Dyke Emplacement*. In hot partially unconsolidated peridotite. Dykes gradually changing from picritic over basaltic to alkaline compositions. Dyke emplacement concluded with nephelenitic pegmatite emplacement on Stjernøy and Seiland at Ma 531 to 521, after continental break-up between Laurentia and Gondwana. Red broken lines show surface exposure of ultramafic complexes in Fig. 14. Essentially, Reinfjord features a deeper section through the volcanic conduit-system. Melkvann and Nordre Brumandsfjord comprises roof sections of the transient magma-chambers with strong gabbro contamination and Kvalfjord features an intermediate position.

8. Left-lateral transport of the SIP hosting micro-continent to the outboard of the Baltican craton and obduction of the SIP during the Scandian event of the Caledonian orogeny (c. Ma 420).

11. Future work

This review highlights the significance of the SIP in understanding the deep crustal assembly of a giant magmatic system, perhaps a LIP and the passage of mantle derived magmas through the lower crust. There are still several key areas in which the SIP is poorly understood. Firstly, whilst the mafic and alkaline rocks have been dated, accurate estimates of the ages of the ultramafic complexes and the later dyke-swarms are absent and this makes it difficult to determine the time frame in which the SIP formed. This is no easy task considering that the majority of the ultramafic rocks are dominated by olivine and pyroxene ± plagioclase, with few accessory phases that are datable by conventional methods. Secondly, a comprehensive stable isotope data set is lacking for the ultramafic intrusions and the late dykes. The available data sets for radiogenic isotopes are restricted to Sm-Nd and Hf-Hf for mafic and alkaline rocks (Roberts 2007; Roberts et al., 2010) and Sr-Sr for Hasvik (Tegner et al., 1999) together with O and C for Lillebukta carbonatite and S for Reinfjord sulphides (Larsen et al., 2016). It is therefore clear that there is considerable scope in which to explore a greater range of isotopes and obtain further isotopic data in the SIP. Further isotopic data may reveal important characteristics of the mantle source(s) of the magmas in the SIP and provide more numerical estimates of the degrees of crustal contamination in the ultramafic complexes. Thirdly, new data indicate that the Reinfjord Ultramafic Complex is a promising location in which to explore economic Ni-Cu-PGE deposits. Due to the similarities with the other major ultramafic complexes, it is possible that similar deposits could be found in Melkvann, Nordre Brumandsfjord and/or Kvalfjord. Additionally, studying the deposits could provide transformative knowledge on the formation of Ni-Cu-PGE deposits in deep crustal intrusions in LIPs, which are generally poorly understood. A further area of discussion is how to link the SIP-event to other magmatic provinces of comparable ages such as the dyke swarms throughout Scandinavia (Andreasson et al., 1998), Canada and NE USA (Ernst and Bell, 2010) and not least the kimberlite/lamproite/carbonatite complexes in SW Greenland and Labrador (Tappe et al., 2011). More accurate pressure and temperature estimates are required; particularly for the crystallisation temperatures for the ultramafic complexes. From the available data it appears that the SIP underwent a counter-clockwise P-T path, but this must be more accurately measured in order to be certain of the post-magmatic tectonic history and to determine if and to what degree the SIP was affected by the Caledonian metamorphism. We also have the importance of volatile constituents for the emplacement, igneous evolution and ore-forming potential of the SIP-suite. I.e does relatively high volatile contents lower the densities sufficiently to facilitate emplacement of dense ultramafic melts? Perhaps due to the high pressure, volatile constituents such as carbonates, hydrous phases and also sulphides are remarkably abundant in these traditionally “dry” mafic and ultramafic rocks and SIP may be a key-locality to understanding asthenosphere-lithosphere-biosphere fluxing of mantle volatiles.

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Figure 1: Revised map of the regional geological setting of SIP with main localities discussed in the text. Based on Bennett (1986), Cadow (1993), Elvevold & Andersen (1993), Tegner, (1999), Griffin et al. (2013), Grant (2016). 1) Breivikbotn Carbonatite-Syenite Complex, 2) Hasvik Layered Gabbro, 3) Nordre Brumannsfjord UM-Complex, 4) Melkvann UM-Complex, 5) Kvalfjord UM-Complex, 6) Lillebukta Carbonatite-Syenite Complex, 7) Lokkarfjord Hornblendite (PGE-Cu-Ni deposits), 8) Tappeluft alkaline and UM-Complex, 9) Reinfjord UM-Complex (PGE-Cu-Ni deposits).

Figure2: (a) Geometry of the density model of the SIP as derived by 3D gravity modelling. Location of modelling sections are projected onto the gravity data (compilation; Gellein,2003; Olesen et al., 2010; Fairhead, 2015) and the geological map. b) Map of the base of the modelled mafic/ultramafic body of the SIP forming an annular pattern. (c) Depth contours of the base of the modelled mafic/ ultramafic bodies of the SIP superimposed on the geological map (modified after Roberts, 2007): (1) syenite; (2) carbonatite and nepheline syenite; (3) diorite; (4) olivine gabbro; (5) layered gabbro; (6) unspecified gabbro; (7) layered, foliated gabbro; (8) tholeiitic gabbro; (9) anorthosite; (10) peridotite; (11) metasediments interlayered with mafic intrusions; (12) metasediments.

Figure 3: Metasedimentary xenoliths in the Hasvik Layered Intrusion. a and c) Numerous thin flakes of metasedimentary country rocks, now pyroxene hornfels, enclosed in apatite–oxide–norite of the Upper Zone. The dark layers in (a) are rich in Ca-poor pyroxene; b) Large metasedimentary xenolith showing relict regional folding enclosed in apatite–oxide–norite of the Upper Zone

Figure 4: Stratigraphic profile throughout the Hasvik layered gabbro showing the Plagioclase compositions in terms of the anorthite component (left) and the gradual increase in Sr-isotope ratio towards the top of the intrusion. Essentially, the figure demonstrates how the parental melts becomes progressively more contaminated with stratigraphic height due to an increase in the density of country rock meta-sediments.

