A coupled Lu-Hf and O isotope in zircon approach to granite genesis and crustal evolution

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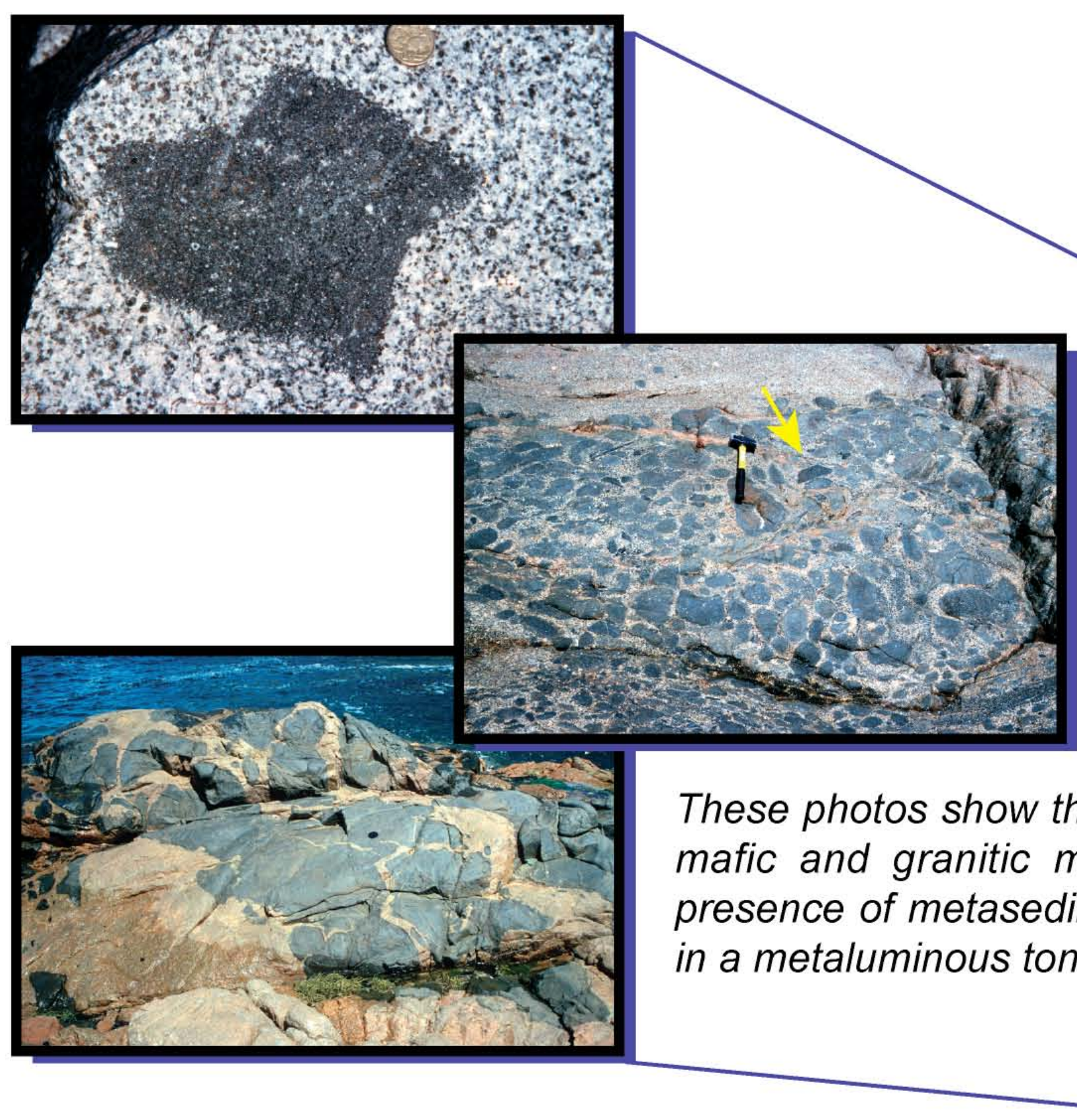
Understanding the formation and differentiation of silicic magmas is fundamental to models of crustal evolution, but the source rocks of granitic batholiths remain contentious. For example, although recent experimental evidence suggests that granitic liquids can be generated from basaltic precursors (Sisson *et al.* 2005), many metaluminous 'I-type' granites have isotopic compositions of Sr, Nd, O and/or Pb that are incompatible with juvenile mantle sources. Supracrustal (metasedimentary or metavolcanic) source components are commonly implicated. To deconvolve the protoliths of granitic plutons, a record of their magmatic evolution is required, which is difficult to retrieve from bulk rock data. A promising approach involves unravelling the isotopic information encoded within the growth zoning of certain minerals by *in situ* microanalysis. Hf isotopes in zircon are ideal for this purpose (e.g. Griffin *et al.* 2002), especially since this refractory phase may survive partial melting and preserve unique information about the protolith. Variations in ^{176}Hf/^{177}Hf potentially track open-system processes operative during crystallisation. The ^{176}Hf/^{177}Hf ratio also reflects the time since the source rocks of the magmas separated from the mantle, allowing the continental growth history to be reconstructed. These Hf 'model' ages are ambiguous if the host magma had a mixed or (meta)sedimentary source component, but the latter can be diagnosed by oxygen isotopes, which are most strongly fractionated by rock-hydrosphere interactions. To provide more robust constraints on granite genesis and crustal evolution, we report an integrated oxygen (ion microprobe) and Lu-Hf isotope (laser ablation ICP-MS) study of magmatic and inherited zircons of three I-type granite suites (Cobargo, Jindabyne and Why Worry) from the Palaeozoic Lachlan Fold Belt (SE Australia, **Figure 1**). Detrital zircons from an Ordovician country rock greywacke were also analysed to explore crustal evolution. All grains were dated *in situ* by SIMS U-Pb isotope analysis before O and Hf isotope determination.



