Zircon U–Pb age for the Orkney lamprophyre dyke swarm, Scotland, and relations to Permo-Carboniferous magmatism in northwestern Europe

A. Mattias Lundmark1*, Roy H. Gabrielsen1 & John Flett Brown2

1Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, N-0316 Oslo, Norway
2The Park, Hillside Road, Stromness, Orkney KW163AH, Scotland
*Corresponding author (e-mail: mattias@geologi.uio.no)

Magnetic zircon in the syenite (bostonite) part of a composite NE–SW-trending cogenetic bostonite–camptonite dyke in Orkney, Scotland, yields a laser ablation inductively coupled plasma mass spectrometry age of 313 ± 4 Ma and εHf(313 Ma) values of +6 to +11. This suggests that the NE–SW-, east–west- and NW–SE-trending Scottish lamprophyre dyke swarms were emplaced during one late Carboniferous magmatic event, contrasting with published K–Ar dates ranging between c. 325 and 250 Ma. This magmatism is interpreted as a response to late Variscan regional extension or an early response to the Skagerrak mantle plume. Lamprophyre magmatism was initiated some 10 Ma earlier in Scotland than in the Oslo Rift.

Supplementary material: Thin-section images of the investigated rocks, geochemical data and an REE plot, U–Pb and Hf isotopic data, and a HF v. time diagram are available at www.geolsoc.org.uk/SUP18501.

Alkaline (lamprophyre) dyke swarms in Scotland are part of widespread Permo-Carboniferous magmatism in NW Europe that can be interpreted as the result of extension in the Variscan foreland, or of a mantle plume centred in the Skagerrak area (Upton et al. 2004). The Scottish lamprophyre dyke swarms comprise >3000 dykes, mainly occurring NW of the Great Glen Fault. The dykes can be divided into three groups with preferred east–west, NW–SE and NE–SW strike directions, the last group being centred on the Orkney Islands (Rock 1983; Fig. 1). The three groups have been dated with the K–Ar method to c. 325 Ma, 290 Ma and 250 Ma, respectively (Speight & Mitchell 1979; Baxter & Mitchell 1984), and interpreted to represent separate tectonomagmatic events implying c. 70 Ma of discontinuous alkaline magmatism (e.g. Baxter & Mitchell 1984). However, Smythe et al. (1995) pointed out that the strikes of the lamprophyre dyke swarms conform to an arcuate trend defined by c. 300 Ma (Monaghan & Parrish 2006) tholeiitic quartz dolerite dykes in northern Britain and the North Sea, and argued for roughly coeval emplacement under one stress regime.

In the literature the age of the Orkney lamprophyre dyke swarm is typically quoted as c. 250 Ma, but four reported K–Ar studies have yielded ages of 245 ± 12 Ma (Brown 1975), c. 240 Ma (Halliday et al. 1977), 288 ± 9 Ma (Shelling, reported by Mykura 1976), and 249–268 Ma with a preferred age of 252 ± 10 Ma obtained from three dykes in the Thuro area considered to belong to the Orkney lamprophyres (Baxter & Mitchell 1984). Ages above published before 1977 were reevaluated with the decay constants of Steiger & Jäger (1977) by Baxter & Mitchell (1984). Although the age spread may reflect magmatic pulses of different ages, the apparent difficulty in isolating isotopically undisturbed material for the analyses makes the age of the Orkney dyke swarm suspect.

In the present study we report zircon in situ U–Pb and Hf data from a bostonite in a composite bostonite–camptonite dyke on West Mainland, Orkney, and the geochemistry of the composite dyke. The new data are used to assess the relation to the Orkney lamprophyre dyke swarm, and the age and tectonic setting of the Scottish lamprophyre dyke swarms.

The Orkney lamprophyres and the Garthna Geo composite dyke. The Orkney camptonite–monchiquite (mafic alkaline lamprophyre) suite comprises >200 dykes and sills (Flett 1935). The general NE–SW strike of the dykes may reflect the regional Caledonian grain (Baxter & Mitchell 1984), or, alternatively, a regional palaeo-stress field (Smythe et al. 1995). The monchiquites are the most primitive of the alkaline rocks, whereas the camptonites have undergone crystal fractionation. More evolved compositions (i.e. bostonite (syenite lamprophyre)) are present on Orkney (Flett 1935), but are volumetrically insignificant on a regional scale (Baxter 1987). The lamprophyres probably reflect low-degree melting of a heterogeneous, enriched mantle source related to decompression melting during a phase of regional extension (Kirstein et al. 2006).

