Radiogenic and stable isotope studies of zircon and related minerals: the petrogenesis of the late Caledonian granites revisited

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Introduction

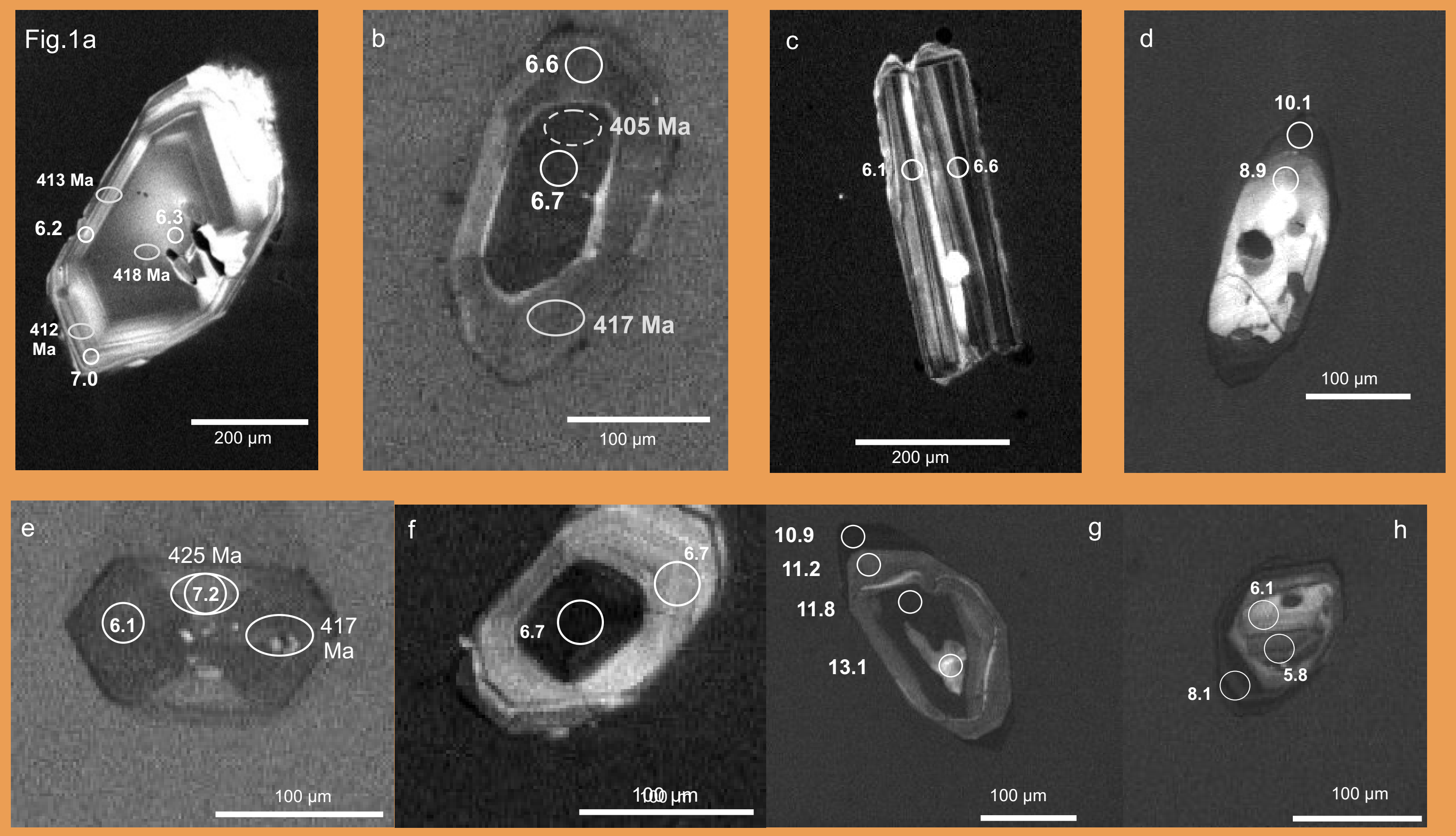
Although the origin and evolution of granites have been studied for more than a century, their petrogenesis remains elusive. Previous whole-rock studies led to the distinction between granites derived from igneous (I-type) and those derived from sedimentary (S-type) precursors. However, recent studies of zircons suggest that this distinction is simplistic and that most granites have more than one magma source [1].

