Radiogenic heat production of Archaean to Permian geological provinces in Norway

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A compilation of ca. 4000 new and old geochemical data is used to produce a hitherto unique map of radiogenic heat production in Norwegian bedrock. The data show that heat production generally varies more within than between different geological provinces, and is generally tied to variation in lithology, which is well known from other studies. Mafic rocks yield the lowest heat-production rates with an average of 0.74 μW m^{-3}, and granitic rocks yield the highest heat-production rates with an average of 2.95 μW m^{-3}. Granodioritic and metasedimentary rocks yield similar, intermediate heat-production rates with averages of 1.54 and 1.55 μW m^{-3}, respectively. The variation in heat production of the magmatic rocks is clearly attributable to processes related to the formation and evolution of their parent magmas, whereas the sedimentary rocks display variations that can be ascribed to sedimentary processes. Age and metamorphic grade does not appear to affect heat production significantly, whereas tectonic setting appears to have some effect in that extensional or within-plate rocks have higher heat production than lithologically similar rocks formed along plate margins.

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Introduction

Internal radiogenic heat production is a major factor determining the thermal structure of continental crust (e.g., Turcotte & Schubert 1982) and variation in internal heat production may have important implications for temperature-dependent crustal processes such as metamorphism, magmatism and deformation (Bea et al. 2003; Andreoli et al. 2006; Sandiford & McLaren 2006). Regional investigations of heat production at the surface, coupled with heat flow data that provide information about heat production at depth in the crust (e.g., Jaupart & Mareschal 2003), are necessary for understanding the present-day thermal structure of the crust, which in turn may be used to reconstruct the thermal structure of the crust prior to, during and after past tectonic events (Ranalli & Murphy 1987; Karlstrom & Williams 1998). Numerical modelling shows that insight into how heat-producing elements are distributed in pre-orogenic crust is vital for understanding how orogens evolve (Beaumont et al. 2001).

Another, more practical aspect related to the thermal structure of continental crust is the utilisation of geothermal energy as a zero-emission alternative energy source. At present, geothermal energy is profitable in areas where the geothermal gradients are exceptional (e.g., in volcanic areas); however, as drilling costs are reduced due to improved technology and/or energy prices increase, geothermal energy will become a viable source of energy in thermally more quiescent regions. However, even in these regions, some areas will be more favourable than others, to a large extent reflecting variation in heat production. The dataset presented herein represents a first step towards targeting such areas in Norway.

In an effort to further our understanding of the thermal and geological structure of Scandinavia and the continent-ocean transition of the western Baltic Shield, the Geological Survey of Norway (NGU), in collaboration with Statoil, have undertaken a project involving determination of radiogenic heat production, heat flow and thermal conductivity in Norway. As part of this work, ca. 2000 new chemical analyses and an equal number of previously published analyses have been compiled to produce the first heat-production map covering a major part of Norway. The entire dataset is available as an electronic supplement to this paper, downloadable at http://www.geologi.no/njg. Further sampling and analysis on a national scale is continuously being carried out, mainly through NGU's LITO-project (ngu.no/lito).

Sources of heat-production data

More than 98% of present-day heat production is the result of the decay series ^{238}U and ^{232}Th and the single-step decay of ^{40}K. The isotope ^{235}U has a significantly shorter half-life than ^{238}U (ca. 0.7 billion years and 4.5 billion years, respectively) and is now reduced to 0.7% of the total naturally occurring uranium. Other, short-lived radioactive isotopes may have made significant thermal contributions in early stages of the Earth's history, but they are not detectable now. Other long-lived radioactive isotopes also exist, but their decay rates are so slow that they have never made any significant contribution to the Earth's heat (e.g., ^{87}Rb with a half-life of ca. 49 billion years and ^{147}Sm with a half-life of ca. 106 billion years). The heat-production rate of a rock can thus be calculated based on the rock's K, U and Th concentrations and density (Rybach 1988), as shown in Equation 1. C_U and C_{Th} represent U and Th concentrations in ppm, respectively, C_K represents K concentration in wt.%, and δ is density.

$$A=\delta*(9.52C_U+2.56C_{Th}+3.48C_K)*10^{-5} \quad (1)$$

Table 1. Sources of heat-production data.

Source	n	Analytical method
LITO-project	1613	XRF, LA–ICP–MS
Various NGU samples	623	XRF, LA–ICP–MS
Killeen & Heier (1975)	629	γ-ray spectrometry
Raade (1973)	967	γ-ray spectrometry
Ormaasen (1976)	102	γ-ray spectrometry

The chemical data used to calculate heat production here come from various sources, summarised in Table 1. The majority of the samples have been analysed by XRF (K) and LA–ICP–MS (U, Th), thus a complete set of major and trace element data exists for each of these samples. Flem et al. (2005) describe the procedures for LA–ICP–MS analysis in detail. The remaining samples have been analysed by γ-ray spectrometry, and for these samples only the concentrations of heat-producing elements are available. The analytical procedure, detection limits, accuracy and precision of the γ-ray spectrometry method are described by Raade (1973) and Killeen & Heier (1975). For several geological units, heat-production estimates based on both XRF/LA–ICP–MS and γ-ray spectrometry exist. Average heat-production rates for such units are similar regardless if they are based on the older γ-ray data or more modern XRF/LA–ICP–MS data, suggesting that the quality of the former are good. For the majority of the samples, densities have been determined using Archimedes' principle by weighing the samples in air and immersed in water, or, if geometrically simple samples are available (e.g., drill cores), weighing the samples and dividing by the calculated volume. For samples where the original authors reported densities, these densities have been used. If density data are unavailable, density was estimated based on lithology.

Geological evolution and heat production of Archaean to Permian geological units in Norway

A number of factors of which lithology, tectonic setting, tectonometamorphic history and age are the most obvious, may influence the heat production of a geological unit or province. The work presented here is part of a larger effort to enhance our understanding of the geological and thermal structure of the continental margin of Norway (and the Baltic Shield). This means that heat-production values must be assigned to geological units onshore that can be correlated offshore onto the continental margin using seismic or potential field data. With these objectives in mind, I present and discuss the heat-production data with reference to specific geological provinces, subdivided according to lithology, tectonic setting, tectonometamorphic history and age. The subdivision includes nine major and several minor provinces, ranging in age from Archaean to Permian; however, geochemical data are not presently available from all of these provinces. Table 2 presents a summary of geological and heat-production information. The numbers in parentheses below refer to provinces on the simplified geological map (Fig. 1a) and Table 2. The heat-production data are presented graphically in Figures 1b and c, and Figure 2 shows calculated average heat production for geological units as defined by Sigmond (1996).

Archaean gneissic rocks (1)

Rocks of Archaean crystallisation or depositional age are found in several areas in northern Norway. The most intensely studied area is a chain of islands running from southern Lofoten to the island Vanna in west Troms (Fig. 1a). This area is underlain by intermediate metavolcanic rocks, migmatised during the Late Archaean, tonalitic to granitic gneisses, and greenstone remnants (Griffin et al. 1978; Zwaan 1995; Corfu et al. 2003). Pb–Pb whole rock isochrons and Rb/Sr isotopic data from migmatite and granite on Langøya and Hinnøya yield ages of ca. 2700 Ma and ca. 2600 Ma, respectively (Griffin et al. 1978). Magmatic activity in this area between 2700 and 2600 Ma is corroborated by an interpreted U–Pb zircon crystallisation age of 2689±6 Ma for a granite on Kvaløya (Corfu et al. 2003). The rocks are typically in upper amphibolite- to granulite-facies, and the tectonometamorphic history includes a Late Archaean event responsible for migmatisation of the metavolcanic rocks (Griffin et al. 1978), as well as a Late Palaeoproterozoic (1870–1790 Ma) granulite-facies event related to emplacement of the Lofoten–Vesterålen anorthosite-mangerite-charnockite-granite suite (Corfu 2004a), discussed below.

Other areas underlain by Archaean rocks include Finnmarksvidda, where rocks belonging to the Raiseatnu and Jergol Complexes are exposed, and large tracts of the Sør-Varanger area. Lithologically, the Raiseatnu and Jergol Complexes are rather similar and composed dominantly of medium- to high-grade orthogneisses of tonalitic, granitic and dioritic composition (Siedlecka et al. 1985), whereas the Sør-Varanger area is more varied and comprises mica schists and mica gneisses in addition to tonalitic to granitic orthogneisses (Levchenkov et al. 1993).

Ninety-five samples of Archaean gneisses from west Troms yield a median heat production of 0.81 ± 1.48 μW m^{-3} and an area-weighted heat production of 1.25 μW m^{-3} (Fig. 2). No heat-production data are available for Archaean gneisses in Finnmark.

Table 2. Simplified geological history and heat-production rates of geological provinces in Norway. See text for details and references.

	Geological province	n	Age (Ma)	Lithology	Tectonic setting	Tectonometamorphic history	Heat-production rate ($\mu W\ m^{-3}$)	
							Area wtd. mean[1]	Median ±1σ
1	Archaean gneisses	95	3000–2500	Dominantly tonalitic to granitic gneisses		Early Proterozoic (c. 2.0–1.8 Ga) amphibolite- to granulite-facies metamorphism.	1.25	0.81 ± 1.48
2	Proterozoic gneissic rocks							
2a	Karasjok-Kautokeino greenstone belts, NE Norway	n.d.	2100-2000	Tholeiitic metabasalts, amphibolites and interlayered metasedimentary rocks	Continental rifting and oceanic subduction	Metamorphosed under greenschist- to amphibolite-facies conditions during obduction onto the Karelian craton at c. 1.9 Ga.	n.d.	n.d.
2b	Palaeoproterozoic gneisses	17	2000–1900	Garnet-quartz-feldspar paragneiss and hypersthene-plagioclase orthogneiss	Deposition in continental back-arc basin	High-grade metamorphism during continent-continent collision at c. 1900 Ma	1.42	0.54 ± 1.44
2c	Transscandinavian Igneous Belt (TIB)	571	1810–1770	Alkali-calcic to calc-alkaline quartz monzonites to granites	Active continental margin, back-arc extension	Deformation and metamorphism at c. 1.46–1.42 and 1.0 Ga in SW Sweden. Variable Caledonian effects in NW Norway at c. 420 Ma.	2.57	2.57 ± 2.03
2d	Sveconorwegian Province, S Norway	385	1500–1000	Tholeiitic to calc-alkaline, intermediate to felsic, metavolcanic and –plutonic suites	Active continental margin and continental back-arc.	Local crustal reworking at 1.26–1.16 Ga. Continent-continent collision and associated medium- to high-grade metamorphism at c. 1.0 Ga. Very low-grade Caledonian metamorphism at c. 400 Ma in western areas.	1.76	1.73 ± 1.45
2e	Western Gneiss Region, W Norway	332	1750–1000	Dominantly tonalitic to granitic gneisses	Active continental margin	Sveconorwegian and Caledonian high-grade metamorphism at c. 1000 and 400 Ma, respectively.	1.36	1.41 ± 0.82
3	Lofoten anorthosite-mangerite-charnockite-granite (AMCG) complex	130	1800–1790	Mangerite, smaller volumes of gabbro, anorthosite, charnockite and granite	Related to TIB 1 magmatism	Crystallised under low-P granulite-facies conditions. No significant later metamorphic events.	0.65	0.61 ± 0.32
4	Post-Sveconorwegian granites, S Norway	473	930–920	Dominantly granite, locally grading to diorite	Extensional, post-tectonic magmatism	Generally no significant metamorphic overprinting.	4.61	3.92 ± 2.54
5	Egersund anorthosite-mangerite-charnockite (AMC) complex	47	930	Massive anorthosite, lesser volumes of leuconorite, mangerite and charnockite	Extensional, post-tectonic magmatism	Very low-grade Caledonian metamorphism at c. 400 Ma.	0.57	0.71 ± 0.42

