Detrital zircon SHRIMP U-Pb age study of the Cordillera Darwin Metamorphic Complex of Tierra del Fuego: sedimentary sources and implications for the evolution of the Pacific margin of Gondwana

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Words: 6900
Figures: 8
Tables: 0

Supplementary material: Geographical coordinates of analysed samples, SHRIMP U-Th-Pb analytical data and representative cathodoluminescence (CL) images of zircon grains analysed are available at http://www.geolsoc.org.uk/SUP00000.

Abbreviated title: Cordillera Darwin Zircon Dating

Abstract

The Cordillera Darwin Metamorphic Complex in the southernmost Andes includes a basement of probable Palaeozoic age, a mid-Jurassic and younger volcano-sedimentary cover, and a suite of Jurassic granites, all of which were jointly metamorphosed during the Cretaceous. Detrital zircon ages presented here show that some of the amphibolite facies metamorphic rocks previously mapped as basement have a Jurassic protolith. Overall the detrital zircon age patterns for

samples of the Cordillera Darwin basement differ from those of the Madre de Dios Terrane of the western Patagonian Andes with which they had been correlated; instead they are more comparable to those from the Eastern Andes Metamorphic Complex, which apparently developed in a passive margin setting. The paucity of Cambrian detrital zircons indicates that the meta-igneous basement of the Magallanes foreland basin of central and northern Tierra del Fuego was not the main source of detritus for the protolith of the Cordillera Darwin Metamorphic Complex. The possibility is envisaged that the Magallanes Fagnano transform fault boundary between the Scotia and South America plates resulted from reactivation of an older, pre-Jurassic suture zone between the basement terranes of north-central Tierra del Fuego and Cordillera Darwin.

Cordillera Darwin (Fig. 1) is the topographic culmination of the Fuegian Andes. Its core is occupied by the Cordillera Darwin Metamorphic Complex (CDMC, Kohn *et al*. 1995), which includes a “basement unit” formed by metapelitic and metapsammitic rocks together with previously undated meta-igneous rocks, a cover of mainly rhyolitic volcanic rocks of the Upper Jurassic Tobífera Formation, and intrusive plutonic bodies of different ages. The main structural, metamorphic, intrusive and uplift history of Cordillera Darwin was revealed in a programme of pioneering field-work based research (Dalziel & Cortés 1972; Nelson *et al*. 1980; Dalziel 1981, 1986; Nelson 1982, among others). It was shown that both basement and cover were involved in deformation and metamorphism that also affected Late Jurassic granitoids of the Cordillera Darwin suite (Hervé *et al*. 1981; Mukasa & Dalziel 1986).

The CDMC is unique among the metamorphic complexes of the southern Andes in having a high metamorphic grade, resulting in kyanite- and sillimanite-bearing amphibolite facies rocks, notwithstanding the occurrence of amphibolite-facies metamorphic rocks containing staurolite and sillimanite elsewhere in southern Patagonia, at Puerto Eden (Watters 1964; Calderón *et al.* 2007a). The CDMC basement rocks may contain relicts of a pre-Andean fabric (Dalziel and Cortes 1972; Nelson *et al*., 1980; Dalziel & Brown 1989), but according to Kohn *et al*. (1995) metamorphic conditions “evidently did not exceed lower greenschist grade prior to the Cretaceous”; these authors also established that peak high-grade metamorphism in the CDMC occurred between 90 and 100–120 Ma, based on stratigraphical relationships, K–Ar and Ar–Ar metamorphic mineral ages, and the ages of cross-cutting plutons.

The main deformation and high-grade metamorphism of the CDMC has been associated with the closure of the Rocas Verdes Basin (RVB) (Dalziel *et al*. 1974; Calderón *et al*. 2007b). Development of this quasi-oceanic extensional basin was synchronous with the initial stages of Gondwana break-up (Dalziel & Cortes 1972). The RVB was the depositional locus for the thick succession of Lower Cretaceous volcaniclastic sedimentary rocks of the Yaghan Formation (Katz & Watters 1966). Studies carried in the Ultima Esperanza region indicate that final closure of the northern RVB uplift, ophiolite obduction, and flexural loading of the South American margin occurred after the Cenomanian (93 Ma) as shown by the age of detrital zircons in the first turbidites infilling the subsequent Magallanes foreland basin (Fildani *et al*. 2003).

Previous constraints on the age of the CDMC protolith

The age and nature of the protolith of the CDMC basement is largely unknown. A depositional age can be constrained by regional stratigraphical relations with Mesozoic cover rocks. At Peninsula Staines, 350 km to the northwest of Cordillera Darwin, metamorphic rocks are unconformably overlain by the Middle to Upper Jurassic siliceous volcanic strata of the Tobífera Formation (Allen *et al*. 1980). The same stratigraphical relationship is seen in the northern slope of the Cordillera Darwin at Seno Almirantazgo (Dalziel & Cortés 1972), where Johnson (1990) described a succession of conglomerate and sandstone up to 80 m thick (Basal Clastic Complex, BCC), which overlies the basement with an erosional unconformity, and concordantly underlies Tobífera Formation volcanic rocks. A Rb–Sr whole rock errorchron of 240 ± 40 (2σ) Ma was obtained for metamorphic rocks from Bahía Pluschow belonging to the basement unit by Hervé *et al*. (1981). Kohn *et al*. (1995) suggested that the CDMC basement corresponds to a Palaeozoic to lower Mesozoic (?) metasedimentary and metavolcanic unit, believed to have been originally deposited as an accretionary wedge on the pre-Mid Jurassic Pacific margin of South America (Dalziel & Cortés 1972; Nelson *et al*. 1980; Dalziel 1981, 1986). An alternative possibility has been suggested recently (Hervé *et al*. 2008), that it might be correlative with the Eastern Andes Metamorphic Complex, deposited in a passive margin environment and cropping out in the Patagonian Andes inboard of the Patagonian Batholith.

Barbeau *et al*. (2009) analysed detrital zircons from a sample (SONIA 1) "from the Cordillera Darwin complex", for which the youngest significant age peak spans 260–370 Ma. A statistically preferred calculated age of 289.3 ± 2.7 Ma was interpreted as the best maximum depositional age; one grain gave a younger age of 163 ± 8 Ma, which is "significantly younger than the other estimates and biostratigraphic and detrital-zircon maximum depositional ages for broadly equivalent metasedimentary units in the Patagonian Andes (Hervé & Fanning 2003; Hervé *et a*l. 2003)". Nevertheless, part of the protolith of the CDMC includes Tobífera Formation rhyolites, particularly on the southern slope of Cordillera Darwin (along the Beagle Channel), where strongly deformed and metamorphosed rhyolite lenses appear to be tectonically interleaved with the metasedimentary basement units (Nelson *et al*. 1980).

The basement rocks of the CDMC are intruded by granitoid plutons, which Nelson (1981) grouped into two suites, confirmed by various dating methods: the foliated Mid Jurassic Darwin Suite (157 ± 7 Ma, Hervé *et al*. 1981; 164 ± 4 Ma, Mukasa & Dalziel 1996) and the essentially post-metamorphic Cretaceous Beagle Suite (70–90 Ma; Kohn *et al*. 1995; Mukasa & Dalziel 1996). The former suite was metamorphosed together with the CDMC basement in Late Cretaceous times (Kohn *et al*. 1995), the granites being transformed into orthogneisses and the mafic dykes that intrude them (considered as lateral equivalents of the mafic rocks of the Rocas Verdes Basin) into amphibolites. The protolith of the high-grade (staurolite and kyanite–sillimanite) metamorphic rocks of Cordillera Darwin could thus have been the Palaeozoic basement rocks, the Mesozoic cover rocks, or both.

North of Cordillera Darwin, U–Pb dating of basement samples from the bottom of oil-well boreholes drilled through the Cretaceous–Cenozoic sedimentary fill of the Magallanes foreland basin (Fig.1) establishes that the local basement includes Cambrian igneous and metamorphic rocks (Söllner *et al*. 2000; Pankhurst *et al*. 2003) below an erosional unconformity at the base of the Tobífera Formation. Thus, the basement complexes of the Magallanes Basin and of Cordillera Darwin appear to differ significantly in their ages and lithology; they were the depositional surface for the Tobífera Formation in both areas, but their mutual contact relationships are not exposed.

We have determined U–Pb SHRIMP ages on detrital zircons from metasedimentary rocks from the CDMC in an attempt to resolve their depositional ages and to examine their possible provenance from the adjacent Ediacaran to earliest Cambrian basement of eastern Tierra del Fuego. Detrital zircon ages were also obtained from three low-grade metasedimentary rocks from the basal unit of the unconformably overlying Tobífera Formation, and from a granitic clast included in them, as further constraints on the age of the CDMC from which they were derived. Magmatic protolith ages were also determined on two metamorphic borehole samples from Lago Mercedes (see Fig. 1).

