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Age Constraints on the Tectonic Evolution and Provenance of the Pie de Palo Complex, Cuyania Composite Terrane, and the Famatinian Orogeny in the Sierra de Pie de Palo, San Juan, Argentina

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Abstract

New U-Pb age determinations confirm earlier interpretations that the strongly deformed and metamorphosed mafic and intermediate igneous rocks of the Pie de Palo Complex represent a Mesoproterozoic fragment of suprasubduction zone oceanic crust.

A gabbroic pegmatite, interpreted to have formed during arc rifting or subsequent back-arc spreading, yielded a U-Pb age of 1204 $^{+5.3}/_{-4.7}$ Ma. Highly tectonized ultramafic-mafic cumulates, occurring at the structural base of the Pie de Palo Complex and previously interpreted to represent remnants of a primitive arc phase, prior to rifting and back-arc spreading, could not be dated, but should be older than 1204 Ma if these inferences are correct. Tabular, sill-like bodies of leucogabbro/diorite and calc-alkaline tonalite/granodiorite sills yielded ages of 1174±43 and 1169 $^{+8}/_{-7}$ Ma respectively. They may represent a younger, more evolved arc phase established after arc rifting or a younger, tectonically unrelated Mesoproterozoic arc. SHRIMP-analysis of metamorphic zircon rims with low Th/U ratios in VVL 110 gave a $^{206}Pb/^{238}U$ age of 455±10 Ma, similar to lower intercept dates determined by discordia lines. Combined, these data indicate that the bulk of the amphibolite facies metamorphism present in the Pie de Palo Complex was generated during the Famatinian Orogeny.

Analysis of six single detrital zircon grains in a metasedimentary, quartzofeldspathic garnet-mica schist, tectonically interleaved with the igneous rocks of the Pie de Palo Complex, and tentatively correlated with the Difunta Correa metasedimentary sequence of other workers, yielded three age populations: 1150–1160 Ma; 1050–1080 Ma and 665 Ma, indicating that these sedimentary rocks were deposited during the late Neoproterozoic or Early Paleozoic. In addition, they confirm structural evidence that intercalation of rocks of the Pie de Palo Complex with isolated slivers of these sedimentary rocks is due to tectonic imbrications. These ages are also consistent with a Laurentian provenance, and earlier interpretations that these rocks once represented a sedimentary cover to the Pie de Palo Complex. The zircon population of 1050–1080 Ma could be derived from Grenville-age felsic plutons identified elsewhere in the Pie de Palo Complex by other workers. However, no evidence has been found in our samples for a Grenville-age orogenic event, invoked previously to explain accretion of the oceanic Pie de Palo Complex to Laurentia prior to the late Neoproterozoic/Early Cambrian rifting and drift of Cuyania.

Key words: Cuyania, Grenville, island arc, back-arc, ophiolite.

Introduction and Regional Setting

The provenance, mode and timing of accretion of the Cuyania composite terrane in west-central Argentina are matters of considerable debate. One hypothesis, based on mainly Cambrian-Ordovician paleontological and stratigraphic arguments, interprets Cuyania as an allochthonous Laurentian block, that either drifted across Iapetus independently as a microcontinent (e.g., Ramos et al., 1986; Astini et al., 1995; Rapela et al., 1998; Astini and Thomas, 1999; Thomas et al., 2002; Thomas and Astini, 2003), or was left behind following a short-lived Middle to Late Ordovician Laurentian-Gondwana (Famatinian) collision, and subsequent rifting (e.g., Dalla Salda et al., 1992a, b; Dalziel, 1997). An alternative hypothesis involves a low-latitude, peri-Gondwanan provenance with accretion mainly due to Ordovician-Devonian margin-parallel strike-slip movements (e.g., Aceñolaza et al., 2002; Finney et al., 2003). However, earlier evidence for a Gondwanan provenance on basis of detrital zircon studies is severely weakened, because of accidental switching of samples during analysis (Finney et al., 2004). Furthermore, a Gondwanan provenance and Paleozoic accretion solely by strike-slip faulting fails to explain the evidence for the deep metamorphic burial (garnet-albite-amphibolites) as a result of Middle Ordovician, east-directed underthrusting of Pie de Palo rocks (see below, Casquet et al., 2001 and van Staal et al., 2002).