	Geological province	n	Age (Ma)	Lithology	Tectonic setting	Tectonometamorphic history	Heat-production rate (μW m^{-3})	
							Area wtd. mean[1]	Median ±1σ
6	Caledonian thrust-sheets							
6a	Late Proterozoic to Palaeozoic metasedimentary and metamafic rocks	561	500–450	Metagreywacke, phyllite, mica schist, lesser volumes of marble and greenstone.	Passive margin sequences. Greenstones formed in oceanic arc / back-arc.	Low- to high-grade metamorphism during the Caledonian orogeny at c. 450–400 Ma.	1.47	1.40 ± 1.39
6b	Caledonian intrusive rocks	167	480–430	Dominantly calc-alkaline diorite, tonalite, granodiorite and granite. Minor trondhjemitic intrusions.	Active continental margin.	Variable overprinting during the Caledonian orogeny at c. 430–410 Ma.	1.85	1.74 ± 1.85
6c	Seiland igneous province	n.d.	570–560	Gabbro, lesser volumes of ultramafic rocks and intermediate granitoid rocks.	Intracontinental rift.	Variable overprinting during the Caledonian orogeny at c. 420 Ma.	n.d.	n.d.
6d	Precambrian gneissic rocks	35	1690–950	Syenitic to monzonitic gneisses, anorthosite-mangerite-charnockite-granite suites	Active continental margin. AMCG suite formed in intraplate setting (?)	Late Sveconorwegian, high-grade metamorphism at c. 930 Ma. Variable, but locally high-grade metamorphism at c. 450 Ma.	2.01	1.70 ± 1.78
6e	Neoproterozoic metasedimentary rocks	48	1000–500	Quartzitic to arkosic sandstone, mica schist, pelite and volumetrically subordinate carbonate	Continental shelf	Variable high- to low-grade Scandian and pre-Scandian metamorphism in Finnmark. Low-grade overprinting in Lillehammer during the Scandian phase at c. 430-400 Ma.	1.35	1.31 ± 0.82
7	Devonian sedimentary rocks	15	400–390	Fluvial sandstones, conglomerate, breccia	Post-orogenic extension	No metamorphic overprinting.	1.33	1.23 ± 0.47
8	Cambro–Silurian sedimentary rocks	37	540–420	Marine shales, carbonates, sandstones	Epicontinental basin, later foreland basin	Low-grade metamorphism and deformation during the Caledonian orogeny at c. 420 Ma; local contact metamorphism during formation of Oslo rift at c. 300–280 Ma.	1.89	1.56 ± 1.45
9	Oslo Rift	1044	300–280	Tholeiitic basalts, monzonite, syenite and granite	Intracontinental rift.	No metamorphic overprinting.	2.93	2.50 ± 1.64

[1] The area-weighted heat production of a geological province is calculated by first calculating the average heat production of all polygons on Sigmond's (1996) map from which heat-production data are available. The average value for each polygon is then multiplied by the area of the polygon and divided by the total area of all polygons belonging to a particular geological province, giving the area-weighted heat production.

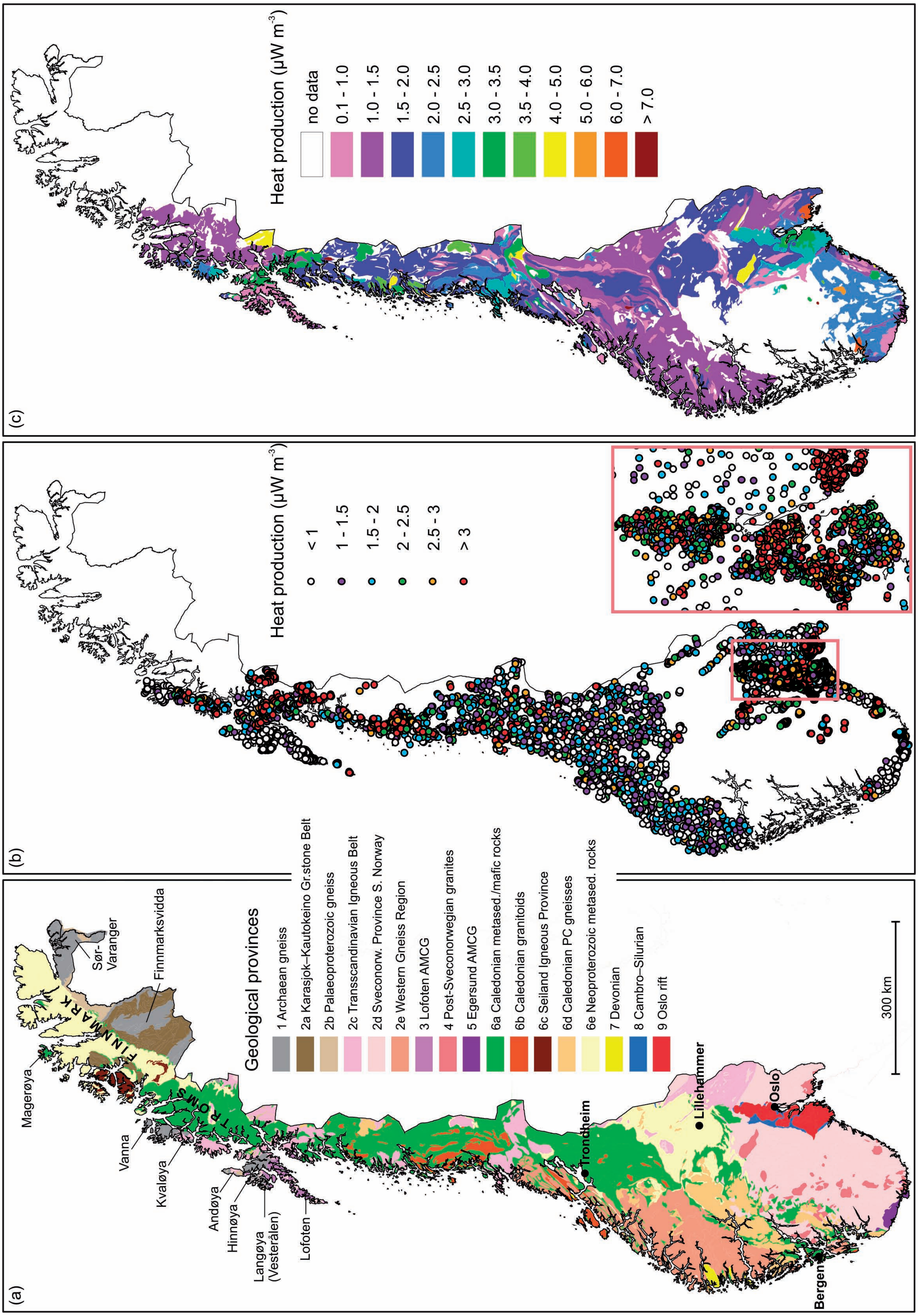

Fig. 1: (a) Simplified geological map, modified after Sigmond (1996). (b) Heat-production data. (c) Average heat-production rates for geological units where data are available.

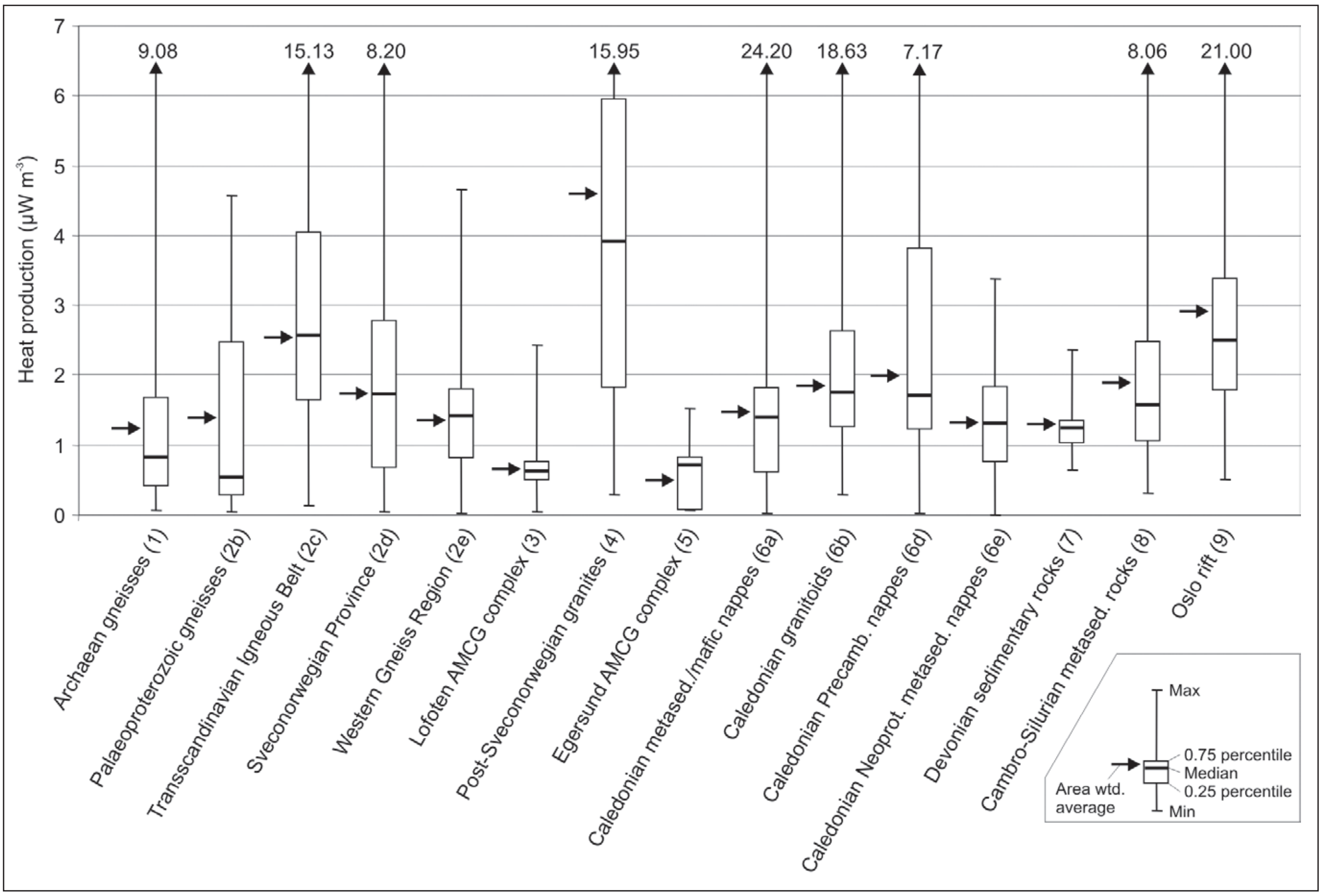

Fig. 2: Heat-production statistics for geological units presented in Fig. 1. The area-weighted average heat production is calculated from the averages of the different polygons that constitute a unit in the map in Fig. 1a, weighted according to areal extent.

Proterozoic gneissic rocks (2)

Karasjok–Kautokeino Greenstone Belts, northeast Norway (2a)

The Karasjok and Kautokeino Greenstone Belts in east Finnmark (Fig. 1a) consist of tholeiitic metabasalts, tuffaceous greenstones and amphibolites interlayered with metasedimentary rocks (Siedlecka et al. 1985). A Sm–Nd whole-rock age of ca. 2100 Ma from komatiites of the Karasjok Greenstone Belt was interpreted by Krill et al. (1985) to date crystallisation of the komatiite. The Greenstone Belts are believed to have formed as a result of crustal extension and/or rifting at ca. 2100 Ma, producing various mafic volcanic rocks, followed by subduction and formation of arc-related magmatic rocks at ca. 2000 Ma (Krill et al. 1985; Marker 1985). These oceanic provinces were thrust westwards onto the Archaean Karelian craton at ca. 1.9 Ga (Krill et al. 1985; Braathen & Davidsen 2000). The rocks were mostly metamorphosed under low to medium conditions (sub-greenschist to amphibolite-facies) (Siedlecka et al. 1985) during this event.

Unfortunately, no heat-production data are available for the Karasjok–Kautokeino Greenstone Belts at present; however, judging from the lithological make up of this province, relatively low heat production appears likely.