Figure 5: Primary magmatic features of the ultra-mafic complexes exemplified with the Reinfjord Complex. A) Contact between the Marginal Zone of the ultramafic complex to the left and layered gabbro to the right. Note the giant ultramafic apophyses emplaced subparallel to the layering and extending for c. 500 m's into the gabbro. B) Rheomorphic gabbro at contact. White patches are anorthosite restites remaining after partial melting of cpx/opx/ol during emplacement of ultramafic complex. C) Slumping structures in 3-D. Heavier wehrlitic cumulates are slumping towards left on top of dunitic cumulates. D) Macrorythmic layering with crossbedding (insert). E) Lensoid inclusions of the country-rock gabbro (arrows) included in wherlitic cumulates. F) Diapirism of lighter dunitic cumulates into heavier wehrlitic cumulates. Note green colour of diopsidic pyroxene in wehrlite.

Figure 6: Recharge events, dyke emplacement and replacive structures. A) Recharge of pyroxenitic melts, now pegmatitic opx, emplaced in to dunitic cumulus mushes and sinking through the mushes. Pegmatitic enstatite crystal forms a layer in the bottom of the photo and intersect the layering in the central parts. B) Recharge of pyroxenitic melts in to partially consolidated dunitic cumulates. Forming a well defined dyke to the right but dissipating in to a mix of dunite and pegmatitic pyroxene towards the left. Note cm-size cpx-oikocrysts dotting the dunite. C) Dyke complex in the central portion of dunitic cumulates; c. 500 m's across in top of photo. D) Details from dyke complex showing 8 generations of dykes. The

oldest dykes were emplaced in to unconsolidated cumulus mushes and show fussy contacts towards the dunite host (arrows). Later dykes have sharp boundaries and were emplaced in to more consolidated dunite. However, most dykes are coarse-grained from contact to contact, i.e. they were emplaced in a hot host-rock. E) Large scale replacive dunite showing up as bright structures (arrows) intersecting wehrlitic cumulates (dark-coloured). The structures are c. 5 m's wide and continues for hundreds of metres in to the photo. E) Small-scale example of replacive dunite (arrow) emplaced in to wehrlite. Cpx in the wehrlitic cumulates is assimilated by the dunite forming melts.

Figure 7: Reinterpretation of the three largest ultramafic complexes in SIP. For geographic reference, see Fig. 1 please. Nordre Brumannsfjord is excluded because detailed geological maps of this complex remain to be done. Based on Yeo (1984), Svensen (1991), Grant et al. (2016), Grannes (2016). The overall chronology of igneous events is: 1) gabbro, 2) Olivine Clinopyroxenite with simultaneous formation of Marginal Zone, 3) Wehrlite, 4) Dunite, 5) Ultramafic dykes, 6) Gabbro dykes, 7) Alkaline Dykes including nepheline-syenite pegmatite. See text for details.

Figure 8: Drill-core log showing the distribution of Ni, Cu, PGE and S in drillhole RF-4. The PGE-reef is decupled from both the Cu and the Ni reefs. The lowermost Cu-reef occur at the transition between Marginal Series pyroxenite and Central Series dunite.

Figure 9: Textural features characterizing the most PGE rich parts of the RF-1 drill-core. Right image show the dunites in transmitted light with olivine as colorless, sulphides in black and orthopyroxene in pale brown. PGM's are framed in orange, and blue depending on their types (see legend). Minerals are colour coded in the image to the left (see legend). Note that

opaque minerals are Cu-Ni-Fe sulphides. On this image, the relatively high abundance of dolomite (red) and amphibole (blue) is evident. Insert in left image, show the close association of Pt-Te minerals with exsolutions of pentlandite (pn) in pyrrhotite (po) tenors.

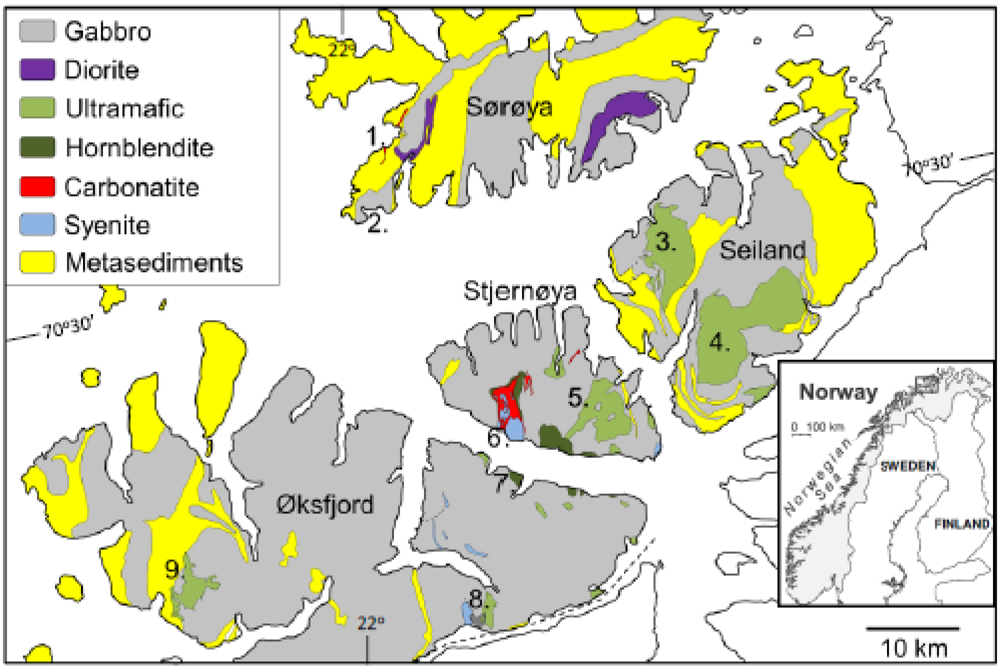
Figure 10: Whole rock MgO versus Al2O3 of ultramafic rocks from Reinfjord, Melkvann, Nordre Brumannsfjord and Kvalfjord, respectively. The diagram show the influence of assimilation of mostly gabbroic host rock during emplacement of the ultramafic complexes. Ultramafic rocks with minimal gabbro assimilation plot at or close to the clinopyroxen (Cpx)-olivine (Ol) tie line. Strong assimilation of gabbro pulls the ultramafic rocks towards the plagioclase (Plag) apex. Solid black square corresponds to the contaminant gabbro in Griffin et al. (2013). Solid dots imply ultramafic cumulates whereas solid triangles are hybrid rocks in the marginal zone lose to the contacts.