At Garthna Geo (59°00′58″N, 03°21′52″W), Yesnaby, a subvertical, ENE–WSW-striking, c. 3 m wide composite dyke consisting of bostonite margins with sharp contacts to a c. 1 m wide central camptonite dyke is exposed in the palaeo-escarpment of a pre-Caledonian granitic basement. The dyke cuts the oldest of the Orcadian deposits, the Early Devonian coarse-grained Hara Ebb sediments, but no contacts to overlying sediments are exposed. The fine-grained bostonite is dominated by flow-banded potassic feldspar and albite laths, with interstitial carbonates (Fe-dolomite > calcite) and quartz. Accessory minerals include apatite, Fe-oxides and zircon. The feldspars have locally undergone minor illite alteration.

The camptonite is an augite-phyric rock with a matrix dominated by plagioclase, kaersutite, augite and Fe–Ti oxides and accessory apatite. Both the phenocrysts and the matrix minerals tend to be subhedral. Oval millimetre-sized ocelli are common and define flow banding. The ocelli consist of potassic feldspar surrounding and intergrown with a carbonate core, with subordinate albite, kaersutite and biotite, and accessory quartz and Yb-rich zircon. Feldspar crystals are (sub) parallel, suggesting flow orientation. Octahedral porphyric pseudomorphs made up of calcite, Fe–Mg carbonate, quartz and an unidentified clay mineral, and rimmed by Ti–Fe oxides, are common, and interpreted as the remains of olivine crystals. Olivine phenocrysts
at various stages of breakdown have previously been reported from the camptonites (Flett 1935).

**Analytical techniques.** To aid classification and petrogenetic interpretation, bostonite and camptonite from the Garthna Geo composite dyke were analysed for major and trace elements by whole-rock inductively coupled plasma atomic emission spectrometry (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS), respectively, at Canadian Activation Laboratories Ltd.

Polished zircon grains mounted in epoxy were imaged in cathodoluminescence on a JEOL-JSM6460LV scanning electron microscope at the University of Oslo. U–Pb and Lu–Hf isotopic compositions were determined separately by LA-ICP-MS using a Nu Plasma HR mass spectrometer and a NewWave LUV213 laser microprobe at the Department of Geosciences, University of Oslo. The analytical protocols described in detail by Andersen et al. (2009) and Rosa et al. (2009) were used for U–Pb zircon geochronology and those of Heinonen et al. (2010) for Lu–Hf analyses.

During the Lu–Hf run standard zircons Temora-2 and Mud Tank were run as unknowns at intervals. Because of the small size of most zircons in the sample several Hf analyses were cut short owing to lack of material, resulting in slightly low precision in four analyses.

The U–Pb data from the mass spectrometer were calibrated to reference zircons GJ-01 and 91500. The U–Pb ages were calculated from data uncorrected for common lead using ISOPLOT version 3 (Ludwig 2003; Fig. 2). Fourteen analyses of the reference zircon Plesěvice (Sláma et al. 2008) were run as unknowns at intervals. Of these, 13 yield a concordant 337.6 ± 1.4 Ma age (MSWD of concordance 0.7 at 2σ confidence limit including decay constant errors). The remaining analysis was excluded from the age calculation owing to its anomalously low 206Pb/204Pb ratio (c. 2800) and high degree of discordance (23%).

**Results.** Both parts of the composite dyke are alkaline (Irvine & Baragar 1971) and belong to the potassic series of Middlemost (1975). The felsic part is a quartz syenite or trachyte in the QAPF classification (Le Maitre 2002), but lacks mafic minerals apart from oxides. It contains interstitial carbonate, and the feldspar laths form an interlocking texture. Comparable dykes on Orkney are traditionally referred to as bostonites (Flett 1935; compare the definition by Le Maitre 2002). The mafic dyke is an alkaline lamprophyre based on the K2O v. SiO2 ratio (Rock 1987), and is assigned to the camptonite group based on mineralogical criteria (Le Maitre 2002). The camptonite chemistry conforms to previous analyses from the Orkney dyke swarm, with trace element abundances showing similarities to
they represent one alkaline magmatic suite, dated by the bostonite to 313 ± 4 Ma.