Levajok Granulite Complex (2b)

The Levajok Granulite Complex is sparsely exposed in Norway, but widens towards the east and southeast into Finland and Russia and forms a unit of regional extent; it is therefore included here as a separate unit. The granulite complex consists of two main lithologies (Marker 1985; Siedlecka et al. 1985) of which the oldest is a garnet-quartz-feldspar paragneiss that most likely represents continental back-arc basin flysch deposits. Younger, hypersthene-plagioclase orthogneisses probably represent intrusions into the paragneiss at ca. 2000–1900 Ma, possibly coeval with granulite-facies metamorphism during continent-continent collision (Bernard-Griffiths et al. 1984).

Seventeen samples of Palaeoproterozoic gneisses from a small area on Andøya, west Troms, yield a median heat production of 0.54 ± 1.44 µW m^{-3} and an area-weighted heat production of 1.42 µW m^{-3} (Fig. 2). Unfortunately, no heat-production data are available from the Granulite Complex in Finnmark; the heat production of this province is therefore poorly constrained even though the available data yield reasonable values.

Transscandinavian Igneous Belt (TIB) (2c)

The Transscandinavian Igneous Belt (discussion limited to TIB 1 as defined by Åhäll & Larson 2000) forms a ca.

1400 km long and up to 200 km wide belt of ca. 1810–1770 Ma magmatic rocks from southeastern Sweden to northwestern Norway (Fig. 1a). The belt is composed of alkali-calcic to calc-alkaline quartz monzonitic to granitic plutons and associated volcanic rocks, and subordinate mafic and hybrid rocks (Åhäll & Larson 2000). These include juvenile crustal components as well as a significant mantle contribution (Andersson 1991). Most workers favour an active continental margin setting for the TIB, involving eastward subduction beneath the western margin of Baltica and back-arc extension (e.g., Wilson 1980; Andersson 1991). In central Sweden, the TIB rocks are generally undeformed and unmetamorphosed, whereas in southwest Sweden they have a polymetamorphic history involving deformation and amphibolite-facies metamorphism at ca. 1.46–1.42 Ga, during the Hallandian orogeny, and during the Sveconorwegian orogeny at ca. 1.0 Ga (Christoffel et al. 1999; Söderlund et al. 2002; Möller et al. 2007). In northwestern parts of the TIB (i.e. in northwest Norway), the TIB rocks display variable Caledonian effects, locally with migmatisation at ca. 420 Ma (Skår 2002).

Five hundred and seventy-one samples from the Transscandinavian Igneous Belt in southeast, central and north-central Norway yield a median heat production of 2.57 ± 2.03 μW m^{-3} and an area-weighted heat production of 2.57 μW m^{-3} (Fig. 2).

Sveconorwegian Province, south Norway (2d)

The Sveconorwegian Province in south Norway and southwest Sweden is generally divided into four Palaeoproterozoic to Mesoproterozoic domains (Fig. 1a). The easternmost domain (aptly referred to as the Eastern Segment) consists mainly of reworked granitoid orthogneisses of TIB affinity and is included in the discussion above. The remaining part of the Sveconorwegian Province consists mainly of greenschist to amphibolite-facies (locally granulite-facies) tholeiitic and calc-alkaline, intermediate to felsic, metavolcanic and –plutonic suites that formed at around 1.5 Ga (Bingen et al. 2005 and references therein). Most of these rocks probably formed along an active continental margin at that time (Bingen et al. 2005; Slagstad and Marker, unpublished data). In addition, rhyolite-dominated, bimodal volcanic suites underlie large tracts of south Norway. These rocks formed at ca. 1.26–1.16 Ga and attest to crustal reworking, possibly in a continental back-arc setting (Bingen et al. 2002; Brewer et al. 2004). The last event to affect the area was the Sveconorwegian orogeny, which is generally ascribed to continent-continent collision at ca. 1.0 Ga. In addition, western areas were affected by very low-grade Caledonian overprinting at ca. 400 Ma (Verschure et al. 1980).

Three hundred and eighty-five samples from the Sveconorwegian Province in south Norway yield a median heat production of 1.73 ± 1.45 μW m^{-3} and an area-weighted heat production of 1.76 μW m^{-3} (Fig. 2).

Western Gneiss Region, west Norway (2e)

The Western Gneiss Region (Fig. 1a) represents the westward continuation of the Sveconorwegian Province and Transscandinavian Igneous Belt, metamorphosed under low- to high-grade conditions, locally with the formation of eclogite, during the Caledonian orogeny (Milnes et al. 1997). Lithologically, the Western Gneiss Region is dominated by tonalitic to granitic gneisses, locally migmatitic, and augen gneisses. Most of the rocks formed in the interval 1.75–1.5 Ga (Gaál & Gorbatschev 1987; Tucker et al. 1990; Skår & Pedersen 2003), probably along the active margin of Baltica. In addition, some granitic units formed during the Sveconorwegian orogeny (Skår & Pedersen 2003). The rocks record both Sveconorwegian and Caledonian high-grade metamorphism at ca. 1000 and 400 Ma, respectively (Tucker et al. 1990; Skår & Pedersen 2003).

Three hundred and thirty-two samples from the Western Gneiss Region yield a median heat production of 1.41 ± 0.82 μW m^{-3} and an area-weighted heat production of 1.36 μW m^{-3} (Fig. 2).

Lofoten AMCG complex (3)

More than half of the surface area in Lofoten–Vesterålen (Fig. 1a) is underlain by a distinct suite of rocks dominated by mangerite and retrogressed equivalents that intruded Archaean gneisses and Early Palaeoproterozoic supracrustal rocks (Griffin et al. 1978). This suite of rocks is typically referred to as the Lofoten anorthosite-mangerite-charnockite-granite (AMCG) complex. Detailed U–Pb zircon geochronological work by Corfu (2004a) shows that the AMCG complex was emplaced during two distinct event. The first event at 1870–1860 Ma included emplacement of the composite Hopen pluton, consisting of gabbro, mangerite and charnockite, and the granitic Lødingen pluton. The second, main event at 1800–1790 Ma also included a variety of rock types, ranging from gabbro and anorthosite, through mangerite and charnockite, to granite. A subsequent period, lasting for 30–40 million years, included intrusion of pegmatite dykes and local hydration of the dry AMCG rocks. Formation of the Lofoten AMCG complex was most likely linked to prolonged and widespread tectonic and magmatic activity along the Baltic margin related to the first and major phase of formation of the Transscandinavian Igneous Belt between ca. 1810–1770 Ma (TIB 1 of Åhäll & Larson 2000), but the exact tectonic setting is poorly known. Petrogenetic models suggest that the suite formed by polybaric fractionation of tholeiitic basaltic magmas combined with assimilation of country rocks (Wade 1985; Markl & Höhndorf 2003). Pressure estimates of ca. 400 MPa (Markl et al. 1998) suggest emplacement at mid-crustal levels, which begs the question as to whether the granulite-facies metamorphism of the Archaean country rocks represents regional metamorphism (cf., Griffin et al. 1978) or is a contact metamorphic effect. The Lofoten AMCG complex and the surrounding Archaean gneissic rocks were only weakly affected by the Caledonian orogeny, and evidence of Caledonian effects is limited to local resetting of titanite (Corfu 2004b) and mica (Steltenpohl et al. 2004).

One hundred and thirty samples from the Lofoten AMCG complex yield a median heat production of 0.61 ± 0.32 μW m^{-3} and an area-weighted heat production of 0.65 μW m^{-3} (Fig. 2).

Post-Sveconorwegian granites, south Norway (4)

A distinct geological feature of south Norway is post-Sveconorwegian granite forming subcircular intrusions in older Mesoproterozoic crust (Fig. 1a). Several of these granites are well known for having anomalously high heat-production rates (Killeen & Heier 1975; Slagstad 2006), and include the Iddefjord and Flå granites. Although granite is the dominant lithology, some plutons grade into more intermediate to mafic (diorite) compositions (Pedersen & Maaloe 1990). U–Pb zircon dating of some of these granites yields ages around 920–930 Ma (Eliasson & Schöberg 1991; Nordgulen et al. 1997). The source characteristics, petrogenesis and tectonic setting in which these granites formed is uncertain, though most studies suggest they may have formed in an extensional tectonic regime by partial melting of middle to lower crustal source rocks with some input of mantle-derived magmas (Eliasson 1992; Andersen et al. 2001).

Four hundred and seventy-three samples of post-Sveconorwegian granites in south Norway yield a median heat production of 3.92 ± 2.54 μW m^{-3} and an area-weighted heat production of 4.61 μW m^{-3} (Fig. 2).

Egersund AMCG complex (5)

The Egersund AMCG complex in southwest Norway (Fig. 1a) formed at ca. 930 Ma (e.g., Schärer et al. 1996), post-dating Sveconorwegian metamorphism and deformation by ca. 60 million years. Formation of the Egersund AMCG complex was contemporaneous with widespread post-Sveconorwegian granitic magmatism elsewhere in south Norway. The Egersund AMCG complex consists of massive anorthosite and lesser volumes of leuconorite, mangerite and charnockite (e.g., Bolle et al. 2003) and probably formed by partial melting of a lower crustal gabbronoritic source (Schiellerup et al. 2000; Vander Auwera et al. 2003). The rocks of the Egersund AMCG complex are generally unmetamorphosed, possibly with the exception of local, very low-grade Caledonian overprinting at ca. 400 Ma (Verschure et al. 1980).

Forty-seven samples from the Egersund AMCG complex yield a median heat production of 0.71 ± 0.42 μW $^{m-3}$ and an area-weighted heat production of 0.57 μW m^{-3} (Fig. 2), i.e., similar to that of the Lofoten AMCG complex.

Caledonian thrust-sheets (6)

Late Proterozoic to Palaeozoic metasedimentary and metamafic rocks (6a)

This group is by far the largest and diverse of the Caledonian units discussed here and extends from Magerøya in the north to Bergen in the south (Fig. 1a). Lithologically, the group is dominated by metagreywackes, phyllites and mica schists, but also encompasses marbles and ophiolitic greenstones (Sigmond et al. 1984). These metasedimentary and metavolcanic rocks constitute nappes and nappe complexes that also include a variety of Caledonian granitoid rocks; the latter are discussed separately below because they are lithologically distinct and are expected to have different heat-production rates from the former. Most of the rocks included in this group were deposited in Cambro–Silurian time (ca. 500–450 Ma) and metamorphosed under greenschist- to upper amphibolite-facies conditions, and locally eclogite-facies conditions (Bryhni & Andréasson 1985) at ca. 450–400 Ma during the Caledonian orogeny.

Five hundred and sixty-one samples from a major portion of the Caledonian orogen yield a median heat production of 1.40 ± 1.39 μW m^{-3} and an area-weighted heat production of 1.47 μW m^{-3} (Fig. 2).

Caledonian intrusive rocks (6b)

Rocks of this group are found mainly in central and north-central Norway (Fig. 1a) and are dominated volumetrically by the Smøla–Hitra and Bindal Batholiths (Gautneb & Roberts 1989; Nordgulen et al. 1993). Lithologically, the two batholiths encompass dominantly calc-alkaline diorite, tonalite, granodiorite and granite that probably formed in a magmatic arc setting at ca. 480–430 Ma (Gautneb & Roberts 1989; Nordgulen et al. 1993; 2001). In addition, several smaller, dominantly trondhjemitic intrusions (Size 1985) dated at ca. 490–435 Ma (Dunning & Grenne 2000; Roberts et al. 2002; Nilsen et al. 2003) are included in this group. The rocks display variable metamorphic and deformational overprinting related to the Caledonian orogeny at ca. 430–410 Ma (Tucker et al. 2004).

One hundred and sixty-seven samples of mainly granitoid intrusive rocks within the Caledonian orogen yield a median heat production of 1.74 ± 1.85 μW m^{-3} and an area-weighted heat production of 1.85 μW m^{-3} (Fig. 2).