Methodology

Field work was carried out during four seasons of boat cruises in the area. After petrographical inspection of over 100 samples, 20 were selected for isotopic analysis. Zircon concentrates were prepared at the Departamento de Geología, Universidad de Chile. The U–Pb ages determined during this investigation were obtained using SHRIMPs I, II and RG at the Research School of Earth Sciences, The Australian National University, Canberra. The measurement techniques are similar to those of Williams (1998) and Hervé *et al.* (2003). Cathodoluminescence (CL) images were used throughout to select areas for analysis. In the case of the detrital zircon analyses, CL images were used to locate the youngest component within any single zircon grain. Representative CL images of zircon grains analysed are given with the electronic supplementary material. The Temora reference zircon (Black *et al*. 2003) was used to calibrate the U/Pb ratios, except for samples FO0508, FO0524 and FO0545 where the Duluth Gabbro FC1 zircon was used (Paces & Miller 1993).The data were processed using SQUID Excel Macro of Ludwig (2001), plots and age calculations have been made using ISOPLOT (Ludwig 2003) incorporating the mixture modelling algorithm of Sambridge & Compston (1994). The number of grains analysed varied depending on whether the sample was for age determination or for provenance (see figures and the supplementary material for the number of grains analysed for individual samples). For grains that were obviously older than 1000 Ma, ^{204}Pb-corrected ^{207}Pb/^{206}Pb ages were preferred, whereas for the younger grains ^{207}Pb-corrected ^{238}U-^{206}Pb ages were considered more meaningful. Uncertainties are given as 1σ on the analytical measurements in the supplementary material and as 95% confidence limits on all calculated weighted mean ages reported in this paper. The initial analyses of samples FO0508, FO0539 gave unexpected and anomalous Jurassic dates. Additional SHRIMP sessions were carried out to check these anomalies and carry out further analyses; for sample FO0508 a second piece of the same rock was separated at ANU. Results are summarized in Table 1 and plotted in Figs. 2 to 7 (the full U-Th-Pb data tabulation is given in the supplementary material). The geological time-scale used is that of IUGS-ICS 2009 (www.stratigraphy.org).

Analysed samples

Basal Clastic Complex of the Tobífera Formation

Rocks of this complex, assigned to the base of the Tobífera Formation by Johnson (1990), crop out in the northern slope of Cordillera Darwin (Fig.1); they show only a faint foliation and weak metamorphism. Three arenite samples were collected at Seno Almirantazgo. FO0524 is a feldspathic litharenite cropping out at Puerto Demonio, Bahía Ainsworth, with quartz, plagioclase, slate/phyllite, quartzite and marble clasts. It is part of a succession in which clast-supported conglomerates containing 1–10 cm pebbles of quartz, micaschist and volcanic rocks predominate. FO0531 is a sub-litharenite with phyllite, quartz and quartzite clasts from Bahía Ainsworth; it is part of a succession where conglomeratic sandstones and quartz conglomerates predominate. The sandstones have shale laminae, cross-bedding, and 1–2 m thick conglomerate beds with channelized bases. FO0539 is a foliated quartzose phyllite from a conglomeratic succession at Puerto Hernández, Fiordo Brookes, which conformably underlies an ignimbrite bed dated at 168.7 ± 1.4 Ma (unpublished data by the authors). Finally, FO0516 is a 10 cm diameter granitic clast from a matrix-supported foliated conglomerate bed at Fiordo Parry, with mainly aphanitic siliceous volcanic rock clasts.

Cordillera Darwin Metamorphic Complex

We analysed three sets of samples from our Cordillera Darwin Metamorphic Complex collections. The first set (samples FO0508, FO0518, FO0622, FO0533) came from the northern flank of the cordillera around Seno Almirantazgo. The second set (FO0635 and FO0642) consists of samples from the Seno Searle region, to the southwest of the highest peaks of the cordillera. Finally, samples PIA1, PIA7C, GA17 and GA26 were collected from the fjords north of the Beagle Channel, along the southern flank of Cordillera Darwin. All locations are shown in Fig. 1 (GPS coordinates are given in the supplementary material).

Northern flank of Cordillera Darwin: FO0508 is a quartz-rich amphibole-bearing foliated rock with seams rich in biotite, from Fiordo Parry. FO0518 is a schist with fine-grained bands consisting of quartz, biotite (including zircon with metamict halos), chlorite, traces of titanite and tourmaline, and quartz veinlets; it has a well developed crenulation cleavage. Ortiz (2007) determined the peak metamorphic conditions for rocks in this area, which include biotite-garnet bearing schists, at 550–580ºC and 5.0–5.4 kbar. A lower-temperature post-foliation metamorphic imprint can also be observed, mainly transforming biotite to chlorite. FO0622 is a mica-schist with small-scale folds, cropping out on the northern shore of Seno Keats, just below the unconformity with the Tobífera Formation. Nelson (1981) described the structure here as a major synclinal fold that allowed the preservation of the Tobífera. The sample contains detrital white micas and intensely folded quartz veins. FO0533 is a poly-deformed banded phyllite from Seno Ainsworth. The bands consist of granoblastic quartz, finer-grained plagioclase, coarser amphibole and epidote intergrowths, with minor biotite and garnet.

Southern flank of Cordillera Darwin: Samples labelled PIA were collected at Bahía Pia, in the garnet–staurolite zone of the amphibolite facies metamorphic rocks of the CDMC. PIA1 is a staurolite-bearing quartz-biotite schist and PIA7C is a kyanite-bearing schist (Alvarez 2007). Samples labelled GA were collected from Seno Garibaldi from biotite-grade metamorphic rocks (Alvarez 2007): GA17 is a rhyolitic dyke intruding the metamorphic basement in the Schists Unit (Alvarez 2007), and GA26 a poly-deformed silicic volcanic rock.

South-western Cordillera Darwin (Seno Searle): FO0635 is a weakly foliated white mica–biotite metapelite from Seno Searle. It is interlayered with greenschist and rocks interpreted in the field as silicic tuffs. FO0642 is a poorly foliated hornfelsic quartzite, consisting of an aggregate of fine-grained quartz, plagioclase and chloritized biotite, with epidote-bearing veinlets, from the northern shore of Seno Searle. The outcrop displays small-scale shear zones and is intruded by mafic dykes and a Jurassic diorite. Their locations are shown in Fig. 1.

Northwest of Cordillera Darwin

The basement rocks in this area are low-grade metasedimentary rocks. FO0545 is a grey banded phyllite with complexly folded bands rich in quartz, white mica and biotite, from a small island at the entrance of Seno Inman. FO0751 is a micaschist with abundant granoblastic quartz veins and aggregates, in bands of fine-grained quartz, white mica, chlorite, titanite with crenulation cleavage, and some coarser-grained white mica aggregates. FO0718 is a foliated carbonaceous metapelite with decussate biotite, white mica and quartz bands, with accessory tourmaline crystals and secondary white mica-bearing veins. FO0701, from the northern shore of the Strait of Magellan, is a quartzite with relict detrital texture, with quartz and plagioclase clasts in a foliated fine-grained quartz, white mica, chlorite, and epidote matrix; there are pressure-solution seams of opaque minerals, and pressure shadows around some of the clasts.

Basement of the Magallanes foreland basin

Samples LM1 and LM2 were provided by Empresa Nacional del Petróleo (ENAP) and came from the bottom of two deep exploration boreholes at Lago Mercedes, Tierra del Fuego, 60 km north of Seno Almirantazgo (Fig. 1). LM1 is a foliated amphibolite and LM2 a banded orthogneiss.

Results

The analytical data are presented in Table 1 (supplementary material), and in Figures 2 to 7. All calculated ages are reported with 95% confidence limit uncertainties. For close comparison, ages reported from previous literature are quoted with 2σ uncertainties.

Basal Clastic Complex of the Tobífera Formation

The detrital age distribution of sandstone FO0524 exhibits a predominant broad peak which can be unmixed into two components, *c.* 530 and *c.* 550 Ma, both Cambrian in age (see relative probability plots, Fig.2). Scattered ages in the range 350–470 Ma are subordinate to Permian ages, with a more prominent group at *c.* 270 Ma and a smaller one at *c.* 245 Ma. Neoproterozoic grains are scarce. Sandstone FO0531 has a predominant and well defined younger peak at 163.0 ± 1.7 Ma (8 analyses, MSWD = 1.02), with subdued Permian (*c.* 280 Ma), Carboniferous (*c.* 345 Ma) and Cambrian (*c.* 545 Ma) peaks. A very minor group of 1.0–1.2 Ga is seen within a wide dispersion of Proterozoic ages. The quartzose phyllite FO0539 records a wide range of detrital zircon ages, but with dominant Carboniferous peaks at 337.2 ± 3.9 Ma (11 grains, MSWD = 0.84) and *c.* 360 Ma (5 grains). Also present are Grenville-age peaks (*c.* 1030 Ma and *c.* 1100 Ma, 6 grains in each case), and a smaller late Neoproterozoic one (*c.* 615 Ma, 4 grains), with scattered Late Cambrian–Early Ordovician and Early Devonian ages also recorded. Two grains record Jurassic dates; a second analysis of the original single grain is reproduced and another also recorded during follow-up analyses in second SHRIMP analytical session. Lastly, the granite clast FO0516 has a single population of zoned igneous zircon. Two of the analysed grains appear to have lost radiogenic Pb, but the remaining 18 give a weighted mean $^{206}Pb/^{238}U$ age of 465.6 ± 3.2 Ma (MSWD= 1.08), which is interpreted as the Mid Ordovician age of granite crystallization.