The new U–Pb age of the bostonite is some 20–60 Ma older than the previously reported K–Ar ages. The age spread indicates partial resetting of the K–Ar isotopic system, suggesting that some of the alteration in the dykes is post-magmatic. Alternatively, but less likely, the composite dyke represents a hitherto unknown magmatic event, predating the main lamprophyre magmatism on Orkney.

The presence of <30 μm zircons in the camptonite ocelli suggests that in situ U–Pb ion microprobe dating of the rock is possible, and if zircon saturation is typically achieved in ocelli, this may be applicable to a large number of lamprophyre dyke swarms.

Changes in far-field stresses in NW Europe accompanying the Variscan orogeny, and potentially the Ural orogeny (Coward 1993), were accommodated by adjustments between the crustal blocks that make up northern Britain, leading to a complex pattern of strike-slip, extensional and compressional tectonics (Timmerman et al. 2009), and transitional to alkaline (Smedley 1986) episodic magmatism (Monaghan & Parrish 2006). The short duration and geographical extent of one episode of intense magmatism, particularly voluminous in the Oslo Rift and northern Germany, and represented by tholeiitic quartz dolerite dykes and sills in northern Britain and the North Sea, has been proposed to reflect a 297 ± 4 Ma mantle plume centred in the Skagerrak Sea (Fig. 1; Torsvik et al. 2008). Other researchers have argued that the lack of evidence for a hotspot trace and initial doming (Pedersen & van der Beek 1994), and geochemical characteristics of the various magmas (Kirstein et al. 2006), are more compatible with a passive extensional setting.

The 313 ± 4 Ma age of the Orkney lamprophyre dyke swarm is intermediate between the suggested K–Ar ages of 291 ± 5 Ma (Speight & Mitchell 1979), and 326 ± 8 and 323 ± 9 Ma (Baxter & Mitchell 1984) for the NW–SE-striking and the east–west-striking Scottish lamprophyre dyke swarms, respectively. Given the analytical errors of the ages and the potential for resetting of the K–Ar system (see Smythe et al. 1995), the age data are compatible with emplacement during a relatively brief period. This suggests one tectonomagmatic event, as opposed to 70 Ma of discontinuous alkaline magmatism, and fits with the structural coincidence (Smythe et al. 1995) of the regionally arcuate strikes of the lamprophyre dyke swarms and the c. 300 Ma tholeiitic quartz dolerite dykes in northern Britain and the North Sea.

The quartz dolerites are generally viewed in the context of the intense magmatic episode at the Perm–Carboniferous boundary, and Smythe et al. (1995) argued that they, along with (some of) the Scottish lamprophyres and the 300–260 Ma (Corfu & Dahlgren 2008) magmatism in the Oslo Rift, reflect regional rifting in NW Europe.

The magmatic stage of the Oslo Rift was initiated by lamprophyre dykes and sills, including camptonite and 300 ± 1 Ma (Corfu & Dahlgren 2008) syenitic lamprophyre. We propose that the Scottish lamprophyres reflect a similar but slightly earlier response to incipient regional extension dated by the Orkney bostonite to 313 ± 4 Ma. The magmatism thus coincides with the Moscovian (312–307 Ma; Gradstein et al. 2004) proto-rift stage of the Oslo Rift (Olussen et al. 1994). With progressive extension the Scottish lamprophyre magmatism was succeeded by tholeiitic magmatism in northern Britain and the North Sea at 308 ± 5 Ma (Midland Valley Complex; Monaghan & Parrish 2006).

The arcuate pattern of the lamprophyres and quartz dolerites diverges from the radial pattern expected from a Skagerrak
centred mantle plume. However, if the lamprophyres are related to the proposed mantle plume, the new age of the Orkney lamprophyres suggests that it affected northern Britain some 10 Ma earlier than previously proposed. The early appearance and the non-radial strikes of the Scottish lamprophyre dyke swarms could reflect the interaction of the plume with a pre-existing extensional stress field.

This project was funded by ConocoPhillips. M. Erambert helped with mineral identification. S. L. Simonsen and T. Andersen provided support for the LA-ICP-MS work. S. Sherlock, B. Bingen, M. J. Timmerman and an anonymous reviewer are acknowledged for valuable comments on the paper.

