Geol. Mag. **143** (*6*), *2006, pp. 887–903.* © *2006 Cambridge University Press*
doi:10.1017/S0016756806002512 *Printed in the United Kingdom*

Short-lived mafic magmatism at 560–570 Ma in the northern Norwegian Caledonides: U–Pb zircon ages from the Seiland Igneous Province

R. J. ROBERTS*†, F. CORFU‡, T. H. TORSVIK§, L. D. ASHWAL* & D. M. RAMSAY¶

*School of Geosciences, Private Bag 3, University of the Witwatersrand, Johannesburg 2050, Republic of South Africa
‡Department of Geology, University of Oslo, Oslo, Norway
§Geodynamic Centre, Geological Survey of Norway, Leiv Erikssonsvei 39, N-7491 Trondheim, Norway; and Institute for Petroleum Technology and Applied Geophysics, NTNU, N-7491 NTNU, Norway
¶27 Marlee Road, Dundee, Scotland, UK

(*Received* 2 February 2005; *accepted* 13 March 2006)

Abstract – The Seiland Igneous Province (SIP) of northern Norway comprises a suite of mainly gabbroic plutons, with subordinate ultramafic, syenitic and felsic intrusions. Several intrusions from the Seiland Igneous Province have been dated by ID-TIMS U–Pb zircon and monazite analyses. The Hasvik Gabbro on the island of Sørøy, previously assigned an age of 700 ± 33 Ma by Sm–Nd, yields a U–Pb zircon age of 562 ± 6 Ma, within error of the Storelv Gabbro (569 ± 5 Ma) and a diorite associated with the Breivikbotn Gabbro (571 ± 4 Ma). Various intrusions on the Øksfjord peninsula give nearly identical ages of 565 ± 9 Ma (gabbro), 566 ± 4 Ma (monzonite), 565 ± 5 Ma (monzodiorite), 570 ± 9 Ma (norite), and 566 ± 1 Ma (orthopyroxenite). These ages overlap with those from Sørøy, and define a single and short-lived period of gabbroic (to felsic) magmatism for the region between 570 and 560 Ma, pre-dating a subordinate episode of alkalic magmatism at 530–520 Ma. The U–Pb ages contradict the previous geochronological interpretation for the Finnmark area, which implied a period of 250 m.y. for the emplacement of the SIP intrusions. The new age data also clearly distinguish the Seiland intrusions, emplaced into the Sørøy Group metasediments of the Kalak Nappe Complex, from several older granitic intrusions (*c.* 850 to 600 Ma) that cut the Sørøy Group farther east and south. The coincident ages of the different Seiland intrusive bodies also contradict the previous structural model for the area, which posits that the different gabbro bodies were emplaced at intervals, with compressional deformation affecting the gabbros between periods of intrusion. The short time span between the main plutonic phases strongly suggests that the mechanism for the emplacement of mafic magma operated in a single, probably extensional, tectonic regime. The mafic intrusions were later deformed and metamorphosed to at least amphibolite facies, most likely by the Scandian (420 Ma) phase of the Caledonian Orogeny.

Keywords: Seiland, age, magmatism, zircon, Caledonides.

1. Introduction

The need to determine accurate and precise formation ages for rocks or structures, and the rates at which geological processes occur, pervades nearly all aspects of Earth science research. An accurate and reliable geochronological framework is especially required for the interpretation and understanding of regions with complex tectonic and magmatic histories to untangle problematic sequences of events. The Finnmark area in northern Norway (Fig. 1) is such a region, where several orogenic events have been proposed to have contributed to the complexity of the geology.

The continent of Baltica collided with and became attached to Laurentia in Silurian times (Torsvik *et al.* 1996) and it is commonly accepted that the Norwegian Caledonides were formed during this collision (Gayer, Hayes & Rice, 1985). The Caledonides are a thrust belt stretching from Newfoundland, through Ireland and Scotland, to Sweden and along the entire northern coast of Norway, as well as along the east coast of Greenland. In general, this orogeny involved the thrusting of numerous allochthonous nappe complexes onto para-autochthonous or autochthonous basement during Scandian times (420–400 Ma) (e.g. Stephens & Gee, 1989). While most of these crustal slices came from the Baltica craton, some of the tectonic slices appear to have been transferred across from the Laurentian plate to Baltica (Stephens & Gee, 1989). Subsequent to their collision, the plates of Baltica and Laurentia (and the island Greenland) separated during the opening of the North Atlantic during the late Cretaceous and early Tertiary periods.

However, it has long been postulated that evidence for pre-Scandian deformation exists along the margins of Baltica (e.g. Sturt & Ramsay, 1965; Roberts, 2003).

† Author for correspondence: james@armoury.co.za

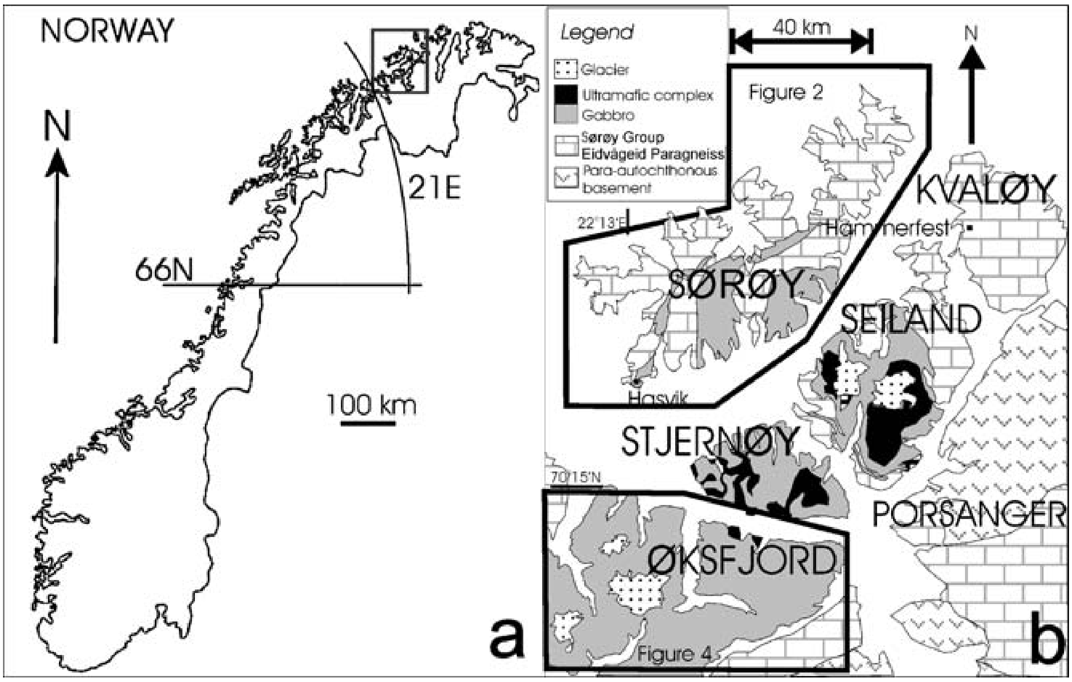

Figure 1. (a) Map of Norway, with location of the Seiland Igneous Province, Finnmark, marked by box. (b) Schematic geological map of the western portion of the province of Finnmark, giving locations mentioned in the text.

Such evidence is preserved in structural features, such as crenulation cleavages, as well as in the Ar–Ar systematics (e.g. Dallmeyer, 1988; Rice & Frank, 2003). In a review of the Caledonides, Roberts (2003) proposed four different pre-Scandian events, but the evidence for some of these events, as well as their timing, is controversial and inconclusive (e.g. Krill & Zwaan, 1987), being based on incomplete and outdated geochronological data and structural observations. Only one of these pre-Scandian events is believed to have affected the western part of the Finnmark province and the rocks under discussion in this paper.

This paper presents U–Pb geochronological results from a suite of mafic to felsic intrusions in the Finnmark region of Norway that alter our understanding of one of these proposed pre-Scandian events.

2. The geology of the Seiland area and its surroundings

The fold and thrust belt of the Scandinavian Caledonides in Finnmark, northern Norway, was originally held to comprise an Eocambrian to Cambrian sequence, thrust over a Precambrian basement and its unconformable cover of late Proterozoic to Ordovician sediments (Sturt, Pringle & Ramsay, 1978; Ramsay *et al*. 1985). The overthrust package consists of a major upper nappe, the Kalak Nappe Complex, resting on smaller and thinner parautochtonous nappes (Holtedahl & Dons, 1960). In general, each nappe of the complex is characterized by a basal plinth of Precambrian rocks, which can be banded orthogneiss, paragneiss or some combination of both (Sturt, Pringle & Ramsay, 1978; Ramsay *et al*. 1985). This plinth is covered by an unconformable metasedimentary cover sequence. A type succession for regional correlation between the members of the Kalak Nappe Complex is provided by the lithostratigraphy of the Sørøy Group on the island of Sørøy. The basal member of the Sørøy Group, the Klubben Psammite, is widely distributed in Finnmark, whereas the younger sequence comprising the Storelv Formation schists, Falkenes Formation marbles and Hellefjord Formation schists is more limited in extent.

Dominant features of the Sørøy Nappe, west of Kvaløy, are the igneous rocks generally referred to as the Seiland Igneous Province (SIP), shown in Figure 1. The complex crops out over an area of *c*. 7000 km^2 and comprises numerous plutons ranging in composition from calc-alkalic to tholeiitic and alkaline gabbros (Robins & Gardner, 1975; Robins, 1996). Some of these mafic plutons intrude, and are intruded by, small amounts of coeval felsic rocks such as monzonite and diorite. Ultramafic bodies, containing abundant xenoliths of the surrounding gabbros, cut the mafic plutons, although these ultramafic rocks have subsequently been affected by the same tectonic events that metamorphosed and deformed the mafic rocks (Bennett *et al*. 1986). Pyroxenite and hornblendite are the most voluminous ultramafic rocks.

Robins & Gardner (1975) subdivided the gabbroic rocks in the Seiland Igneous Province (but principally those on the islands of Seiland and Sørøy) on the basis of petrography. They distinguished plutons that crystallized from a tholeiitic parent with strong iron-enrichment during crystallization, those that crystallized from a tholeiitic parent and are associated with quartz-saturated derivatives, and those that crystallized from an alkaline olivine basalt parent. The last group of plutons contains calcic plagioclase and alumina-rich clinopyroxene, and is consistently nepheline-normative.

A mainly alkaline plutonic suite comprising syenites, feldspathoidal syenites and carbonatites appears to have concluded the magmatic development of the Seiland Igneous Province (Sturt & Ramsay, 1965; Robins, 1972; Pedersen, Dunning & Robins, 1989). At some point after the emplacement of the plutons, a regional event metamorphosed some of the rocks to amphibolite facies, locally producing deformation fabrics such as foliations (e.g. Sturt & Ramsay, 1965).

3. The tectonic history of the Seiland Igneous Province

The Finnmark region of northern Norway has long been held to show the effects of an orogenic event prior to the *c*. 420 Ma Scandian phase of the Caledonian Orogeny (Sturt, Pringle & Roberts, 1975; Sturt, Pringle & Ramsay, 1978). This 'Finnmarkian' event (Sturt, Pringle & Roberts, 1975; Sturt, Pringle & Ramsay, 1978), originally considered a phase of the Caledonian Orogeny and later upgraded to a separate orogeny, was defined based on the field relationships between the voluminous intrusions of the Seiland area and the Kalak Nappe Complex that hosts the intrusions. The intrusive rocks crosscut pre-existing fabrics, and were themselves subsequently deformed along with the Kalak Nappe Complex.