Cordillera Darwin Metamorphic Complex

Northern flank of Cordillera Darwin (Fig. 3). Amphibole-bearing schist FO0508 is dominated by detrital zircons at around 400 Ma; 43 analyses from the 122 grains analysed are within uncertainty of a weighted mean $^{206}Pb/^{238}U$ age of 404.1 ± 5.2 Ma (MSWD =1.7). There are 8 analyses (from 6 grains) that are within uncertainty of a younger peak at 166 ± 2 Ma (MSWD = 1.14) – these ages come from grains that are predominantly igneous in origin. A second separation of this sample was made, but no Jurassic ages were identified from the 50 grains analysed. Some scattered early Palaeozoic ages are recorded, but the main pre-Devonian provenance is from 600–680 Ma sources.

Sample FO0518 shows two ill-defined main groupings around 600 Ma (500 to 750 Ma) and around 1000 Ma (800 to 1200 Ma) with a tail to 2600 Ma of Mesoproterozoic to Archaean grains.

Micaschist FO0622 shows a zircon age spectrum (ignoring spot #28.1, *c.* 110 Ma) that is characterized by numerous peaks or groupings, but with no stand-alone significant age grouping. There are two peaks at *c.* 385 and *c.* 405 Ma, an age gap, then a series of approximately equal, closely-spaced peaks at *c.* 510, *c.* 530, *c.* 565, *c.* 600 and *c.* 620 Ma. A broad Meso-Neoproterozoic range of ages is observed with a more prominent peak at about 1040 Ma, as well as some Palaeoproterozoic grains (1880–2000 Ma).

The data for phyllite FO0533 show a dominant concentration at 440–480 Ma, with a dominant age defined by 12 grains at 450.2 ± 4.6 Ma (MSWD = 0.76) and a subordinate group at 473.1 ± 5.3 Ma (10 analyses, MSWD = 0.92). Eight grains have ages between 560 and 670 Ma, and further nine between 985 and 1150 Ma. There is a significant presence of earliest Palaeoproterozoic and Archaean grains, with 13 having ages between 2460 and 2660 Ma, and a sub-peak at about 2620 Ma.

Southern flank of Cordillera Darwin (Fig. 4). The staurolite-bearing schist sample PIA1 yielded relatively few zircons; they range up to 100μm in length though many are less than 50 μm. They are round to sub-round, elongate to equant in shape, and exhibit both zoned igneous and more homogeneous CL structure, the latter interpreted as metamorphic. The relative probability plot is characterized by a number of closely spaced age peaks, seemingly a continuum from *c.* 300 Ma to *c.* 700 Ma, with other groupings at 880 to 900 Ma and *c.* 975 to *c.* 1180 Ma. There are some scattered older Palaeoproterozoic ages. For the 300–700 Ma age range, small but significant peaks occur at *c.* 330, *c.* 430, *c.* 465, *c.* 520 and *c.* 560 Ma, with subordinate clusters of Brasiliano ages (approximately 650–700 Ma). No zircon grains younger than *c.* 300 Ma were recorded.

The relative probability distribution of ages for kyanite schist PIA7C also shows a range of peaks, mainly between *c.* 480 Ma and *c.* 630 Ma. The most prominent peaks are at *c.* 480 Ma and *c.* 520 Ma, and lesser ones at *c.* 550 Ma, *c.* 590 Ma and *c.* 630 Ma. There are scattered older grains, some with Brasiliano ages between *c.* 630 and *c.* 710 Ma, as well as a spread of 'Grenvillian' ages, and three grains with Palaeoproterozoic and Archaean ages.

The rhyolite dyke GA17 contains a relatively uniform population of euhedral, prismatic zircons that have a simple zoned igneous internal structure under CL imaging. The relative probability plot of $^{206}Pb/^{238}U$ ages is skewed slightly to the older side; there also appears to have been some radiogenic Pb loss. A weighted mean of 16 of the 20 analyses gives 159.1 ± 1.4 Ma (MSWD =1.7) and this is interpreted as the time of zoned igneous zircon crystallization in the rhyolite dyke. GA26, a silicic volcanic rock, has a disparate population of zircons that range from low-U (100–350 ppm) euhedral and oscillatory-zoned igneous zircon to extremely high-U (up to 13,850 ppm), dark to opaque, metamict zircon. The latter constitute the majority of the grains in the heavy mineral concentrate and were mostly not suitable for analysis; moreover, the SHRIMP U/Pb ratio calibration does not hold well for such extreme U contents (Williams & Hergt 2000), so that the variable ages obtained from the few analysed high-U grains are not considered reliable. The low-U grains tend to group at about 155 Ma and this is the likely time of zoned igneous zircon formation.

South-western Cordillera Darwin (Seno Searle)(Fig. 5). Metapelite FO0635, from which 70 zircon grains were analysed, displays a predominant peak at *c.* 130 Ma (Early Cretaceous), a Permian peak at *c.* 270 Ma, a smaller peak at *c.* 370 Ma; there are dispersed grains in the interval 430 to 555 Ma (Silurian to latest Proterozoic), a small peak at 460 Ma (Ordovician), and a few scattered Proterozoic grains.

Permian zircons were also found in quartzite FO0642, with 26 of 60 analysed grains recording ages between 255 and 300 Ma; these can be sub-divided, a group of 9 grains yielding a mean age of *c.* 260 Ma, a second group of 11 grains yielding *c.* 275 Ma and a third group of 6 grains yielding *c.* 290 Ma. Among the older ages, there is a minor Carboniferous group at about 320 Ma and then a continuum from *c.* 385 to 520 Ma, albeit with 6 ages concentrated around *c.* 485 Ma (Early Ordovician). Some scattered Neoproterozoic ages are also present.

Northwest of Cordillera Darwin

Grey banded phyllite FO0545 shows a very wide range of detrital zircon ages, with many between 490 and 700 Ma (Fig. 6). Isolated grains younger than 490 Ma are interpreted as having lost radiogenic Pb and are not considered further in this discussion. There is a prominent group of 11 analyses within uncertainty of 596 ± 6 Ma and a subordinate group of 6 analyses at 504 ± 6 Ma, with lesser groupings around *c.* 540 and *c.* 630 Ma. A significant group of 15 grains with ages between 950 and 1150 Ma indicates a component of Grenville-age provenance, with an apparent peak at *c.* 1045 Ma. Some Palaeoproterozoic and Archaean grains are also present, but in isolation their significance is difficult to interpret.

The areas analysed from the quartz-rich micaschist FO0751 from Bahia Morris are enriched in common Pb and this seems to be a mount-related problem and leads to a scattered Tera-Wasserburg plot (not shown). However, the ^{204}Pb-corrected Grenville-age and older grains are within uncertainty of concordia, so the corrected ^{206}Pb/^{238}U ratios are probably reasonable, at least for the main peaks. The peaks include a predominant latest Proterozoic one, with minor groupings and individual ages from Late Proterozoic to Archaean.

The areas analysed from FO0718 on the same mount as FO0751 are similarly enriched in common Pb. The ^{204}Pb-corrected Grenville-age and older grains are within uncertainty of concordia, and for the younger grains the corrected ^{206}Pb/^{238}U ratios are probably reasonable. The latter dominantly give Permian dates and the weighted mean for 26 grains is 277 ± 3 Ma, with a subordinate slightly older grouping close to 290–295 Ma.

Sample FO0701 is dominated by Carboniferous zircons. There is a broad concentration of data at around 300–360 Ma, with two possible peaks unmixed at about 330 and 345 Ma, but it is not possible to identify any specific major events.

Basement of the Magallanes foreland basin

Banded amphibolite sample LM1 has a population of relatively coarse-grained, homogeneous glassy zircon, with broad internal CL zoning commonly seen in igneous zircons from gabbroic rocks (see supplementary material). A large number of grains were analysed and the relative probability plot shows a dominant single age peak, with a significant tail on the younger side, interpreted as due to loss of radiogenic Pb during metamorphism of this basic igneous rock. The well-defined Cambrian weighted mean $^{206}Pb/^{238}U$ age of 527.2 ± 5.2 Ma (MSWD = 1.5, 60 grains out of 72; Fig. 7) is interpreted as the time of igneous zircon crystallization in the pre-metamorphic protolith. Sample LM2 (granitic orthogneiss) is also dominated by igneous zircon occurring as elongate grains up to 100–200μm in length with oscillatory-zoned interiors. The relative probability plot shows a dominant age peak with a tail on the younger side and a series of younger U-Pb ages. From the Tera-Wasserburg plot, these younger analyses are interpreted as areas that have lost radiogenic Pb (grain 4 has 5,300 ppm U and has clearly lost radiogenic Pb). The main group yields a well-defined weighted mean $^{206}Pb/^{238}U$ age of 536.8 ± 3.3 Ma (MSWD = 1.4, 39 grains out of 60; Fig.6), giving the time of zoned igneous zircon crystallization.