Figure 11: spinel compositions in terms of Fe and Al_2O_3. Nordre Brumannsfjord (NB) and Melkvann utramafic complexes are clearly distinguishable from Reinfjord spinels. Data from Kvalfjord are absent.

Figure 12: apparent P-T loop of the Reinfjord ultramafic complex with Caledonian data from the Hasvik gabbro. 1) The pre-intrusion temperature. 2) Conditions of contact metamorphism. A) P-T of the picritic/komatiitic melts. B) cooling temperatures of the Reinfjord complex from two-pyroxene thermometry. C) crystallisation temperatures of lamproitic dykes. D) P-T from pseudosections of extensional shearzones (see Fig. 13 for details). III) PT-condition of the Caledonian uplift from the Hasvik gabro. IV) Late alteration of dolomite and olivine to form brucite + calcite and chalcopyrite to form native copper.

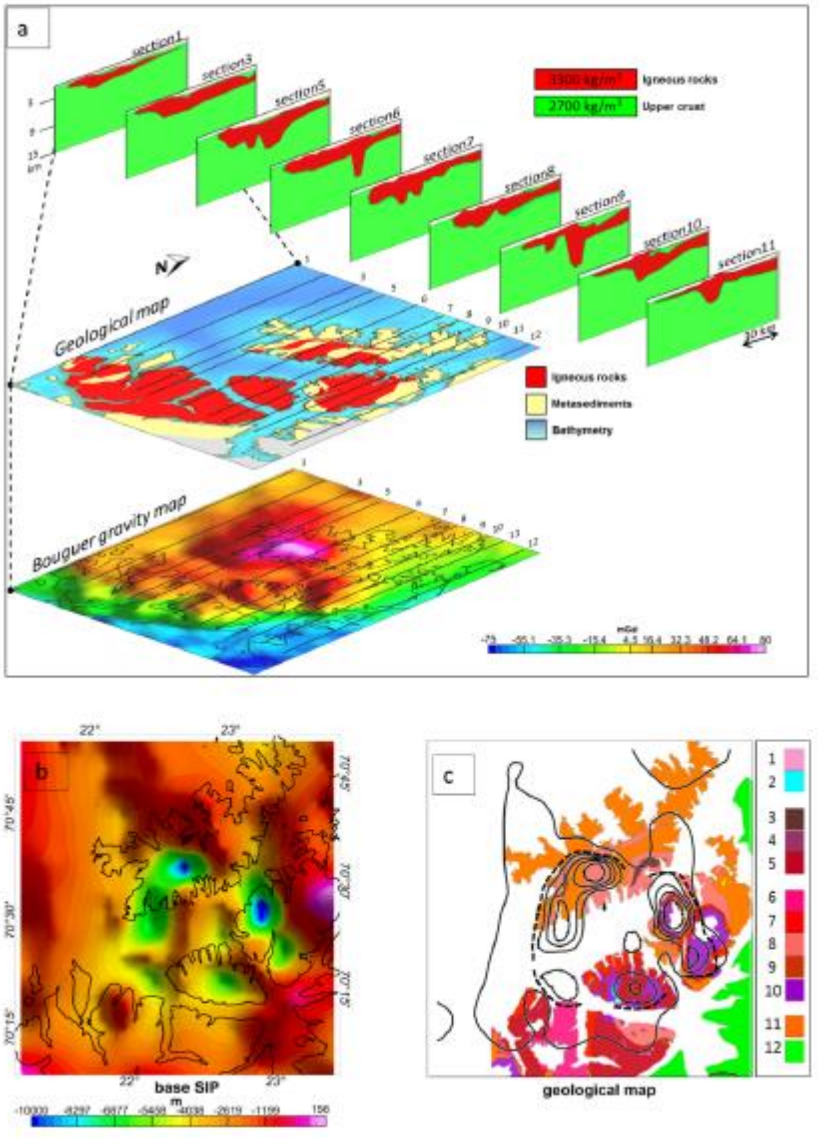
Figure 13: Peak P in SIP (pseudo section) of the dolomite-orthopyroxene assemblage in the shearzones based on EPMA analyses of dolomite and orthopyroxene. Green isopleths are X_{Ca} in the carbonate phase and red are the volume percentage of carbonate. Note the sudden increase in carbonate volume along with the onset of dolomitisation. Calculated with perplex_671 using bulk in molar amounts: SiO_2 = 1.976008185, Al_2O_3 = 0.023569876, FeO = 0.4507254, Fe_2O_3 = 0.00042194, MgO = 2.448162469, CaO = 1.077120316 and CO_2 = 2.00000.

Figure 14: Evolution of main conduit systems and assembly of ultramafic complexes in the SIP. A) ASSIMILATION. Shortly after emplacement of gabbros while they are still hot, emplacement of Picritic-komatiitic melts at T=1400-1500 ^{o}C. Partial melting and assimilation of cpx+opx in the gabbro. B) THERMO-CHEMICAL INSULATION of conduit system, formation of olivine melagabbro to olivine clinopyroxenite and the hybrid Marginal Zone. Repetitive recharge events. C) MAGMACHAMBER GROWTH, T-rise and formation of wehrlitic cumulates during multiple recharge events. D) MAGMACHAMBER GROWTH and T-rise; assimilation of wehrlitic pyroxene, formation of replacive dunite and dunite cumulates. Formation of Cu-Ni-PGE reefs. Homogenization of olivine compositions. E) AQUEOUS-CARBONIC alkaline melts infiltrate unconsolidated dunitic cumulates. Localized remobilization of PGE-Au-reefs, particularly Au and Pd. F) LATE DYKE emplacement with compositions gradually evolving from komatiitic/picritic over gabbroic to alkaline compositions (carbonatite and nepheline-syenite pegmatites). Relative position of the four major ultramafic complexes shown with red broken line. Essentially, Reinfjord Ultramafic Complex features a deeper section of the magmatic conduit systems whereas the other complexes are situated closer to the roof hence display more hybrid compositions.