The Cuyania composite terrane comprises the Precordillera and Pie de Palo terranes (Ramos et al., 1998; Ramos, 2004), which at present form an integral part of the Andean basement situated within the modern Pampean flat subduction segment (latitude 27°S to 33°S) (Ramos et al., 2002). Crystalline Precambrian basement is not exposed in the Precordillera terrane area, but Mesoproterozoic (Grenville) felsic to mafic xenoliths have been found in Tertiary volcanic rocks (Leveratto, 1968; Abbruzzi et al., 1993; Abbruzzi, 1994; Kay et al., 1996), which have been interpreted to represent fragments of the original basement to the Precordillera terrane. The Pie de Palo terrane occurs along the eastern margin of Cuyania, near the boundary with the adjacent Gondwanan Pampia terrane, and contains intensely polyphase deformed and metamorphosed rocks involving basement (Pie de Palo complex) and cover (Ramos et al., 1998; Casquet et al., 2001; van Staal et al., 2002), recently exhumed following Tertiary/Quaternary uplift and erosion (Ramos and Vujovich, 2000; Ramos et al., 2002). The Pampia terrane preserves the remnants of a west-facing Cambro-Ordovician magmatic arc, indicating Early Paleozoic subduction of Iapetan oceanic lithosphere beneath South American Gondwana (Pankhurst et al., 1998, 2000; Quenardelle and Ramos, 1999). A major lineament, the Desaguadero-Bermejo or Valle Fértil fault, separates the Pie de Palo and Pampia terranes.

The main exposure of the Pie de Palo terrane occurs in the Sierra de Pie de Palo, a 80 km long by 30 km wide recent structural uplift, immediately east of the city of San Juan (Fig. 1). Related small exposures of coeval igneous-metamorphic rocks have been recognized in the San Rafael and Las Matras blocks (Astini et al., 1996; Cingolani and Varela, 1999; Sato et al., 2000, 2004). The Pie de Palo terrane comprises a tectonic collage of Mesoproterozoic (McDonough et al., 1993; Ramos et al., 1993; Varela and Dalla Salda, 1993; Pankhurst and Rapela, 1998) dominantly igneous rocks of the Pie de Palo Complex, a Neoproterozoic to Lower Paleozoic metasedimentary sequence generally inferred to correlate with part of the Precordillera to the west: the Caucete Group (Borrello, 1969; van Staal et al., 2002; Vujovich, 2003) (see Fig. 2) and the Difunta Correa metasedimentary sequence (Baldo et al., 1998) or Esquistos de Bajo Grado Formation (Dalla Salda and Varela, 1984). The latter was interpreted as para-autochthonous cover over the Pie de Palo Complex because it contains Grenville-age detrital zircons metamorphosed during the Middle Ordovician (~ 460 Ma, Casquet et al., 2001). In addition, the Pie de Palo Complex is generally inferred to be the basement to the Caucete Group. The Caucete Group is generally considered to be the metamorphosed equivalent of the Paleozoic cover of the Precordillera terrane (Ramos et al., 1998; Vujovich and Kay, 1998). If correct, this firmly links the Pie de Palo and Precordillera terranes into a composite Cuyania terrane. A persistent problem is that relationships between the Caucete Group and the Pie de Palo Complex are always structural where exposed (e.g., Vujovich and Ramos, 1994) and other means are necessary to determine the relationship between these units. Deformation of the Sierra de Pie de Palo rocks is generally strong and polyphase (van Staal et al., 2002). The oldest tectonic fabric (S_1) is parallel to compositional layering (bedding) in the metasediments and is equivalent to a generally strong schistosity/gneissosity in the metaigneous rocks. S_1 is probably related to early imbrication and folded by at least three phases of folds (F_{2-4}). The first two generations of folds (F_{2-3}) are generally recumbent or strongly westerly overturned isoclinal structures, associated with late, west-directed thrusts.