Discussion

Identifying basement and cover in the CDMC

Since one of the main goals of this contribution was to investigate the nature, age and provenance of the CDMC, it was first necessary to establish reliable criteria to separate the basement and cover, as metamorphosed “cover” (of Jurassic–Lower Cretaceous rocks) is an important component of the CDMC. Clearly, those metamorphic rocks analysed that contain Jurassic and/or Cretaceous zircons were most probably part of the cover sequences. This obviously applies to the BCC sample FO0531, but could also include sample FO0508, which was collected from an area mapped as basement but which contains rare grains of zoned igneous zircon, clearly not related to a post-depositional *in situ* metamorphic event. The interpretation that best matches the data is that this amphibolite-grade rock is a metamorphosed age-equivalent of the BCC. A similar situation may be represented by sample SONIA1 analysed by Barbeau *et al*. (2009), which was collected from an area shown as basement on their Figure 1 but as Tobífera Formation on our map (based on SERNAGEOMIN 2002). The possibility that rocks such as these are equivalents of the BCC rather than part of the CDMC basement unit proper illustrates the difficulty of distinguishing the two where deformation is high. It also emphasizes that in such widespread metamorphic terrains it is not always possible to confidently assign outcrops to specific mapped units; in some ways better insight may be obtained through detailed isotope studies such as herein. The mid-to-Late Cretaceous high-grade metamorphism might well have affected these Jurassic (early Cretaceous?) rocks and erased the original structural fabric of the protolith, although this has remained recognisable, for example, in the Jurassic rhyolites and dyke (samples GA17, GA26) at Seno Garibaldi, where metamorphic grade is lower. In the south-western part of the Cordillera Darwin, at Seno Searle, metapelites with zircons of Cretaceous ages (FO0635) have been deformed, metamorphosed and incorporated in the CDMC, but their metamorphic grade is, once more, lower than in most of the CDMC. These rocks probably are metamorphosed equivalents of the Yaghan Formation, and thus belong to the cover of the CDMC.

The presence of Jurassic zircon grains cannot be considered the only trustworthy distinguishing criterion, since such grains are not recorded in all BCC samples. However, the analysed BCC samples (except FO0539) consistently record Permian detrital zircon age peaks, whereas in most of the samples clearly assigned to the CDMC basement the youngest detrital zircon population is Carboniferous in age. We thus consider, as a working principle, that CDMC rocks with Permian and younger zircon populations represent part of the Cordillera Darwin cover sequence and samples with older zircon age spectra are part of the CDMC basement.

It was not possible during this research to identify and date basement igneous rocks, whose existence has been previously indicated (e.g., Hervé *et al*. 1981)

The basements of the CDMC and of the Magallanes foreland basin: two distinct terranes?

Detrital zircon age spectra from metasedimentary rocks considered as part of the CDMC basement, according to the above mentioned criteria, show mainly early Palaeozoic, Proterozoic and even Archaean peaks. The dominant Palaeozoic peaks differ between individual samples: 500 Ma (Late Cambrian) in FO0545, 480 Ma (Early Ordovician) in PIA7C, 450 Ma (Late Ordovician) in FO0533, and 400–405 Ma (Early Devonian) in FO0508 and FO0622. Together with the Precambrian detritus, these spectra indicate a mixture of igneous sources derived from different parts of Gondwana. It is possible that detrital zircons in this area had a source in Laurentia, and we cannot rule out the idea that there was a collision between Gondwana and Laurentia near the Proterozoic–Phanerozoic boundary (e.g., Dalziel 1997, Dalla Salda *et al*. 1992).

Cambrian detrital zircons are not very abundant in the three samples from the northern CDMC, but significant in those from the south. Additionally, the latter also have sizeable Ordovician peaks of *c.* 470–480 Ma, an age usually associated with the Famatinian orogenic belt that extends from north-western Argentina as far south as the North Patagonian Massif, but hitherto unknown from southern Patagonia. Yet, the 465.6 ± 3.2 Ma age for the FO0516 granite clast from the

Basal Clastic Complex implies that igneous rocks of this age were exposed reasonably close to the Cordillera Darwin region during the Jurassic.

The youngest significant zircon grains in each sample give maximum early Palaeozoic (Ordovician to Devonian) ages for their deposition. These ages vary considerably between different samples. Despite some uncertainties over possible radiogenic Pb-loss, maximum sedimentation ages may be assigned as Early Devonian for FO0508, Late Ordovician for FO0533, Early Ordovician (*ca*. 490 Ma) for FO0545, and mid-Ordovician for the host rock of FO0516. In the first two cases the dominance of the younger peaks over older ages could be taken to suggest erosion of a penecontemporaneous magmatic arc. On the southern flank of the CDMC, sample PIA7C has minimum zircon ages of 405 Ma (Early Devonian), but also has single-grain ages extending into the Carboniferous (*ca*. 365 and 340 Ma). PIA1 has a significant Early Carboniferous peak at *c.* 330 Ma. Since the significance of single-grain based ages may not be reliable, we suggest that the patterns presented indicate deposition mainly during the Early Palaeozoic in the north and Late Palaeozoic in the southern slope of Cordillera Darwin.

The SHRIMP U-Pb zircon age spectra of rocks from the basement of the Magallanes foreland basin collected from the oil wells at Lago Mercedes differ significantly from those of the Cordillera Darwin Metamorphic Complex. The well-defined Early Cambrian ages of the former are interpreted here as crystallization ages of igneous rocks, i.e., the protoliths of the present-day foliated gneiss and amphibolites. Foliated granitoids of *c.* 530 Ma have previously been demonstrated to underlie the Tobífera Formation of northern Tierra del Fuego (Söllner *et al*. 2000; Pankhurst *et al*. 2003) and are part of the Tierra del Fuego Igneous and Metamorphic Complex (TFIMC; Hervé *et al*. in revision); together with our new data, this suggests that such Cambrian igneous rocks are widespread in the basement of the Magallanes Basin. The scarcity of Cambrian detrital zircons in the CDMC is at odds with the occurrence of extensive Cambrian orthogneisses and amphibolites in the basement of central and northern Tierra del Fuego. It might be expected that these Cambrian rocks should be one the most likely candidates to provide detrital zircons for CDMC protolith in the early Palaeozoic, as is the case with samples FO0545 and FO0751. However, significant Cambrian detrital zircon populations appeared in sedimentary rock of the Cordillera Darwin region only in the Jurassic, when the “Basal Clastic Complex” was deposited unconformably over the CDMC at Seno Almirantazgo.

Thus, according to standard definitions (Howell 1989), the basements of the Magallanes foreland basin and the CDMC constitute two separate and distinct tectonostratigraphic terranes. The basement of the Magallanes foreland basin is currently found 4 km below sea level, whereas that of the CDMC crops out at up to 2 km above sea level. These two basement terranes lie respectively to the north and south of the left-lateral Magallanes–Fagnano transform fault system (MFFS, Fig. 1), which forms the boundary between the Scotia and South American plates; the CDMC is located within the Scotia plate and the Fuegian foreland in the South American plate. Although strike-slip motion along the Magallanes Fagnano transform during the Cenozoic may explain the juxtaposition of the two terranes, estimated displacement along the transform boundary seems to be rather modest

(55 km according to Rossello 2005). This, together with the fact that the distribution of Jurassic and younger units and early Cenozoic structures can be matched across the fault regardless of displacement, leads us to suggest that the MFFS possibly resulted from the reactivation of and old, pre-Jurassic suture between the Cordillera Darwin and Tierra del Fuego basement terranes. The two terranes amalgamated before the deposition of the Basal Clastic Complex.

Regional correlations of the CDMC basement

The data presented here can be interpreted as indicating that the clastic protolith of the CDMC basement was not mainly derived from the presently adjacent, though buried, igneous/metamorphic basement of the Magallanes foreland basin. Furthermore, the zircon age spectra for most of the CDMC basement samples make untenable earlier correlations with the Madre de Dios Terrane that forms part of the western Patagonian archipelagos, north of the Strait of Magellan, as the latter includes clastic metasediments (Duque de York Complex; Forsythe & Mpodozis 1979, 1983; Sepúlveda *et al*. 2007) characterized by prominent Permian detrital zircons (Hervé *et al*. 2003). However, one sample (FO0642) from the strongly tectonized Seno Searle region, the south-westernmost locality sampled, and sample FO0718, northwest of Cordillera Darwin have a youngest prominent Permian peak, so that these samples might represent either fragments of the Duque de York Complex or younger sediments tectonically interleaved with the CDMC basement, and deformed and metamorphosed together during the Cretaceous. Despite this, most CDMC basement samples are more comparable in their detrital zircon age spectra to some samples of the Eastern Andes Metamorphic Complex. This complex crops out along the eastern Andean foothills north of 50ºS (Hervé *et al*. 2003; Augustsson & Bahlburg 2007; Hervé *et al*. 2008), and was considered by Hervé and Mpodozis (2005) as an exotic terrane (Fitz Roy terrane) accreted against southern Patagonia in, probably, early Jurassic times. Notwithstanding these similarities, at present the Cordillera Darwin basement cannot be considered an integral part of the former as the intervening Cambrian meta-igneous terrane of Tierra del Fuego disrupts the geographic continuity of these two separate tectonic domains.