Early work in the Finnmark region identified only two phases of deformation in the Kalak Nappe Complex, denoted D1 and D2 (Sturt & Ramsay, 1965). However, later work recognized an additional earlier schistosity in rocks of the Sørøy Group (Sturt, Pringle & Roberts, 1975; Sturt, Pringle & Ramsay, 1978). Consequently, the most recently postulated structural framework for the region involves three episodes of deformation (D1–D3), of which D2 and D3 are by far the most prominent (Ramsay *et al*. 1985). Thus, the Hasvik Gabbro, originally described as 'post-D1' in age (Sturt & Taylor, 1971), is now described as 'post-D2' by Sturt, Pringle & Ramsay (1978). In the ensuing sections, the D1–D3 deformation scheme of Sturt, Pringle & Ramsay (1978) is used.

The earliest deformation event (D1) is poorly preserved in Finnmark. The evidence for its existence comes mainly from a widespread schistosity developed in pelitic and semi-pelitic lithologies of the Sørøy Group. The second deformation event (D2) is by far the most dominant one in Finnmark (Sturt & Ramsay, 1965; Sturt, Pringle & Roberts, 1975; Sturt, Pringle & Ramsay, 1978; Ramsay *et al*. 1985). Recumbent folds, with large (kilometre) amplitudes and wavelengths, and an axial planar foliation, herald an event that was associated with amphibolite facies metamorphism. The subsequent D3 event, the last significant episode of deformation, involved a lower metamorphic grade (greenschist facies), and can be seen in the refolding and reorientation of D2 structures and the development of a weak axial planar cleavage.

Assessing these three deformational events and placing them in their correct spatial and temporal context has long been a problem for geologists working in the area. Before the identification of ages older than 420 Ma in the rocks of the area, the D2 event was considered to represent an early stage of the Caledonian Orogeny (e.g. Sturt & Ramsay, 1965). As older ages emerged and a time gap between D2 and D3 was identified, a separate orogeny, the Finnmarkian (490–540 Ma), was proposed as the source of D2 deformation (Sturt, Pringle & Roberts, 1975; Sturt, Pringle & Ramsay, 1978; Ramsay *et al*. 1985). The D3 deformation was then tentatively correlated with Scandian (Caledonian) deformation at 420 Ma (Ramsay *et al*. 1985).

These deformational structures were originally correlated across much of Finnmark, creating numerous problems of interpretation. It is now known (Daly *et al*. 1991) that comparable structures developed at different locations during totally unrelated events ranging in age from the Precambrian to the Silurian eras. The inconsistent interpretations led to various debates and to the formulation of alternative models (e.g. Binns, 1989; Rice, 1990). Krill & Zwaan (1987) questioned the original structural interpretation by Ramsay *et al*. (1985) and postulated that the Seiland Igneous Province formed in an extensional environment. However, their contention that there were no undeformed mafic dykes in the area was widely contested (e.g. Sturt and Ramsay, 1988) and can be readily disproved in the field. Daly *et al*. (1991) used a variety of isotopic methods (Rb–Sr, Sm–Nd, U–Pb) to date various igneous intrusions and demonstrated that the 'D2' deformation of the Klubben Psammite on the Porsanger peninsula took place before 800 Ma. The model resulting from their work questioned the existence of the Finnmarkian Orogeny, and proposed a 250 m.y. period in the Precambrian during which rifting took place. This idea was further developed by Elvevold *et al*. (1994), who proposed a three-stage metamorphic history reflecting early rifting and magmatism followed by crustal thickening and contraction. Such a long period of rifting seems unusual, and would imply the opening of a sizeable ocean basin or multiple episodes of rifting.

4. Isotopic dating in the Seiland area

The dating of the Finnmarkian Orogeny has always been contentious. Initial palaeontological evidence

(Holland & Sturt, 1970) implying an early Cambrian age for calc-silicate rocks in the Sørøy Group has been disproved (Debrenne, 1984), but early K–Ar and Rb–Sr studies from Sørøy indicated an age of 540–490 Ma for mafic rocks (Sturt, Miller & Fitch, 1967; Sturt, Pringle & Ramsay, 1978). A Rb–Sr age of 612 ± 17 Ma (all Rb–Sr ages calculated using $\lambda^{87}Rb = 1.42 \times 10^{-11}\ a^{-1}$) was reported for a suite of syenite–monzonite gabbro and peridotite from the Øksfjord peninsula (Brueckner, 1973), but was not widely accepted. The occurrence of a metamorphic event at *c*. 490 Ma, as well as the later Scandian event (420–400 Ma), was indicated by Ar–Ar geochronological studies in northern Norway (Dallmeyer, 1988). The wide spread of ages was used in constructing a petrological framework for the emplacement of the different gabbros by Robins & Gardner (1975), who argued for an Andean-margin-style tectonic setting, with gabbroic intrusions evolving from tholeiitic to calc-alkaline compositions with time.

More recent Sm–Nd geochronology resulted in a complicated scenario for the evolution of the Finnmark region. In a paper incorporating numerous studies on the area, Daly *et al*. (1991) provided ages for different intrusions in western Finnmark spanning a period of 250 m.y. from 851 ± 130 Ma to 604 ± 44 Ma. Other workers obtained intrusion ages in the same range, using both Rb–Sr and Sm–Nd techniques (Mørk & Stabel, 1990; Krogh & Elvevold, 1991). Not only were some of these ages significantly older than all previous dates from the area, they also implied episodic magmatism over a very long period. Determining the tectonic setting capable of producing basic magmatism over such a long period has proved difficult, and has resulted in complex models involving multiple rifting events and several ocean closures (e.g. H. Reginiussen, unpub. Ph.D. thesis, Univ. Trømso, 1996).

Only three igneous bodies in the Finnmark area were dated by the U–Pb zircon isotope dilution method prior to the current study. The Litlefjord Granite on the Porsanger peninsula, emplaced into the Klubben Psammite of the Sørøy Group, was dated at 804 ± 19 Ma using a lower Concordia intercept age (Daly *et al*. 1991). On the basis of this result, a new late Proterozoic 'Porsanger' Orogeny was proposed, which was tentatively placed at 850–800 Ma or older on the basis of the age from Litlefjord and the Rb–Sr age of 851 ± 130 Ma from a granitoid at Repvåg (Daly *et al*. 1991). Nepheline syenite pegmatites that intrude mafic to ultramafic complexes on the islands of Seiland and Stjernøy were dated by U–Pb at 531 ± 2 and 523 ± 2 Ma, respectively (Pedersen, Dunning & Robins, 1989). These pegmatites were argued to be the latest intrusions in the Seiland Igneous Province, as they crosscut all other intrusive bodies in the sampling areas and are considered post-tectonic, and these ages have therefore been interpreted to represent a lower limit on deformation in the area.

5. Analytical methodology

All U–Pb analyses in this study were conducted by isotope dilution thermal ionization mass spectrometry at the University of Oslo, following the methods established by Krogh (1973). The samples were crushed and zircons and monazites retrieved from the powders. Some zircons were analysed using cathodoluminescence (CL), but most were handpicked on the basis of morphological observations. Selected zircons were abraded in an air-abrader after handpicking to remove altered rims (Krogh, 1982). Both zircons and monazites were then cleaned thoroughly with dilute nitric acid, followed by ionized water and acetone rinses. The zircons were then dissolved in Teflon bombs and the monazites in Savillex vials, along with a mixed spike of ^{205}Pb–^{235}U. After dissolution, the solutions were passed through ion exchange columns in order to remove Zr, Hf, and the rare earth elements, which can potentially interfere with the analytical signal obtained from the sample (Corfu & Noble, 1992). After chemical separation of U and Pb was complete, the samples were analysed on a Finnigan MAT 262 spectrometer, using both static Faraday cups and dynamic counting using a secondary ion-counting electron multiplier (SEM). Corrections for isotopic fractionation and SEM analytical bias were performed prior to correcting the analyses for the analytical blank (2 pg Pb and 0.1 pg U) and initial common Pb content (Stacey & Kramers, 1975).

Final analysis and presentation of the data was conducted using the program ISOPLOT (Ludwig, 2003). In many cases, the array of concordant zircon analyses requires a synthetic anchoring point to be added in order to calculate an age. It may be that an anchoring point at 420 ± 20 Ma, the Scandian age of Caledonian orogenesis (Gayer, Hayes & Rice, 1985), would be a reasonable age for the alteration and growth of metamorphic overprints on the zircons, but this is currently an assumption. The use of an anchoring point of 200 ± 200 Ma covers a multitude of possibilities, eliminating bias on the part of the analyst. All errors are reported at the 2-sigma confidence interval, except where noted.

6. Results: field relationships and U–Pb age dating

6.a. Hasvik intrusion, Sørøy

The Hasvik layered intrusion on the island of Sørøy is one of the best studied of the Seiland Province intrusions (Fig. 2). The gabbroic intrusion is easily accessible and its igneous petrogenesis has been intensively studied (Sturt, 1969; Robins & Gardner, 1974; Tegner *et al*. 1999). The layered intrusion has been divided into a Marginal Series, located at the edge of the pluton and comprising hybrid magmas and a massive gabbronorite, and a Layered Series (Robins & Gardner, 1974; Tegner *et al*. 1999). The Layered Series comprises

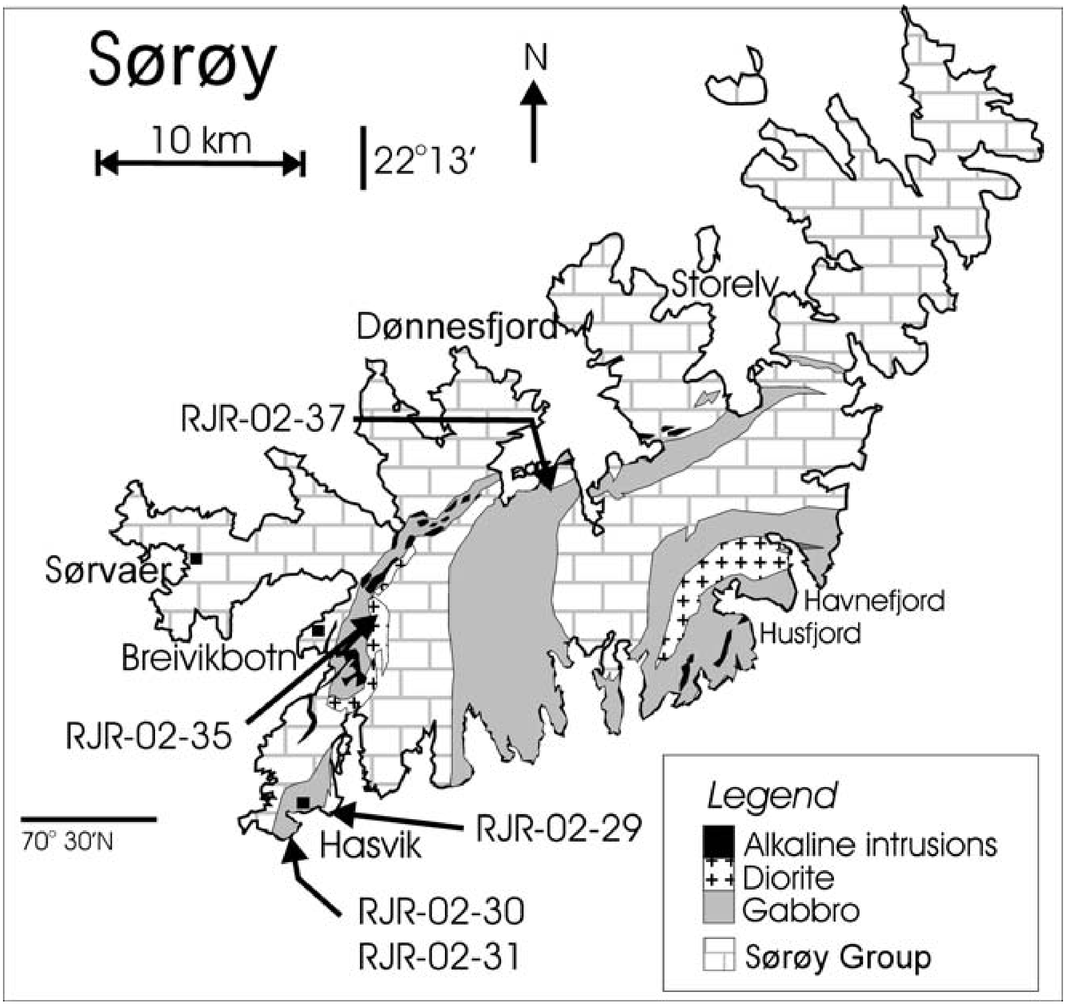

Figure 2. Geological map of the island of Sørøy, northern Norway, showing the locations of igneous intrusions mentioned in the text and sampling locations for analyses reported in Table 2.

a Basal Zone (75 m of gabbronorite), a Lower Zone (340 m of olivine gabbro with modal layering), a Middle Zone (1000 m of gabbronorite, marked by the disappearance of cumulus olivine and the appearance of cumulus orthopyroxene and Fe–Ti oxides), and an Upper Zone (200 m of ferro-norite, marked by the presence of apatite and absence of augite). The Lower Zone is the most primitive magma, with the Basal Zone and Marginal Series having been heavily contaminated by crustal material (Tegner *et al*. 1999).