References

ANDERSEN, T., ANDERSON, U.B., GRAHAM, S., ÁBERG, G. & SIMONSEN, S.L. 2009. Granitic magmatism by melting of juvenile continental crust: New constraints on the source of Paleoproterozoic granitoids in Fennoscandia from Hf isotopes in zircon. Journal of the Geological Society, London, 166, 233–248, doi:10.1144/0016-76492007-166.

BAXTER, A.N. 1987. Petrochemistry of late Palaeozoic alkali lamprophyre dykes from N Scotland. Transactions of the Royal Society of Edinburgh, Earth Sciences, 77, 267–277.

BAXTER, A.N. & MITCHELL, J.G. 1984. Campionite–monchiquite dyke swarms of Northern Scotland: age relationships and their implications. Scottish Journal of Geology, 20, 297–308.

BROWN, J.F. 1975. Potassium–argon evidence of a Permian age for the campionite dykes: Orkney. Scottish Journal of Geology, 11, 259–262.

CORFU, F. & DÄHLGREN, S. 2008. Petrovskite U–Pb ages and the Pb isotopic composition of alkaline volcanism initiating the Permo-Carboniferous Oslo Rift. Earth and Planetary Science Letters, 265, 256–269, doi:10.1016/j.epsl.2007.10.019.

COWARD, M.P. 1993. The effect of Late Caledonian and Variscan continental escape tectonics on basement structure, Paleozoic basin kinematics and subsequent Mesozoic basin development in NW Europe. In: PARKER, J. R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 1095–1108.

FLEET, J.S. 1935. Petrography. In: WILSON, G.V., EDWARDS, W., KNOX, J., JONES, R.C.B. & STEVENS, J.V. (eds) Geology of the Orkneys. Memoirs of the Geological Survey of Scotland, 173–188.

GRADSTEIN, F.M., OGG, J.G., SMITH, A.G., BLEEKER, W. & LOUBEN, L. 2004. A new geological time scale, with special reference to Precambrian and Neogene. Episodes, 27, 83–100.

HALLIDAY, N., HALLIDAY, A.D. & MITCHELL, J.G. 1977. The age of the Hoy Lavas, Orkney. Scottish Journal of Geology, 13, 43–52 (and Erratum in Scottish Journal of Geology, 15, 79).

HEINONEN, A.P., ANDERSEN, T. & RÁMÖ, O.T. 2010. Re-evaluation of rapakivi petrogenesis: Source constraints from the Hf isotope composition of zircon in the rapakivi granites and associated mafic rocks of southern Finland. Journal of Petrology, 51, 1687–1709, doi:10.1039/pet10035c.

IRVINE, T.N. & BARAGAR, W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences, 8, 523–548.

KIRSTEN, L.A., DAVIES, G.R. & HEEREMANS, M. 2006. The petrogenesis of Carboniferous–Permian dyke and sill intrusions across northern Europe. Contributions to Mineralogy and Petrology, 152, 721–742, doi:10.1007/s00410-006-0129-9.

LE MAITRE, R.W. 2002. Igneous Rocks: A Classification and Glossary of Terms. Recommendations of the International Union of Geological Sciences Sub-commission on the Systematics of Igneous Rocks, 2nd edn. Cambridge University Press, Cambridge.

LITVINOVSKY, B.A., JAHN, B.M., ZANVILEVICH, A.N. & SHADAEV, M.G. 2002. Crystal fractionation in the petrogenesis of an alkalai monzodiorite–syenite series: the Oshurbuko plutonic sheeted complex, Transbaikalia, Russia. Lithos, 64, 97–130, doi:10.1016/S0024-4937(02)00179-2.

LUDWIG, K.R. 2003. Isoplot 3.0—a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center, Special Publication, 4, 75 pp.

MIDDLEMONT, E.A.K. 1975. The basaltic clan. Earth-Science Reviews, 11, 337–364.

MONAGHAN, A.A. & PARRISH, R.R. 2006. Geochronology of Carboniferous–Permian magmatism in the Midland Valley of Scotland: implications for regional tectonomagmatic evolution and the numerical time scale. Journal of the Geological Society, London, 63, 15–28, doi:10.1144/0016-764904-142.