Seiland Igneous Province (6c)

The Seiland Igneous Province in western Finnmark (Fig. 1a) is dominated by tholeiitic, calc-alkaline and alkaline gabbros and rarer monzonitic, dioritic and ultramafic bodies (e.g., Robins & Often 1996). Recent dating of the voluminous gabbros shows that they formed during a comparatively short time interval, from ca. 570 to 560 Ma (Roberts et al. 2006), most likely in an intracontinental rift setting (Krill & Zwaan 1987; Roberts et al. 2006). The province was subjected to Scandian deformation and medium- to high-grade metamorphism at ca. 420 Ma, and evidence of a preceding tectonic event is lacking (Krill & Zwaan 1987; Roberts et al. 2006; Slagstad et al. 2006). Unfortunately, no heat-production data are available from the Seiland Igneous Province; however, judging from the lithological make up of this province, relatively low heat production appears likely.

Precambrian gneissic rocks (6d)

The most prominent and well-studied units included in this group are the Jotun, Lindås and Dalsfjord nappes in southwestern Norway (Fig. 1a). These nappes are commonly regarded as erosional remnants of a once continuous nappe complex covering much of south Norway (Hossack 1984; Norton 1986). The nappes consist of syenitic to monzonitic gneisses that formed at ca. 1690 Ma (Schärer 1980), synchronous with widespread magmatism along the Baltic continental margin. These gneissic rocks were intruded by gabbroic magmas at ca. 1450 Ma (Corfu & Emmet 1992) and anorthosite-charnockite-mangerite-granite suites at ca. 1250 and 950 Ma (Bingen et al. 2001). The rocks underwent late Sveconorwegian amphibolite- to granulite-facies metamorphism at ca. 930 Ma (Schärer 1980; Corfu & Emmet 1992; Bingen et al. 2001), and locally high-grade (up to eclogite-facies) metamorphism at ca. 450 Ma (Bingen et al. 2001) during the Caledonian orogeny.

Thirty-five samples from small occurrences in southeast and north-central Norway yield a median heat production of 1.70 ± 1.78 µW m^{-3} and an area-weighted heat production of 2.01 µW m^{-3} (Fig. 2); however, no data are available from either the Jotun, Lindås or Dalsfjord nappes, and their heat production can only be regarded as poorly constrained.

Late Mesoproterozoic to Neoproterozoic metasedimentary rocks (6e)

Rocks belonging to this unit are widespread in Finnmark and the Lillehammer area in southeast Norway (e.g., Nystuen 1981; Roberts 1985) (Fig. 1a). Lithologically, the rocks range from quartzitic to arkosic sandstone, mica schist, and pelite to volumetrically subordinate carbonate. Deposition mainly took place at various times beginning in the Late Mesoproterozoic and continuing through the Neoproterozoic, and in most cases the rocks appear to represent continental or shelf deposits. The rocks were deformed and metamorphosed during the Scandian phase of the Caledonian orogeny at ca. 430–420 Ma (Siedlecka et al. 1987; Kirkland et al. 2006b; Slagstad et al. 2006), and in Finnmark there is evidence of older Neoproterozoic deformation (Kirkland et al. 2006a). The grade of metamorphism varies from high to low in Finnmark, whereas it is generally low in the Lillehammer area.

Forty-eight samples of Neoproterozoic sedimentary rocks in south Norway yield a median heat production of 1.35 ± 0.82 µW m^{-3} and an area-weighted heat production of 1.35 µW m^{-3} (Fig. 2); however, considering the small number of samples and the lack of data from northern Norway, I regard this unit as poorly constrained in terms of heat production.

Devonian sedimentary rocks (7)

The Devonian basins along the west coast of Norway between Bergen and Trondheim (Fig. 1a) consist dominantly of fluvial sandstones, conglomerates and breccias (Osmundsen & Andersen 2001). Most of the rocks were deposited during a short time interval between 400 and 390 Ma and rest on the underlying Western Gneiss Region basement with an extensional tectonic contact. The basement locally preserves evidence of Caledonian eclogite-facies metamorphism at ca. 400–420 Ma (Griffin et al. 1985; Kullerud et al. 1986), i.e. just preceding deposition of the overlying rocks. No significant post-depositional metamorphic activity has affected the rocks.

Fifteen samples of Devonian sedimentary rocks yield a median heat production of 1.23 ± 0.47 µW m-3 and an area-weighted heat production of 1.33 µW m-3 (Fig. 2). The small number of samples makes this estimate highly uncertain.

Cambro–Silurian sedimentary rocks within the Oslo Rift (8)

Metasedimentary rocks of Cambro–Silurian age are preserved within the downfaulted Oslo Rift (Fig. 1a). The majority of the Cambro–Silurian rocks consist of marine shales, carbonates and sandstones. The rocks were deposited first in an epicontinental basin on the Baltic Shield (Cambrian through much of the Ordovician), later in the foreland basin to the Caledonian orogeny to the west (Late Ordovician to Late Silurian) (Bjørlykke 1974). The rocks were deformed and metamorphosed at low-grade during the Scandian phase of the Caledonian orogeny at ca. 420 Ma, and underwent local contact metamorphism during formation of the Oslo Rift at ca. 300–280 Ma (Goldschmidt 1911). Of particular interest here is the presence of relatively thick layers of black alum shale, well known for its high contents of U (Andersson et al. 1985; Samuelsson & Middleton 1998), near the base of the Cambro–Silurian sequence. The alum shales occur extensively in Scandinavia, from Finnmark in northernmost Norway to south Sweden and Denmark, and were deposited along the Baltoscandian margin in Mid Cambrian to earliest Ordovician time, possibly in response to early Caledonian subduction of the margin (Gee 1987).

Thirty-seven samples of Cambro–Silurian sedimentary rocks yield a median heat production of 1.65 ± 1.45 µW m^{-3} and an area-weighted heat production of 1.89 µW m^{-3} (Fig. 2). The low number of samples makes the estimate uncertain. Only 1 sample of alum shale is included in the database; however, since this rock type by no means dominates the Cambro–Silurian suite, this is unlikely to affect the value significantly.

Permian magmatic rocks of the Oslo Rift (9)

The Oslo Rift is an intracontinental rift that formed in the Late Carboniferous–Early Permian as a result of regional extensional strain in northern Europe at that time (Fig. 1a). Peak magmatic activity was concentrated in a rather narrow time interval from ca. 300 to 280 Ma (Neumann et al. 2004 and references therein). The rifting and associated magmatic activity took place in 5 stages, starting with widespread basaltic volcanism of tholeiitic and alkaline composition, intrusion of larvikite (monzonite) and extrusion of trachytic rhomb porphyry lavas. The latest stages of rift evolution were dominated by the intrusion of large batholiths of monzonitic, syenitic and granitic composition (Neumann et al. 2004 and references therein). No post-magmatic metamorphic activity has affected the rocks.

A large dataset consisting of 1044 analyses is available from the magmatic rocks of the Oslo Rift, yielding a median heat production of 2.50 ± 1.64 μW m^{-3} and an area-weighted heat production of 2.93 μW m^{-3} (Fig. 2).

Discussion

The already extensive, and growing, geochemical database from Norwegian bedrock allows for comprehensive investigations into the factors that control the distribution of the heat-producing elements. Since the purpose of this paper is to characterise the heat production of the main geological provinces in Norway, a major part of this discussion focuses on average heat-production rates obtained from a variety of rock types that in some cases formed at different times and in different tectonic settings. However, in general the geological provinces delineated here are dominated by a comparatively limited number of lithologies that display rather modest geological variation (i.e., composition, age, metamorphic grade, tectonic setting) to make such a discussion meaningful. Because granite (sensu lato) is the main host for the heat-producing elements, the heat production of Norwegian granites is discussed in particular, emphasising the relationship between the tectonic setting in which the granite formed and its heat-production rate.

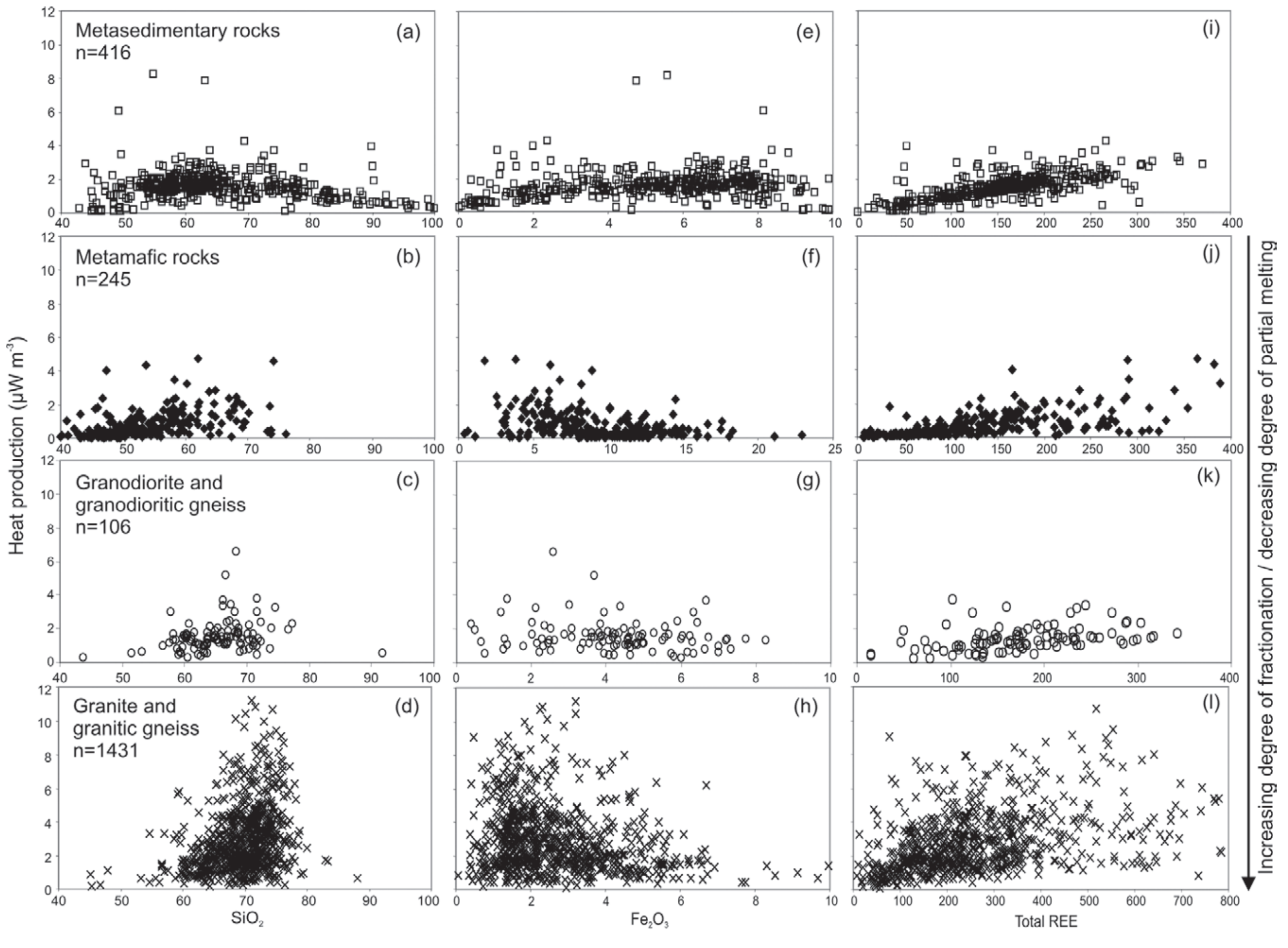

Fig. 3: Heat production vs. chemical composition for different rock types.