The main objective of this paper is to present new U-Pb ages (TIMS and SHRIMP) and chemical data relevant to understanding the provenance, basement–cover relationships, and tectonic setting of the metamorphic basement rocks of the Pie de Palo Complex. Particularly, the U-Pb ages of the oceanic part of the Pie de Palo Complex are significant, because these units were never dated by U-Pb before. Future paper will deal with the structural history, metamorphism and tectonostratigraphy of the Caucete Group (van Staal et al., in prep).

Precise ages of the basement and cover rocks are essential for tracing correlative units in either Laurentia or Gondwana and testing and refining the tectonic model of Vujovich and Kay (1998). Their model invokes a Mesoproterozoic oceanic suprasubduction zone setting for the Pie de Palo Complex, analogous to the Tofua arc - Lau back-arc basin system (Hawkins, 1995), that collided with a continental block (basement to the future Precordillera terrane) during the Grenville orogeny. Collision was followed by formation of a Mesoproterozoic, dominantly felsic arc, whose magmas erupted through the thickened crust. The few existing igneous and metamorphic ages in the Pie de Palo Complex, which range between 1030 and

1100 Ma (McDonough et al., 1993; Pankhurst and Rapela, 1998; Casquet et al., 2001), were overall consistent with such a tectonic scenario.

Critical to understanding the tectonic setting and evolution of the Pie de Palo Complex are the relationships between the structurally lower, cumulate mafic-ultramafic sequence, interpreted to represent primitive oceanic arc basement of the remnant arc, the units integrated as a back-arc sequence (Villar, 1985; Vujovich, 1993; Vujovich et al., 1994; Vujovich and Kay, 1996, 1998; Ramos et al., 2000), and the younger felsic arc stage mainly represented by tonalite and granodiorite sills and dykes. Vujovich and Kay's model requires that (1) the bulk of the back-arc magmatic rocks should be younger than the pre-rifting,