1. Breivikbotn, 2. Hasvik, 3. Nordre Brumandsfjord, 4. Melkvann, 5. Kvalfjord, 6. Lillebukt, 7. Lokkarfjord, 8. Tappeluft, 9. Reinfjord

Figure 1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3300 kg/m³
Igneous rocks
2700 kg/m³
Upper crust
Geological map
Igneous rocks
Metasediments
Bathymetry
10 km
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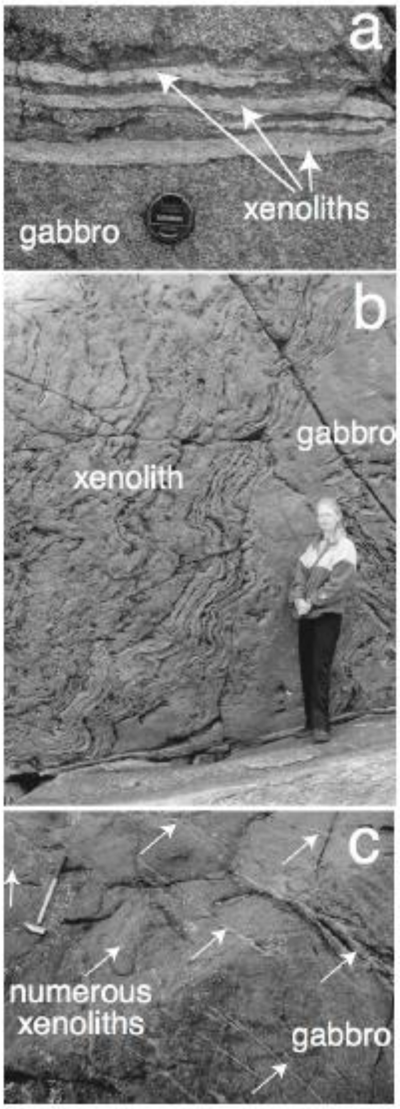
mGal
b
base SIP
m
c
geological map

Figure 2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gabbro
b
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xenolith
c
numerous
xenoliths
gabbro

Figure 3

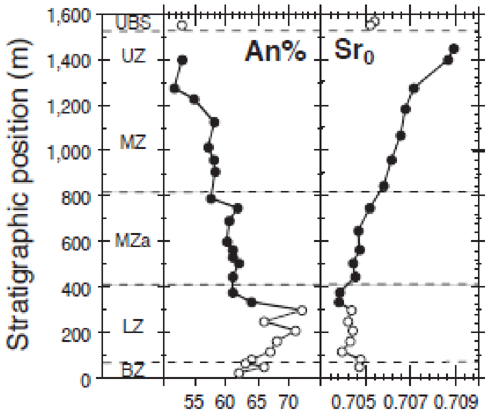


Figure 4 (Larsen et al., 2017)