Modern analytical techniques using electron, ion and laser beam imaging and micro-analysis of ***zircon*** now enable the investigation of the sources, evolution and crustal interactions of granitic magmas.

This project applies these modern micro-analytical techniques, and combines **oxygen isotope, trace element analyses** and **U-Pb age dating** in order to re-assess the petrogenesis and origins of "Caledonian" granitic rocks of the Scottish Grampian Highlands, a classic suite of syn- and post-orogenic granites.

Why study zircon?

Zircon is the most abundant accessory mineral in most igneous rocks. It is extremely chemically and mechanically robust, remaining essentially unaffected by hydrothermal alteration and/or metamorphic events. It can, therefore, reveal important information about the origins and evolution of the host granites.



Zircon crystals display a range of sizes, morphologies and internal textures (Fig.1). However, magmatic zircons often show zoning patterns, which reflect the incorporation of trace elements into the zircons crystal during growth (Fig.1a-b, d, f-h) [2]. Furthermore, they commonly contain cores inherited from their source or from crust assimilated during magma ascent (Fig.1d, g-h).

The application of modern *in situ* microbeam techniques permits data acquisition from individual zones within single grains. Circles on the images display results from oxygen isotope analysis, ellipses from U-Pb age dating. This illustrates that intra-grain variations can be detected and inherited components may be analysed, in order to decipher the age and crystallization history of the zircon and, therefore the host rock.