These photos show the co-existence of mafic and granitic magmas, and the presence of metasedimentary enclaves in a metaluminous tonalite (arrowed).

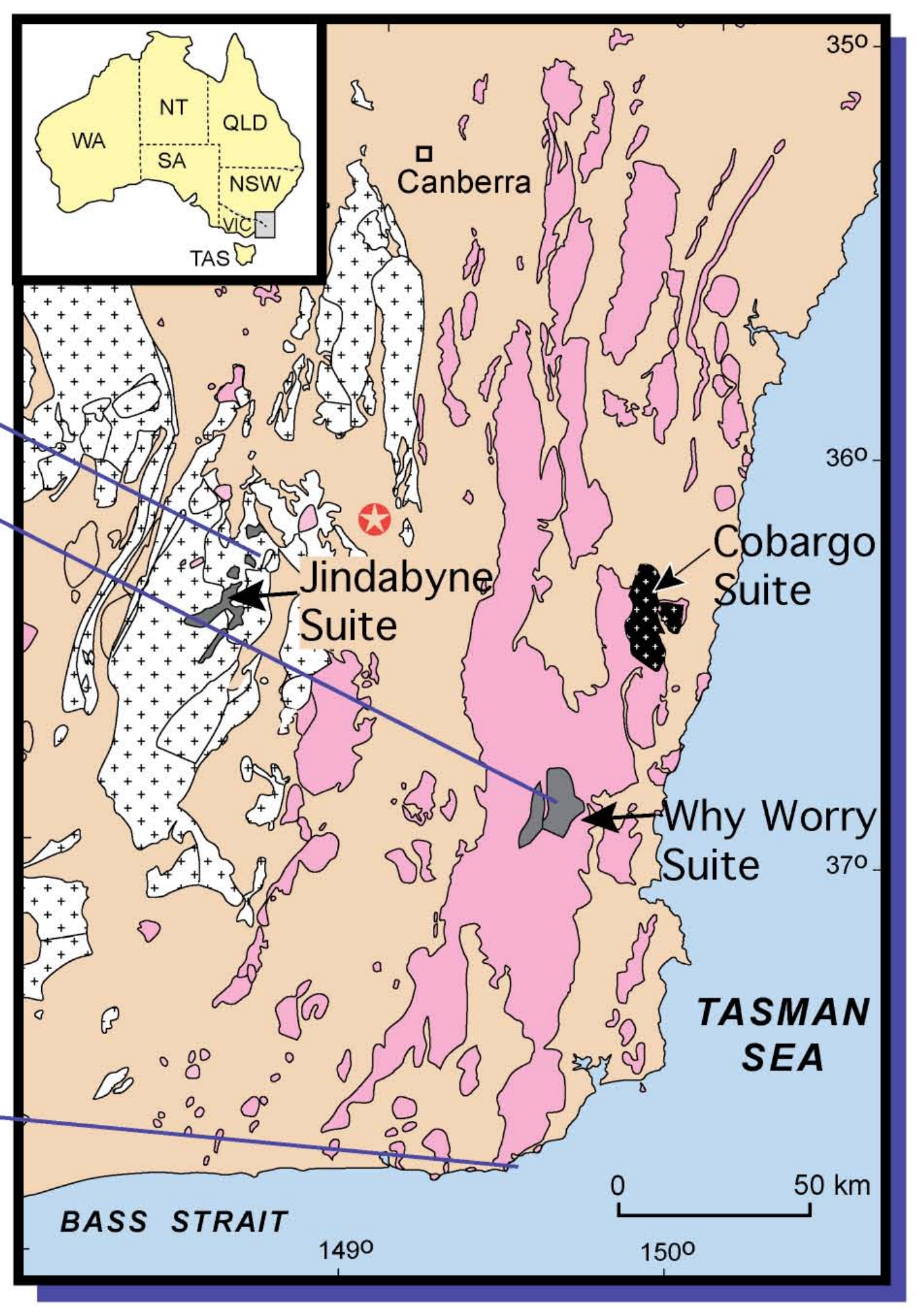
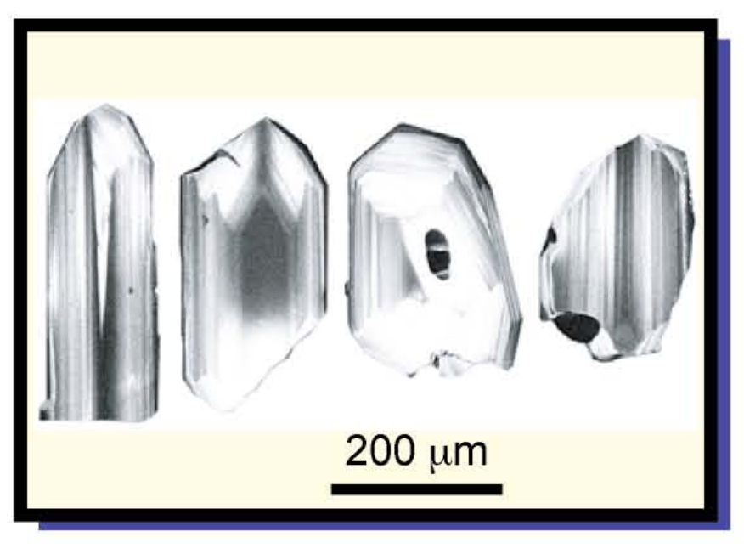
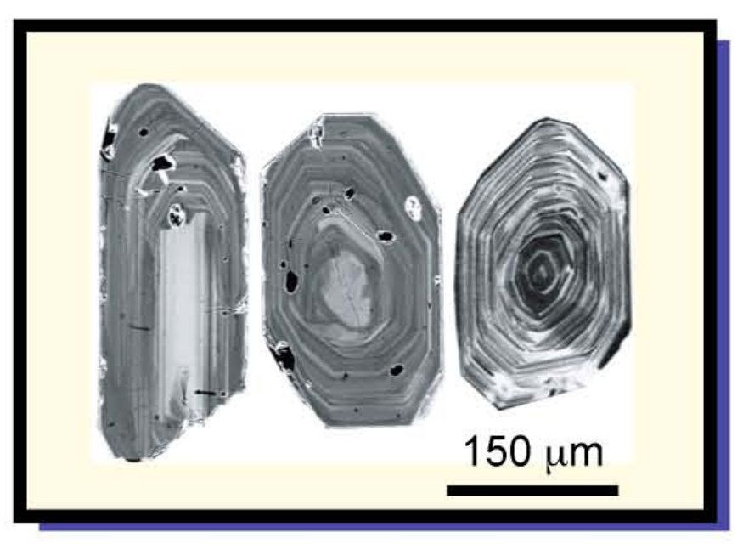


