Age constraints for rare felsic mantle xenoliths from Elie Ness, Scottish Midland Valley

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Introduction

Xenoliths of the Scottish "anorthoclasite suite", commonly hosted by Permo-Carboniferous igneous rocks (and rarely by Cenozoic volcanics), are one of the most widespread (occurring in all major Scottish terranes), hence they are arguably the most significant xenolith group in Scotland (e.g., Aspen et al. 1990; Upton et al. 1999; 2009). However, their crystallization ages are poorly constrained.

Samples of the "anorthoclasite suite" principally consist of Na-rich, low K, Ca-poor feldspar (anorthoclase, Aspen et al., 1990, Upton et al., 2009). These materials occur as single megacrysts, composite megacrysts (megacrysts with minor amounts of mineral inclusions) and lithic (polycrystalline) xenoliths. Salic feldspars in composite megacrysts and xenoliths are usually accompanied by zircon, apatite, biotite, magnetite, Fe-rich pyroxene and occasionally by garnet and corundum with Nb-rich oxide minerals.

Aspen et al. (1990) and Upton et al. (1998; 1999; 2009) suggested that the "anorthoclasite suite" originated in the upper mantle – lower crust where they form (syenitic) vein- or dyke-like bodies. The petrogenesis of the anorthoclasite suite is still controversial, though small fraction melting of metasomatized mantle and subsequent melt–solid phase reactions are likely to have been involved (Upton et al. 1999; 2009).

Based on timing of silicic glass formation in mantle xenoliths (Witt-Eickschen et al. 1998; Beccaluva et al. 2001), Upton et al. (2009) proposed that crystallization of the "anorthoclasite suite" occurred shortly before, or during their entrainment.

Early attempts to date the "anorthoclasite suite", focused on a xenolith-bearing alkali basaltic diatreme at Elie Ness, Fife (Fig. 1). Euhedral zircon xenocrysts yielded a U-Pb age of 319 ± 4 Ma, while euhedral feldspars yielded a K-Ar whole-rock age of c. 294 Ma (Macintyre et al. 1981).

This poster reports an attempt to date the crystallization of the "anorthoclasite suite" using laser-ablation ICPMS and ion microprobe U-Pb dating of zircon and LA-ICPMS U-Pb dating of apatite and rutile from a rare albitite xenolith (EN-101) from Elie Ness.

The Elie Ness xenolith locality

Elie Ness is an alkali basaltic diatreme emplaced during upper Carboniferous to Early Permian volcanism (Fig. 1c). Elie Ness has a complex eruptive history. Explosive eruptions gradually became phreatomagmatic, with later pyroclastic episodes and magmatic intrusions (Gernon et al., 2013). The Elie Ness vent intruded into tightly folded Viséan (Lr Carboniferous) siliciclastic sedimentary rocks (Pathhead Formation, Strathclyde Group, Forsyth et al., 1977).

The vent is especially abundant in mantle xenoliths, and megacrysts of clinopyroxene, amphibole, garnet, feldspar, magnetite, zircon, and composite feldspar xenocrysts with magnetite and apatite inclusions. (Colvile 1968; Chapman 1976; Macintyre et al. 1981; Donaldson 1984; Aspen et al. 1990; Hinton & Upton 1991; Thirlwall & Walder 1995; Upton et al. 1999; Upton et al. 2009).

The clinopyroxene, garnet and feldspar megacrysts are considered cogenetic with the host magma (Gernon et al. 2016). The euhedral and unresorbed nature of the garnet suggests rapid transport to the surface.

The rare albitite EN-101 xenolith (Fig. 2) together with xenocrysts of zircon and feldspar (+inclusions of magnetite and apatite) are considered to belong to the "Scottish anorthoclasite suite".

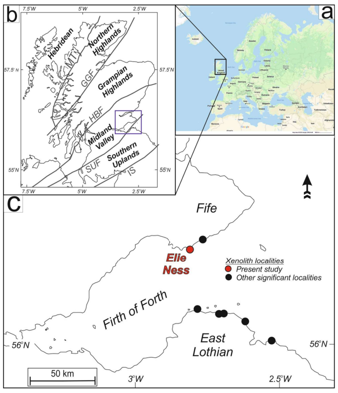


Fig. 1 (a) Location of Scotland; (b) Location of Fig. 1c showing major Scottish terranes and bounding faults: MT = Moine Thrust; GGF = Great Glen Fault, HBF = Highland Boundary Fault, SUF = Southern Uplands Fault; IS = Iapetus Suture; (c) Location of Elie Ness diatreme and sample EN101.