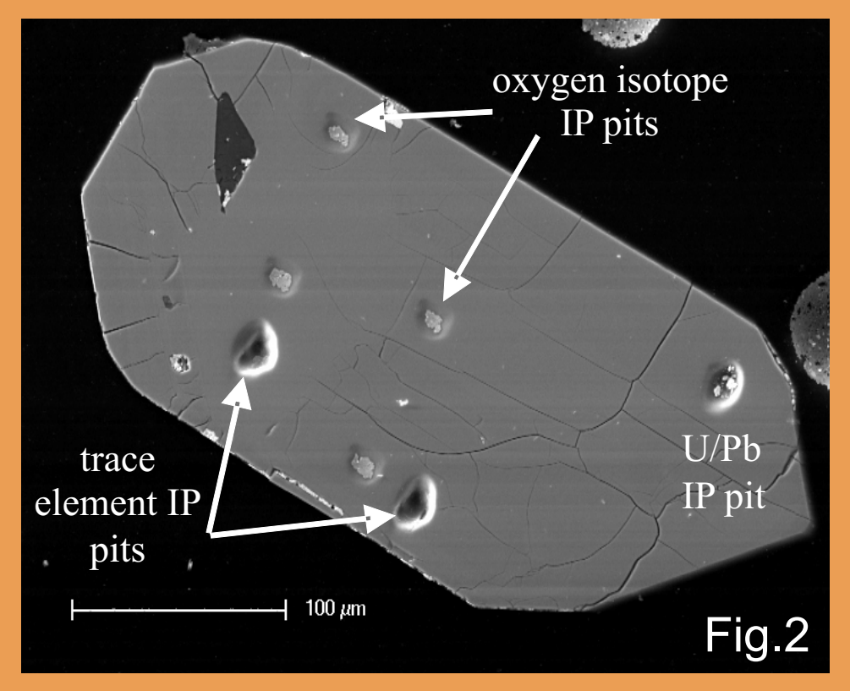


Fig.2

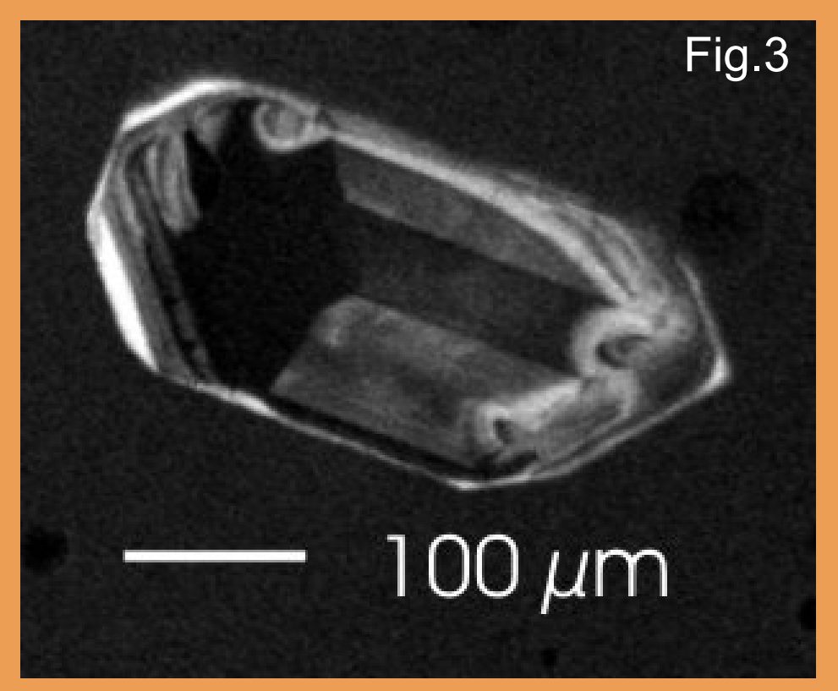


Fig.3

The backscattered electron image of a zircon grain (Fig.2) shows pits (resulting from ablation by the ion beam) from individual ion probe analyses. Here a combination of trace element and oxygen isotope analyses and U-Pb age dating was carried out. Cores and rims were targeted (Fig.3).