Heat production vs. lithology and chemical composition

Lithological variation is the primary factor controlling the distribution of heat production in the crust (Kukkonen & Lahtinen 2001). In general, granitic rocks have relatively high heat production whereas intermediate and mafic lithologies produce less heat, though in reality heat production within the same lithology may vary by an order of magnitude or more. To facilitate the discussion of heat production and its dependence on lithology, I have subdivided the samples for which we have a complete geochemical data set (from XRF and LA–ICP–MS analyses) into four lithological groups. 'Metasedimentary rocks' encompass arkose, quartzite, mica schist, phyllite and greywacke; 'Metamafic rocks' include gabbro, amphibolite, diorite and greenstone/-schist; 'Granite and granitic gneiss' and 'Granodiorite and granodioritic gneiss' are self-explanatory. As expected, the mafic rocks yield the lowest heat production with an average of 0.74 µW m^{-3}, and the granitic rocks the highest heat production with an average of 2.95 µW m^{-3}. The granodioritic and metasedimentary rocks yield similar, intermediate heat production with averages of 1.54 and 1.55 µW m^{-3}, respectively. These values are as expected, and the variation within each lithological group in relation to chemical composition is perhaps more interesting. Figure 3 shows heat production vs. SiO_2, Fe_2O_3 and total rare earth element (REE) contents for the different lithological groups. SiO_2 and Fe_2O_3 represent the samples' major element composition and reflect the mineralogical composition of the samples, whereas total REE represents trace elements mainly hosted by accessory phases including zircon and monazite, which are also the main hosts of the heat-producing elements (e.g., Bea 1996). The metasedimentary rocks show a small increase in heat production with increasing SiO_2 at low SiO_2 levels, then a gentle decrease at higher SiO_2 levels (Fig. 3a). The trend is opposite with respect to Fe_2O_3 (Fig. 3e). In contrast, the other 3 groups, consisting of magmatic rocks and orthogneisses, display increasing heat production with increasing SiO_2 (Figs. 3b-d) and vice versa with respect to Fe_2O_3 (Figs. 3f-h). These variations reflect different mechanisms controlling the mineralogical and major element composition of sedimentary and magmatic rocks (Kukkonen & Lahtinen 2001). The composition of sediments partly reflects their source, resulting in correlations that are similar to those observed in magmatic rocks, and partly sedimentary sorting due to variation in the size and density of different minerals. The variation in heat production with SiO_2 and Fe_2O_3 in the metasedimentary rocks reflects both these processes. Mica-rich rocks such as schist and phyllite represent low degrees of sedimentary sorting whereas quartz-rich rocks such as arkose and quartzite represent high degrees of sorting. Since U- and Th-bearing minerals are commonly hosted by micas, sedimentary sorting results in an inverse correlation between heat production and degree of sorting. Between 45 and 60 wt.% SiO_2, heat production increases with increasing SiO_2. The rocks in this range include mica schist and phyllite, representatives of poorly sorted sediments, and the variation in heat production most likely reflects that of the source. Rocks with >60 wt.% SiO_2 consist of mica schist and phyllite at low SiO_2 levels and arkose and quartzite at higher SiO_2 levels, representing increasing degrees of sorting, resulting in an inverse correlation between SiO_2 and heat production. The other lithological groups represent magmatic rocks of mafic to intermediate ('Metamafic rocks'), intermediate to felsic ('Granodioritic rocks'), and felsic ('Granitic rocks') composition. The increase in heat production with SiO_2 and opposite for Fe_2O_3 is consistent with magmatic processes where low degrees of partial melting and/or high degrees of fractionation result in high SiO_2/low Fe_2O_3 melts with high incompatible element (including U and Th) contents. At very high SiO_2 and low Fe_2O_3, the relationship breaks down due to crystallisation of accessory phases that deplete the residual melt in incompatible elements; thus, further fractionation and concomitant increase and decrease in SiO_2 and Fe_2O_3, respectively, do not lead to increased levels of elements which were incompatible earlier in the fractionation process.

Figures 3i–l show how heat production varies with total REE content. In most rocks, REE are hosted by accessory phases and REE content may therefore be used as a proxy for the amount of accessory phases in a rock. All rock types show a relatively well-defined positive correlation between total REE content and heat production, supporting the general consensus that the heat-producing elements are hosted dominantly by accessory phases (e.g., Fountain 1986; Kukkonen & Lahtinen 2001)

Heat production vs. tectonic setting

Differences in chemical composition have long been used to discriminate between different tectonic settings (e.g., Pearce & Cann 1973). From the above discussion on heat production and chemical composition, one may therefore expect similarly consistent differences in heat production. Since the purpose of this contribution is to characterise the heat production of different geological units or provinces, there is a certain lumping of different lithologies formed in different tectonic settings. I therefore base this discussion on 3 provinces that display rather narrow lithological variation and where the tectonic setting is relatively well defined. The Palaeoproterozoic Transscandinavian Igneous Belt consists of granitic rocks formed along the active margin of Baltica in a subduction setting, and yields a median heat production of 2.57 µW m^{-3}. The post-Sveconorwegian granites formed during the Early Neoproterozoic, and followed the Sveconorwegian orogeny. Although the process(es) leading to their formation are uncertain, they clearly formed in an intracontinental setting. The post-Sveconorwegian granites yield a median heat production of 3.92 µW m^{-3}. The Permian Oslo Rift represents magmatic rocks formed in an intracontinental rift and yields a median heat production of 2.50 µW m^{-3}. However, the Oslo Rift consists of a variety of rock types including syenites and other intermediate rocks, as well as basalts. When including only Permian granites in the calculation, a median heat production of 3.23 µW m^{-3} is obtained. These results compare well with numerous investigations showing that rocks formed in continental, extensional settings, be it continental back-arcs, continental rifts, or post-orogenic extension, are enriched in incompatible elements (Frost et al. 1999; Slagstad et al. 2004; Anderson & Morrison 2005). There are probably a number of reasons for the difference in composition between rocks formed in intraplate and plate margin settings. The most obvious difference is that most plate margin magmas form by partial melting in the mantle wedge overlying a subduction zone, whereas intraplate magmas commonly form in areas where upwelling of hot asthenospheric melts induces partial melting of lower crustal rocks. Lower crustal rocks, although generally depleted in heat-producing and other incompatible elements relative to upper crustal rocks, are significantly more enriched in these elements than the mantle wedge, thus providing a source for relatively enriched magmas. Tectonic setting can therefore be used as a rough guide to a province's heat production.

Heat production vs. age

In some areas, radiogenic heat production is found to decrease with increasing age (e.g., McLaren et al. 2003), although other studies fail to find such a correlation (e.g., Kukkonen & Lahtinen 2001). Figure 2 shows the heat-production rates of the various geological provinces considered here, broadly arranged in chronological order. Figure 2 shows that there is no clear-cut relationship between geological age and heat production, despite the fact that the Archaean gneisses display relatively low heat-production rates, with a median of 0.81 ± 1.48 µW m^{-3}. This is similar to that of Archaean gneisses in Finland (0.79 ± 1.33 µW m^{-3}) (Kukkonen & Lahtinen 2001). However, both the Palaeoproterozoic Lofoten and the Early Neoproterozoic Egersund AMCG complexes display significantly lower heat-production rates. Notably, the two AMCG complexes display similar heat-production rates despite an age difference of ca. 900 million years. This shows that lithological variation exerts a first-order control on heat production. It is therefore more relevant to compare the Archaean gneisses with younger provinces with a similar lithological make up, in particular the Sveconorwegian province in south Norway and the Western Gneiss Region. These provinces consist mainly of Mesoproterozoic intermediate to felsic gneisses, not unlike the Archaean gneisses, but have heat-production rates that are somewhat higher (Table 2, Figure 2). The available data indicate that a correlation between heat production and geological age may exist, but that this correlation is weak and in most cases obscured by lithological variation. This conclusion is further supported by data from the Palaeoproterozoic Transscandinavian Igneous Belt and the Permian Oslo Rift, which both consist largely of granitoid rocks and display virtually identical heat production despite an age difference of nearly 1.5 billion years. Thus, predicting heat-production rates based on geological age clearly is not feasible, a conclusion which is in agreement with that proposed by Kukkonen & Lathinen (2001).

Heat production vs. metamorphic grade/crustal depth

Relationship to metamorphic grade

Many workers assume that heat production decreases with increasing metamorphic grade or crustal depth because during orogenesis, partial melting at lower to middle crustal levels commonly forms melts rich in incompatible elements, including the heat-producing elements, that may migrate to higher structural levels (Heier 1965) (see Slagstad et al. 2005 for a discussion of this process). This should lead to a depletion of heat-producing elements at deep crustal levels, and concomitant enrichment at higher crustal levels where the melts are emplaced as plutons (e.g., Sandiford & McLaren 2002; Sandiford et al. 2002). However, exceptions to this 'rule' have also been found. For example, Andreoli et al. (2006) reported that radiogenic heat production in the Western Namaqualand Belt, South Africa, increases with increasing metamorphic grade and suggested that the introduction of CO_2-rich fluids (cf., Frost & Frost 1987), rather than removal of H_2O-rich melts, was the cause of granulite-facies metamorphism and possibly enrichment in heat-producing elements. Thus, granulite-facies metamorphism may be brought about in different ways that may have widely different impacts on the composition and thus heat production of the affected rocks.

Although the concept of a rather homogeneous, low heat-producing lower crust is clearly oversimplified (cf., Flowers et al. 2006), it has long been recognised that the middle and lower crust must be depleted in heat-producing elements relative to the upper crust to avoid impossibly high temperatures at depth within the crust (e.g., Morgan & Sass 1984). Unfortunately, true lower crustal rocks are exposed in only a few locations in the world, but several studies investigating the variation in heat production in vertical cross sections through the middle to upper crust have been undertaken. Ashwal et al. (1987) investigated a ca. 25 km vertical section through amphibolite- to granulite-facies Archaean rocks in the Kapuskasing area, Superior Province, Ontario. Their work showed no relationship between vertical depth/metamorphic grade and heat production, which they suggested could be a typical feature of rather 'mafic' geological provinces, whereas more 'granitic' provinces are more likely to display such a relationship. Brady et al. (2006) presented heat-production data from the Sierra Nevada Batholith, California, and showed that it increased from ca. 2 to 3 µW m^{-3} in the uppermost 5 km, then dropped to 0.5–1 µW m^{-3} at 15 km depth and remained constant at that level to the

Moho. These studies show that heat production does not vary continuously or predictably with crustal depth, but that abrupt changes related to lithological variation is the norm.

The Lofoten–Vesterålen area in north Norway, including the Lofoten AMCG complex, is sometimes cited as an example of lower crustal rocks having undergone depletion in incompatible elements due to regional metamorphism (Heier & Adams 1965). However, more recent work suggests that the amphibolite- to granulite-facies transition in this area, interpreted by Heier (1960) to be a gradual metamorphic transition, could be a contact metamorphic effect (Corfu 2004a). It is notable that the Lofoten AMCG complex has a heat production that is nearly identical to the unmetamorphosed Egersund AMCG complex, suggesting that the low heat production of the former is lithologically/tectonically controlled rather than determined by metamorphic grade.

Relationship to density

Knowledge of heat production is crucial for interpreting terrestrial heat-flow patterns and for developing thermal models of the continental crust. Since there is no direct method for measuring heat production at depths greater than those penetrated by boreholes (typically only the uppermost few hundred metres), several attempts have been made at determining a relationship between heat production and other petrophysical parameters, such as density and seismic velocity, which can be determined with some accuracy even at great crustal depths (e.g., Rybach & Buntebarth 1982; Kukkonen & Peltoniemi 1998).