The crystallization of the intrusion involved a significant amount of crustal assimilation, and xenoliths from the surrounding Sørøy Group are present throughout the layered sequence. A complete geochemical sampling programme incorporating Rb–Sr and Sm–Nd analyses (Tegner *et al*. 1999) indicates that up to 21 % of the volume of the initial melt was composed of assimilated crustal rock. The contaminants were identified as sedimentary rocks from the Klubben Psammite of the Sørøy Group.

The intrusion has a well-defined contact metamorphic aureole of at least 500 m that displays evidence of dehydration and partial melting, and the growth of garnet and hercynitic spinel (H. Reginiussen, unpub. Ph.D. thesis, Univ. Trømso, 1996). Estimates obtained by geothermobarometry indicate an emplacement pressure of 6–8 kbar (H. Reginiussen, unpub. Ph.D. thesis, Univ. Trømso, 1996). However, the interpretation of structural relationships in the aureole and, hence, the timing of the intrusion of Hasvik Gabbro in the deformational framework of the Finnmark region, has been contentious. The earliest work on the Hasvik Gabbro considered the gabbro to have been emplaced within the earliest phase of deformation within the nappes (Sturt, 1969). The contact aureole was observed to post-date one phase of folding and, in the two-stage structural framework of the time, was assigned to a post-D1 age. It can be readily observed that the xenoliths preserved within the gabbro display isoclinal folding, indicating that folding had already occurred in the country rocks at the time of intrusion. This post-D1 identification was carried through the literature until Daly *et al*. (1991) described two phases of deformation within the aureole of the intrusion, and assigned the Hasvik intrusion to a post-D2 event. The evidence provided was that the contact of the intrusion truncates both the S1 and the S2 foliations (according to the newer scheme of deformation; Ramsay *et al.* 1985) in the country rocks. Subsequent observations by Reginiussen (H. Reginiussen, unpub. Ph.D. thesis, Univ. Trømso, 1996) and Tegner *et al.* (1999) support this interpretation. It is now also evident that Klubben Psammite underwent deformation and metamorphism during orogenic events pre-dating the Seiland Igneous Province (Daly *et al.* 1991; Corfu *et al.* 2005).

A variety of ages has been obtained for the Hasvik Gabbro by different workers. The most recent age of 700 ± 33 Ma, based on a Sm–Nd mineral isochron using plagioclase and clinopyroxene, was obtained by combining data from two samples, which have individual age estimates of 706 ± 37 Ma and 688 ± 58 Ma (Daly *et al.* 1991). By contrast, Rb–Sr dating yielded an age of 528 ± 27 Ma (Sturt, Pringle & Ramsay, 1978). To evaluate these inconsistencies the Hasvik Gabbro was selected for U–Pb analysis.

Three rock samples were collected for analysis. One sample, from the Upper Zone (the same layer sampled by Daly *et al.* 1991) is a norite, composed of plagioclase, orthopyroxene, oxide minerals and apatite. The oxides are primarily magnetite and ilmenite. In places, quartz occurs as an intercumulus mineral, and intergrowths of quartz and K-feldspar are also present. However, no zircon was retrieved from this sample. The two samples that did provide zircons were collected from the Marginal Series, along the road at the southwestern edge of the pluton (Fig. 2, GPS coordinates in Table 1). Both samples were collected from small (< 0.5 m) pegmatitic patches in the pluton. These coarse-grained patches are igneous in origin and grade into finer-grained gabbro at the edges. These rocks consist of large (3–5 mm) plagioclase crystals (50 %), orthopyroxene (25 %) and clinopyroxene (20 %), with opaque minerals making up the rest. The pegmatites appear undeformed, and no significant differences exist between the two samples.

The results of the U–Pb analyses are shown in Table 2. The two samples (RJR-02-29I and 29J) each provided ± 20 zircons, comprising mostly fragments.

Table 1. GPS locations for sampling points

Sample	Latitude	Longitude
RJR-02-03B	N 70.13′26.6″	E 22.20′4.2″
RJR-02-29I	N 70.29′03.9″	E 22.14′42.1″
RJR-02-29J	N 70.29′03.9″	E 22.14′42.1″
RJR-02-35	N 70.35′50.0″	E 22.21′08.7″
RJR-02-37A	N 70.37′47.3″	E 22.34′30.0″
RJR-02-37B	N 70.37′47.3″	E 22.34′30.0″
RJR-02-40B	N 70.13′52.0″	E 22.20′41.7″
RJR-02-41C	N 70.12′56.8″	E 22.20′06.0″
RJR-03-129A	N 70.17′15.2″	E 22.10′27.3″
RJR-03-129C	N 70.17′15.2″	E 22.10′27.3″
RJR-03-129D	N 70.17′15.2″	E 22.10′27.3″

The zircons are generally yellow–brown, and show good crystal shape. Whole grains are slightly rounded and up to 200 μm wide. The morphology of the crystals is not generally indicative of a metamorphic origin, as the zircons do not show obvious cores under the microscope or under CL, and do not show rounded edges indicating resorption. For RJR-02-29J, several grains and some fractions were analysed. However, all of the analyses are reversely discordant, reflecting either undetected analytical problems or open system behaviour with Pb gain or U loss, and causing uncertainty in the interpretation. For this reason the data cannot yield a good age and are not used in Figure 3. However, in light of the age extracted for RJR-02-29I, we can infer that the reverse discordance was probably due to some U–Pb fractionation process. Three fractions of large zircon grains (80–150 μg) from RJR-02-29I yield concordant to slightly discordant data forming a linear array with an upper intercept age of 562 ± 6 Ma (Fig. 3a). Since the zircons are generally concordant and do not show either significant alteration or a younger component on the Concordia, it is likely that the zircons are magmatic in origin. Further discussion of the origin of the zircons can be found below.

6.b. The Breivikbotn Gabbro and Diorite, Sørøy

The Breivikbotn Gabbro (Fig. 2) is the least characterized of the mafic plutons on Sørøy. It is mentioned in passing in one paper dealing with the alkaline rocks intruded into the pluton and a carbonatite intruded into the nearby country rocks (Sturt & Ramsay, 1965). The pluton is well exposed on the coastal road between Hasvik and Breivikbotn (Fig. 2). It is compositionally and texturally heterogeneous, ranging from pyroxenite to gabbro, and from coarse-grained and massive to fine-grained and foliated. Large bodies of diorite are associated with the mafic rocks. Although considered a single intrusion by Sturt & Ramsay (1965), it is possible that the pluton contains several different mafic intrusions, judging from the variety of mafic rocks present.

Fine-grained mafic dykes are found throughout the pluton, and the density of the dykes is so great in some places that none of the host gabbro is observed. Several generations of these dolerite dykes are present within the pluton. The situation is further complicated by the presence of large alkaline bodies within the pluton. These rocks range from sedimentary screens and xenoliths altered to alkaline compositions, to nepheline syenite dykes that clearly post-date all other igneous rocks. Significant fenitization (Sturt & Ramsay, 1965) is associated with these alkaline dykes, altering the mineralogy of both the surrounding gabbro and the country rocks.

The mafic plutons are also metamorphosed. All mafic rocks have been affected by metamorphism

Table 2. U–Pb results from the Seiland Igneous Province

Sample	No.	Type	Weight (µg)	U (ppm)	Th/U[a]	Pb com[b] (pg)	$^{206}Pb/^{204}Pb$[c]	$^{207}Pb/^{235}Pb$[d]	$^{206}Pb/^{238}Pb$[d]	rho	$^{207}Pb/^{206}Pb$[d]	$^{207}Pb–^{206}Pb$ Age (Ma)[e]
Hasvik Gabbro	A	2 clear rounded	1	1424	0.41	7.2	1146	0.74046 ± 0.00470	0.09145 ± 0.00052	0.77	0.05872 ± 0.00024	556.8 ± 9.0
RJR-02-29J	B	1 brown euhedral	1	447	0.39	0.9	2973	0.75086 ± 0.00424	0.09275 ± 0.00050	0.80	0.05870 ± 0.00021	556.3 ± 7.7
	C	6 clear frags	9	55	0.43	1.7	1691	0.74499 ± 0.00502	0.09228 ± 0.00050	0.69	0.05854 ± 0.00029	550.4 ± 10.7
	D	4 brown frags	3	446	0.49	1.0	7679	0.75015 ± 0.00428	0.09222 ± 0.00051	0.91	0.05899 ± 0.00014	566.8 ± 5.0
	E	1 clear rounded	1	1128	0.95	0.6	10152	0.74813 ± 0.00301	0.09215 ± 0.00036	0.84	0.05887 ± 0.00013	562.6 ± 4.9
	F	4 large brown euhedral	10	213	0.87	4.0	3143	0.74683 ± 0.00369	0.09272 ± 0.00028	0.62	0.058414 ± 0.00023	545.3 ± 8.4
Hasvik Gabbro	A	4 brown rounded	143	1375	0.80	38.9	28492	0.72980 ± 0.00270	0.08995 ± 0.00032	0.98	0.05884 ± 0.00040	561.3 ± 1.6
RJR-02-29I	B	1 brown rounded	82	231	0.58	12.1	8941	0.73800 ± 0.00260	0.09084 ± 0.00031	0.67	0.05892 ± 0.00007	564.1 ± 2.4
	C	3 brown rounded	95	779	0.42	8.5	48827	0.72740 ± 0.00250	0.08962 ± 0.00029	0.98	0.05887 ± 0.00004	562.2 ± 1.4
Breivikbotn Diorite	A	13 blocky frag	13	238	0.36	14.4	1261	0.75328 ± 0.00385	0.09259 ± 0.00037	0.79	0.05900 ± 0.00018	567.3 ± 6.8
RJR-02-35	B	14 large brown tips	100	307	0.36	465.8	401	0.76029 ± 0.00624	0.09281 ± 0.00033	0.44	0.05941 ± 0.00044	582.3 ± 15.9
	C	Numerous clear tips	15	329	0.37	4.7	6151	0.75209 ± 0.00279	0.09227 ± 0.00030	0.87	0.05911 ± 0.00011	571.3 ± 3.9
	D	Numerous small tips	72	300	0.37	2.6	47707	0.76038 ± 0.00450	0.09282 ± 0.00055	0.93	0.05941 ± 0.00013	582.3 ± 4.7
	E	Numerous clear frags	20	437	0.39	3.9	12843	0.74199 ± 0.00454	0.091073 ± 0.00063	0.85	0.05908 ± 0.00022	570.3 ± 7.9
Storelv Gabbro	A	1 large brown euhedral	1	6650	0.19	2.0	19385	0.73752 ± 0.00395	0.09072 ± 0.00051	0.92	0.05896 ± 0.00013	565.7 ± 4.8
RJR-02-37B	B	1 large clear euhedral	1	15624	0.88	24.6	3700	0.75406 ± 0.01501	0.09264 ± 0.00184	1.00	0.05903 ± 0.00007	568.2 ± 2.6
	C	1 large brown euhedral	1	4488	0.99	1.0	25068	0.74742 ± 0.00462	0.09175 ± 0.00056	0.98	0.05907 ± 0.00007	570.0 ± 2.5
	D	1 brown euhedral	1	12979	1.31	2.4	30935	0.73756 ± 0.00278	0.09075 ± 0.00033	0.98	0.05894 ± 0.00005	565.0 ± 1.7
	E	1 brown euhedral	1	8418	0.90	1.9	26054	0.74949 ± 0.00327	0.09187 ± 0.00040	0.96	0.05916 ± 0.00008	573.1 ± 2.8
Storelv Granodiorite	A	12 clear tips	8	204	0.35	7.1	1327	0.74595 ± 0.00403	0.09144 ± 0.00044	0.61	0.05916 ± 0.00027	573.1 ± 9.8
RJR-02-37A	B	20 blocky frags	20	685	0.19	15.8	5138	0.80066 ± 0.00204	0.09457 ± 0.00022	0.92	0.06139 ± 0.00006	653.2 ± 2.2
	C	13 clear tips	10	750	0.33	21.2	2056	0.75231 ± 0.00207	0.09193 ± 0.00021	0.76	0.05935 ± 0.00011	580.0 ± 3.9
	D	2 prismatic needles	1	553	0.09	42.1	102	0.91076 ± 0.02896	0.10237 ± 0.00064	0.21	0.06452 ± 0.00201	758.7 ± 64.3
Øksfjord Gabbro	A	Numerous clear frags	17	411	0.88	2.7	14553	0.73676 ± 0.00215	0.09069 ± 0.00026	0.91	0.05892 ± 0.00007	564.1 ± 2.7
RJR-02-3B	B	15 cracked brown frags	14	1421	0.72	2.9	38614	0.74052 ± 0.00210	0.09102 ± 0.00024	0.96	0.05900 ± 0.00005	567.2 ± 1.8
	C	Numerous brown frags	164	399	0.85	16.0	22974	0.72582 ± 0.00246	0.08959 ± 0.00029	0.98	0.05875 ± 0.00004	558.1 ± 1.6
	D	12 clear euhedral	15	416	0.70	23.5	1515	0.72935 ± 0.00314	0.09001 ± 0.00046	0.65	0.05876 ± 0.00024	558.4 ± 8.7
	E	10 blocky clear frags	9	2025	0.72	65.8	1567	0.72659 ± 0.00278	0.08935 ± 0.00030	0.74	0.05897 ± 0.00016	566.1 ± 5.7