Petrography

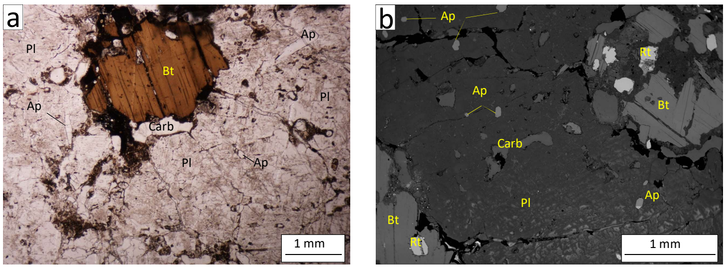


Fig. 2 Xenolith mineralogy: Pl +Bt +Rt +Ap +Zrn. (a) Photomicrograph of xenolith EN-101. Note the pervasive carbonate alteration making plagioclase "dusty" looking (b) BSE image of EN101. Plagioclase contains abundant apatite inclusions.
Ap = apatite, Bt = biotite, Rt = rutile, Zrn = zircon, Pl = plagioclase, Carb = carbonate alteration.

- ## Zircon U-Pb geochronology

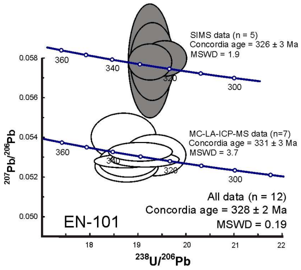


Fig. 3 U-Pb geochronology of EN-101 zircons. SIMS and LA-ICPMS results are presented on a Tera-Wasserburg plot as 2 sigma error ellipses.

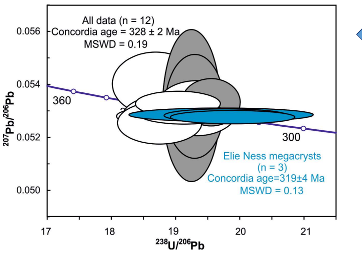


Fig. 4 U-Pb zircon data from the EN-101 albitite xenolith (Fig. 3) compared with IDTIMS analyses of zircon megacrysts from the Elie Ness diatreme (Macintyre *et al.*, 1981).

- ## Zircon Lu-Hf isotopic analyses

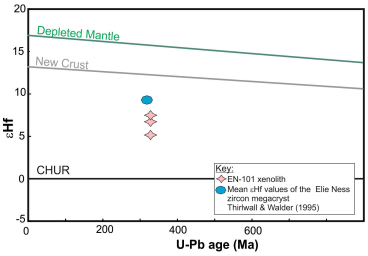


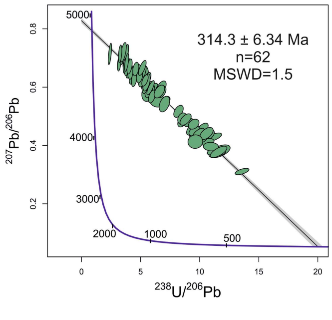
Fig. 5 Hf isotopic evolution of EN-101 zircons compared to Elie Ness zircon xenocryst (Thirlwall & Walder, 1995).

Hf isotopic evolution of new crust and depleted mantle (DM) after Dhuime et al. (2011), calculated using the ^{176}Lu decay constant of Söderlund et al. (2004) relative to CHUR (Bouvier et al., 2008).

- ## Apatite U-Pb geochronology

Fig. 6 LA-ICPMS U-Pb dating of apatite in thin section yields an age for the EN-101 albitite xenolith (314 ± 6 Ma, Fig. 3) that is clearly younger than the zircons from the same xenolith (Fig. 3) and is interpreted to date the cessation of Pb loss, coincident with the time of volcanism.

The apatite age is indistinguishable from the U-Pb age of the euhedral zircon xenocrysts from Elie Ness (Fig. 4) which were previously considered to belong to the "anorthoclasite suite". This suggests that the zircon megacryst ages also date the host volcanism rather than the age of the xenolith suite.



- ## Rutile geochronology and thermometry

Laser-ablation ICPMS analysis in thin section unfortunately shows that EN-101 rutile does not contain sufficient U (< 100 ppb) for U-Pb dating .

Zr-in-rutile thermometry (Tomkins et al., 2007) yielded a mean temperature of 615 ºC, significantly lower than expected for an upper mantle rock. However it can also mean that:

a) rutile did not grow in equilibrium with a Zr-phase -> but textural equilibrium of the sample does not support this; or

b) temperatures during rutile growth really were low -> which would contradict the assumed upper mantle origin of these samples.

Conclusions

- U-Pb dating of zircon mineral separates (by both LAICPMS and SIMS) from the EN-101 albitite xenolith yielded an age of 328 ± 2 Ma, interpreted as the crystallization age of the xenolith.
- *In situ* LA-ICPMS U-Pb age of 314 ± 6 Ma from EN-101 apatite is significantly younger but it agrees with the 319 ± 4 Ma U-Pb TIMS age of euhedral zircon megacrysts from the diatreme (Macintyre et al 1981). These ages are interpreted to date the xenolith host volcanism.
- These new dating results agree with Upton et al. (2009) who suggested that "anorthoclase suite" (and the felsic vein system they represent) formed shortly before the host volcanism.
- The low temperature value of c. 615 ºC from Zr-in-rutile thermometry is challenging to explain and requires further investigation.