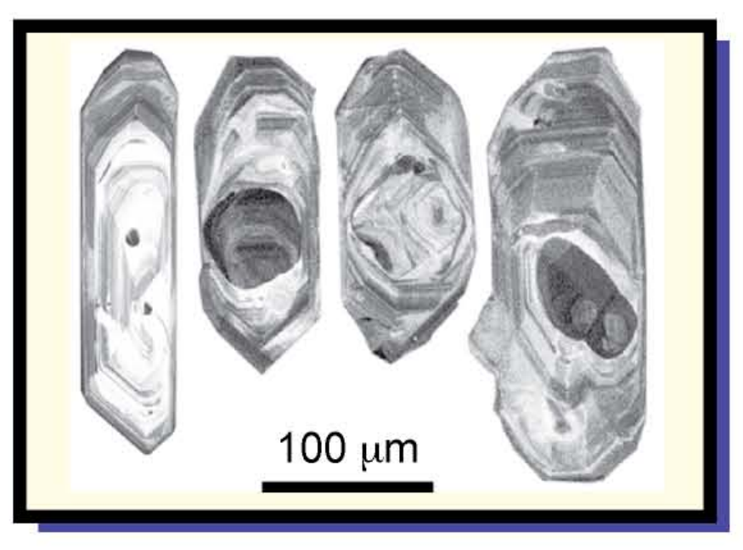
Figure 1.
Geological map of eastern Australia highlighting the location of the three I-type suites considered here, and the sampled metagreywacke (red star). Other 'I-type' (pink) and 'S-type' (crosses) intrusions are also shown. The country rock mostly comprises Ordovician-Silurian turbidites.



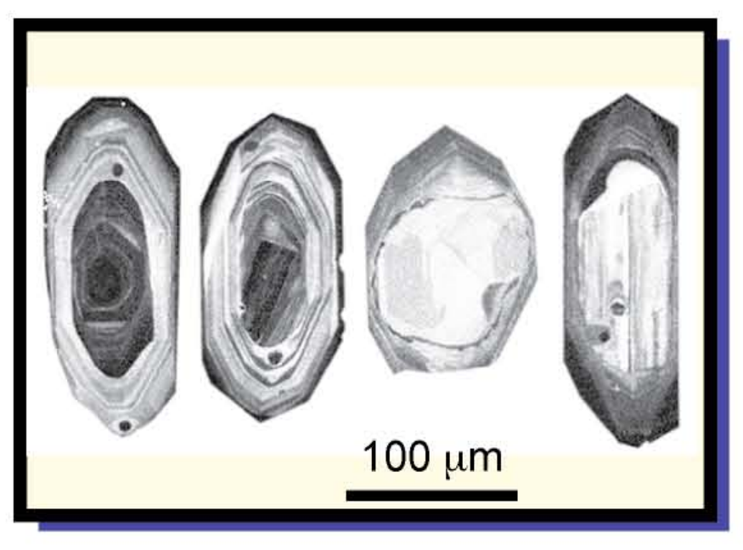
Cobargo diorite (395 Ma)



Cobargo monzogranite



WW Tonalite (400 Ma)



Jindabyne Tonalite (415 Ma)