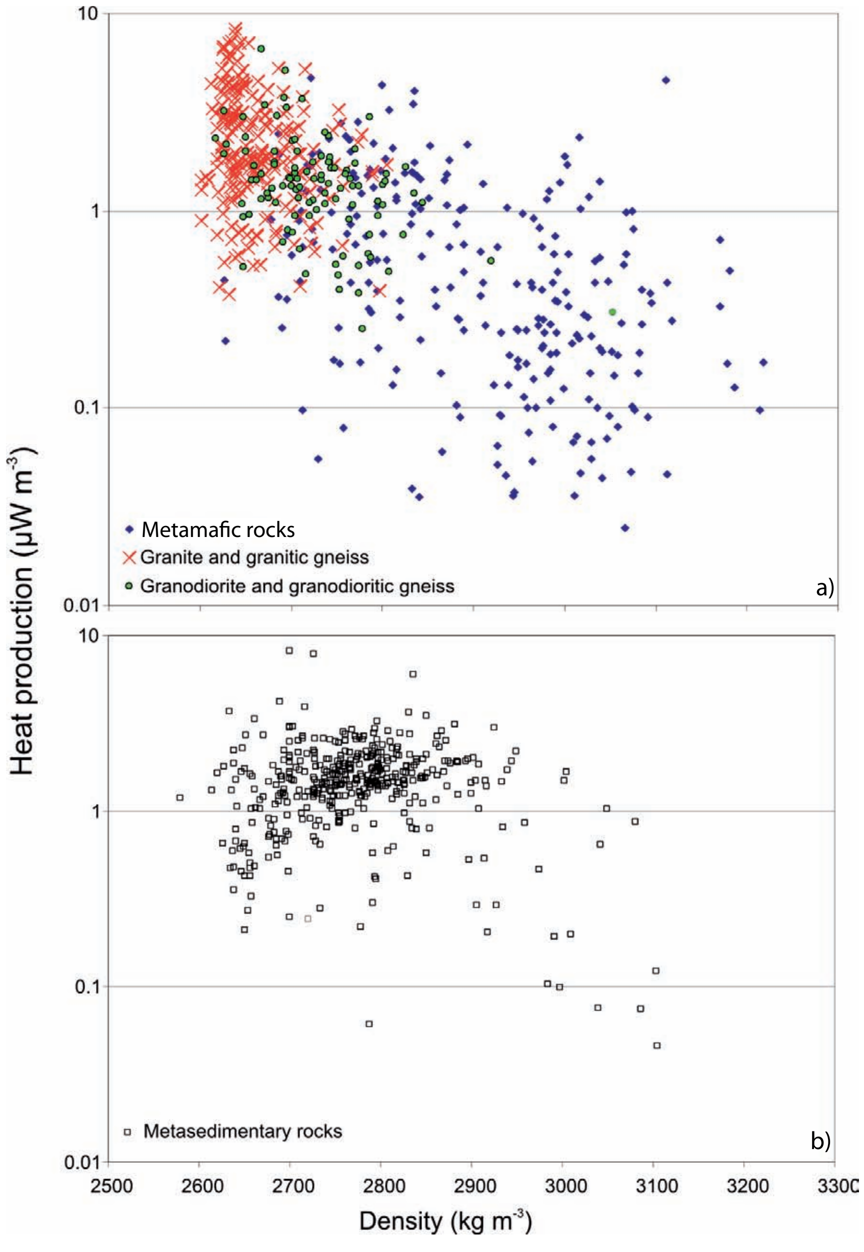

Fig. 4: Heat production vs. density for (a) magmatic rocks and (b) metasedimentary rocks. Only samples where density has been measured are included.

Figure 4 shows a log-normal plot of density vs. heat production for those samples where density has been determined (i.e., samples with assumed densities have been omitted). Figure 4a shows an overall decrease in heat production with increasing density for magmatic rocks, but that the scatter in heat production for a given density is large. Rocks with densities lower than ca. 2800 kg m^{-3} vary by about an order of magnitude, whereas rocks with higher densities vary by about two orders of magnitude. The heat production in metasedimentary rocks (Fig. 4b) increases slightly from low to intermediate densities, before decreasing at higher densities. Metasedimentary rocks display somewhat less scatter in heat production than magmatic rocks (around one order of magnitude). However, this is at least in part a result of a more restricted range in density. A similarly scattered relationship was observed from rocks from Finland (Kukkonen & Peltoniemi 1998; Kukkonen & Lahtinen 2001).

Fountain (1986) argued, based on observations from the Superior Province, Canada, that although a relationship exists between heat production and other petrophysical parameters, the scatter is too great for this relationship to be of any use in constraining thermal models of the crust. The same is true for the data presented here—a thermal model that employed such a relationship would only be accurate to within one to two orders of magnitude. The reason that the heat production-density relationship is so poorly defined is that density is controlled by the major phases in a rock, whereas the heat-producing elements tend to reside within accessory phases that do not influence density significantly (cf., Fountain 1986). This explanation fits the observed relationship between heat production and chemical composition discussed above.

Insight from the Sognefjorden transect?

The above discussion shows that considerations of the impact of metamorphic grade/crustal depth on heat production are hampered by the strong effect of lithological variation. This means that comparing lithologically different high- and low-grade rocks is useless, and even comparing lithologically similar high- and low-grade rocks may be meaningless due to the large variation observed among similar rock types. These complexities imply that meaningful investigations into the distribution of heat-producing elements and the controlling processes can only be undertaken in areas where the geological setting is particularly favourable. One such area is the Sognefjorden transect in southwest Norway, where Caledonian folding and thrusting has resulted in the exposure of a ca. 30 km vertical cross section through Sveconorwegian crust (Milnes et al. 1997). The cross section includes Sveconorwegian granulites (source?), migmatites (melt transfer zone?) and granites (shallow crustal sinks of heat-producing elements?) (Skår & Pedersen 2003), that may preserve evidence of processes related to crustal differentiation. Syn-orogenic granites are also found elsewhere in southwest Norway (Slagstad and Marker, unpub. data, 2006), suggesting that the middle to lower crust underwent relatively widespread melting during Sveconorwegian orogenesis. This evolution would have had a major impact on the distribution of heat-producing elements and thus the thermal structure of the Sveconorwegian crust, which in turn may have affected its behaviour during subsequent Caledonian orogenesis. The Sognefjorden transect is therefore an obvious candidate for further investigation into the 'hows', 'whys' and 'whens' regarding distribution of heat-producing elements in the crust, and would provide significant new knowledge on the thermal structure of the continental crust in southwest Norway in particular.

Crustal differentiation in Norway

The distribution and redistribution of heat-producing elements may be strongly coupled to tectonic processes such as magmatism, metamorphism and deformation. This ordering of heat-producing elements may take place in close relation to crustal formation, for example in evolving magmatic arcs (e.g., Lee et al. 2007), or significantly later, for example in zones of intraplate deformation (e.g., Sandiford et al. 2001; Sandiford & McLaren 2002), magmatism (e.g., Sandiford et al. 2002; Bea et al. 2003), and fluid flux (e.g., Andreoli et al. 2006). Regardless of timing, processes related to crustal differentiation and redistribution of heat-producing elements may be fundamental to cratonisation by producing an overall cooling of the crust.

Although a discussion regarding a coupling between heat production and tectonic processes in Norway is considered outside the scope of this paper, one particular region in Norway may retain evidence of relatively large-scale redistribution of heat-producing elements. The Sveconorwegian Province in south Norway is riddled with post-tectonic granites dated at 960–920 Ma (e.g., Pasteels et al. 1979; Eliasson & Schöberg 1991), many of which contain anomalously high concentrations of heat-producing elements (Killeen & Heier 1975; Slagstad 2006). Although the petrogenesis and sources of these granites is uncertain, isotopic studies have shown that they contain a significant crustal component (Andersen et al. 2001). The large volumes of granite involved and their geographical spreading imply that the lower/middle crust in south Norway was significantly depleted in heat-producing elements as a result of this magmatic event. This implication also leads to another, namely that the crust was significantly warmer during and just after the Sveconorwegian orogeny, which in turn would have affected the crust's strength and thus style of deformation/metamorphism.

This situation may have a direct analogue in Central Iberia, where Bea et al. (2003) found that post-Variscan granites, post-dating orogenesis by ca. 50 million years, formed at mid-crustal depths by partial melting of certain high heat-producing and fertile metasedimentary rocks. In their view, the mid-crustal partial melting was responsible for the observed post-tectonic orogenic extension (collapse) of the Central Iberian Zone of the Variscides.

The timing of granitic magmatism (and implied lower-/mid-crustal partial melting) coincides with proposed post-tectonic orogenic extension of the Sveconorwegian orogeny (Bingen et al. 2006). However, the style of orogenesis both during and after the peak-Sveconorwegian event is rather poorly known, and evidence for post-orogenic extension has not yet been substantiated by field observations. Thus, although post-Sveconorwegian magmatism was probably significant in redistributing heat-producing elements in the crust, the tectonic significance of this redistribution as well as the significance of the prior distribution remainspeculative.

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References

Åhäll, K.-I. & Larson, S. Å. 2000. Growth-related 1.85-1.55 Ga magmatism in the Baltic Shield; a review addressing the tectonic characteristics of Svecofennian, TIB 1-related and Gothian events. *Geologiska Föreningen i Stockholm Förhandlingar 122*, 193-206.

Andersen, T., Andresen, A. & Sylvester, A. G. 2001. Nature and distribution of deep crustal reservoirs in the southwestern part of the Baltic Shield: Evidence from Nd, Sr and Pb isotope data on late Sveconorwegian granites. *Journal of the Geological Society of London 158*, 253-267.

Anderson, J. L. & Morrison, J. 2005. Ilmenite, magnetite, and peraluminous Mesoproterozoic anorogenic granites of Laurentia and Baltica. *Lithos 80*, 45-60.

Andersson, A., Dahlman, D., Gee, D. G. & Snäll, S. 1985. The Scandinavian alum shales. *Sveriges Geologiska Undersökning Ca 56*, 1-50.

Andersson, U. B. 1991. Granitoid episodes and mafic-felsic magma interaction in the Svecofennian of the Fennoscandian shield, with main emphasis on the ca. 1.8 Ga plutonics. *Precambrian Research 51*, 127-149.

Andreoli, M. A. G., Hart, R. J., Ashwal, L. D. & Coetzee, H. 2006. Correlations between U, Th content and metamorphic grade in the Western Namaqualand Belt, South Africa, with implications for radioactive heating of the crust. *Journal of Petrology 47*(6), 1095-1118.

Ashwal, L. D., Morgan, P., Kelley, S. A. & Percival, J. A. 1987. Heat production in an Archean crustal profile and implications for heat flow and mobilization of heat-producing elements. *Earth and Planetary Science Letters 85*, 439-450.

Bea, F. 1996. Residence of REE, Y, Th, and U in granites and crustal protoliths: Implications for the chemistry of crustal melts. *Journal of Petrology 37*, 521-552.

Bea, F., Montero, P. & Zinger, T. 2003. The nature, origin, and thermal influence of the granite source layer of Central Iberia. *Journal of Geology 111*, 579-595.

Beaumont, C., Jamieson, R. A., Nguyen, M. H. & Lee, B. 2001. Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. *Nature 414*, 738-742.

Bernard-Griffiths, J., Peucat, J. J., Postaire, B., Vidal, P., Convert, J. & Moreau, B. 1984. Isotopic data (U-Pb, Rb-Sr, Pb-Pb, Sm-Nd) on mafic granulites from Finnish Lapland. *Precambrian Research 23*, 325-348.

Bingen, B., Davis, W. J. & Austrheim, H. 2001. Zircon U-Pb geochronology in the Bergen arc eclogites and their Proterozoic protoliths, and implications for the pre-Scandian evolution of the Caledonides in western Norway. *Geological Society of America Bulletin 113*, 640-649.

Bingen, B., Mansfeld, J., Sigmond, E. M. O. & Stein, H. J. 2002. Baltica-Laurentia link during the Mesoproterozoic: 1.27 Ga development of continental basins in the Sveconorwegian Orogen, southern Norway. *Canadian Journal of Earth Sciences 39*, 1425-1440.

Bingen, B., Stein, H. J., Bogaerts, M., Bolle, O. & Mansfeld, J. 2006. Molybdenite Re–Os dating constrains gravitational collapse of the Sveconorwegian orogen, SW Scandinavia. *Lithos 87*, 328-346.

Bingen, B., Skår, Ø., Marker, M., Sigmond, E. M. O., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R. D. & Liégeois, J.-P. 2005. Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. *Norwegian Journal of Geology 85*, 87-116.