Conclusions

The metasedimentary basement unit present in the Cordillera Darwin Metamorphic Complex, characterized by mainly Early Palaeozoic detrital zircons as the youngest components, differs from the Cambrian meta-igneous basement of the Magallanes foreland basin. It also differs from the Duque de York Complex, part of the Madre de Dios Terrane, in that samples of the latter have a prominent Early Permian detrital zircon component. The detrital zircon patterns of the CDMC are more comparable to those of the Eastern Andes Metamorphic Complex further north in the Patagonian Andes, interpreted as having been deposited in a passive margin setting. However, at present, both areas are spatially separated by the Cambrian meta-igneous basement of the Magallanes foreland basin in Tierra del

Fuego, and they cannot be considered to form a continuous rock body. The presence of Ordovician detrital zircons and granitic clasts complicates the identification of the source areas, as granites of such ages are not known in southern Patagonia.

The CDMC lies in the Scotia Plate, whose Cenozoic boundary with the South America plate is the left lateral wrench Magallanes–Fagnano fault system (MFFS). The detrital zircon patterns of the CDMC basement unit are more complex than if they had the exclusively Cambrian igneous source of the presently adjacent Magallanes foreland basin basement. This suggests that the two areas were not side-by-side during the Early Palaeozoic, but that their amalgamation occurred prior to the Middle Jurassic, as indicated by Jurassic Tobífera volcanic rocks unconformably deposited over both basements. The MFFS was thus probably developed along the site of an older suture, located in the contact between the CDMC and the meta-igneous Cambrian Magallanes foreland basin basement.

Jurassic detrital zircons are present in some samples of the CDMC, including some from outcrops assigned to the basement in some maps; their zircon age patterns resemble those in the sedimentary rocks that lie unconformably over the basement unit of the CDMC and concordantly below the Tobífera Formation. Thus zircon data and field relationships are consistent in showing that the CDMC cover units were deposited in Jurassic times and were deformed and metamorphosed to high grades along with the CDMC basement during Cretaceous times.

Acknowledgements

Field trips were undertaken in the yachts *Penguin* and *Foam*, with captains Conrado Alvarez and David Lleufo. Additionally, a field trip in southern Cordillera Darwin by KK was made on the *Ocean Tramp* with Captain Charles Porter. Projects FONDECYT 1050431 and 7050431 (FH), Anillo-Antártico (ARTG-04), and NSF EAR0635940 (KK) financed most of the field and laboratory work. M. Ortiz, A. Sanchez, C.F. Prades, F. Poblete and J. Alvarez, geology students from Universidad de Chile, were excellent field collaborators. KK also thanks Prof. Geoffrey Clarke from the University of Sydney for his assistance in the field during the *Ocean Tramp* cruise. RJP acknowledges assistance with travel costs by NERC Isotope Geosciences Laboratory. Thorough reviews by D. Barbeau and an anonymous referee helped to greatly improve the original text.

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Figure captions

Figure 1. (A) Map indicating outcrop areas of metamorphic complexes in southern Patagonia and present day plate boundaries. (B) Geological sketch map of the Cordillera Darwin area, with indication of the sampling localities. Samples LM1 and LM2 are more than 4 km deep, the rest at sea level. BM, Bahia Morris; BP, Bahía Pia; BPl, Bahía Pluschow; CM, Caleta Murray; CW, Caleta Wood; FB, Fiordo Brookes; FP, Fiordo Parry; SA, Seno Ainsworth; SG, Seno Garibaldi; SI, Seno Inman; SK, Seno Keats; SS, Seno Searle; MFFS, Magallanes Fagnano Fault System.

Figure 2. Three age vs. probability diagrams for samples from the Basal Clastic Complex (of the Tobífera formation) on the northern slope of Cordillera Darwin; inset plots are subsets for ages below 800 Ma. Lower right: Tera–Wasserburg diagram and inset of age vs. probability plot for the granitic clast (sample FO0516). NB, n is the number of analyses.

Figure 3. Age vs. probability diagrams for samples from the Cordillera Darwin Metamorphic Complex in the northern flank of Cordillera Darwin; inset plots are subsets for ages below 800 Ma. Note, n is the total number of analyses.

Figure 4. Three age vs. probability diagrams for samples from the Cordillera Darwin Metamorphic Complex in the southern flank of Cordillera Darwin; inset plots are subsets of the larger plots for ages below 800 Ma. Lower right: Tera–Wasserburg diagram and inset of age vs. probability plot for the metavolcanic rock (sample FO0516). Note, n is the total number of analyses.

Figure 5. Age vs. probability diagrams for samples from the Cordillera Darwin Metamorphic Complex in south-western Cordillera Darwin (Seno Searle); inset plots are subsets for ages below 800 Ma. Note, n is the total number of analyses

Figure 6. Age vs. probability diagrams for samples from the metamorphic basement to the northwest of Cordillera Darwin; inset plots are subsets for ages below 800 Ma. Note, n is the number of analyses.

Figure 7. Tera–Wasserburg and probability vs. age diagrams for samples LM1 and LM2 from the bottom of the Magallanes basin in the Lago Mercedes area; inset plots are subsets for ages below 800 Ma. Note, n is the number of analyses.

Figure 8. Multiple age histograms and probability plots for the different tectonostratigraphic units for the restricted age interval 100–800 Ma.

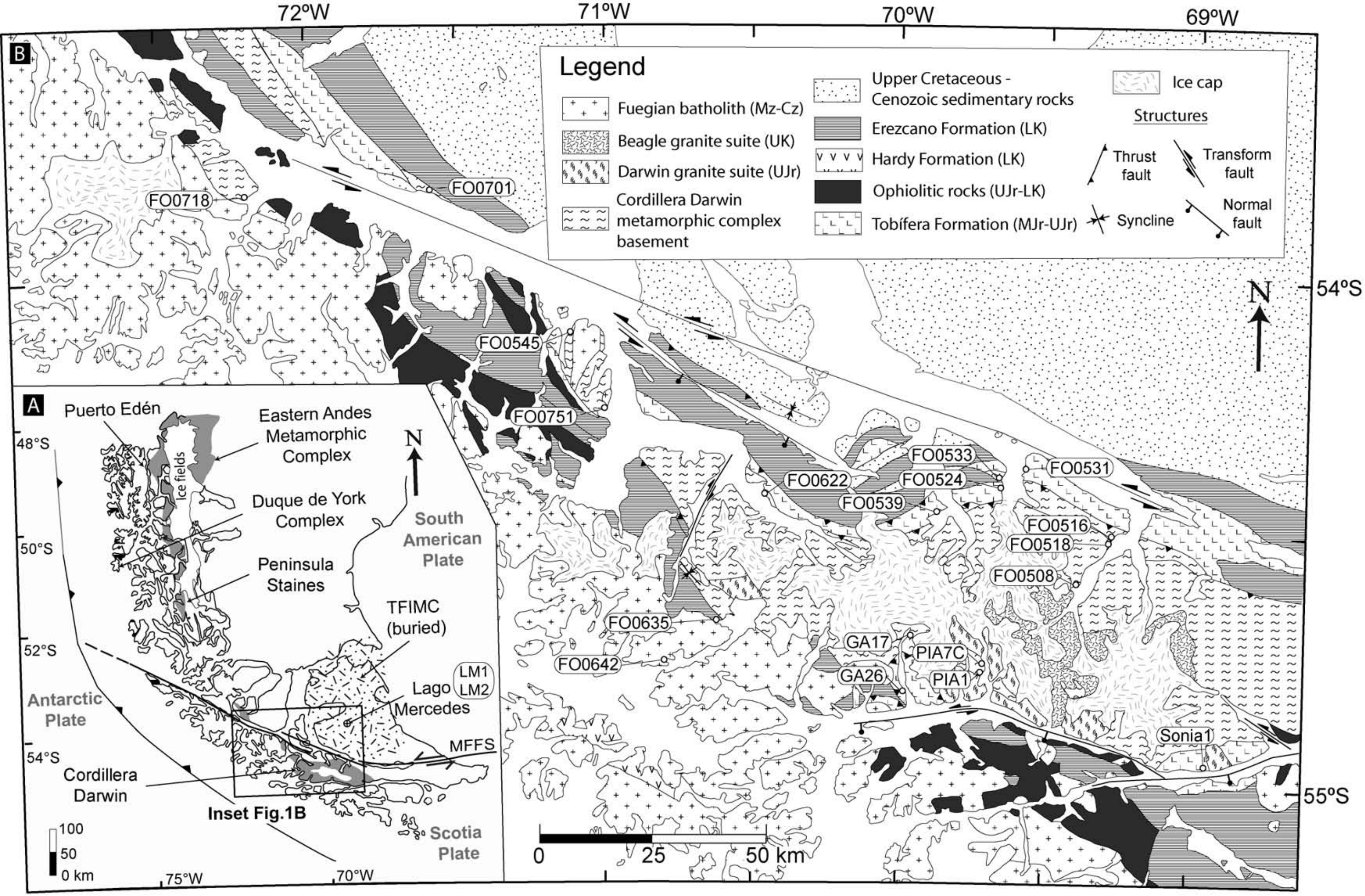


FIGURE 1. Hervé et al.