Future work

- Detailed rutile imaging and chemical mapping.
- Zircon (Ti-in-zircon) thermometry?
- Analyse trace elements in apatite, rutile and zircon.
- Collect more samples from Elie Ness, including zircon megacrysts, and other anorthoclasite suite samples from a wider range of localities.

References

Aspen, P., Upton, B. G. J. & Dickin, A. P. (1990) Anorthoclase, sanidine and associated megacrysts in Scottish alkali basalts: high pressure syenitic debrish from upper mantle sources? . European Journal of Mineralogy 2, 503-517
Beccaluva, L., Bonadiman, C., Coltori, M., Salvini, L. & Siena, F. (2001)Depletion Events, Nature of Metasomatizing Agent and Timing of Enrichment Processes in Lithospheric Mantle Xenoliths from the Veneto Volcanic Province. J. Petrology 42, 173-188
Bouvier, A., Vervoort, J. D. & Patchett, P. J. (2008) The Lu–Hf and Sm–Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. Earth and Planetary Science Letters 273, 48-57
Chapman, N. A. (1976) Inclusions and Megacrysts from Undersaturated Tuffs and Basanites, East Fife, Scotland. J. Petrology 17, 472-498
Colvine, R. J. L. (1968) Pyrope from Fife. Scottish Journal of Geology 4, 283-286
Dhuime, B., Hawkesworth, C. & Cawood, P. (2011) When Continents Formed. Science 331, 154-155
Donaldson, C. H. (1984) Kinetics of pyrope megacryst reaction in ascendind basaltic magma - relevance to high-pressure magmatic crystallization at Elie Ness, East Fife Geological Magazine 21, 615-620
Forsyth, I. H., Chisholm, B. S. & Chisholm, J. I., (1977) Geology of East Fife In: Memoirs of the Geological Survey of Great Britain, Scotland.
Gernon, T. M., Upton, B. G. J. & Hincks, T. K. (2013) Eruptive history of an alkali basaltic diatreme from Elie Ness, Fife, Scotland. Bulletin of Volcanology 75, 1-20
Gernon, T. M. Upton, B. G. J., Ugra, R., Yücel, C., Taylor, R. N. &Elliott, H. (2016) Complex subvolcanic magma plumbing system of an alkali basaltic maar-diatreme volcano (Elie Ness, Fife, Scotland). Lithos 264, 70-85
Hinton, R. W. & Upton, B. G. J. (1991) The chemistry of zircon: Variations within and between large crystals from syenite and alkali basalt xenoliths. Geochimica et Cosmochimica Acta 55, 3287-3302
Macintyre, R. M., Cliff, R. A. & Chapman, N. A. (1981) Geochronological evidence for phased volcanic activity in Fife and Caithness necks, Scotland. Transactions of the Royal Society of Edinburgh: Earth Sciences, 72, 1-7
Söderlund, U., Patchett, P. J., Vervoort, J. D. & Isachsen, C. E. (2004) The 176Lu decay constant determined by Lu–Hf and U–Pb isotope systematics of Precambrian mafic intrusions. Earth and Planetary Science Letters 219, 311-324
Thirlwall, M. F. & Walder, A. J. (1995) In situ hafnium isotope ratio analysis of zircon by inductively coupled plasma multiple collector mass spectrometry. Chemical Geology 122, 241-247
Tomkins, H.S., Powell, R., Ellis, D.J. (2007) The pressure dependence of the zirconium-in-rutile thermometer. Journal of Metamorphic Geology 25, 703-713
Upton, B. G. J., Aspen, P., Rex, D. C., Melcher, F. & Kinny, P. D. (1998) Lower crustal and possible mantle sample from beneath the Hebrides: evidence from a xenolithic dyke at Gribun, western Mull Journal of the Geological Society, London 155, 813-828
Upton, B. G. J., Hinton, R. W., Aspen, P., Finch, A. & Valley, J. W. (1999) Megacrysts and associated xenoliths: Evidence for migration of geochemically enriched melts in the upper mantle beneath Scotland. Journal of Petrology 40, 935-956
Upton, B. G. J., Finch, A. A. & Slaby, E. (2009) Megacrysts and salic xenoliths in Scottish alkali basalts: derivatives of deep crustal intrusions and small-melt fractions from the upper mantle. Mineral Mag 73, 943-956
Witt-Eickschen, G., Kaminsky, W., Kramm, U. & Harte, B. (1998) The Nature of Young Vein Metasomatism in the Lithosphere of the West Eifel (Germany): Geochemical and Isotopic Constraints from Composite Mantle Xenoliths from the Meerfelder Maar. J. Petrology 39, 155-185

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