Table 2. *(Contd.)*

Sample	No.	Type	Weight (µg)	U (ppm)	Th/U[a]	Pb com[b] (pg)	^{206}Pb/^{204}Pb[c]	^{207}Pb/^{235}Pb[d]	^{206}Pb/^{238}Pb[d]	rho	^{207}Pb/^{206}Pb[d]	^{207}Pb–^{206}Pb Age (Ma)[e]
Øksfjord Monzonite	A	Numerous clear euhedral	148	870	1.05	7.0	103588	0.73420 ± 0.00445	0.09030 ± 0.00054	0.99	0.05896 ± 0.00004	565.9361572
RJR-02-41C	B	Numerous clear frags	217	483	0.86	24.6	24441	0.74231 ± 0.00402	0.09132 ± 0.00048	0.99	0.05895 ± 0.00004	565.4298096
	C	Numerous clear euhedral	213	974	1.22	43.6	27010	0.73527 ± 0.00291	0.09055 ± 0.00034	0.99	0.05889 ± 0.00004	563.0814819
	D	Numerous clear euhedral	264	1390	1.43	34.2	61242	0.73881 ± 0.00234	0.09100 ± 0.00027	0.98	0.05888 ± 0.00004	562.7235718
Øksfjord Monzodiorite	A	Numerous clear euhedral	327	143	0.54	14.6	18171	0.73602 ± 0.00273	0.09064 ± 0.00032	0.97	0.05888 ± 0.00005	563.0 ± 1.8
RJR-02-40B	B	Numerous brown tips	239	59	0.41	5.8	13713	0.73691 ± 0.00197	0.09070 ± 0.00022	0.93	0.05892 ± 0.00006	564.3 ± 2.1
	C	Numerous brown frags	58	137	0.62	6.3	7192	0.73919 ± 0.00307	0.09110 ± 0.00040	0.79	0.05884 ± 0.00016	561.4 ± 6.1
	D	Numerous blocky frags	35	80	0.43	13.4	1208	0.73346 ± 0.00278	0.09042 ± 0.00025	0.68	0.05882 ± 0.00016	560.8 ± 6.0
	E	Numerous clear euhedral	21	160	0.56	3.5	5462	0.73682 ± 0.00442	0.09077 ± 0.00054	0.91	0.05887 ± 0.00015	562.4 ± 5.5
Øksfjord Norite	A	3 clear euhedral	19	1032	0.77	7.6	14752	0.74300 ± 0.00260	0.09125 ± 0.00032	0.94	0.05905 ± 0.00007	569.0 ± 2.7
RJR-03-129C	B	7 clear euhedral	15	1048	0.77	7.3	12162	0.73230 ± 0.00280	0.09011 ± 0.00034	0.94	0.05894 ± 0.00008	565.0 ± 2.9
	C	9 clear euhedral	26	1706	0.76	30.5	8234	0.73300 ± 0.00390	0.09014 ± 0.00047	0.98	0.05898 ± 0.00006	566.2 ± 2.0
	D	10 clear frags	23	1722	0.67	49.4	4159	0.72730 ± 0.00470	0.08960 ± 0.00057	0.97	0.05888 ± 0.00009	562.5 ± 3.1
Øksfjord Pyroxenite	A	15 brown euhedral	10	418	0.56	14.0	1724	0.74358 ± 0.00282	0.09161 ± 0.00028	0.69	0.05886 ± 0.00016	562.2 ± 6.0
RJR-03-129D	B	Numerous clear frags	252	428	0.63	29.3	21149	0.74570 ± 0.00261	0.09170 ± 0.00031	0.98	0.05897 ± 0.00004	566.1 ± 1.5
	C	Numerous clear frags	25	595	0.72	11.1	7770	0.74790 ± 0.00228	0.09195 ± 0.00026	0.95	0.05899 ± 0.00006	566.8 ± 2.1
Øksfjord Granite	A	12 clear euhedral	22	616	7.46	9.7	8337	0.78020 ± 0.00420	0.09462 ± 0.00053	0.91	0.05980 ± 0.00014	596.4 ± 5.1
RJR-03-129A	B	4 clear euhedral	13	697	0.25	9.7	5310	0.73750 ± 0.00260	0.09061 ± 0.00032	0.90	0.05904 ± 0.00009	568.4 ± 3.4
	C	3 prismatic needles	3	1264	2.11	3.0	7436	0.76430 ± 0.00490	0.09315 ± 0.00058	0.96	0.59500 ± 0.00011	585.5 ± 4.0
	D	11 brown cracked	29	979	0.25	12.7	13058	0.76250 ± 0.00220	0.09291 ± 0.00028	0.87	0.05952 ± 0.00009	586.2 ± 3.3
	Mon1	Monazite	1	2787	23.46	60.1	282	0.73850 ± 0.00990	0.09114 ± 0.00054	0.46	0.05877 ± 0.00070	558.5 ± 25.8
	Mon2	Monazite	1	919	23.13	350.3	33	0.73410 ± 0.14740	0.09072 ± 0.00236	0.11	0.05869 ± 0.01171	555.5 ± 100.0

[a] Model value calculated from ^{208}Pb/^{206}Pb ratio and the age of the sample. [b] Total common lead, including analytical blank and initial common lead in the sample. [c] Corrected for spike contribution and fractionation. [d] Corrected for spike contribution, fractionation, blank and initial common lead (as calculated from Stacey and Kramers, 1975), errors reported at 2σ. [e] 2σ absolute errors reported in Ma.

of at least amphibolite grade, as indicated by the common occurrence of hornblende within the rocks, and primary features are poorly preserved. In places, large shear zones crosscut the pluton. The pluton has been referred to as a 'schistose sheet', and varies from highly foliated in the north to more massive in the south (Sturt & Ramsay, 1965). Shear zones commonly separate foliated gabbro from massive pyroxenite, and no exposures where the original relationships between the different rock types could be evaluated were found.

The Breivikbotn Gabbro is a difficult target for U–Pb zircon dating, as it is generally very mafic in composition. There are pegmatitic horizons of various compositions within the gabbro, but distinguishing late-stage igneous pegmatites from the numerous alkaline intrusions or pegmatites developed in small shear zones proved difficult. Instead, a quartz diorite intruded along the eastern edge of the gabbro was investigated. Although poorly exposed, the unit has been mapped by Sturt & Ramsay (1965), who considered it to be genetically related to the mafic pluton, as both bodies have been deformed and metamorphosed by the same deformation events. However, it is possible that the diorite is significantly younger than the gabbro, so the quartz diorite provides a lower limit on the age of the Breivikbotn Gabbro.

Outcrop at the sample point (Fig. 2, GPS co-ordinates in Table 1) was extremely poor. In hand specimen the quartz diorite is a foliated, medium-grained rock. In thin section, the diorite comprises plagioclase (50 %), quartz (20 %), K-feldspar (10 %), biotite (15 %), and hornblende (5 %). The feldspars and quartz are completely recrystallized, as shown by the presence of triple junctions at the edges of the crystals. Biotite and amphibole are present in thick planar bands marking a foliation, and are considered metamorphic in origin.

A 1 kg sample of quartz diorite (RJR-02-35; Table 2) yielded nearly 20 mg of igneous zircon. Most zircons are brown and cracked, but some crystal shape could be discerned. Five fractions were picked for analysis, composed mainly of whole grains or broken tips from elongate grains. Of these, one analysis (RJR-02-35 E) was conducted on the secondary electron multiplier at low temperatures, and can be considered a poor analysis for technical reasons and excluded from the age calculations. One of the other analyses (RJR-02-35 D) is not concordant, but does plot on a linear regression line (Fig. 3b) with the other three analyses at an age of 571 ± 4 Ma (MSWD = 1.6). This is considered the age of formation of the quartz diorite.

6.c. The Storelv Gabbro and associated Granitoid, Sørøy

The Storelv Gabbro has been described in two papers (Stumpfl & Sturt, 1965; Sturt & Taylor, 1971). It is a mafic sheet some 40 km long comprising gabbro, along with lesser quantities of diorite and monzogranite, and has long been held to be one of the oldest gabbros (along with the Breivikbotn Gabbro) on Sørøy on the basis of the higher metamorphic grade (amphibolite facies) and degree of folding of the Storelv Gabbro compared with that of the Hasvik Gabbro (Sturt & Taylor, 1971). Both diorite and granodiorite intrude the gabbro, with granodiorite being the last intruded. Although the mafic rocks are always metamorphosed, the extent of deformation in the rocks is extremely variable. In the Dønnesfjord area, where samples RJR-02-37A and RJR-02-37B were taken, the rock is undeformed. At this location a melanocratic gabbro (RJR-02-37B) is intruded by K-feldspar megacrystic granodiorite (RJR-02-37A2). This granodiorite, previously referred to as 'adamellite', can clearly be seen to post-date the gabbro. It forms a network of granitic veins running throughout the gabbro, with larger volumes of granitic material intruded at the intersections of several veins. Igneous layering in the gabbro is truncated by the granitic veins. The host gabbro intruded into deformed rocks of the Klubben Psammite, and clearly crosscuts the foliation within the Group.