MYKURA, W. 1976. British Regional Geology: Orkney and Shetland. HMSO, Edinburgh.

NAKAMURA, N. 1974. Determination of REE, Ba, Mg, Na and K in carbonate and ordinary chondrites. Geochimica et Cosmochimica Acta, 38, 757–775.

OLAUlsen, S., LARSEN, B.T. & STEEL, R. 1994. The Upper Carboniferous–Permian Oslo Rift: basin fill in relation to tectonic development. In: EMBRY, A.F., BEAUCHAMP, B. & GLASS, D.J. (eds) Pangea: Global Environments and Resources. Canadian Society of Petroleum Geologists Memoir, 17, 175–197.

PEDERSEN, T. & VAN DEER BEEK, P. 1994. Extension and magmatism in the Orkney rift, southeast Norway: No sign of a mantle plume. Earth and Planetary Science Letters, 123, 317–329.

ROCK, N.M.S. 1983. The Permo-Carboniferous campionite monchiquite dyke-suite of the Scottish Highlands and Islands: distribution, field and petrological aspects. Institute of Geological Sciences, London, Report 82/14.

ROCK, N.M.S. 1987. The nature and origin of lamprophyres: an overview. In: FITTON, J.G. & UPTON, B.J.G. (eds) Alkaline Igneous Rocks. Geological Society, London, Special Publications, 30, 191–226.

ROSA, D.R.N., FINCH, A.A., ANDERSEN, T. & INVERNO, C.M.C. 2009. U–Pb geochronology and Hf isotope ratios of magmatic zircons from the Iberian Pyrite Belt. Mineralogy and Petrology, 95, 47–69.

SLÁMA, J., KOSLER, J., ET AL. 2008. Pleistocene zircon—a new natural reference material for U/Pb and Hf isotopic microanalysis. Chemical Geology, 249, 1–35, doi:10.1016/j.chemgeo.2007.11.005.

SMIDLEY, P.L. 1986. The relationship between calcalkaline volcanism and plate-continental rift volcanism: evidence from Scottish Palaeozoic lavas. Earth and Planetary Science Letters, 77, 113–128.

SMITH, D.K., RUSSELL, M.J. & SKUCE, A.G. 1995. Intra-continental rifting inferred from the major late Carboniferous quartz-dolerite dyke swarm of NW Europe. Scottish Journal of Geology, 31, 151–162.

SPIGHT, J.M. & MITCHELL, J.G. 1979. The Permo-Carboniferous dyke-swarm of northern Argyll and its bearing on dextral displacement on the Great Glen fault. Journal of the Geological Society, London, 136, 3–11.

STEIGER, R.H. & JÄGER, E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters, 36, 359–362.

SUN, S.-S. & MCDONOUGH, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: SAUNDERS, A.D. & NORBY, M.J. (eds) Magmatism in the Ocean Basins. Geological Society, London, Special Publications, 42, 313–345.

THOMPSON, R.N. 1982. Magmatism of the British Tertiary Volcanic Province. Scottish Journal of Geology, 18, 49–107.

TIMMERMAN, M.J., HEEREMANS, M., KIRSTEN, L.A., LARSEN, B.T., SPENCER-DUNWORTH, E.-A. & SUNDTVOLL, B. 2009. Linking changes in tectonic style with magmatism in northern Europe during the late Carboniferous to latest Permian. Tectonophysics, 437, 375–390, doi:10.1016/j.tecto.2009.03.011.

TORSVIK, T.H., SMITHURST, M.A., BURKE, K. & STEINBERGER, B. 2008. Long-term stability in deep mantle structure: evidence from the ca. 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP). Earth and Planetary Science Letters, 267, 444–452, doi:10.1016/j.epsl.2007.12.004.

UPTON, B.J.G., STEPHENSON, D., SMIDLEY, P.M., WALLIS, S.M. & FITTON, J.G. 2004. Carboniferous and Permian magmatism in Scotland. In: WILSON, M., NEUMANN, E.-R., DAVIES, G.R., TIMMERMAN, M.J., HEEREMANS, M. & LARSEN, B.T. (eds) Permo-Carboniferous Magmatism and Rifting in Europe. Geological Society, London, Special Publications, 223, 195–218.

Received 4 February 2011; revised typescript accepted 28 July 2011.

Scientific editing by Bernard Bingen.