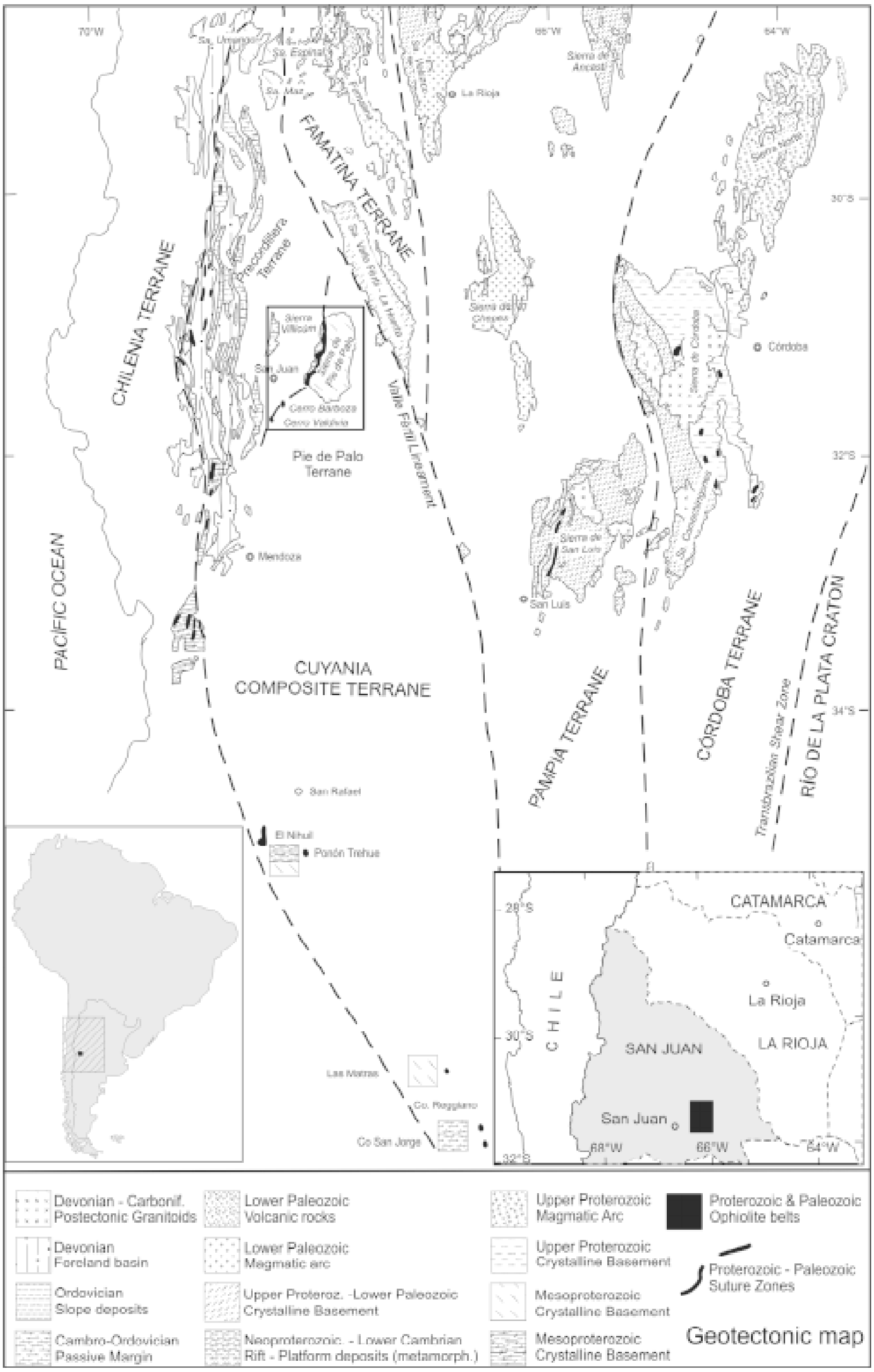

Fig. 1. Geotectonic map of southwestern South America (based on Vujovich and Ramos, 1999; western border of Córdoba terrane modified after Leal et al., 2003).

primitive arc basement preserved in their remnant arc; and (2) the arc tonalitic and granodioritic sills should be demonstrably younger than deformed rocks belonging to the oceanic suprasubduction zone system. Hence, establishment of the age relationships between the rocks, formed in these tectonic settings, is important in constraining and testing their tectonic model.

Pie de Palo Complex and Associated Rocks

The part of the Pie de Palo Complex reported on here mainly consists of a tectonic assemblage of metaigneous rocks with ultramafic to intermediate compositions and minor structurally interleaved metasedimentary rocks. This entire sequence is preserved at amphibolite facies