Figure 5

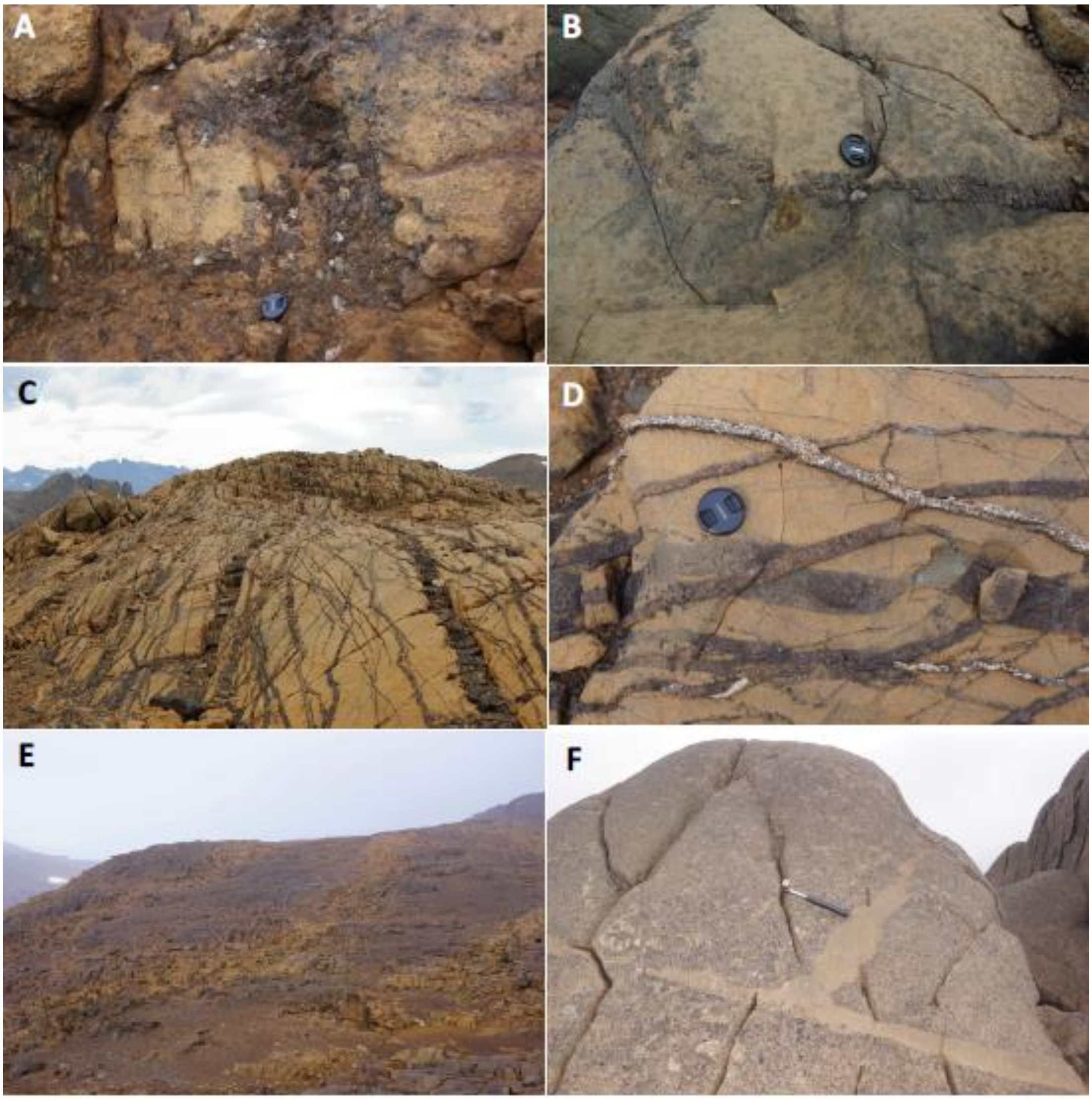
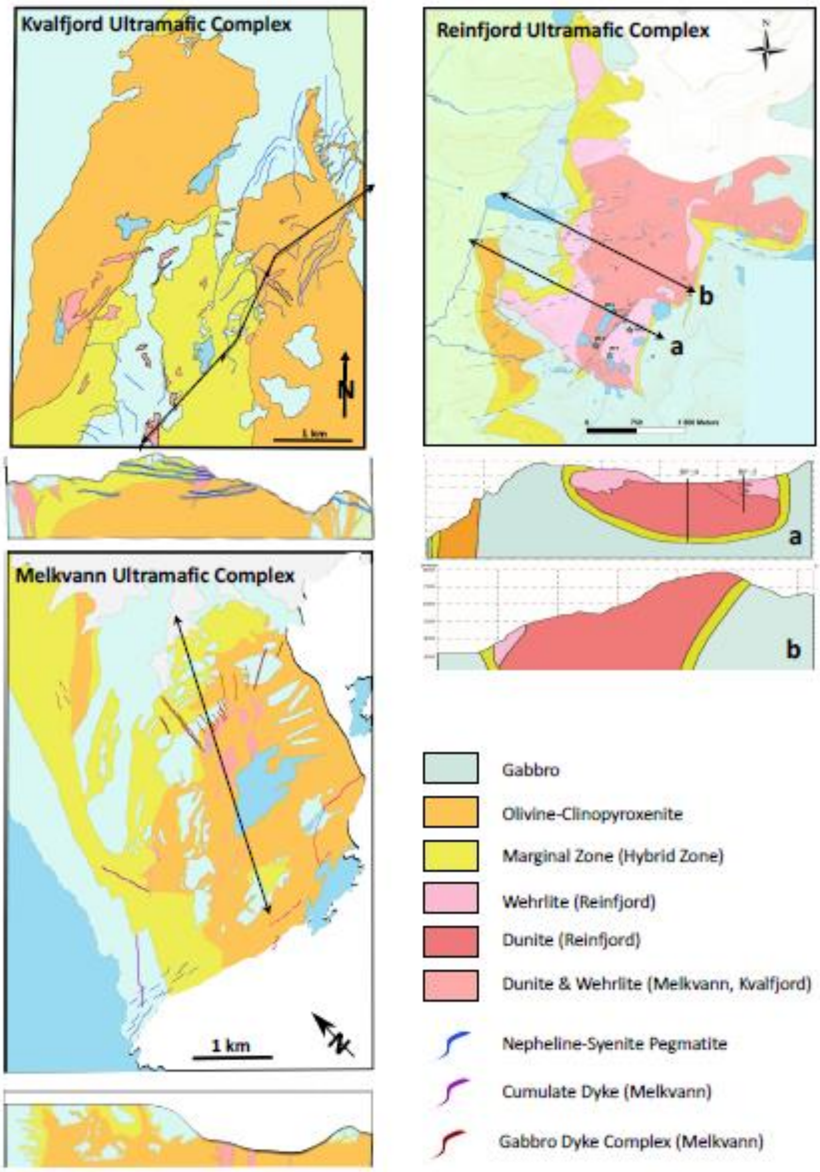


Figure 6


Kvalfjord Ultramafic Complex
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1 km
Reinfjord Ultramafic Complex
b
a
a
b
Melkvann Ultramafic Complex
1 km
N
Gabbro
Olivine-Clinopyroxenite
Marginal Zone (Hybrid Zone)
Wehrlite (Reinfjord)
Dunite (Reinfjord)
Dunite & Wehrlite (Melkvann, Kvalfjord)
Nepheline-Syenite Pegmatite
Cumulate Dyke (Melkvann)
Gabbro Dyke Complex (Melkvann)