Bjørlykke, K. 1974. Depositional history and composition of Lower Palaeozoic epicontinental sediments from the Oslo Region. *Norges geologiske undersøkelse 305*, 1-81.

Bolle, O., Demaiffe, D. & Duchesne, J.-C. 2003. Petrogenesis of jotunitic and acidic members of an AMC suite (Rogaland anorthosite province, SW Norway): A Sr and Nd isotopic assessment. *Precambrian Research 124*, 185-214.

Braathen, A. & Davidsen, B. 2000. Structure and stratigraphy of the Palaeoproterozoic Karasjok Greenstone Belt, north Norway - regional implications. *Norsk Geologisk Tidsskrift 80*, 33-50.

Brady, R. J., Ducea, M. N., Kidder, S. B. & Saleeby, J. B. 2006. The distribution of radiogenic heat production as a function of depth in the Sierra Nevada Batholith, California. *Lithos 86*, 229-244.

Brewer, T. S., Åhäll, K.-I., Menuge, J. F., Storey, C. D. & Parrish, R. R. 2004. Mesoproterozoic bimodal volcanism in SW Norway, evidence for recurring pre-Sveconorwegian continental margin tectonism. *Precambrian Research 134*, 249-273.

Bryhni, I. & Andréasson, P.-G. 1985. Metamorphism in the Scandinavian Caledonides. In Gee, D. G. & Sturt, B. A. (eds.), *The Caledonide Orogen - Scandinavia and Related Areas*, 763-781. John Wiley & Sons Ltd,

Christoffel, C. A., Connelly, J. N. & Åhäll, K.-I. 1999. Timing and characterization of recurrent pre-Sveconorwegian metamorphism and deformation in the Varberg-Halmstad region of SW Sweden. *Precambrian Research 98*, 173-195.

Corfu, F. 2004a. U-Pb age, setting and tectonic significance of the anorthosite-mangerite-charnockite suite, Lofoten-Vesterålen, Norway. *Journal of Petrology 45*, 1799-1819.

Corfu, F. 2004b. U–Pb geochronology of the Leknes Group: an exotic Early Caledonian metasedimentary assemblage stranded on Lofoten basement, northern Norway. *Journal of the Geological Society of London 161*, 619-627.

Corfu, F. & Emmet, T. 1992. U-Pb age of the Leirungsmyran gabbroic complex, Jotun Nappe, southern Norway. *Norsk Geologisk Tidsskrift 72*, 369-374.

Corfu, F., Armitage, P. E. B., Kullerud, K. & Bergh, S. G. 2003. Preliminary U-Pb geochronology in the West Troms Basement Complex, North Norway: Archaean and Palaeoproterozoic events and younger overprints. *Norges geologiske undersøkelse Bulletin 441*, 61-72.

Dunning, G. & Grenne, T. 2000. U-Pb age dating and palaeotectonic significance of trondhjemite from the type locality in the central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin 437*, 57-65.

Eliasson, T. 1992. Magma genesis and emplacement characteristics of the peraluminous Sveconorwegian Bohus granite, SW Sweden. *Geologiska Föreningen i Stockholm Förhandlingar 114*, 452-455.

Eliasson, T. & Schöberg, H. 1991. U-Pb dating of the post-kinematic Sveconorwegian (Grenvillian) Bohus granite, SW Sweden: Evidence of restitic zircon. *Precambrian Research 51*, 337-350.

Flem, B., Grimstvedt, A., Slagstad, T. & Skår, Ø. 2005. Bulkanalyse av Th og U i bergartsprøver med LA-ICP-MS. Metodebeskrivelse. In: *NGU Rapport 2005.031*.

Flowers, R. M., Mahan, K. H., Bowring, S. A., Williams, M. L., Pringle, M. S. & Hodges, K. V. 2006. Multistage exhumation and juxtaposition of lower continental crust in the western Canadian Shield: Linking high-resolution U-Pb and ^{40}Ar/^{39}Ar thermochronometry with pressure-temperature-deformation paths. *Tectonics 25*, doi:10.1029/2005TC001912.

Fountain, D. M. 1986. Is there a relationship between seismic velocity and heat production for crustal rocks? *Earth and Planetary Science Letters 79*, 145-150.

Frost, B. R. & Frost, C. D. 1987. CO_2, melts and granulite metamorphism. *Nature 327*, 503-506.

Frost, C. D., Frost, B. R., Chamberlain, K. R. & Edwards, B. R. 1999. Petrogenesis of the 1.43 Ga Sherman batholith, SE Wyoming, USA: A reduced, rapakivi-type anorogenic granite. *Journal of Petrology 40*, 1771-1802.

Gaál, G. & Gorbatschev, R. 1987. An outline of the Precambrian evolution of the Baltic Shield. *Precambrian Research 35*, 15-52.

Gautneb, H. & Roberts, D. 1989. Geology and petrochemistry of the Smøla-Hitra Batholith, Central Norway. *Norges geologiske undersøkelse Bulletin 416*, 1-24.

Gee, D. G. 1987. The Scandinavian alum shales - Mid Cambrian to Tremadoc deposition in response to early Caledonian subduction. *Norsk Geologisk Tidsskrift 67*, 233-235.

Goldschmidt, V. M. 1911. Die Kontaktmetamorphose im Kristianiagebiet. *Skr. Vidensk. Selsk. I. Mat. Naturv. Kl., 1911 1*, 483.

Griffin, W. L., Austrheim, H., Brastad, K., Bryhni, I., Krill, A. G., Krogh, E. J., Mørk, M. B. E., Quale, H. & Tørudbakken, B. 1985. High-pressure metamorphism in the Scandinavian Caledonides. In Gee, D. G. & Sturt, B. A. (eds.), *The Caledonide Orogen: Scandinavia and Related Areas*, 783-801. Wiley,

Griffin, W. L., Taylor, P. N., Hakkinen, J. W., Heier, K. S., Iden, I. K., Krogh, E. J., Malm, O., Olsen, K. I., Ormaasen, D. E. & Tveten, E. 1978. Archaean and Proterozoic crustal evolution in Lofoten-Vesterålen, N. Norway. *Journal of the Geological Society of London 135*, 629-647.

Heier, K. S. 1960. Petrology and chemistry of high-grade metamorphic and igneous rocks on Langøy, Northern Norway. *Norges geologiske undersøkelse 207*, 1-246.

Heier, K. S. 1965. Metamorphism and the chemical differentiation of the crust. *Geologiska Föreningen i Stockholm Förhandlingar 87*, 249-256.

Heier, K. S. & Adams, J. A. S. 1965. Concentration of radioactive elements in deep crustal material. *Geochimica et Cosmochimica Acta 29*, 53-61.

Hossack, J. R. 1984. The geometry of listric normal faults in the Devonian basins of Sunnfjord, Western Norway. *Journal of the Geological Society of London 141*, 629-637.

Jaupart, C. & Mareschal, J.-C. 2003. Constraints on crustal heat production from heat flow data. In Rudnick, R. L. (ed.), *The Crust*, Treatise on Geochemistry 3, 65-84. Elsevier-Pergamon, Oxford.

Karlstrom, K. E. & Williams, M. L. 1998. Heterogeneity of the middle crust: Implications for strength of continental lithosphere. *Geology 26*, 815-818.

Killeen, P. G. & Heier, K. S. 1975. Radioelement distribution and heat production in Precambrian granitic rocks, southern Norway. *Det Norske Videnskaps-Akademi, I. Mat.-Naturv. Klasse. Skrifter, Ny Serie 35*, 1-32.

Kirkland, C. L., Daly, J. S. & Whitehouse, M. J. 2006a. Granitic magmatism of Grenvillian and late Neoproterozoic age in Finnmark, Arctic Norway - Constraining pre-Scandian deformation in the Kalak Nappe Complex. *Precambrian Research 145*, 24-52.

Kirkland, C. L., Daly, J. S., Eide, E. A. & Whitehouse, M. J. 2006b. The structure and timing of lateral escape during the Scandian Orogeny: A combined strain and geochronological investigation in Finnmark, Arctic Norwegian Caledonides. *Tectonophysics 425*, 159-189.

Krill, A. G. & Zwaan, B. K. 1987. Reinterpretation of Finnmarkian deformation on western Sørøy, northern Norway. *Norsk Geologisk Tidsskrift 67*, 15-24.

Krill, A. G., Bergh, S., Lindahl, I., Mearns, E. W., Often, M., Olerud, S., Olesen, O., Sandstad, J. S., Siedlecka, A. & Solli, A. 1985. Rb-Sr, U-Pb and Sm-Nd isotopic dates from Precambrian rocks of Finnmark. *Norges geologiske undersøkelse Bulletin 403*, 37-54.

Kukkonen, I. T. & Lahtinen, R. 2001. Variation of radiogenic heat production rate in 2.8-1.8 Ga old rocks in the central Fennoscandian shield. *Physics of the Earth and Planetary Interiors 126*, 279-294.

Kukkonen, I. T. & Peltoniemi, S. 1998. Relationships between Thermal and other Petrophysical Properties of Rocks in Finland. *Physics and Chemistry of the Earth 23*(3), 341-349.

Kullerud, L., Tørudbakken, B. O. & Ilebekk, S. 1986. A compilation of radiometric age determinations from Western Gneiss Region, South Norway. *Norges geologiske undersøkelse Bulletin 406*, 17-42.

Lee, C.-T. A., Morton, D. M., Kistler, R. W. & Baird, A. K. 2007. Petrology and tectonics of Phanerozoic continent formation: From island arcs to accretion and continental arc magmatism. *Earth and Planetary Science Letters 263*, 370-387.

Levchenkov, O. A., Levsky, L. K., Nordgulen, Ø., Dobrzhintskaya, L. F., Vetrin, V. R., Cobbing, J., Nilsson, L. P. & Sturt, B. A. 1993. U-Pb zircon ages from Sørvaranger, Norway, and the western part of the Kola Peninsula, Russia. *Norges geologiske undersøkelse Special Publication 7*, 29-47.

Marker, M. 1985. Early Proterozoic (c, 2000-1900 Ma) crustal structure of the northeastern Baltic Shield: Tectonic division and tectogenesis. *Norges geologiske undersøkelse Bulletin 403*, 55-74.

Markl, G. & Höhndorf, A. 2003. Isotopic constraints on the origin of AMCG-suite rocks on the Lofoten Islands, N Norway. *Mineralogy and Petrology 78*, 149-171.

Markl, G., Frost, B. R. & Bucher, K. 1998. The origin of anorthosites and related rocks from the Lofoten Islands, Northern Norway: I. Field relations and estimation of intrinsic variables. *Journal of Petrology 39*, 1425-1452.

McLaren, S., Sandiford, M., Neumann, N., Wyborn, L. & Bastrakova, I. 2003. The hot southern continent: Heat flow and heat production in Australian Proterozoic terranes, *Geological Society of Australia Special Publication, 22*, 151-161.

Milnes, A. G., Wennberg, O. P., Skår, Ø. & Koestler, A. G. 1997. Contraction, extension and timing in the South Norwegian Caledonides: The Sognefjord transect. In Burg, J.-P. & Ford, M. (eds.), *Orogeny Through Time*, Geological Society Special Publication 121, 123-148.

Möller, C., Andersson, J., Lundqvist, I. & Hellström, G. 2007. Linking deformation, migmatite formation and zircon U–Pb geochronology in polymetamorphic orthogneisses, Sveconorwegian Province, Sweden. *Journal of Metamorphic Geology 25*, 727-750.

Morgan, P. & Sass, J. H. 1984. Thermal regime of the continental lithosphere. *Journal of Geodynamics 1*, 143-166.

Neumann, E.-R., Wilson, M., Heeremans, M., Spencer, E. A., Obst, K., Timmermann, M. J. & Kirstein, L. 2004. Carboniferous-Permian rifting and magmatism in southern Scandinavia, the North Sea and northern Germany: A review. In Wilson, M., Neumann, E.-R., Davies, G. R., Timmermann, M. J., Heeremans, M. & Larsen, B. T. (eds.), *Permo-Carboniferous Magmatism and Rifting in Europe,* Geological Society of London, Special Publications 223, 11-40.