In contrast to the Dønnesfjord locality, 10 km away at Storelv the gabbro and other intrusions are highly deformed. Sturt & Taylor (1971) published photographs of foliated gabbro containing boudinaged lenses of monzogranite, along with several other deformation features. It was on the basis of these deformation features that the gabbro was considered syn-tectonic and believed to have been emplaced in the early stages of D2. However, some of the observations made by Sturt & Taylor (1971) must be questioned. On consideration of the large-scale cross-sections provided by Sturt & Taylor (1971), there does not appear to be folding of the magnitude of D2 within the gabbro (as described by Ramsay *et al*. 1985). The cross-sections show only small-scale gentle folds of the sort that is normally associated with D3 (Ramsay *et al*. 1985). Hence, the contention that the gabbro was deformed syn-kinematically with D2 folding is considered suspect and the structural relationships within the Storelv Gabbro should be reassessed in the light of the age dating reported below.

In thin section, the Storelv Gabbro at the sampling location (Fig. 2, GPS co-ordinates on Table 1) is composed of clinopyroxene (50 %) and plagioclase (40 %), with oxides (mainly ilmenite), orthopyroxene, apatite, and zircon as minor phases. Most clinopyroxene has been replaced by green–brown hornblende. However, despite the metamorphism, there are no signs of deformation in the rock, with no planar fabrics developed. The granodiorite sampled at the same location is composed primarily of plagioclase and quartz, with rare large K-feldspar crystals. Clumps of large blue–green poikilitic plates of hornblende and brown biotite occur randomly throughout the rock. Quartz and feldspars have undergone some recrystallization.

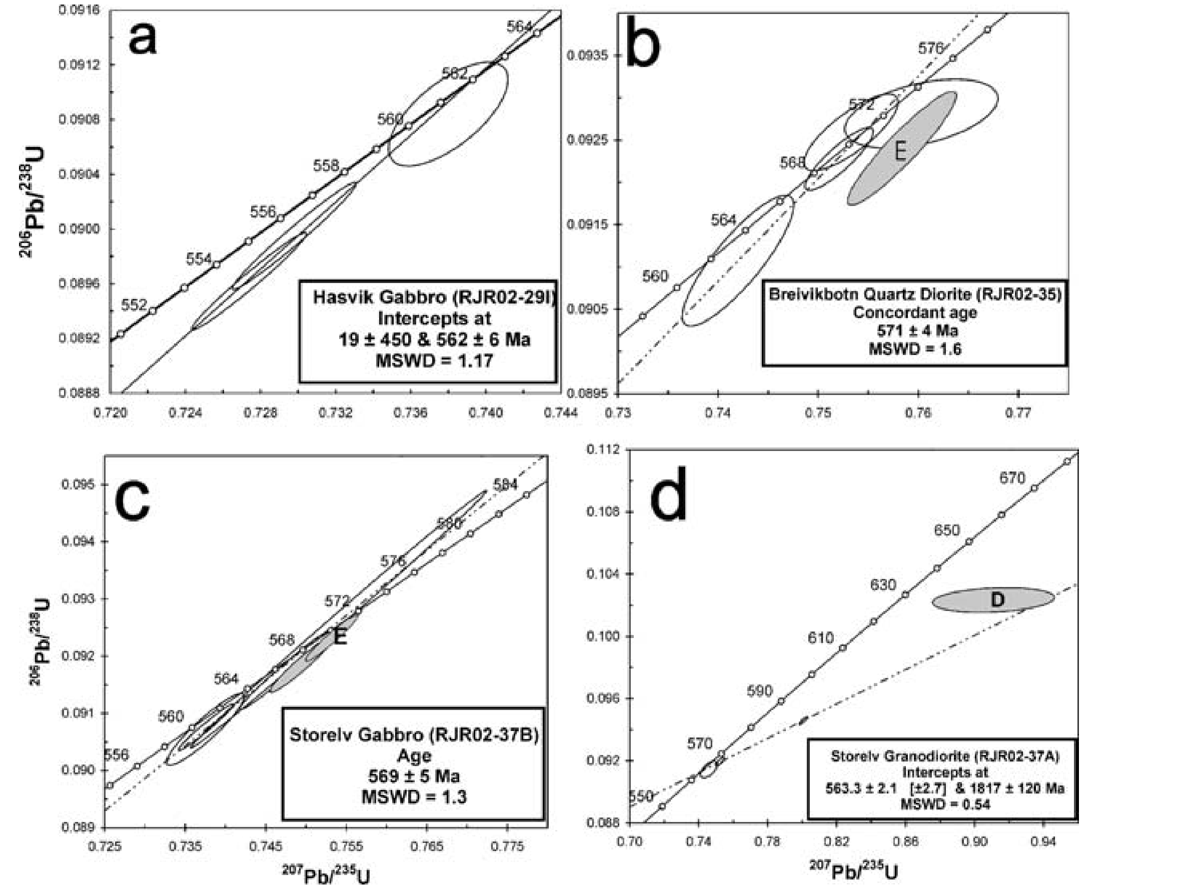

Figure 3. Concordia diagrams for TIMS U–Pb analyses from rock samples from the island of Sørøy, plotted from data given in Table 2. Errors are 2σ except where noted. (a) Hasvik Gabbro RJR-02-29I: unanchored regression. (b) Quartz diorite RJR-02-35 from Breivikbotn: analysis E is discarded for analytical reasons, whereas analysis D is not used to derive the concordant age. Unanchored regression. (c) Storelv Gabbro RJR-02-37B: analysis E is discarded for analytical reasons, and a broad anchoring point of 200 ± 200 Ma is used to calculate the age. (d) Storelv Granodiorite RJR-02-37A: analysis D discarded for analytical reasons. Unanchored regression. Further details on the interpretation of these data may be found in the text.

The zircon analyses obtained from the samples of Storelv Gabbro (RJR-02-37B) and the associated granodiorite (RJR-02-37A) are presented in Table 2. Twenty grains of zircon were retrieved from the gabbro (RJR-02-37B). The zircons were brown, and generally display rounded edges but euhedral crystal shapes. Five single grains were analysed. Of these, one analysis (RJR-02-37B E) is considered suspect, as the $^{207}Pb/^{206}Pb$ ratio measured on the secondary electron multiplier showed significant variation during the analytical run. The remaining analyses, all clustered near Concordia, show some dispersion in U–Pb, suggestive of mild Pb loss (Fig. 3c). A Discordia line anchored at 200 ± 200 Ma, to cover all possible times of Pb loss, yields an upper intercept age of 569 ± 5 Ma (MSWD = 1.3). These zircons show no signs of an older isotopic component, and are most likely igneous in origin.

The granodiorite provided a large amount of zircon (> 1 g). However, granitic melts commonly contain inherited zircons, and this granodiorite is no exception. As inherited cores could not be discerned under the microscope, several small fractions were analysed in order to check for inheritance. In Figure 3d it can clearly be seen that most of the analyses are discordant, but that they do form a linear array. All four fractions yield a regression line with intercepts at 559 ± 18 Ma and 1452 ± 310 Ma (MSWD = 2.3). The three lowermost points alone (omitting point D, which contains much common Pb and whose cores may have a separate source), have a better fit (MSWD = 0.5), and define a more precise lower intercept age of 563 ± 2 Ma, representing the age of formation of the rock, whereas the upper intercept age of 1817 ± 130 Ma points to a Palaeoproterozoic source for the xenocrysts. The 563 ± 2 Ma age of the granodiorite is within error of the age of its host gabbro (569 ± 5 Ma), but field observations suggest it is younger.

6.d. Mafic rocks from the Øksfjord peninsula

The peninsula of Øksfjord (Fig. 4) consists almost entirely of mafic plutons but little work has been done on differentiating and investigating the different gabbros. The relationship between the plutons and the country rocks is not exposed, except on the

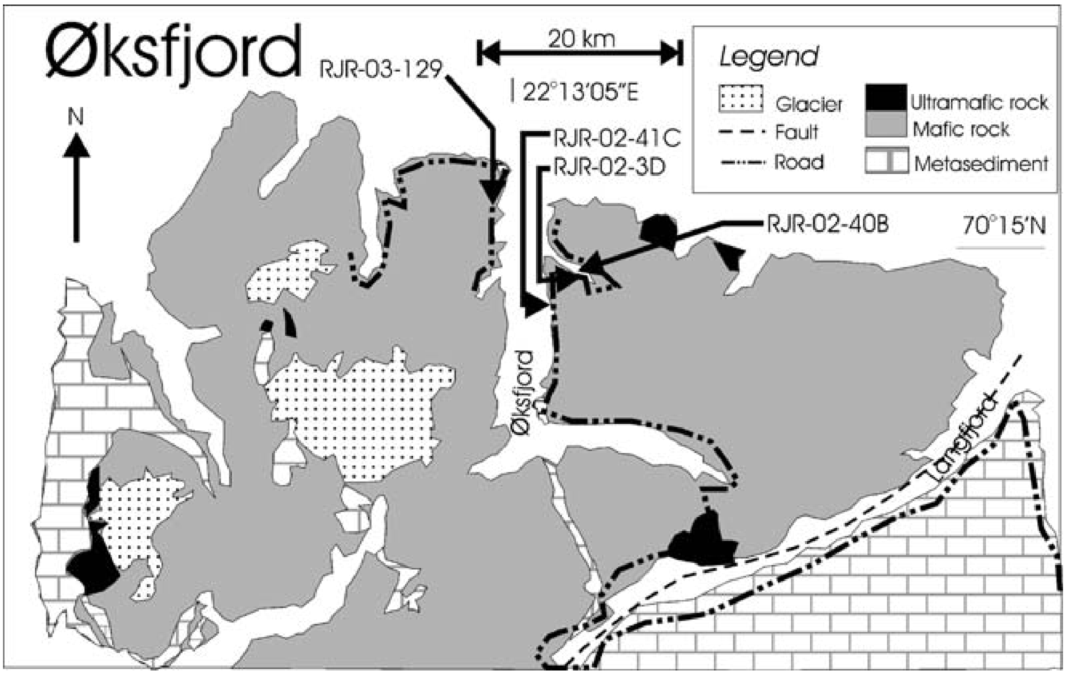

Figure 4. Map of the peninsula of Øksfjord, Northern Norway, showing intrusive bodies mentioned in the text and sampling locations for analyses reported in Table 2.

generally inaccessible western end of the peninsula. Many of these plutons are layered, and are themselves crosscut by other plutons, hampering the identification of individual bodies. Most of them fall into the broad category of nepheline-normative gabbro (Table 3), but they are interlayered with syenites, monzonites and monzodiorites.

The intrusions are generally considered to be of syn-D2 age (Robins & Gardner, 1974), although little proof has been provided to support this conclusion. Deformational fabrics within the intrusions are variable, with some rocks showing a foliation, whereas others show no obvious signs of deformation. Under the microscope, most of the mafic rocks display spinel–orthopyroxene symplectites, indicating post-emplacement breakdown of olivine.

Much of the previous work in the area has been conducted along the road between Langfjord and Øksfjord (Fig. 4), but this study also included rocks to the west of the fjord, which have not previously been studied.

In the first isotopic study of the area, several samples described as 'perthosites', along with gabbro and peridotite, were analysed by Rb–Sr, yielding an age of 612 ± 17 Ma (Brueckner, 1973). At these localities, numerous monzonitic and dioritic bodies are intruded into leucogabbro. Daly *et al*. (1991) reported a similar Sm–Nd age of 604 ± 44 Ma from a gabbro in the eastern part of the Øksfjord peninsula and an age of 612 ± 33 Ma from a gabbro on Stjernøy. Our sampling along the eastern shore of the fjord was aimed at material similar to that in these previous two studies: RJR-02-3B represents gabbro and RJR-02-40B and RJR-02-41C are monzonites (Fig. 4, GPS co-ordinates in Table 1).