Granite Genesis: magmatic zircons

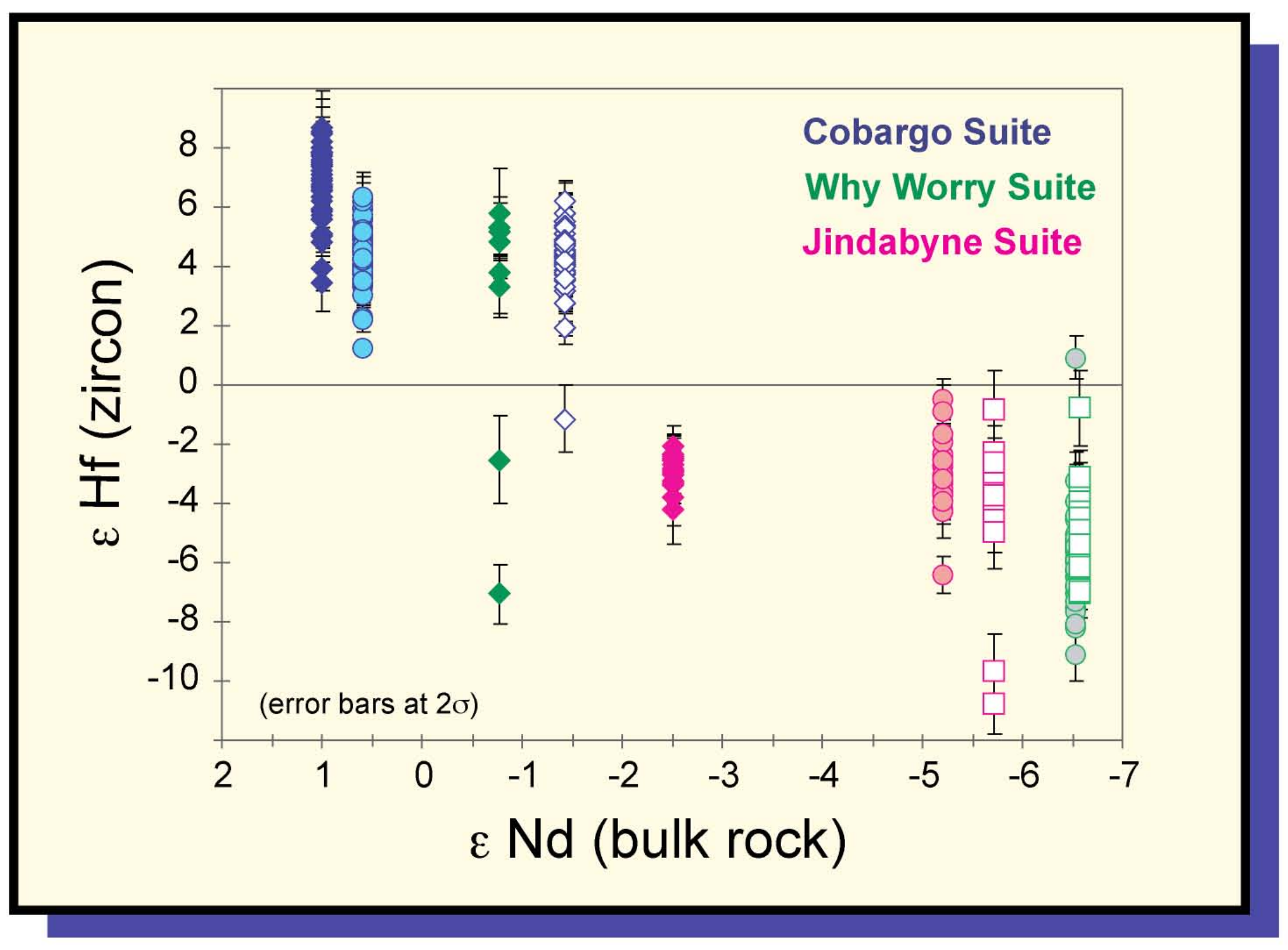


Figure 2.
Plot of εHf (in zircon) versus bulk rock εNd for selected samples from the three I-type suites. Samples with solid symbols correspond to a diorite (Cobargo), high-Al gabbro (Jindabyne) and mafic enclave (Why Worry).