Target plutons

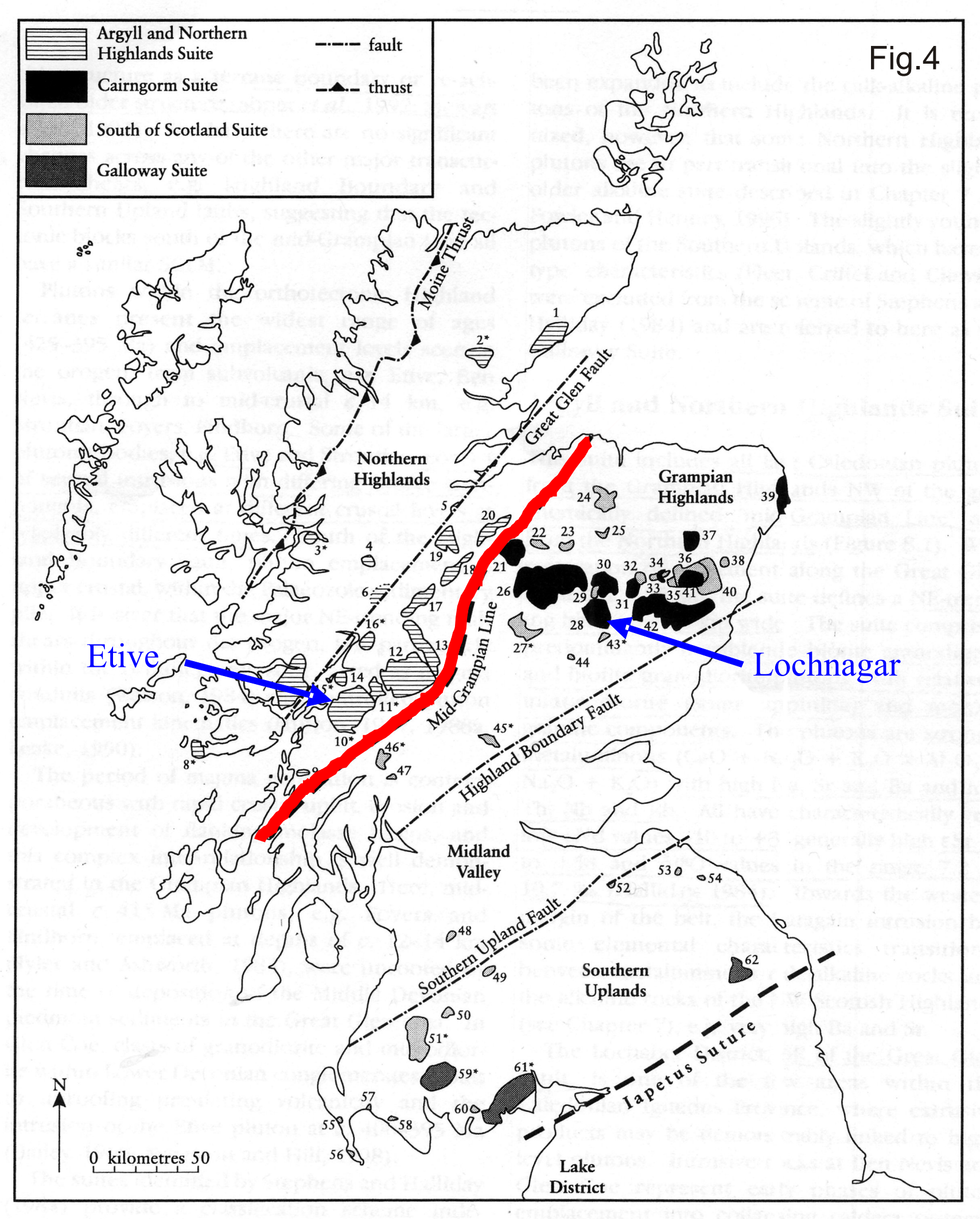


Fig.4

The map shows the Scottish late Caledonian granites (Fig.4). This study investigates two 'I-type' intrusions - Lochnagar and Etive. The plutons lie on either side of the "Mid-Grampian Line", a geochemically-constrained divide, which separates the **Cairngorm suite** (Lochnagar) and the **Argyll suite** (Etive), and may represent an important boundary in the deep crust.

The Lochnagar granite comprises three main phases of intrusion (L1, L2, L3) and several microgranites. Surrounding the Lochnagar Granite several diorite intrusions can be found that may be genetically related to it [3].

To enable comparison between 'I-type' and 'S-type' granites, three c. 475 Ma old 'S-type' intrusions (Kemnay, Cove and Nigg Bay granites) were also sampled.