Figure 7

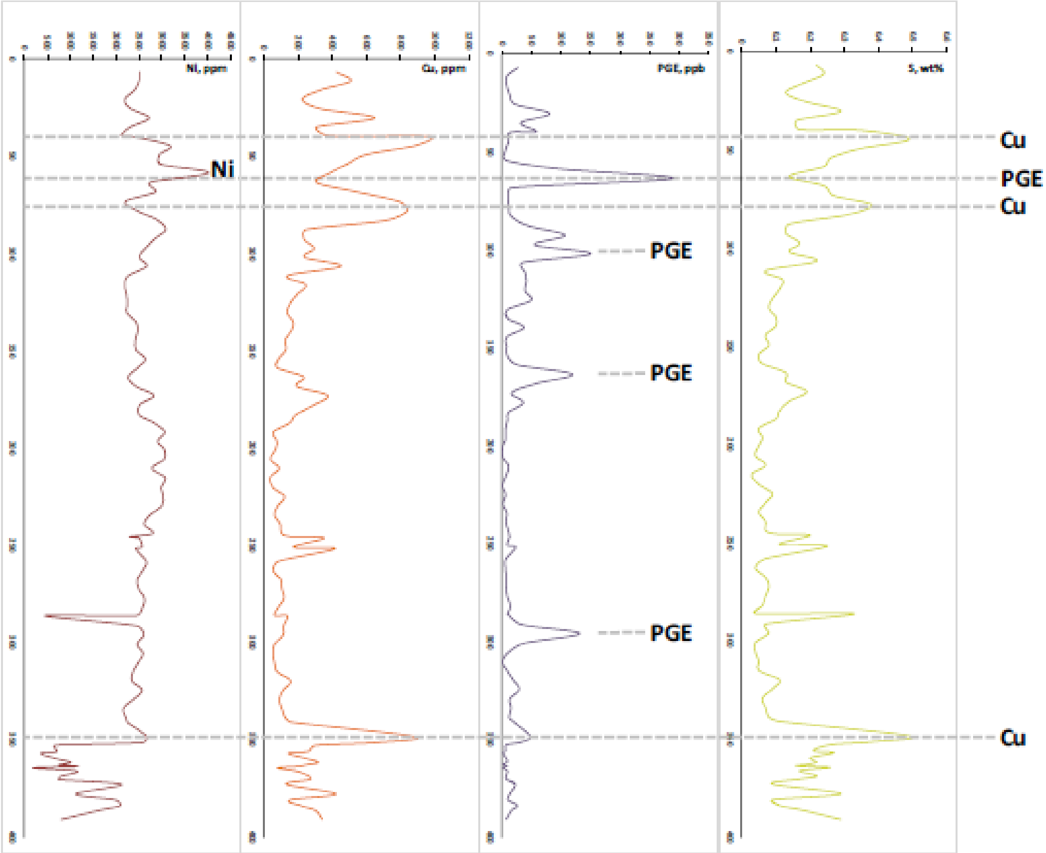


Figure 8

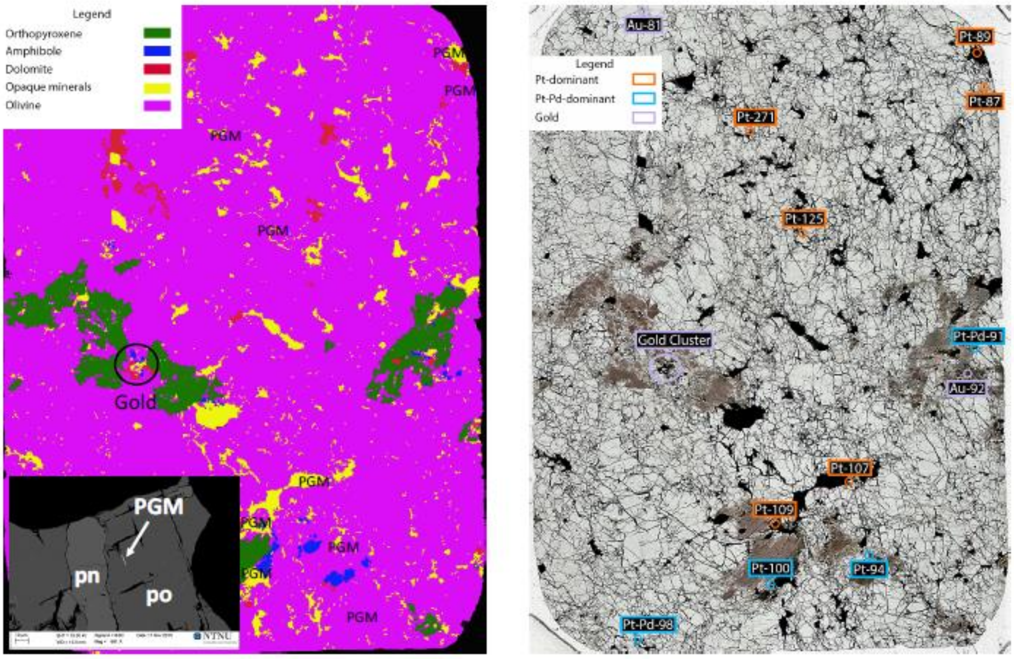
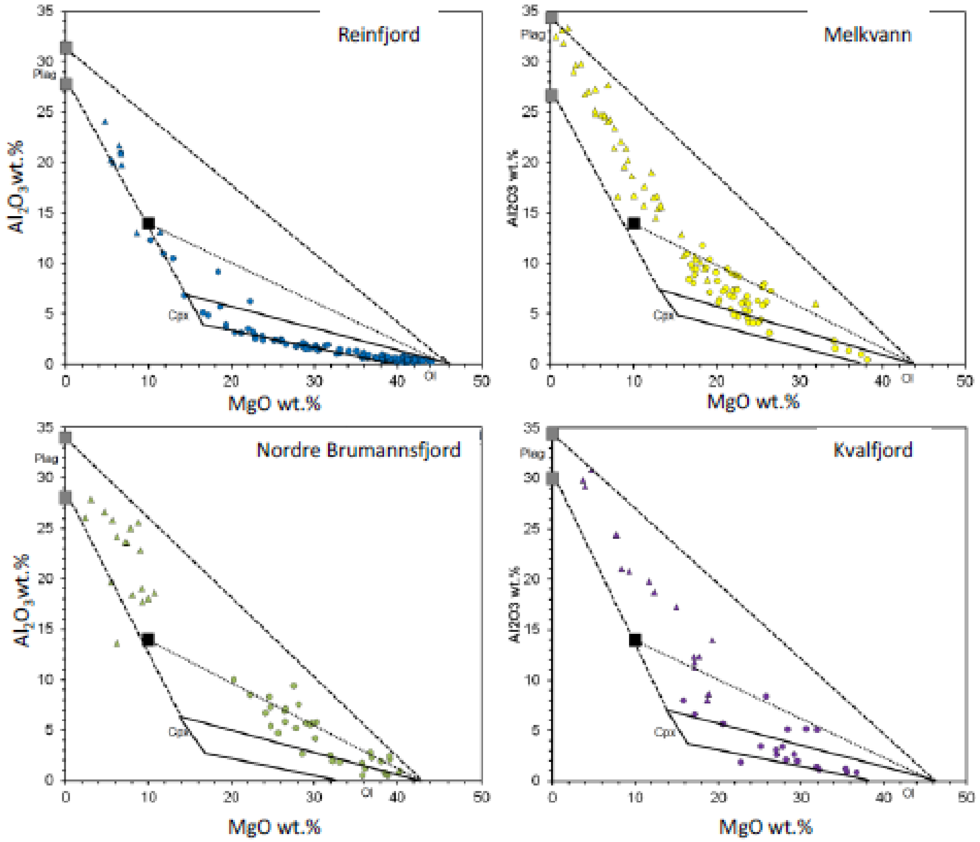