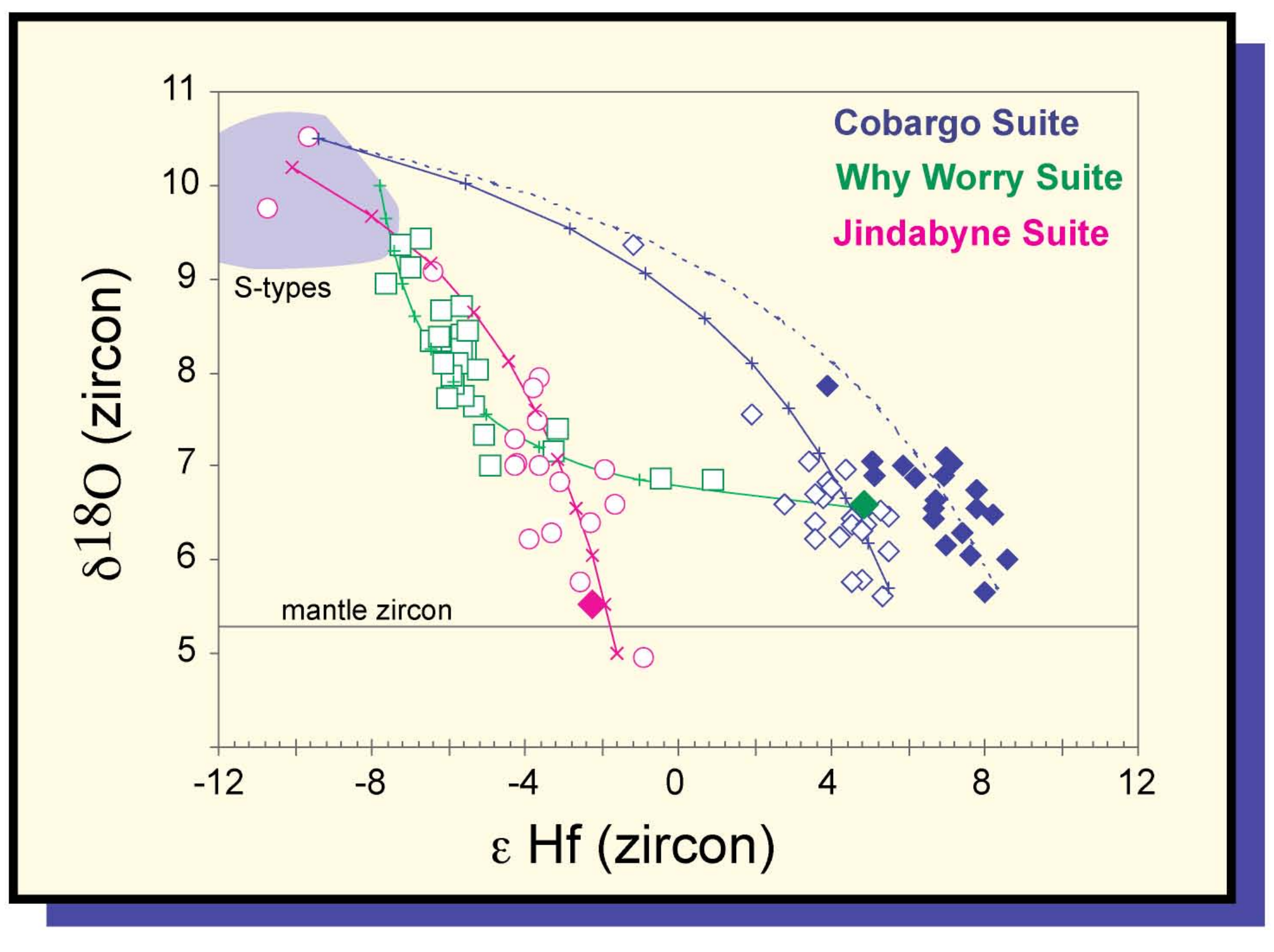


Figure 3.
Diagram showing the covariation between O and Hf isotopes measured from magmatic zircons of the three granitic suites, together with the average composition of zircons from the associated mafic rocks (large solid symbols). Putative mixing curves are shown, as is the field of the metasedimentary-derived 'S-type' granites. Uncertainty in δ^{18}O is ±0.4-0.5‰ at 2σ..

- melt-precipitated zircons of each sample exhibit a spectrum of εHf values (**Figure 3**) that are mildly
  to strongly evolved relative to depleted mantle. An origin by closed-system differentiation of juvenile mantle-derived materials is thus precluded
- correlations between εHf and δ^{18}O suggest that this reflects the interaction between two contrasting components during zircon crystallisation, one having high δ^{18}O values appropriate for a supracrustal material, and the other having low and broadly mantle-like δ^{18}O
- the trajectory of the mixing array of each suite is distinct, testifying to different end-members, but each is anchored at low δ^{18}O by a coeval mafic rock, either a gabbro/diorite or mafic enclave
- the overall sense of core to rim isotopic zonation shown by zircons is consistent with rocks of the three granitic suites forming by progressive contamination of a low δ^{18}O (?mafic) magma by an evolved (probably metasedimentary) component during crystallisation
- the geometry of the mixing curves further suggests that for Cobargo and Jindabyne, the high δ^{18}O component was a crustal melt (relatively low Hf content), whereas bulk assimilation of