Results & Preliminary Conclusions

REE analysis

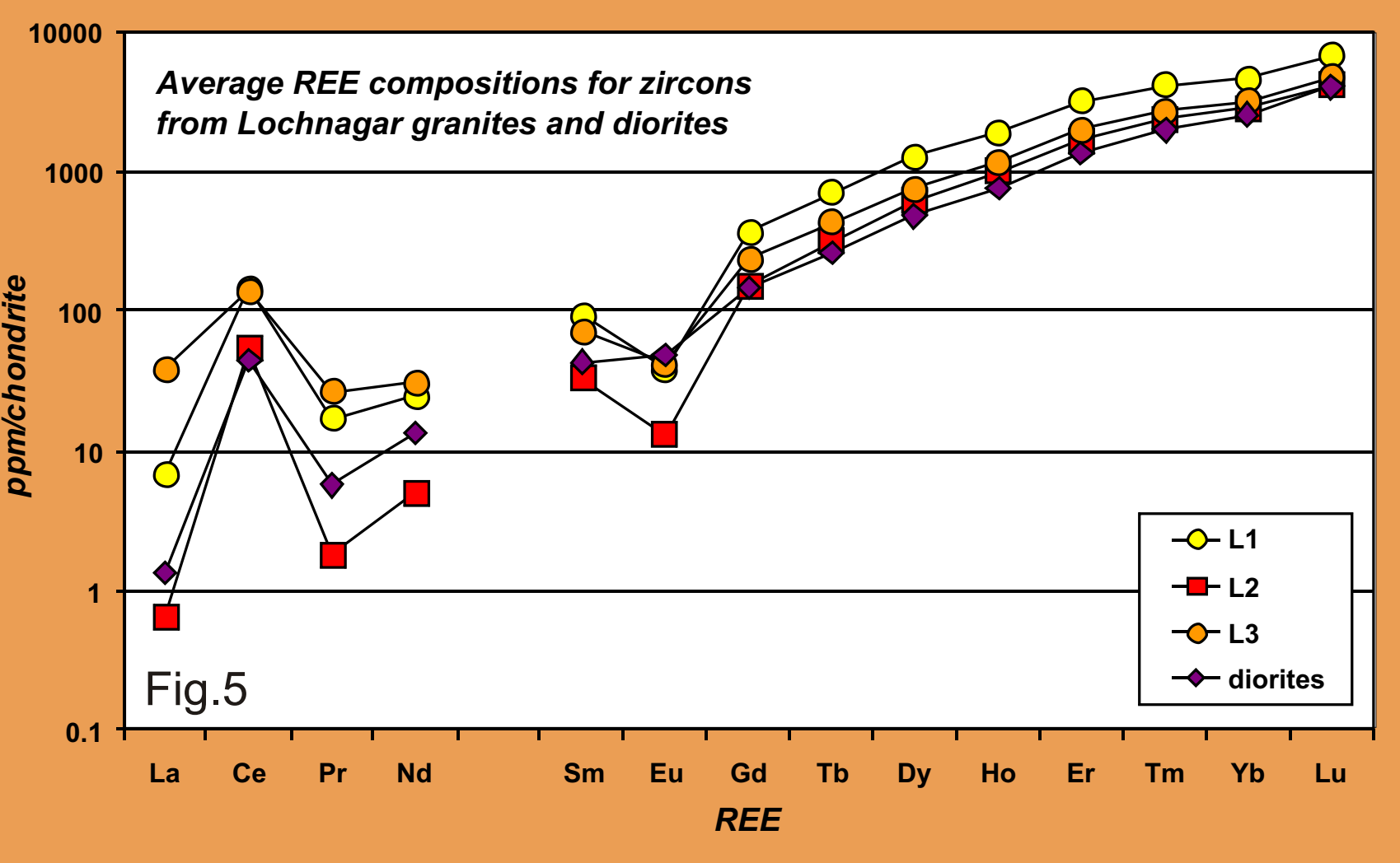
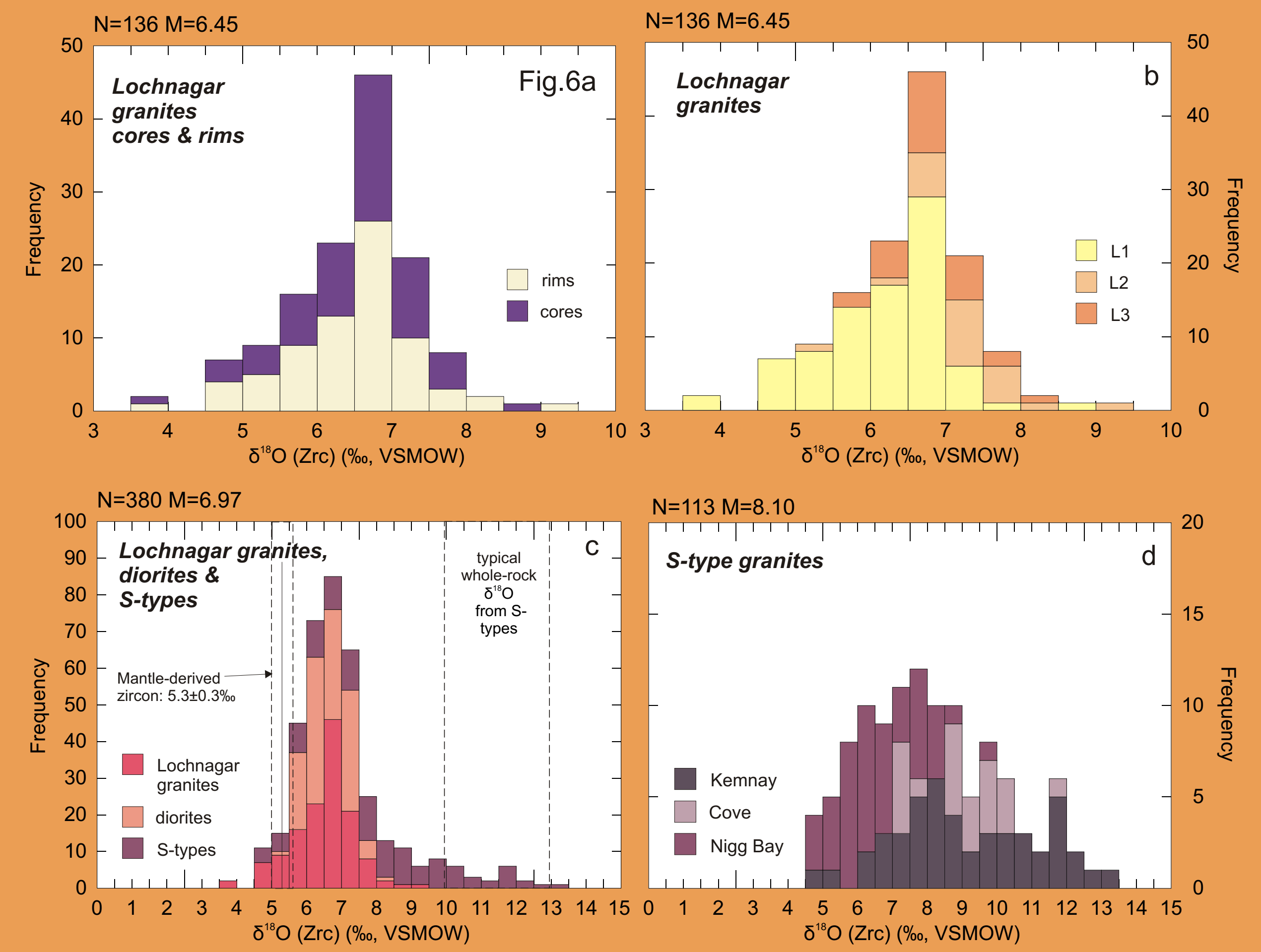