Legend
Orthopyroxene
Amphibole
Dolomite
Opaque minerals
Olivine
PGM
Gold
pn
po
Legend
Pt-dominant
Pt-Pd-dominant
Gold
Au-81
Pt-89
Pt-87
Pt-271
Pt-125
Gold Cluster
Pt-Pd-91
Au-92
Pt-107
Pt-109
Pt-100
Pt-94
Pt-Pd-98

Figure 9


Reinfjord
Melkvann
Nordre Brumannsfjord
Kvalfjord
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Al_2O_3 wt.%
Al2O3 wt.%
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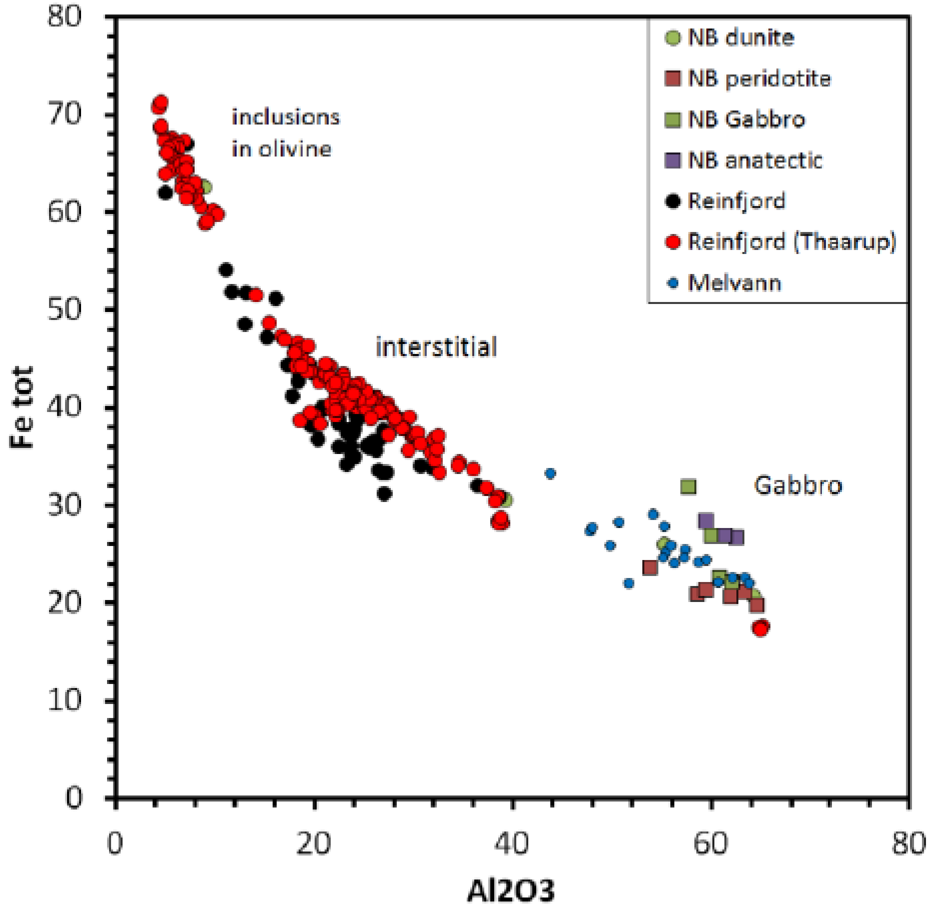
Figure 10



NB dunite
NB peridotite
NB Gabbro
NB anatectic
Reinfjord
Reinfjord (Thaarup)
Melvann
inclusions
in olivine
interstitial
Gabbro
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Figure 11

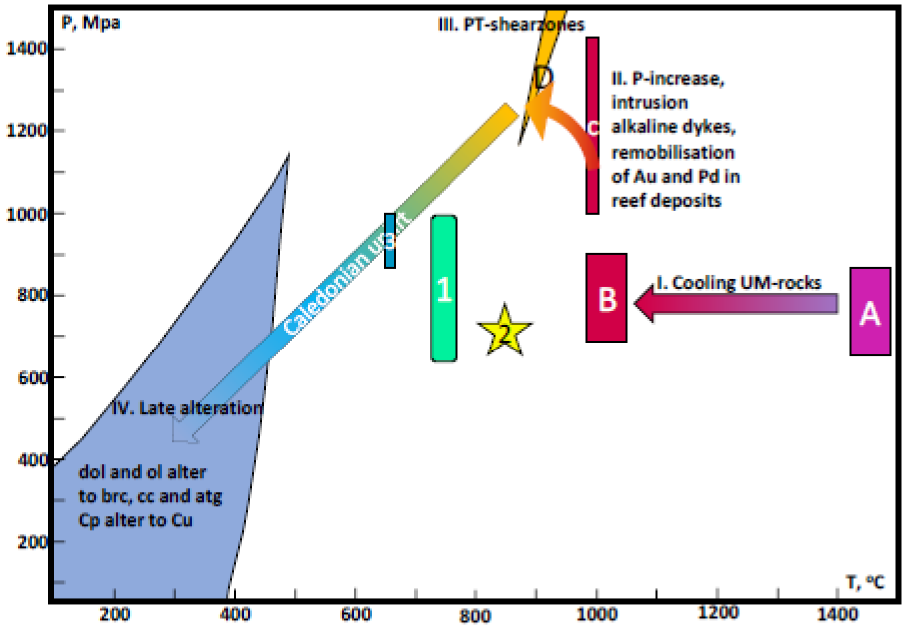
P, Mpa
III. PT-shearzones
II. P-increase, intrusion alkaline dykes, remobilisation of Au and Pd in reef deposits
D
C
1
2
B
A
I. Cooling UM-rocks
Caledonian u3.tt
IV. Late alteration
dol and ol alter to brc, cc and atg Cp alter to Cu
T, °C
1400
1200
1000
800
600
400
200
200
400
600
800
1000
1200
1400