Crustal Evolution: inherited and detrital zircons

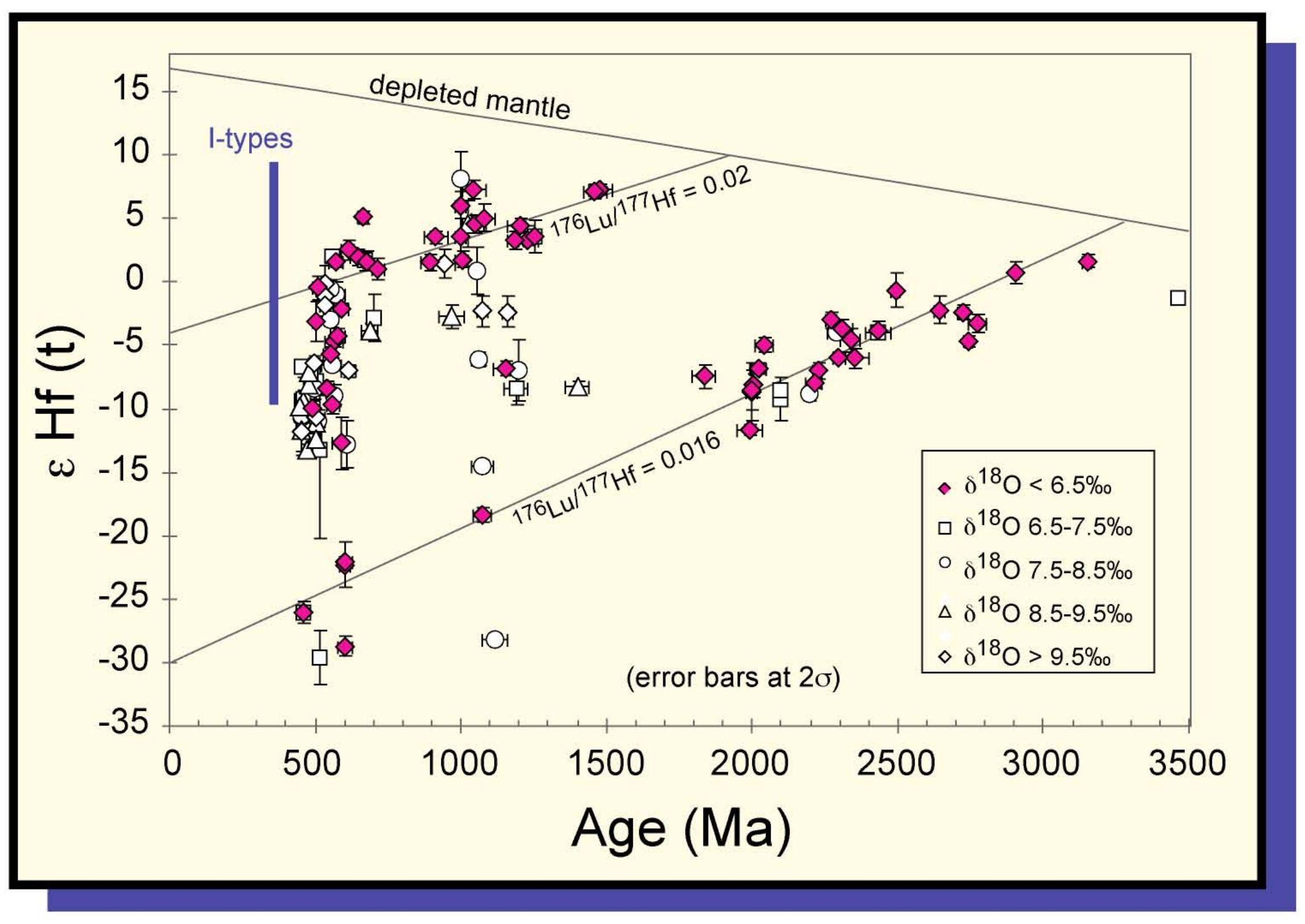


Figure 4.
εHf of inherited and detrital zircons plotted as a function of inferred crystallisation age, and contoured for O isotope composition. Regression lines through the two arrays defined by low δ^{18}O zircons correspond to the Hf isotope evolution of protoliths extracted from the mantle at either 1.9 Ga or 3.2 Ga, respectively. The solid blue line shows the εHf range of the Lachlan I-type granites. The depleted mantle curve was calculated using modern-day values of ^{176}Hf/^{177}Hf = 0.28325 and ^{176}Lu/^{177}Hf = 0.0334, and with λ^{176}Lu = 1.867x10^{-11} yr^{-1}.