RJR-02-3B is the gabbroic host for the other samples. It is a foliated gabbro (plagioclase 40 %, clinopyroxene 30 %) which contains orthopyroxene–spinel symplectites replacing olivine. The gabbro also contains apatite, pyrrhotite and zircon as accessory minerals. The zircons are generally fractured and brown, although there is a population of clear zircons as well. There was some indication of resorption around the edges of some crystals, but some crystal shape could be discerned in most crystals. Five analyses are presented in Table 2. These data do not overlap each other on the Concordia. It is likely that this is partly due to instrumental error, but the generally high uranium content of the samples also indicates that Pb loss is likely to have affected some of the crystals. In order to utilize the analyses in calculating an age for the rock, the analytical errors were doubled and a broad anchoring point (200 ± 200 Ma) used to accommodate the possible Pb loss. The resulting regression (Fig. 5a) yields an age of 565 ± 9 Ma (MSWD $= 2$).

The two samples RJR-02-40B and RJR-02-41C are almost completely composed of feldspar. RJR-02-41C is a monzonite containing perthitic K-feldspar, whereas RJR-02-40B is a monzodiorite with antiperthitic plagioclase. The monzodiorite also shows intergrowths of quartz and feldspar. Triple junctions formed at the edges of quartz and feldspar crystals in both rocks show that they have been recrystallized, but they are not deformed. Furthermore, we consider that the veins of monzonite in the gabbro were plastically deformed during injection into a hot, plastic gabbroic mush. Thus,

Table 3. Major element analyses of rocks sampled from the Øksfjord peninsula

	Gabbro RJR-02-3B	Monzonite RJR-02-41C	Monzodiorite RJR-02-40B	Norite RJR-03-129C	Orthopyroxenite RJR-03-129D	Granite RJR-03-129A
SiO_2	44.77	63.28	62.25	48.96	53.59	78.73
Al_2O_3	16.81	18.27	18.24	14.63	4.67	11.27
Fe_2O_3	1.39	0.34	0.41	1.51	1.34	0.18
FeO	11.29	2.74	3.32	12.22	10.86	1.46
MnO	0.25	0.12	0.12	0.22	0.20	0.03
MgO	4.77	0.49	0.55	4.63	24.74	0.33
CaO	10.00	2.15	2.87	9.03	0.87	1.29
Na_2O	4.08	5.70	6.02	3.82	1.17	3.04
K_2O	1.46	6.53	5.27	0.63	1.54	2.88
TiO_2	3.12	0.40	0.40	3.36	0.27	0.74
P_2O_5	1.72	0.14	0.18	0.59	0.13	0.07
Cr_2O_3	0.02	0.01	0.02	0.01	0.08	0.01
NiO	0.01	0.00	0.00	0.00	0.19	0.00
Total	99.70	100.16	99.65	99.62	99.66	100.02
CIPW norms						
Ne	7.61					
Q						46.35
Or	8.62	38.59	31.14	3.72	9.10	17.02
Pl	43.72	53.21	58.12	53.23	12.84	31.67
Cor						0.97
Cpx	12.62	4.11	5.07	16.76	0.42	
Opx		0.37	1.81	6.60	59.06	2.17
Ol	15.15	2.31	1.71	9.34	15.35	
Ap	3.76	0.31	0.39	1.29	0.28	0.15
Mt	2.02	0.49	0.59	2.19	1.94	0.26
Il	5.93	0.76	0.76	6.39	0.52	1.41
Chr	0.02	0.01	0.03	0.02	0.11	0.02
Total	99.45	100.16	99.62	99.54	99.62	100.02
Mg No.	42.95	24.17	22.79	40.30	80.24	28.71
%An	53.17	9.36	12.35	39.28	22.91	18.77

Ne = nepheline, Q = quartz, Or = orthoclase, Pl = plagioclase, Cor = corundum, Cpx = clinopyroxene, Opx = orthopyroxene, Ol = olivine, Ap = apatite, Mt = magnetite, Il =ilmenite, Chr = chromite.

at least some of the monzonitic material was intruded soon after the gabbro.

Figure 5b,c shows the Concordia diagrams for the two samples. In both cases, a broad anchoring point at 200 ± 200 Ma was used to accommodate any potential Pb loss. As was the case for the gabbro, the data for RJR-02-41C are clustered close to the Concordia but there is some excess scatter, which probably has to be attributed to an underestimated analytical uncertainty. Calculation using double errors yields an age of 566 ± 4 Ma (MSWD = 1.6). A regression through the data for RJR-02-40B has a good fit and yields an age of 565 ± 5 Ma (MSWD = 0.54). All three ages for these rocks overlap within error, and the ages are all considered to be primary (see below).

On the west side of the fjord, a further three samples were collected. Samples RJR-03-129A, RJR-03-129C and RJR-03-129D were taken close to the contact with a large raft of paragneiss (Fig. 4, GPS co-ordinates in Table 1), and were selected for the clear structural relationships between the different rocks. Two different mafic intrusions can be seen alongside the road at this location. A pyroxenite (RJR-03-129D) clearly intrudes a norite (RJR-03-129C) in this outcrop. At the same place, a small granite body intrudes the mafic rocks. This granite (RJR-03-129A), with an augen gneiss texture, encloses large, rounded xenoliths of mafic material, and is obviously the youngest intrusion in the outcrop.

Sample RJR-03-129C is a norite, composed of orthopyroxene (40 %) and plagioclase (40 %), with 15 % clinopyroxene, and minor quantities of opaque minerals, and the original igneous assemblage is well preserved. RJR-03-129D is an orthopyroxenite, with minor phlogopite, and is relatively unmetamorphosed. RJR-03-129A is an augen gneiss, composed primarily of biotite, K-feldspar and quartz, and has obviously been deformed. Both RJR-03-129C and D provided significantly more zircon than is normally expected from mafic rocks, and thin section examination shows that both also contain apatite as an accessory phase. It is likely that both crystallized from crustally-contaminated magmas, similar to the situation with the Hasvik Gabbro (Tegner *et al.* 1999). The zircon analyses are again presented in Table 2. Major element analyses are presented in Table 3, demonstrating that most of these mafic rocks are nepheline-normative in composition.

Four zircon fractions were analysed from RJR-03-129C (Fig. 5d). These fractions form a linear array, with a very tight spread. Unfortunately, none of the zircons is concordant. In this case, the choice of anchoring point influences the resulting age regression considerably. With no anchoring point, the regression

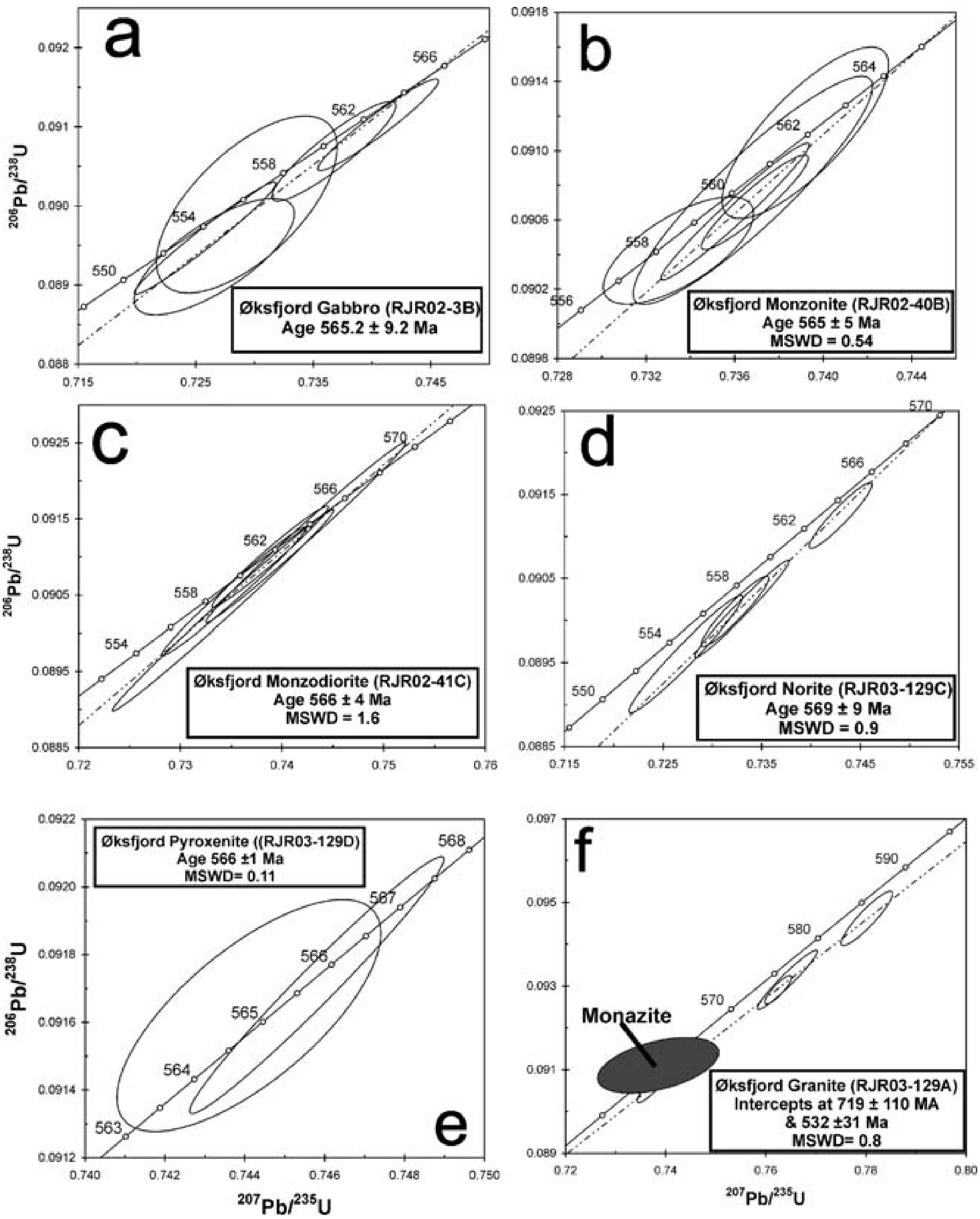

Figure 5. Concordia diagrams for TIMS U–Pb analyses from rocks from the Øksfjord peninsula, plotted from data given in Table 2. Errors are 2σ except where noted. (a) Gabbro RJR-02-3B: an age was obtained by doubling the analytical uncertainty on each analysis to correct for poor instrumentation analysis, and using an anchoring point of 200 ± 200 Ma. (b) Monzonite RJR-02-40B: an age was obtained using a broad anchoring point of 200 ± 200 Ma. (c) Monzodiorite RJR-02-41C: an age was obtained using a broad anchoring point of 200 ± 200 Ma. (d) Norite RJR-03-129C: an age was obtained using a broad anchoring point of 200 ± 200 Ma. (e) Orthopyroxenite RJR-03-129D: no anchoring point was required to calculate this age. (f) Granite RJR-03-129A: displays both monazite and zircon analyses. Further details on the interpretation of these results may be found in the text.

line has intercepts at 580 ± 24 Ma and 366 ± 220 Ma (MSWD = 0.3), possibly indicating early Pb loss. A more precise age of 569 ± 9 Ma is obtained by using an anchoring point of 200 ± 200 Ma (MSWD = 0.94), and this is the preferred age. Three fractions were analysed from RJR-03-129D (Fig. 5e). One analysis plots above Concordia, and is excluded. An unanchored age regression yields an age of 566 ± 1 Ma (MSWD = 0.11).