Figure 12

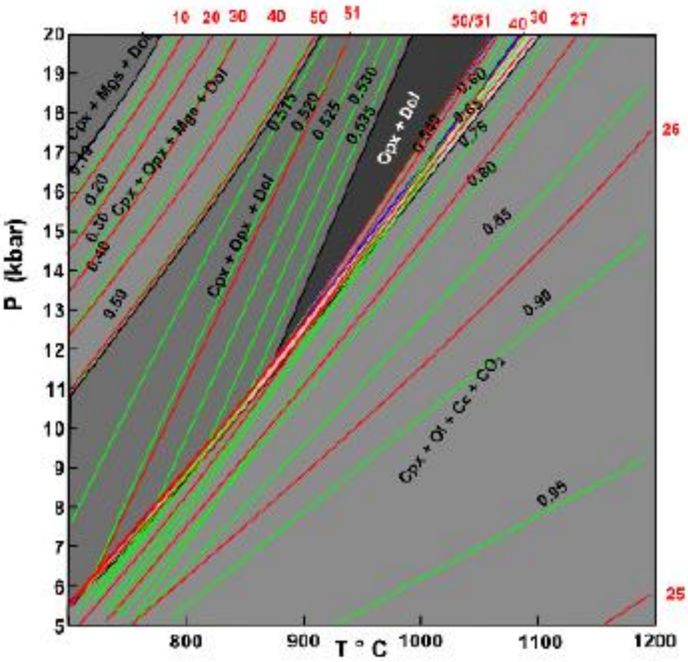
10 20 30 40 50 51
50/51 40 30 27
26
25
Cpx + Mgs + Dol
Cpx + Opx + Mgs + Dol
Cpx + Opx + Dol
Opx + Dol
Cpx + Ol + Cc + CO2
0.20
0.30
0.40
0.50
0.515
0.520
0.525
0.530
0.535
0.60
0.75
0.80
0.85
0.90
0.95
P (kbar)
T ° C
800
900
1000
1100
1200
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Figure 13

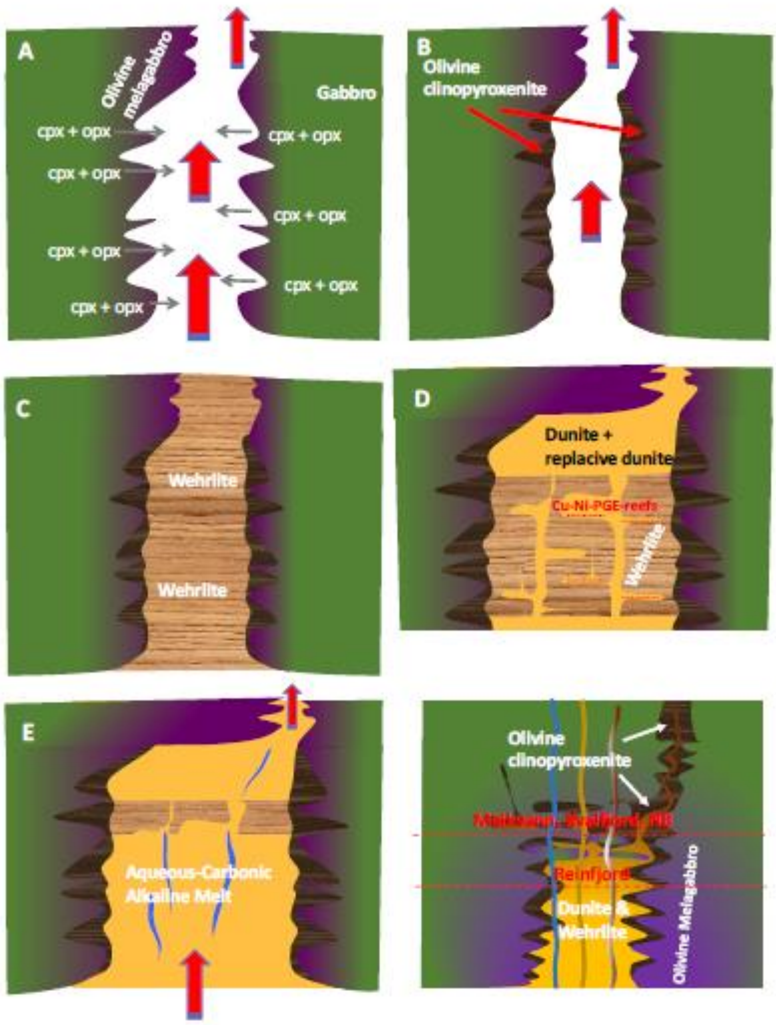
A
Olivine melagabbro
Gabbro
cpx + opx
cpx + opx
cpx + opx
cpx + opx
cpx + opx
cpx + opx
cpx + opx
cpx + opx
B
Olivine clinopyroxenite
C
Wehrlite
Wehrlite
D
Dunite + replacive dunite
Cu-Ni-PGE-reefs
Wehrlite
E
Aqueous-Carbonic Alkaline Melt
Olivine clinopyroxenite
Reinfjord
Dunite & Wehrlite
Olivine Melagabbro

Figure 14

Portrait of an Giant Deep-Seated Magmatic Conduit System: The Seiland Igneous Province

Highlights

- The Ediacaran (580-560 Ma) Seiland Igneous Province (SIP), we hypothesize, is a giant magmatic conduit system at 25-35 km depths conveying thousands of Km^3 of dense mafic ultramafic melts from the asthenosphere to the lithosphere. It is the most deeply exposed parts of the Central Iapetus Magmatic Provence (CIMP) and probably forms above a mantle hot spot.
- Four large ultramafic complexes comprises transient magma-chambers facilitating deep-crustal homogenization and early magmatic evolution of a rich diversity of igneous melts including, komatiitic, picritic, tholeiitic, kimberlitic, lamproitic, carbonatitic and syenitic compositions.
- SIP demonstrates the high abundance of primitive composition of deep-seated melts (komatiitic-picritic) and also show the importance and abundance of mantle volatiles now preserved in the ultramafic rocks as complex hydrous-carbonate clots and dykelets.
- The ultramafic complexes also document that a rich diversity of melts essentially passes through the same conduit system. Both sequentially and simultaneously but the overall evolution is alkaline→gabbroic→komatiitic/picritic→gabbro→alkaline.
- The melts are very fertile and form PGE-Cu-Ni reefs with anomalously high concentrations of Osmium and PGE reefs are decoupled from Cu-Ni reefs.