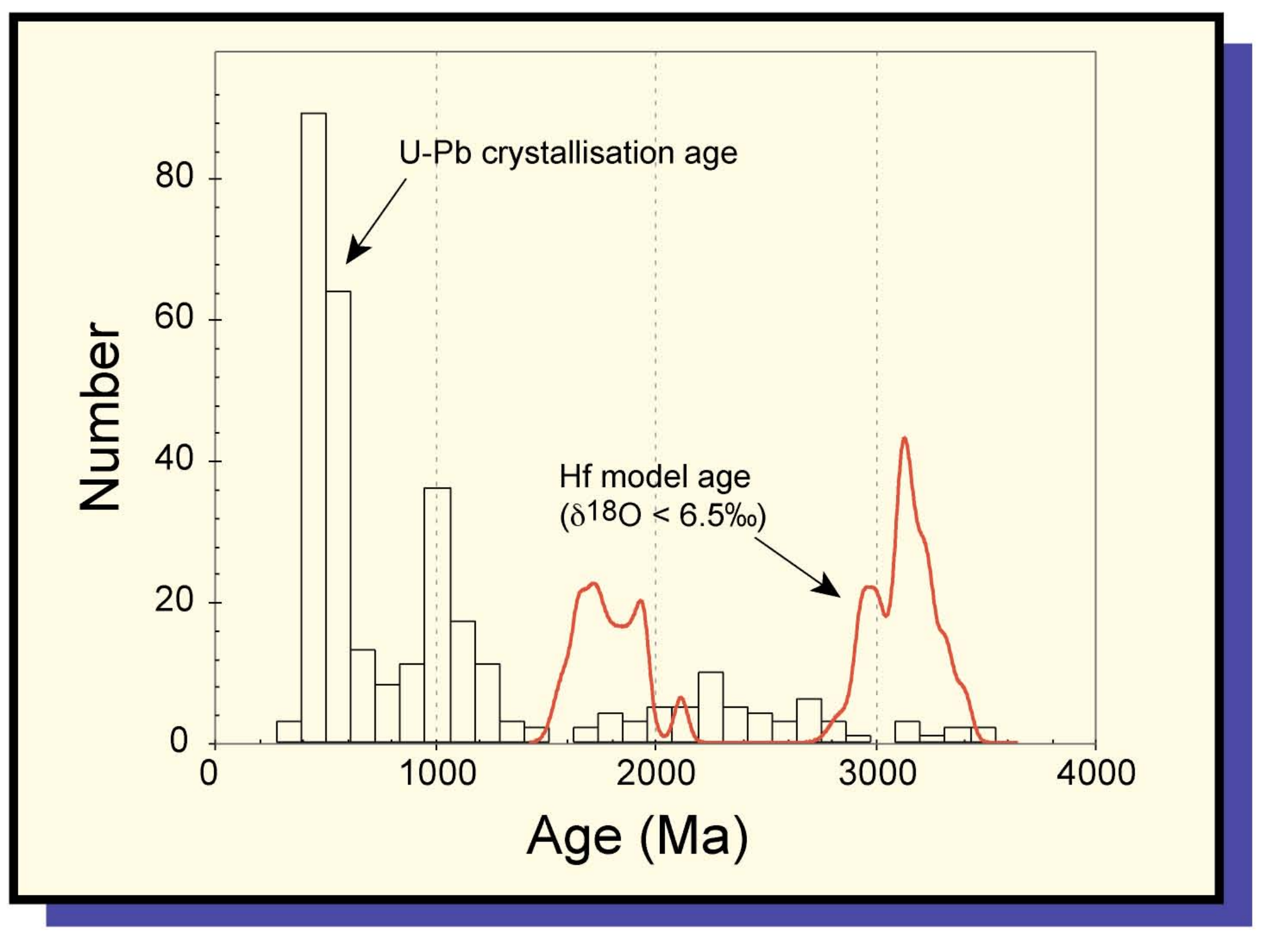


Figure 5.
Comparison between the crystallisation age histogram defined by inherited and detrital zircons and the cumulative gaussian probability curve for Hf model ages of low δ^{18}O zircons. The plot essentially contrasts periods of crustal recycling (U-Pb ages) with times of new crust generation (Hf model ages).

- the age spectra and Hf and O isotope systematics of granite-hosted inherited zircons (both I- and S-type) and detrital zircons are identical (**Figures 4 and 5**)
- no zircons have depleted mantle-like εHf values, indicating that the magmas from which the zircons precipitated were derived by melting pre-existing, rather than juvenile, crustal rocks
- zircons with low and mantle-like δ^{18}O (< 6.5‰) define two linear arrays that record the periodic re-melting of crustal material that was extracted from the depleted mantle at ~1.9 Ga and ~3.2 Ga
- the generation of new crust in the provenance to the Ordovician greywackes was fundamentally episodic and confined to two major pulses at 1.9 Ga and 3.2 Ga
- the zircons that fall between the linear arrays reflect mixing of older igneous material during crustal recycling, some of which had experienced a supracrustal history, thus elevating δ^{18}O
- zircon crystallisation age peaks do not manifest crustal growth, but register magmatic episodes related to intense reworking and stabilisation of older crust. Lachlan orogenesis involved both crustal recycling and crustal addition, reflecting a transition to a different style of crustal evolution
- the processes of crustal growth (episodic) and differentiation (continuous) are intrinsically different.

References

Griffin W *et al.* (2002) Lithos 61: 237-269.
Sisson T *et al.* (2005) Contrib Mineral Petrol, 148: 635-661.

Acknowledgments

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