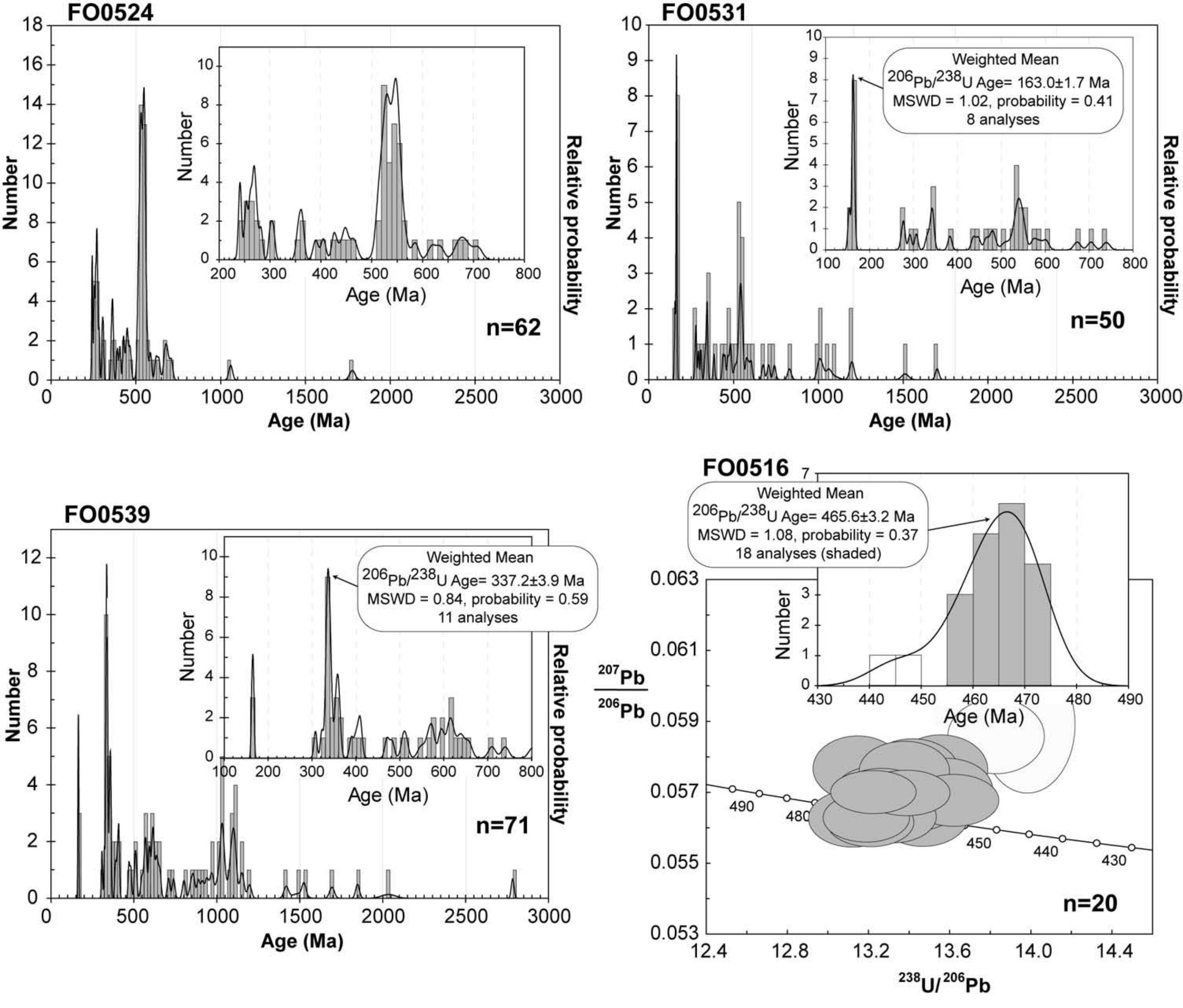
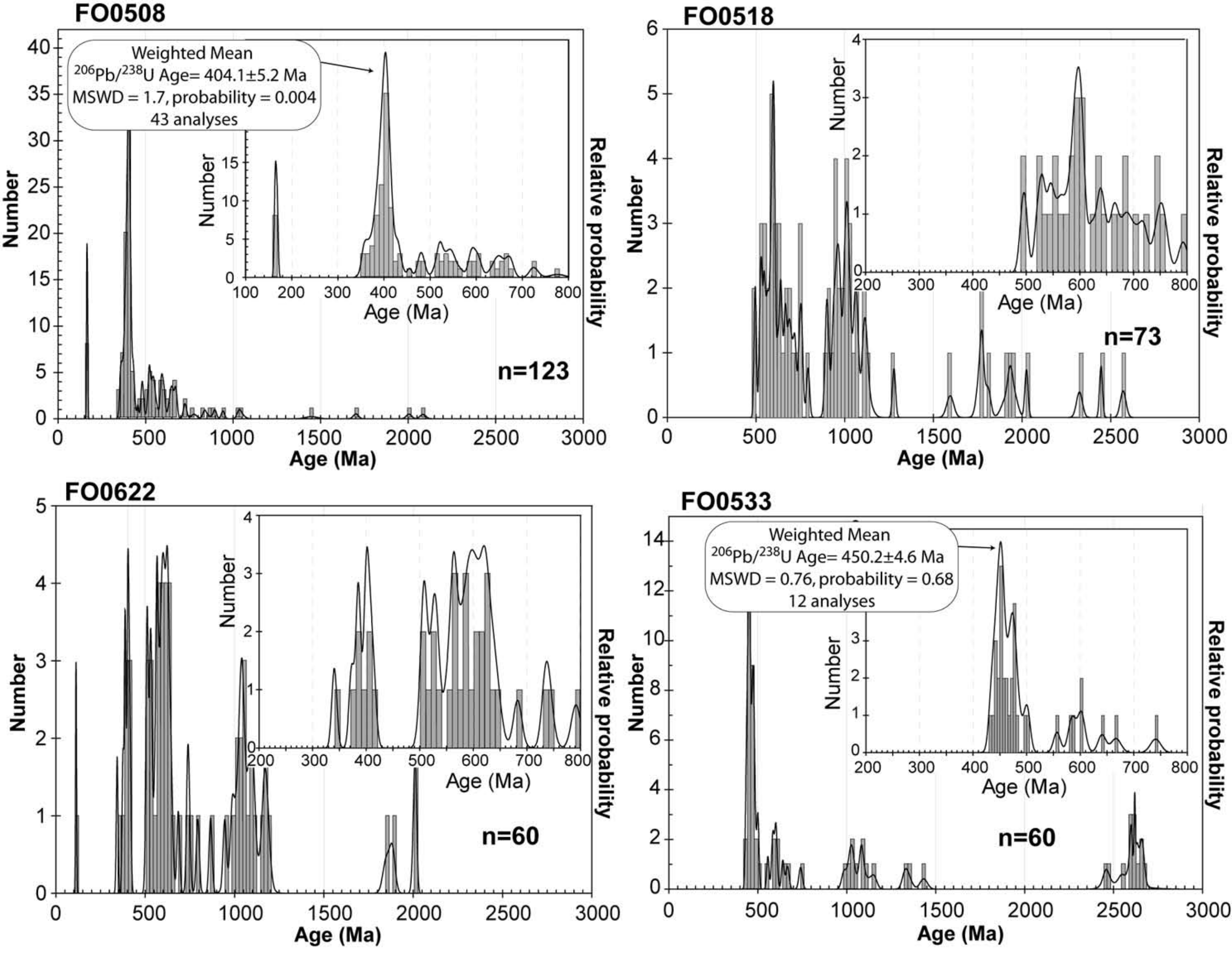


FIGURE 2. Hervé et al.