Nilsen, O., Sundvoll, B., Roberts, D. & Corfu, F. 2003. U-Pb geochronology and geochemistry of trondhjemites and a norite pluton from the SW Trondheim Region, Central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin 441*, 5-16.

Nordgulen, Ø., Bickford, M. E., Nissen, A. L. & Wortman, G. L. 1993. U-Pb zircon ages from the Bindal batholith, and the tectonic history of the Helgeland Nappe Complex, Scandinavian Caledonides. *Journal of the Geological Society of London 150*, 771-783.

Nordgulen, Ø., Lindstrøm, M., Solli, A., Barnes, C. G. & Sundvoll, B.

2001. The Caledonian Smøla-Hitra Batholith, Central Norway. In: *GSA Northeastern Section - 36th Annual Meeting.*

Nordgulen, Ø., Tucker, R. D., Sundvoll, B., Solli, A., Nissen, A. L., Zwaan, K. B., Birkeland, A. & Sigmond, E. M. O. 1997. Paleo- to Mesoproterozoic intrusive rocks in the area between Numedal and Mjøsa, SE Norway. In: *COPENA conference at NGU, August 18-22, 1997* (edited by Nordgulen, Ø., Padget, P., Robinson, P. & McEnroe, S. A.) *Norges geologiske undersøkelse Report 97-113.*

Norton, M. G. 1986. Late Caledonian extension in Norway; a response to extreme crustal thickening. *Tectonics 5* (195-204).

Nystuen, J. P. 1981. The Late Precambrian "Sparagmites" of southern Norway: A major Caledonian allochthon - the Osen-Røa Nappe Complex. *American Journal of Science 281*, 69-94.

Ormaasen, D. E. 1976. Geochemistry and petrology of the mangeritic rocks in Lofoten-Vesterålen. Unpublished Cand. real./M.Sc. thesis, Universitetet i Oslo.

Osmundsen, P. T. & Andersen, T. B. 2001. The middle Devonian basins of western Norway: Sedimentary response to large-scale transtensional tectonics? *Tectonophysics 332*, 51-68.

Pasteels, P., Demaiffe, D. & Michot, J. 1979. U-Pb and Rb-Sr geochronology of the eastern part of the south Rogaland igneous complex, southern Norway. *Lithos 12*, 199-208.

Pearce, J. A. & Cann, J. R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth and Planetary Science Letters 19*, 290-300.

Pedersen, S. & Maaloe, S. 1990. The Iddefjord granite: Geology and age. *Norges geologiske undersøkelse Bulletin 417*, 55-64.

Raade, G. 1973. Distribution of radioactive elements in the plutonic rocks of the Oslo region. Unpublished Hovedoppgave/M.Sc. thesis, Universitetet i Oslo, 162 pp.

Ranalli, G. & Murphy, D. C. 1987. Rheological stratification of the lithosphere. *Tectonophysics 132*, 281-295.

Roberts, D. 1985. The Caledonian fold belt in Finnmark: A synopsis. *Norges geologiske undersøkelse 403*, 161-177.

Roberts, D., Walker, N., Slagstad, T., Solli, A. & Krill, A. 2002. U-Pb zircon ages from the Bymarka ophiolite, near Trondheim, central Norwegian Caledonides, and regional implications. *Norsk Geologisk Tidsskrift 82*, 19-30.

Roberts, R. J., Corfu, F., Torsvik, T. H., Ashwal, L. D. & Ramsay, D. M. 2006. Short-lived mafic magmatism at 560-570 Ma in the northern Norwegian Caledonides: U-Pb zircon ages from the Seiland Igneous Province. *Geological Magazine.*

Robins, B. & Often, M. 1996. The Seiland Igneous Province, North Norway. Field Trip Guidebook, IGCP project 336. Geological Survey of Norway report 96.127, 34.

Rybach, L. 1988. Determination of heat production rate. In Hänel, R., Rybach, L. & Stegena, L. (eds.), *Handbook of Terrestrial Heat-Flow Determination*, 125-142. Kluwer Academic Publishers, Dordrecht.

Rybach, L. & Buntebarth, G. 1982. Relationships between the petrophysical properties density, seismic veolicity, heat generation, and mineralogical constitution. *Earth and Planetary Science Letters 57*, 367-376.

Samuelsson, J. & Middleton, M. F. 1998. The Caledonian foreland basin in Scandinavia: Constrained by the thermal maturation of the Alum Shale. *Geologiska Föreningen i Stockholm Förhandlingar 120*, 307-314.

Sandiford, M. & McLaren, S. 2002. Tectonic feedback and the ordering of heat producing elements within the continental lithosphere. *Earth and Planetary Science Letters 204*, 133-150.

Sandiford, M. & McLaren, S. 2006. Thermo-mechanical controls on heat production distributions and the long-term evolution of the continents. In Brown, M. & Rushmer, T. (eds.), *Evolution and Differentiation of the Continental Crust*, 67-91. Cambridge University Press,

Sandiford, M., Hand, M. & McLaren, S. 2001. Tectonic feedback, intraplate orogeny and the geochemical structure of the crust: A central Australian perspective. In Miller, J. A., Holdsworth, R. E., Buick, I. S. & Hand, M. (eds.), *Continental Reactivation and Reworking. Geological Society of London Special Publication*, 184, 195-218.

Sandiford, M., McLaren, S. & Neumann, N. 2002. Long-term thermal consequences of the redistribution of heat-producing elements associated with large-scale granitic complexes. *Journal of Metamorphic Geology 20*, 87-98.

Schärer, U. 1980. U-Pb and Rb-Sr dating of a polymetamorphic nappe terrain: The Caledonian Jotun Nappe, southern Norway. *Earth and Planetary Science Letters 49*, 205-218.

Schärer, U., Wilmart, E. & Duchesne, J.-C. 1996. The short duration and anorogenic character of anorthosite magmatism: U-Pb dating of the Rogaland complex, Norway. *Earth and Planetary Science Letters 139*, 335-350.

Schiellerup, H., Lambert, D. D., Prestvik, T., Robins, B., McBride, J. S. & Larsen, R. B. 2000. Re-Os isotopic evidence for a lower crustal origin of massif-type anorthosites. *Nature 405*, 781-784.

Siedlecka, A., Nystuen, J. P., Englund, J. O. & Hossack, J. R. 1987. Lillehammer - berggrunnskart M. 1:250,000. Norges geologiske undersøkelse.

Siedlecka, A., Iversen, E., Krill, A. G., Lieungh, B., Often, M., Sandstad, J. S. & Solli, A. 1985. Lithostratigraphy and correlation of the Archean and Early Proterozoic rocks of Finnmarksvidda and the Sørvaranger district. *Norges Geologiske Undersøkelse Bulletin 403*, 7-36.

Sigmond, E. M. O. 1996. Geologisk kart over land- og havområder i Nordvest-Europa, M 1:4 mill. Norges geologiske undersøkelse.

Sigmond, E. M. O., Gustavson, M. & Roberts, D. 1984. Bedrock map of Norway, 1:1 million.

Size, W. B. 1985. Origin of trondhjemite in relation to Appalachian-Caledonide palaeotectonic settings. In Gee, D. G. a. S., B. A. (ed.), *The Caledonide Orogen-Scandinavia and Related Areas,* 735-744. John Wiley and Sons Ltd,

Skår, Ø. 2002. U-Pb geochronology and geochemistry of early Proterozoic rocks of the tectonic basement windows in central Nordland, Caledonides of north-central Norway. *Precambrian Research 116*, 265-283.

Skår, Ø. & Pedersen, R. B. 2003. Relations between granitoid magmatism and migmatization: U-Pb geochronological evidence from the Western Gneiss Complex, Norway. *Journal of the Geological Society of London 160*, 935-946.

Slagstad, T. 2006. Did hot, high heat-producing granites determine the location of the Oslo Rift? *Tectonophysics 412*, 105-119.

Slagstad, T., Jamieson, R. A. & Culshaw, N. G. 2005. Formation, crystallisation, and migration of melt in the mid-orogenic crust: Muskoka domain migmatites, Grenville Province, Ontario. *Journal of Petrology 46*, 893-919.

Slagstad, T., Culshaw, N. G., Jamieson, R. A. & Ketchum, J. W. F. 2004. Early Mesoproterozoic tectonic history of the southwestern Grenville Province, Ontario: Constraints from geochemistry and geochronology of high-grade gneisses. In Tollo, R. P., Corriveau, L., McLelland, J. & Bartholomew, M. J. (eds.), *Proterozoic tectonic evolution of the Grenville orogen in North America*, Geological Society of America, Memoir 197, 209-241.

Slagstad, T., Melezhik, V. A., Kirkland, C. L., Zwaan, K. B., Roberts, D., Gorokhov, I. M. & Fallick, A. E. 2006. Carbonate isotope chemostratigraphy suggests revisions to the geological history of the West Finnmark Caledonides, North Norway. *Journal of the Geological Society of London 163*, 277-289.

Söderlund, U., Möller, C., Andersson, J., Johansson, L. & Whitehouse, M. 2002. Zircon geochronology in polymetamorphic gneisses in the Sveconorwegian orogen, SW Sweden: Ion microprobe evidence for 1.46-1.42 and 0.98-0.96 Ga reworking. *Precambrian Research 113*, 193-225.

Steltenpohl, M. G., Hames, W. E. & Andresen, A. 2004. The Silurian to Permian history of a metamorphic core complex in Lofoten, northern Scandinavian Caledonides. *Tectonics 23*, TC1002, doi: 10.1029/2003TC001522.

Tucker, R. D., Krogh, T. E. & Råheim, A. 1990. Proterozoic evolution and age-province boundaries in the central part of the Western Gneiss Region, Norway: Results of U-Pb dating of accessory minerals from Trondheimsfjord to Geiranger. In Gower, C. F., Rivers, T. & Ryan, A. B. (eds.), *Mid-Proterozoic Laurentia-Baltica*, Geological Association of Canada, Special Paper 38, 149-173.

Tucker, R. D., Robinson, P., Solli, A., Gee, D. G., Thorsnes, T., Krogh, T. E., Nordgulen, Ø. & Bickford, M. E. 2004. Thrusting and extension in the Scandian hinterland, Norway: New U-Pb ages and tectonostratigraphic evidence. *American Journal of Science 304*, 477-532.

Turcotte, D. L. & Schubert, G. 1982. *Geodynamics: Application of Continuum Physics to Geological Problems*. John Wiley and Sons Inc., New York, 464 pp.

Vander Auwera, J., Bogaerts, M., Liégeois, J.-P., Demaiffe, D., Wilmart, E., Bolle, O. & Duchesne, J.-C. 2003. Derivation of the 1.0-0.9 Ga ferro-potassic A-type granitoids of southern Norway by extreme differentiation from basic magmas. *Precambrian Research 124*, 107-148.

Verschure, R. H., Andriessen, P. A. M., Boelrijk, N. A. I. M., Hebeda, E. H., Maijer, C., Priem, H. N. A. & Verdurmen, E. A. T. 1980. On the thermal stability of Rb-Sr and K-Ar biotite systems: Evidence from co-existing Sveconorwegian (ca. 870 Ma) and Caledonian (ca. 400 Ma) biotites in SW Norway. *Contributions to Mineralogy and Petrology 74*, 245-252.

Wade, S. J. R. 1985. Radiogenic isotope studies of crust-forming processes in the Lofoten-Vesterålen Province of North Norway. Unpublished PhD thesis, University of Oxford.

Wilson, M. R. 1980. Granite types in Sweden. *Geologiska Föreningen i Stockholm Förhandlingar 102*, 167-176.

Zwaan, K. B. 1995. Geology of the West Troms Basement Complex, northern Norway, with emphasis on the Senja Shear belt: A preliminary account. *Norges geologiske undersøkelse Bulletin 427*, 33-36.