The granite body (RJR-03-129A) that intrudes the mafic rocks contains zircons that appear to have been inherited from another source (Fig. 5f). The four zircon analyses define a Discordia line between 719 ± 110 Ma, and 532 ± 31 Ma (MSWD = 0.8) whereas one analysis of monazite has a ^{207}Pb–^{235}U age of 561 ± 4 Ma (in this case virtually identical to the Concordia age of 562 ± 3 Ma). Although monazite

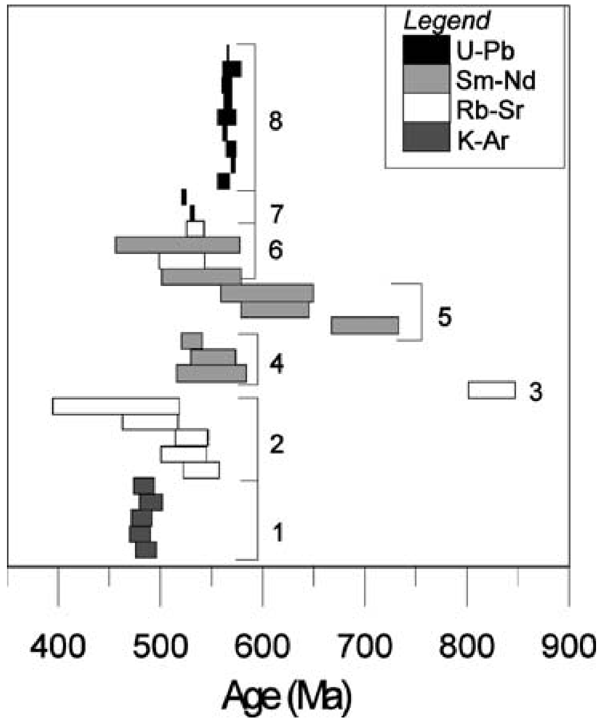

Figure 6. Compilation of published ages and dating methods from the Seiland Igneous Province. Unless marked, rocks are gabbros or monzonites. References: 1 = Sturt, Miller & Fitch (1967), 2 = Sturt, Pringle & Ramsay (1978), 3 = Pedersen, Dunning & Robins (1989), 4 = Krogh & Elvevold (1991), 5 = Mørk & Stabel (1990), 6 = Daly *et al.* (1991), 7 = Cadow (1993), 8 = this study.

can occur as an inherited phase in granitic rock, the age determined from this sample overlaps with other ages in the area and is not considered coincidental. The upper intercept age of this line (719 ± 110 Ma) points to a provenance of the melt from Neoproterozoic crust, broadly consistent with more recent, unpublished results collected during this project.

7. Discussion

7.a. Comparisons with previous isotopic work

The ages in this study differ significantly from some of the other published ages in the area, and this discrepancy needs to be addressed. Figure 6 compares the spread of ages from previous work with the ages obtained in this study. In general, most previous age determinations overlap within error of the U–Pb results reported in this study. The better accuracy and precision of the U–Pb analyses supersedes these earlier results, and the age spread of the U–Pb results is taken to represent the age of intrusion of the Seiland Igneous Province gabbros. However, several analyses, using both Rb–Sr and Sm–Nd techniques, fall well outside the range of ages delimited during this study.

The Sm–Nd and Rb–Sr isotopic dating systems can both yield spurious results, for various reasons. The Rb–Sr isotopic system may remain open, especially in rocks undergoing deformation. Thus, the Rb–Sr system is often reset, producing ages that are younger than the actual formation ages of the rocks. The Sm–Nd system is much more resistant to resetting but can be affected by isotopic disequilibrium. If suites of coexisting minerals or whole rocks were not in isotopic equilibrium with each other, such as occurs occasionally in a layered intrusion, it is possible to obtain ages that are older or younger than the true age of the rock. This would require fractionation and variable assimilation operating simultaneously in the melt to create disequilibrium, and a subsequent mechanism to prevent diffusion and re-equilibration as the melt cools and solidifies. This effect has been reported from many cases, for example Proterozoic anorthosites (Ashwal & Wiebe, 1989) and the Bushveld Complex (Kruger, 1994; Prevec, Ashwal & Mkaza, 2005). If a whole-rock isochron is used, then great care must be taken that all rocks utilized for the isochron are coeval and do not represent different degrees of crustal contamination, or else the isochron will yield a meaningless age.

Because several radiometric dates within the Seiland Igneous Province vary greatly from one isotopic system to another, it is likely that at least one of these effects has biased previous age investigations of the mafic rocks of the Province. Mixing of unrelated rocks may explain some of the biased data obtained in at least two of the previous studies. The Rb–Sr studies by Brueckner (1973) and Krogh & Elvevold (1991) on intrusions from the Øksfjord peninsula produced whole-rock ages of 612 ± 33 Ma and 829 ± 18 Ma respectively, utilizing data from distinct rock types ranging from monzonite to peridotite, which may not necessarily have been comagmatic. The ages older than that obtained by U–Pb analysis suggest that the isochrons are rotated away from the true age, probably due to crustal contamination of the more potassic and Rb-rich rocks.

The Sm–Nd age of 700 ± 33 Ma (v. 562 ± 6 Ma for zircon) reported for the Hasvik Gabbro (Daly *et al.* 1991) is considered to be invalid for a number of reasons. First of all, zircons recovered from the Hasvik Gabbro are generally euhedral, elongate crystals with no obvious core. This morphology is common in magmatic zircon in mafic rocks, and very unlike that of typical metamorphic zircon. If, in spite of that, the zircon age of the Hasvik Gabbro were to record a metamorphic event, one has to wonder about the nature of an event that could totally reset existing zircon, or make new zircon, while leaving the Sm–Nd mineral systems and the main minerals untouched. Logic dictates that if the Sm–Nd age of 700 Ma were correct, then significant metamorphism must have occurred at 560–570 Ma to grow metamorphic zircon and reset the original igneous age in not only the Hasvik Gabbro, but all other rocks in this study. Considering that zircons obtained from the granitoids at Storelv and

Øksfjord still retain much older cores that have not been completely reset, and that none of the other plutons in this study shows any indications of an igneous provenance older than 570 Ma, the idea of an older age for the Hasvik Gabbro must be dismissed. Similar arguments can be made for an igneous origin of the other mafic rocks.

One possible reason for the too-old Sm–Nd date is isotopic disequilibrium. It has been suggested that up to 21 % of the parental melt of the Hasvik Gabbro was composed of assimilated crustal material (Tegner *et al*. 1999). It is thus probable that the isochrons combine data for crystals formed early in a less contaminated melt, with crystals formed later from the same but more contaminated melt, yielding a flawed age determination.

7.b. The origin of the Seiland Igneous Province

The new data suggest the Seiland Igneous Province represents the remains of a short-lived, late Precambrian, igneous intrusive event with a current surface exposure of 5400 km^2. Considering that only the roots of the igneous plutons have been preserved, it is likely that the original magmatism was considerably more voluminous, and may have included extrusive magmatism, all now long eroded. Rough estimation from the surface outcrop of the different rock types shows the composition of the province to be: 50 % gabbro, 35 % ultramafic, 10 % felsic (monzonite, diorite and granitoid), and 5 % alkaline (nepheline syenite, syenite, alkaline gneiss, and minor amounts of carbonatite).

All the ages obtained in this study fall within a narrow time range, from 555 Ma to 579 Ma, if the limits of uncertainty are used (Fig. 6), but it is reasonable to assume that the bulk of the magmatism took place within 10 m.y. (taking the spread of ages without considering the errors), and possibly shorter. This is significantly shorter than previous estimates (e.g. Sturt, Pringle & Roberts, 1975; Sturt, Pringle & Ramsay, 1978; Daly *et al*. 1991), and clarifies a number of problems with the current tectonic framework for the region.

As two plutons emplaced at nearly the same time, the Storelv and Hasvik gabbros illustrate these problems. The Storelv Gabbro is considered to show good structural evidence for syn-kinematic emplacement (Sturt & Taylor, 1971), whereas the Hasvik Gabbro has provided evidence for post-kinematic emplacement (Daly *et al*. 1991). It is unlikely that the Storelv Gabbro was emplaced during constrictional strain (Sturt & Taylor, 1971) at the same time as other gabbros on the island of Sørøy were being intruded without undergoing deformation. Indeed, most outcrops of the Storelv Gabbro reveal well-preserved igneous textures (Sturt & Taylor, 1971; this study), with only small areas showing intense deformation. The discrepancy between the reported deformation in the different gabbros and the coeval age of intrusion for all gabbros would tend to contradict the idea of several extensional deformation events affecting the Finnmark region during the emplacement of the gabbros.

In general, the deformation recorded in rocks of the Seiland Igneous Province can be considered extremely heterogeneous. Undeformed rocks and heavily foliated and metamorphosed rocks are all the same age. Some of the deformation is likely to be related to the Scandian Phase of the Caledonian Orogeny (420 Ma). If the barometric calculations of 6–8 kbar (H. Reginiussen, unpub. Ph.D. thesis, Univ. Trømso, 1996) are correct, then the magma was emplaced into the middle crust under ductile conditions.

A problem with dealing with the Seiland Igneous Province is that possibly only a small portion of the original igneous province remains, leaving questions as to the size and extent of the original magmatism unanswered. Also unknown at this point is the relationship between the Seiland Igneous Province plutons and the younger alkaline rocks that cut across the region (e.g. Pedersen, Dunning & Robins, 1989). The U–Pb ages from this study indicate a gap of at least 25 m.y. between the emplacement of the mafic plutons and the emplacement of the nepheline syenite dykes on Stjernøy and Seiland. However, it seems unlikely that these two periods of magmatism are unrelated, considering the close spatial and relatively close temporal relationships between the two rocks. In addition, there are also generations of nepheline syenite and carbonatite that are broadly coeval with the mafic magmatism at 570–560 Ma on Sørøy (Roberts *et al*. unpub. data), indicating that the different intrusions were emplaced during the same magmatic event.

Considering the different tectonic settings in which significant magmatism can be generated, the following can be said of the Seiland Igneous Province. Firstly, with no proof for orogenic compression and a lack of widespread granitic magmatism resulting from the melting of the lower crust, it is very unlikely that the province represents the remains of an Andean-style margin as postulated by Robins & Gardner (1974). Secondly, the Seiland Igneous Province does not conform to the strictest definition of a large igneous province (LIP; Coffin & Eldholm, 1994), although there is a lack of consensus on the definition of a LIP at depth (Ernst, Buchan & Campbell, 2005). The province comprises calc-alkaline gabbros as well as tholeiitic gabbros, and variety in rock composition is not always a feature of LIPs . Thirdly, the Seiland Igneous Province resembles the remains of an island arc in composition and variety, but is intruded through continental crust (Draut & Clift, 2001).

The most reasonable model for the Seiland Igneous Province is that it represents the eroded roots of an intracontinental rift, similar to the East African Rift system. Carbonatites and nepheline syenites are almost exclusively associated with rifting in those occurrences where the tectonic setting can be determined, such as

East Africa; the Trans-Pecos Province in New Mexico and Texas, USA; and the Lake Superior Rift, USA–Canada (Woolley, 1987). The current time gap between the dominant early mafic magmatism and the late alkaline magmatism (25 m.y.) is not significant in a continental rift setting, and the process of rifting produces not only large quantities of magma but also large chemical and petrological variations. However, this model needs to be refined by further data, especially dating of the carbonatites and associated alkaline rocks, as well as geochemical and isotopic analysis.

The location of the Seiland Igneous Province at the time of emplacement is uncertain. The igneous rocks were emplaced into the allochthonous Kalak Nappes, now located on the Baltica craton but possibly translated significant distances during the Caledonian Orogeny (Ramsay *et al*. 1985; Roberts, 2003). It has long been held that the Kalak Nappe Complex represents the continental shelf of Baltica, making the Seiland Igneous Province a Baltican phenomenon (Ramsay *et al*. 1985; Roberts, 2003). This hypothesis was based on the belief that the sediments of the Sørøy Group were Cambrian or late Precambrian in age, and deposited in the Iapetus Ocean while it was opening (*c*. 600 Ma). However, with the discovery of much older ages for some granitic intrusions in metasediments from the Sørøy Group (e.g. Daly *et al*. 1991; C. Kirkland, pers. comm.), this contention is no longer valid. The sediments of the Sørøy Group cannot be related to the Iapetus Ocean, and there are reasons to believe that the Kalak Nappes may not originate from Baltica at all (Corfu *et al*. 2005).