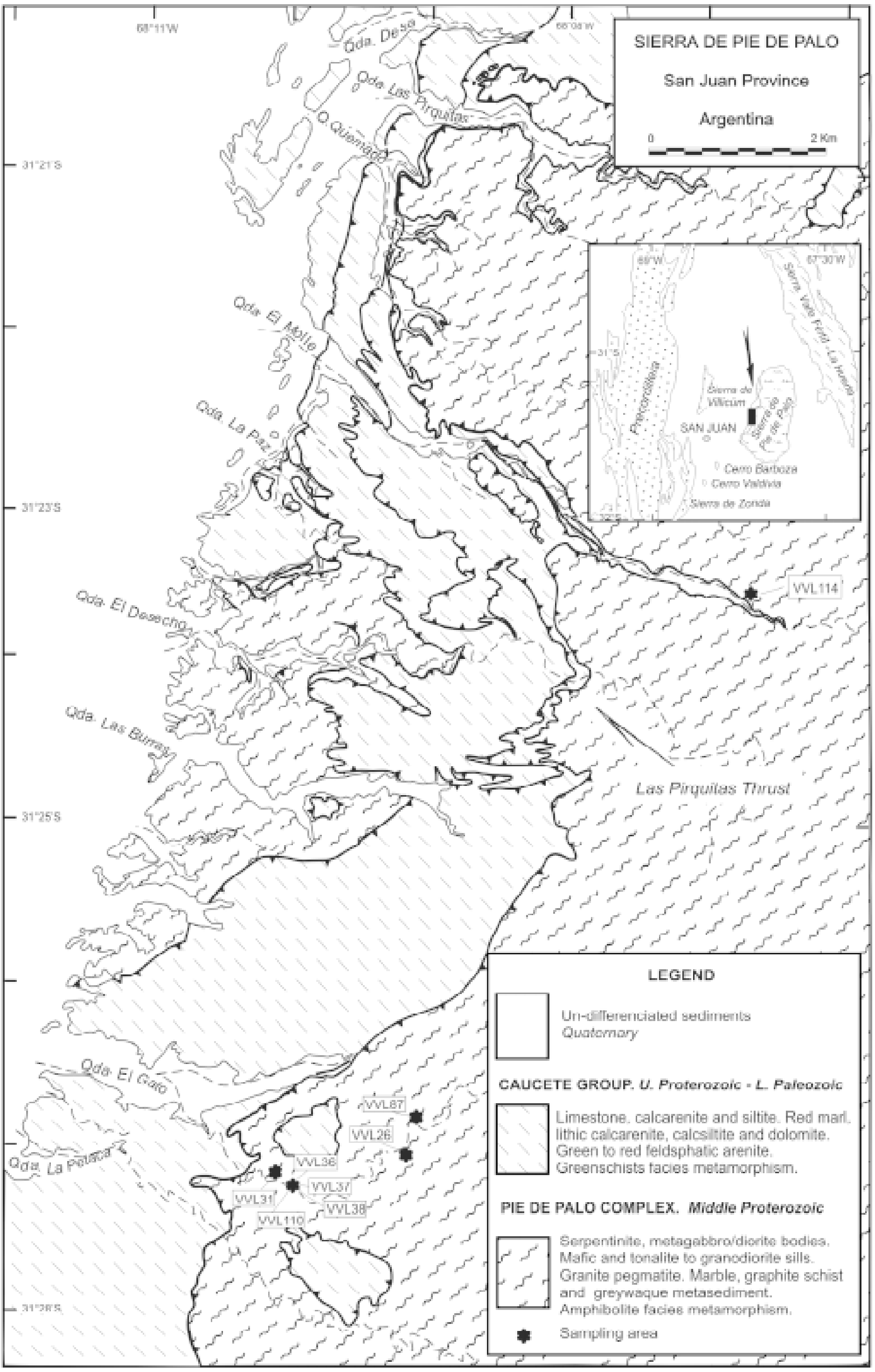

Fig. 2. Geological map of western Sierra de Pie de Palo (based on van Staal et al., in prep.).

metamorphism conditions (Dalla Salda and Varela, 1984; Ramos and Vujovich, 2000 and others therein) attained during the Ordovician (Ramos et al., 1996, 1998; Casquet et al., 2001; van Staal et al., 2002). Retrograde greenschist facies metamorphism is common in deformed rocks affected by shear zones and faults such as the Pirquitas thrust.

A Mesoproterozoic age was originally assigned to the Pie de Palo Complex, based on Rb/Sr and preliminary U-Pb age determinations of felsic intrusive bodies, (McDonough et al., 1993; Varela and Dalla Salda, 1993; Pankhurst and Rapela, 1998). However, the age of the older mafic-ultramafic rocks was poorly constrained (Ramos et al., 1998; Vujovich and Kay, 1998).