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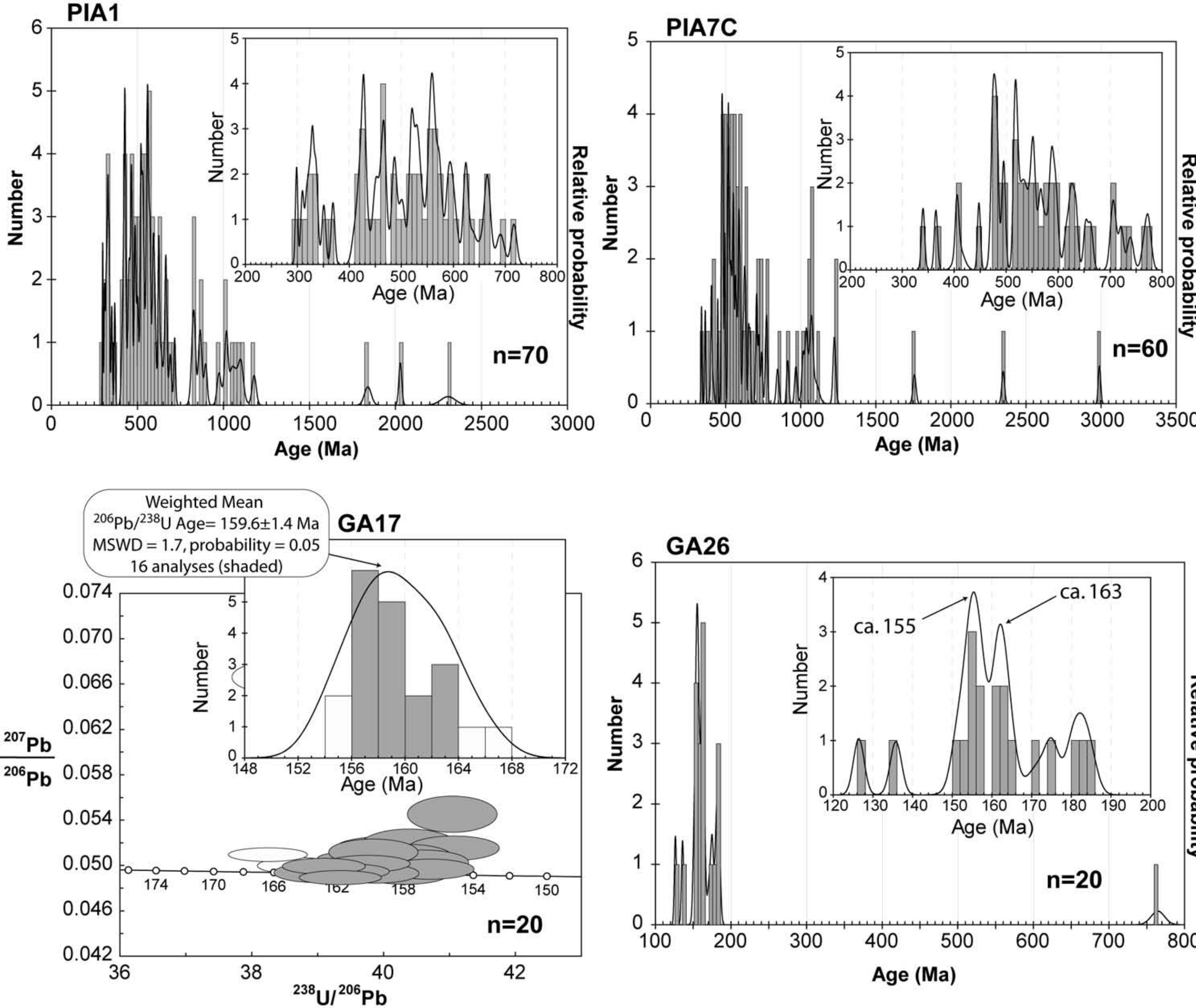
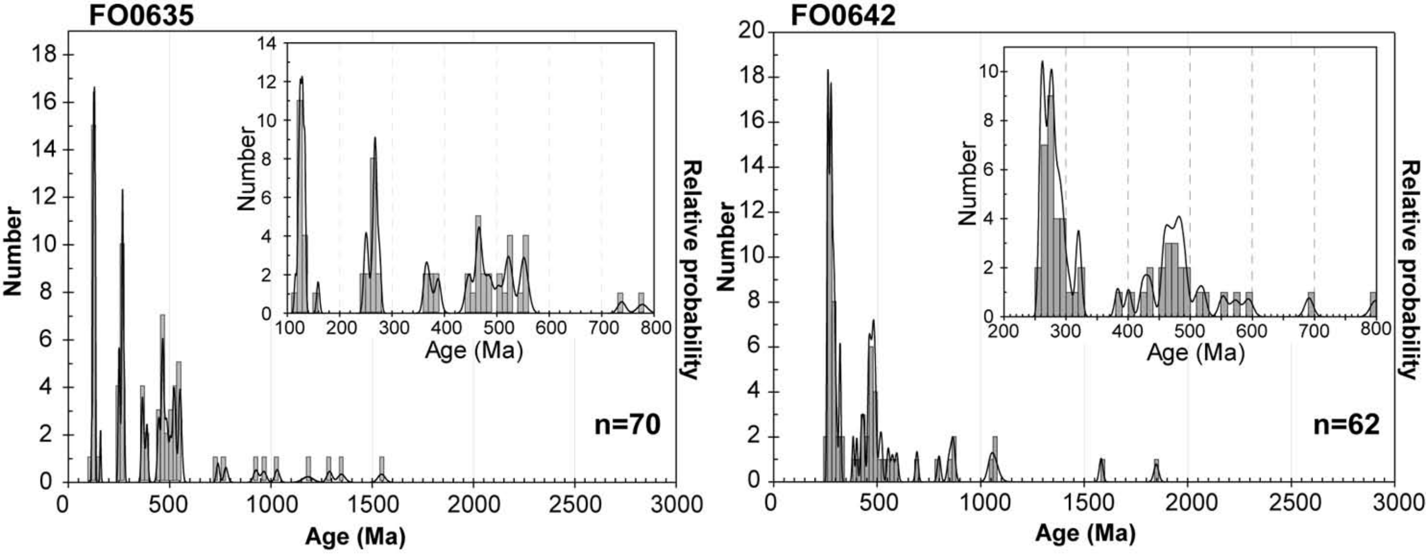


FIGURE 4. Hervé et al.



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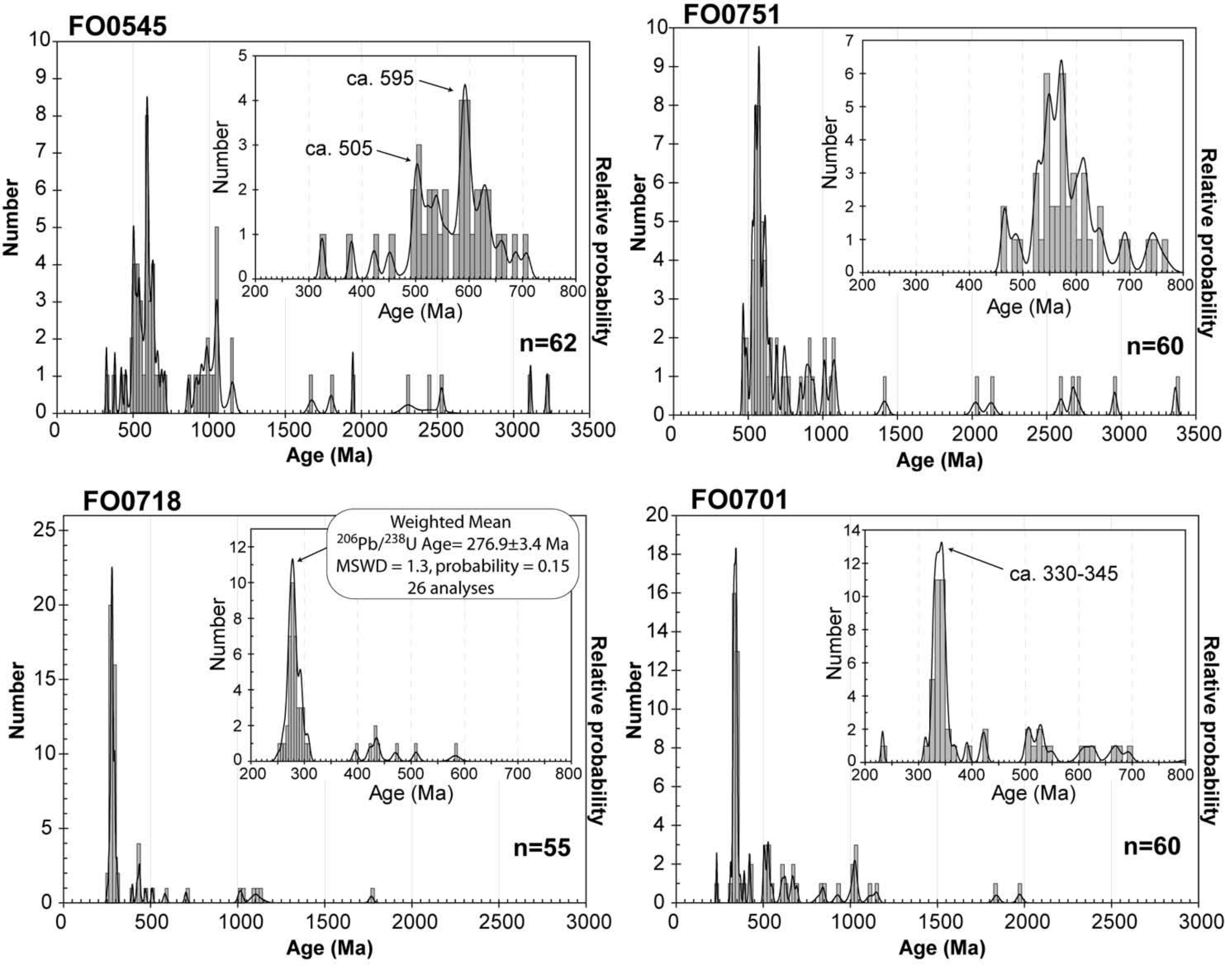