Fig.5

Results (Fig.5):

- steeply positive chondrite normalised REE patterns typical for granite zircons with clear enrichment of the heavy over light REE
- positive Ce anomaly and negative Eu anomaly
- minor variation between the main granite phases (Ce anomalies and light REE abundances)
- no systematic differences between zircons from different granite phases (L1, L2, L3)
- REE patterns of zircon grains from the granites and diorites are also very similar
- diorites typically show a much weaker negative Eu anomaly (granites: Eu/Eu* = 0.33-0.35; diorites: Eu/Eu* = 0.55-0.77). This probably reflects the less feldspar-rich nature of their magma source.

Oxygen isotope analysis



Results:

I-type granite zircons:

- comparison of zircon rims and cores does not show systematic differences, which indicates that no inherited components are present (Fig.6a, Fig.1a-c, e-f)
- L1, L2 and L3 show very similar $\delta^{18}O$ distribution ($\delta^{18}O$ = 3.5-9.5‰, maximum: 6.0-7.0‰; analytical precision for individual analyses is ±0.5‰) (Fig.6b)
- diorites display a very similar distribution, between 5.0 and 8.5‰ with a peak at 6.0-7.5‰ (Fig.6c)
- none of the samples have a dominantly mantle-like composition, but represent a mixture of mantle and crustal material that requires more than one magma source

S-type granite zircons:

- more complicated pattern; zircon $\delta^{18}O$ values range from 4.5 to 13.5‰ (mantle-like to crustal $\delta^{18}O$ values) (Fig.6c-d, Fig.1d, g-h)
- Kemnay Granite displays the broadest range (4.5-13.5‰), Cove Granite ranges from 7.0-12.0‰ and Nigg Bay Granite from 4.5-10.0‰ (Fig.6d)
- $\delta^{18}O$ distributions observed in the S-types do not correlate with either cores or rims, therefore observed variation cannot be caused by inheritance of older cores with mantle-like compositions