In this study we focus on the intensely folded and imbricated igneous and sedimentary rocks of the Pie de Palo Complex exposed along the western rim of the Sierra de Pie de Palo. These rocks were earlier described in detail by Vujovich and Kay (1998), and formed the basis for their Tofua arc-Lau back-arc basin analogue.

Ultramafic-mafic Rocks

Ultramafic rocks primarily occur as intensely foliated structural lenses along a more than 20 kms length between the Quebradas Piedras Pintadas and Guayaupa. They generally occur in the immediate hangingwall of the shallowly east-dipping Las Pirquitas thrust, the major structural discontinuity between the Pie de Palo Complex and the structurally underlying Caucete Group (Vujovich and Kay, 1998), and closely associated subsidiary thrust-related shear zones.

The meta-ultramafic rocks mainly comprise layered antigorite, chlorite, talc and tremolite-bearing schist best exposed between Quebrada Las Pirquitas and La Petaca (Fig. 2). Small talc-serpentinite lenses have been recognized also at Quebrada Las Pirquitas (Castro de Machuca, 1981; Castro de Machuca et al., 1995; Ramos and Vujovich, 2000 and others therein). A metapyroxenite together with chlorite-tremolite schist and scarce serpentinite schist has been described at the Cerro Valdivia (Fig. 1) by Kilmurray and Dalla Salda (1971), Vujovich (1994) and Vujovich and Kay (1998). Fine-grained, dark green hornblendite and amphibolite exposed in Quebrada del Gato, and closely associated with serpentinite, has been included in the ultramafic unit. Geochemical and petrographic studies suggest the ultramafic rocks primarily represent cumulate rocks (peridotite and pyroxenite) formed in a suprasubduction zone oceanic environment, probably near the crustal base of a primitive oceanic arc (Vujovich and Kay, 1998); the few included amphibolite lenses may represent originally crosscutting diabase and gabbroic bodies, now completely transposed into parallelism with the mylonitic fabric due to superimposed very high strains accumulated during the thrust-related shearing.

The ultramafic rocks are structurally overlain by a thick sequence of foliated and lineated, fine- to medium-grained amphibolite, which locally has retained gabbroic textures in low-strain pods. Good examples of well preserved gabbro, locally cut by diabase dykes, occur in Quebradas del Gato and La Petaca. Here, thin slivers of ultramafic-mafic cumulate rocks are repeated several times in a complexly folded imbricate zone (van Staal et al., 2002). Amphibolites form the dominant rock type of the exposed Pie de Palo Complex and comprise both compositionally layered (cumulate?) and homogeneous bodies. They mainly consist of hornblende and albite with epidote, biotite and garnet locally as important additional phases. Albitic plagioclase is locally altered to sericite and epidote, suggesting it was more calcic originally. Near the basal shear zone (Las Pirquitas thrust) and subsidiary thrust faults, the amphibolite commonly has been retrograded partially into a light green chlorite and epidote-rich greenschist. The bulk of the amphibolite in Quebradas del Gato and La Petaca probably represents metamorphosed cumulate and isotropic gabbro and diorite bodies. However, small lenses of amphibolite interlayered with calcite-rich marble (Fig. 3), preserved in the imbricate zone in Quebradas del Gato and La Petaca, suggest that at least part of the amphibolite may represent metabasalt that was extruded nearly contemporaneously with local deposition of limestone; an association that also occurs in some modern seamounts.

Vujovich and Kay (1998) divided the amphibolites on the basis of their composition into a remnant arc and a younger rifted-arc/back-arc stage, although the implied age relationship between these two groups could not be corroborated by field relationships due to the high strain accumulated in the rocks.

Fig. 3. Strongly foliated amphibolite interlayered with marble in Quebrado del Gato. Amphibolite is interpreted to represent metabasaltic flow, because of its intimate association with marble.