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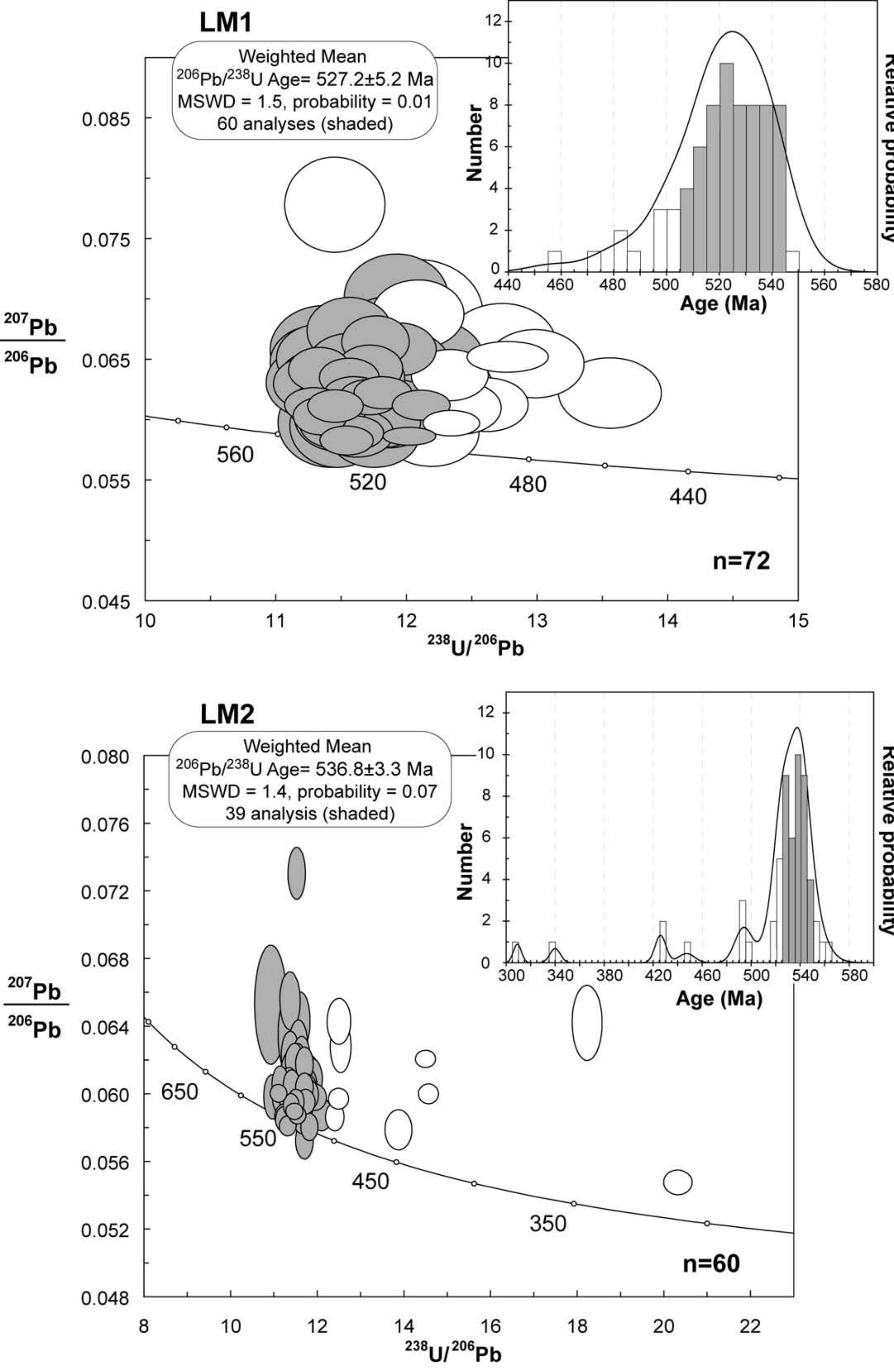

FIGURE 7. Hervé et al.

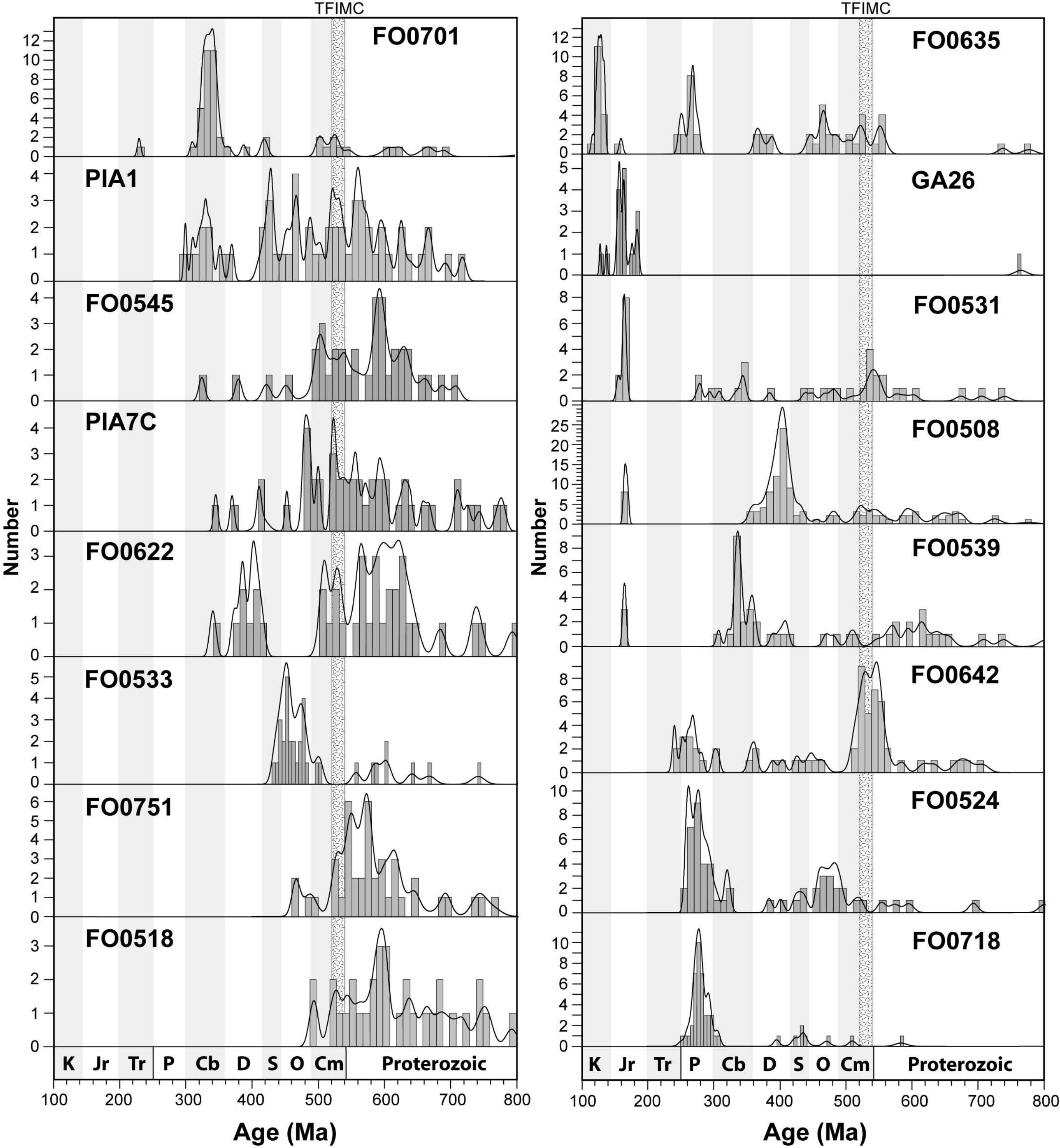

Figure 8. Hervé et al