U-Pb age dating

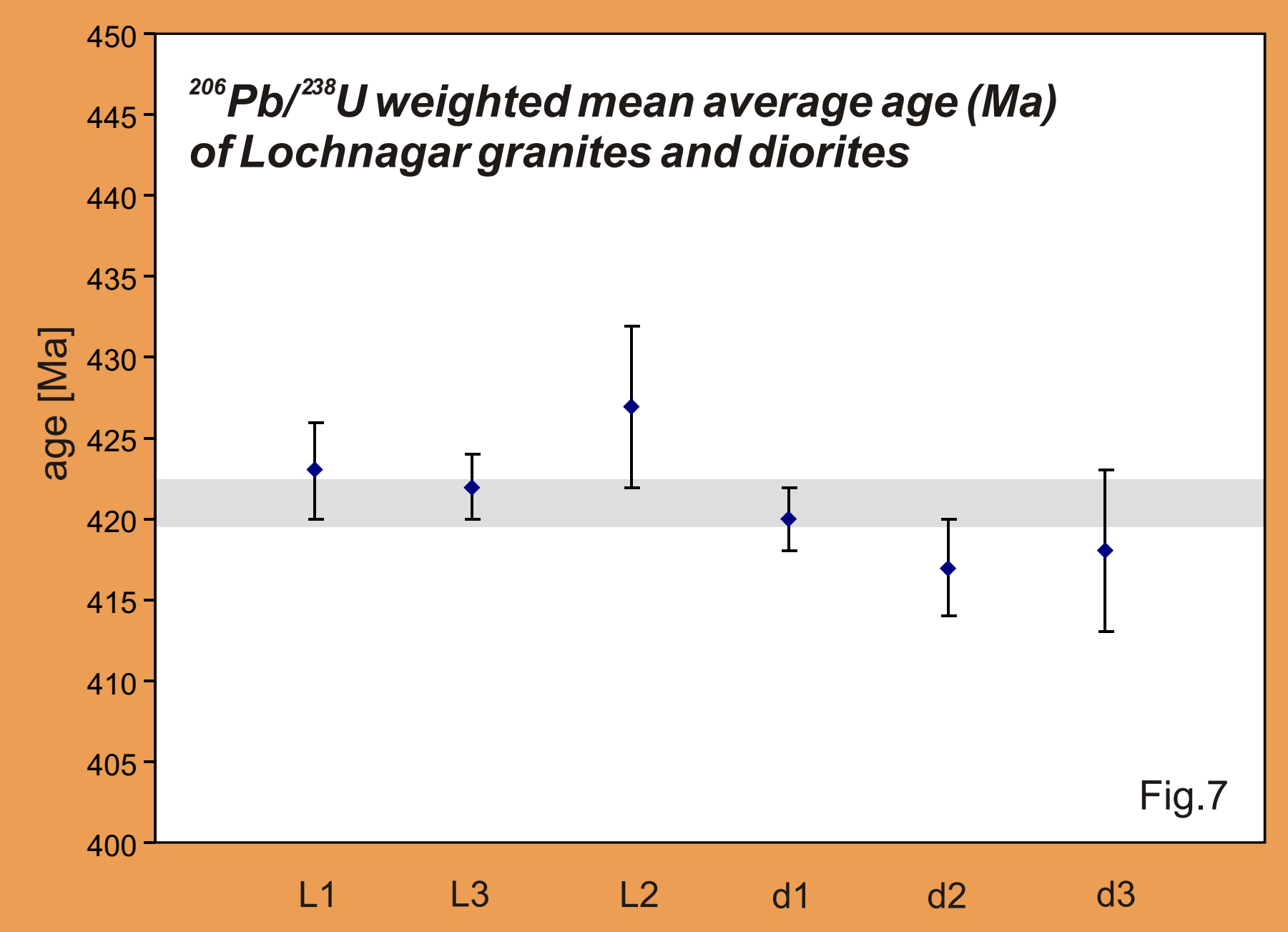


Fig.7

Results (Fig.7):

- no clear age differences between the granite phases (L1, L2, L3) or diorites (d1, d2, d3)
- diorites appear to be slightly younger than the granites, but all ages are within analytical error
- weighted mean average ages indicate that L2 may be the oldest intrusion, but error of analysis is relatively large; actual age may be slightly younger.
- Lochnagar granites and diorites all crystallised at **421±4 Ma**

Conclusions

1. REE patterns are typical for granitic zircons; only minor variation exists between samples
2. Oxygen isotope analyses show that both the I-type and S-type granites studied to date have more than one magma source
3. $^{206}Pb/^{238}U$ crystallisation age of Lochnagar granites and diorites is 421±4 Ma; distinction between individual phases is not possible yet
4. Phanerozoic zircon grains can be dated successfully and with high precision (c.1%)

Future work

1. U-Pb age dating of zircons of remaining Lochnagar and S-type granite samples
2. REE, trace element and oxygen isotope analyses and U-Pb age dating of zircons from Etive granite samples
3. Lu-Hf isotope analysis of Lochnagar and Etive samples
4. Comparison of Lochnagar and Etive intrusions; testing of models for granite sources and deep crustal structure

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