8. Conclusion

The new ages presented in this study indicate that the magmatism that created the Seiland Igneous Province took place between 570 Ma and 560 Ma. These new ages also reveal deficiencies in the previous Rb–Sr and Sm–Nd studies of the Seiland Igneous Province intrusions. During the period of magmatism, numerous mafic (and ultramafic to felsic) plutons were emplaced into continental crust now located onboard the craton of Baltica. The coeval timing of the magmatism refutes the previous model of emplacement during and after a compressive tectonic event. The previous structural model implies that different plutons were intruding during different deformation events, and are thus of different ages themselves. This model is now clearly shown to be incorrect. The magmatism itself was most likely related to intracontinental rifting, as other models for the emplacement of the magma are improbable.

Acknowledgements. We thank the National Research Agencies of Norway and South Africa for their generous support for this project, under a joint research agreement between the two countries (project 1523225/730). We would also like to thank Maryna Prins for all her work on the maps in this paper, and Callum Hetherington for early comments on the manuscript. The reviewers J. S. Daly and Christian Tegner also contributed greatly to the finally product.

References

ASHWAL, L. D. & WIEBE, R. A. 1989. Isotopic disequilibrium in the internal Sm–Nd and Rb–Sr systematics of Proterozoic anorthosites. *EOS* **70**, 486.

BENNETT, M. C., EMBLIN, S. R., ROBINS, B. & YEO, W. J. A. 1986. High-temperature ultramafic complexes in the North Norwegian Caledonides: I – Regional setting and field relationships. *Norges Geologiske Undersøkelse, Bulletin* **405**, 1–40.

BINNS, R. E. 1989. Regional correlations in NE Troms-W Finnmark: the demise of the 'Finnmarkian' orogeny? In *The Caledonide Geology of Scandinavia*, pp. 27–45, (ed. R. A. Gayer). London: Graham and Trotman.

BRUECKNER, H. K. 1973. Reconnaissance Rb–Sr investigation of salic, mafic and ultramafic rocks in the Øksfjord area, Seiland Province, northern Norway. *Norsk Geologisk Tidsskrift* **53**, 11–23.

CADOW, R. 1993. Sm–Nd and Rb–Sr ages of hornblende pyroxenite and metagabbro from the Lillebukt Alkaline Complex, Seiland Igneous Province. *Norsk Geologisk Tidsskrift* **73**, 243–9.

COFFIN, M. F. & ELDHOLM, O. 1994. Large igneous provinces: crustal structure, dimensions, and external consequences. *Reviews in Geophysics* **32**, 1–36.

CORFU, F. & NOBLE, S. 1992. Genesis of the southern Abitibi greenstone belt, Superior Province, Canada: evidence from zircon Hf analysis using single filament technique. *Geochimica et Cosmochimica Acta* **56**, 2081–97.

CORFU, F., ROBERTS, R. J., GERBER, M., TORSVIK, T. H., ANDERSEN, T. B., RAMSAY, D. M. & ASHWAL, L. D. 2005. Exotic terranes in the Finnmarkian Caledonides: U–Pb evidence for Peri-gondwanan and Laurentian elements. *Norwegian Geological Wintermeeting, Røros, January 9–12, 2005, Abstracts and Proceedings No. 1*, p. 22.

DALLMEYER, R. D. 1988. Polyorogenic ^{40}Ar–^{39}Ar mineral record within the Kalak Nappe Complex, Northern Scandinavian Caledonides. *Journal of the Geological Society, London* **145**, 705–16.

DALY, J. S., AITCHESON, S. J., CLIFF, R. A., GAYER, R. A. & RICE, A. H. N. 1991. Geochronological evidence from discordant plutons for a Late Proterozoic orogen in the Caledonides of Finnmark, northern Norway. *Journal of the Geological Society, London* **148**, 29–40.

DEBRENNE, F. 1984. Archaeocyatha from the Caledonian rocks of Sørøy, North Norway – a doubtful record. *Norsk Geologisk Tidsskrift* **64**, 153–4.

DRAUT, A. E. & CLIFT, P. D. 2001. Geochemical evolution of arc magmatism during arc-continent collision, South Mayo, Ireland. *Geology* **29**, 543–6.

ELVEVOLD, S., REGINIUSSEN, H., KROGH, E. J. & BJØRKLUND, F. 1994. Reworking of deep-seated gabbros and associated contact metamorphosed paragenesis in the south-eastern part of the Seiland Igneous Province. *Journal of Metamorphic Geology* **12**, 539–56.

ERNST, R. E., BUCHAN, K. L. & CAMPBELL, I. H. 2005. Frontiers in large igneous province research. *Lithos* **79**, 271–97.

GAYER, R. A., HAYES, S. J. & RICE, A. H. N. 1985. The structural development of the Kalak Nappe Complex of Eastern and central Porsangerhalvøya, Finnmark, Norway. *Norges Geologiske Undersøkelse, Bulletin* **400**, 67–87.

HOLLAND, C. H. & STURT, B. A. 1970. On the occurrence of archaeocyathids in the Caledonian metamorphic rocks of Sørøy, and their stratigraphical significance, *Norsk Geologisk Tidsskrift* **50**, 345–55.

HOLTEDAHL, O. & DONS, J. A. 1960. *Geologisk kart over Norge*. Norges Geologiske Undersøkelse, Bulletin 208, 15p.

KRILL, A. G. & ZWAAN, B. 1987. Reinterpretation of Finnmarkian deformation on western Sørøy, northern Norway. *Norsk Geologisk Tidsskrift* **67**, 15–24.

KROGH, T. E. 1973. A low contamination method for hydrothermal decomposition and extraction of U and Pb for isotopic age determinations. *Geochimica et Cosmochimica Acta* **37**, 485–94.

KROGH, T. E. 1982. Improved accuracy of U–Pb zircon ages by creation of more concordant systems using air abrasion technique. *Geochimica et Cosmochimica Acta* **46**, 637–49.

KROGH, E. J. & ELVEVOLD, S. 1991. A Precambrian age for an early gabbro-monzonitic intrusion on the Øksfjord peninsula, Seiland Igneous Province, northern Norway. *Norsk Geologiske Tidsskrift* **70**, 267–73.

KRUGER, F. J. 1994. The Sr-isotope stratigraphy of the western Bushveld Complex. *South African Journal of Geology* **97**, 393–8.

LUDWIG, K. R. 2003. *Isoplot 3.0. A geochronological toolkit for Microsoft Excel*. Berkeley Geochronology Center Special Publication No. 4, 70p.

MØRK, M. B. E. & STABEL, A. 1990. Cambrian Sm–Nd dates for an ultramafic intrusion and for high-grade metamorphism on the Øksfjord peninsula, Finnmark, North Norway. *Norsk Geologiske Tidsskrift* **70**, 275–91.

PEDERSEN, R. B., DUNNING, G. R. & ROBINS, B. 1989. U–Pb ages of nepheline syenite pegmatites from the Seiland Magmatic Province, N. Norway. In *The Caledonide Geology of Scandinavia* (ed. R. A. Gayer), pp. 3–8. London: Graham and Trotman.

PREVEC, S. A., ASHWAL, L. D. & MKAZA, M. S. 2005. Mineral disequilibrium from the Merensky pegmatoid, western Bushveld Complex, South Africa: new Sm–Nd isotopic evidence. *Contributions to Mineralogy and Petrology* **149**, 306–15.

RAMSAY, D. M., STURT, B. A., ZWAAN, K. B. & ROBERTS, D. 1985. Caledonides of Northern Norway. In *The Caledonian Orogen – Scandinavia and Related Areas* (eds D. G. Gee and B. A. Sturt), pp. 163–84. New York: Wiley.

RICE, A. H. N. 1990. Possible basement rocks in the Kalak Nappe Complex on Søroy, Finnmark, N. Norway. *Norsk Geologisk Tidsskrift* **70**, 159–72.

RICE, A. H. N. & FRANK, W. 2003. The early Caledonian (Finnmarkian) event reassessed in Finnmark: ^{40}Ar–^{39}Ar cleavage data from NW Varangerhalvøya, N. Norway. *Tectonophysics* **374**, 219–36.

ROBERTS, D. 2003. The Scandinavian Caledonides: event chronology, paleogeographic settings, and likely modern analogues. *Tectonophysics* **365**, 283–99.

ROBINS, B. 1972. Syenite–carbonatite relationships in the Seiland Gabbro Province, Northern Norway. *Norges Geologiske Undersøkelse, Bulletin* **253**, 43–58.

ROBINS, B. 1996. *Field Trip Guidebook: The Seiland Igneous Province, North Norway*. Norges Geologiske Undersøkelse Report 96.127, 30p.

ROBINS, B. & GARDNER, P. M. 1974. Synorogenic layered basic intrusions in the Seiland petrographic province, Finnmark. *Norges Geologiske Undersøkelse, Bulletin* **312**, 91–130.

ROBINS, B. & GARDNER, P. M. 1975. The magmatic evolution of the Seiland Province, and Caledonian plate boundaries in northern Norway. *Earth and Planetary Science Letters* **26**, 167–78.

STACEY, J. S. & KRAMERS, J. D. 1975. Approximation of terrestrial lead isotope evolution using a two-stage model. *Earth and Planetary Science Letters* **26**, 221–97.

STEPHENS, M. B. & GEE, D. G. 1989. Terranes and polyphase accretionary history in the Scandinavian Caledonides. *Geological Society of America, Special Paper* **230**, 17–30.

STUMPFL, E. F. & STURT, B. A. 1965. A preliminary account of the geochemistry and ore mineral parageneses of some Caledonian basic igneous rocks, from Sørøy, N. Norway. *Norges Geologiske Undersøkelse, Bulletin* **234**, 196–230.

STURT, B. A. 1969. Wrench-fault deformation and annealing recrystallization during almandine facies regional metamorphism. *Journal of Geology* **77**, 319–32.

STURT, B. A., MILLER, J. A. & FITCH, F. J. 1967. The age of alkaline rocks from West Finnmark, northern Norway, and their bearing on the dating of the Caledonian orogeny. *Norsk Geologiske Tidsskrift* **47**, 255–73.

STURT, B. A., PRINGLE, I. R. & RAMSAY, D. M. 1978. The Finnmarkian phase of the Caledonian Orogeny. *Journal of the Geological Society, London* **135**, 597–610.

STURT, B. A., PRINGLE, I. R. & ROBERTS, D. 1975. Caledonian nappe sequence of Finnmark, Northern Norway, and the timing of orogenic deformation and metamorphism. *Geological Society of America Bulletin* **86**, 710–18.

STURT, B. A. & RAMSAY, D. M. 1965. The alkaline complex of the Breivikbotn area, Sørøy, Northern Norway. *Norges Geologiske Undersøkelse, Bulletin* **231**, 1–142.

STURT, B. A. & RAMSAY, D. M. 1988. Reinterpretation of Finnmarkian deformation on western Sørøy, northern Norway: a comment. *Norsk Geologisk Tidsskrift* **68**, 213–19.

STURT, B. A. & TAYLOR, J. 1971. The timing and environment of emplacement of the Storelv gabbro, Sørøy. *Norges Geologiske Undersøkelse, Bulletin* **272**, 1–34.

TEGNER, C., ROBINS, B., REGINIUSSEN, H. & GRUNDVIG, S. 1999. Assimilation of crustal xenoliths in a basaltic magma chamber: Sr and Nd isotopic constraints from the Hasvik Layered Intrusion, Norway. *Journal of Petrology* **40**, 363–80.

TORSVIK, T. H., SMETHURST, M. A., MEERT, J. G., VAN DER VOO, R., MCKERROW, W. S., BRASIER, M. D., STURT, B. A. & WALDERHAUG, H. J. 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic: A tale of Baltica and Laurentia. *Earth Science Reviews* **40**, 229–58.

WOOLLEY, A. R. 1987. *Alkaline Rocks and Carbonatites of the World, Part 1: North and South America*. Austin: University of Texas Press, 216p.