To better constrain the age of the pre-rifting arc and/ or back-arc phase, we sampled a pegmatite phase (VVL 37) of one of the low-strain, non-layered gabbroic bodies (VVL 38), and a leucocratic gabbro/diorite (VVL 36 and 110) that intruded it (see Fig. 4). The samples were collected in Quebrada del Gato, about 100 meters from the highly strained cumulate ultramafic rocks with arc signatures described by Vujovich and Kay (1998). Geochemical investigations were carried out to test whether these rocks belong to the arc or back-arc phase.

Mafic sills

Fine- to medium-grained, amphibolite sills, up to 20 m thick, are abundant in the central part of the Cerro Valdivia (Fig. 1) where they intrude garnet-muscovite-biotite schists. Hornblende and plagioclase are the main mineral phases displaying a nematoblastic texture together with quartz and rare epidote crystals. Biotite and almandine-rich garnet are common. Titanite, apatite and opaque are common accessory minerals.

Tonalite-granodiorite sills

Tabular, white to greenish gray felsic sills (Fig. 5), and less commonly dykes (Fig. 6), with thickness up to tens of meters, occur throughout the Pie de Palo Complex and intrude the amphibolite. The main mineral constituents are sub-euhedral, Na-rich plagioclase, quartz, biotite, hornblende and epidote. Garnet occurs locally. Intrusive crosscutting relationships such as nearly undeformed mafic-ultramafic xenoliths of variable size (Fig. 6) have been preserved locally in low-strain pods, particularly in the interior parts of Quebrada del Gato. The sills and dykes are generally overprinted by the deformation structures and metamorphism present in the host mafic rocks (Fig. 7), although in low strain areas, the main foliation in the host gabbro is less strongly developed or absent, and locally the dykes and sills appear to cut through a weak foliation (Fig. 6) These felsic intrusives thus may post-date part of the earliest deformation recorded in the host mafic rocks. However, it cannot be overruled at present that the mineralogy of the felsic intrusives, which is dominated by quartz and feldspar, may have prevented development of observable mesoscopic structures, other than the noticeable ductile-brittle faults (Fig. 6), in areas of relatively low strain. Age relationships between the felsic intrusives and the earliest structures in the host gabbro are thus at present inconclusive.

Fig. 4. Gabbroic pegmatite (VVL37) intruding isotropic metagabbro body (VVL38) from Pie de Palo Complex at Quebrada del Gato.

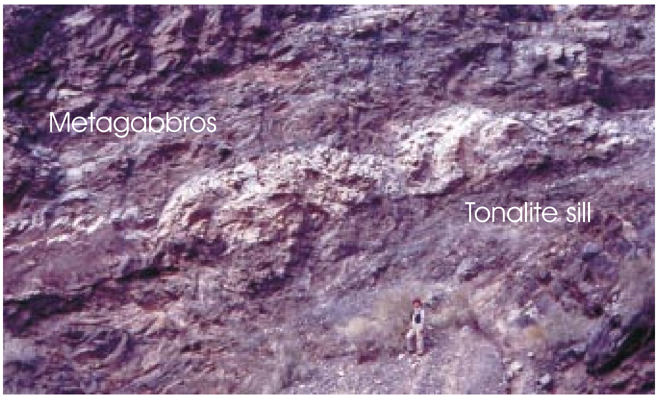

Fig. 5. Tonalite sill that has intruded metagabbro from Pie de Palo Complex in Quebrada del Gato.

A tabular-shaped, 20 m wide, light grey tonalite sill (VVL 28) was sampled from the cliff at the end of Quebrada del Gato, to constrain the age of the tonalite-granodiorite intrusive phase and to test whether it could form part of a younger calc-alkaline arc that was erupted through thickened crust following an inferred Grenville collision with the Mesoproterozoic basement of the Precordillera terrane (Vujovich and Kay, 1998). The tonalite is composed of quartz, epidote, albite and small biotite crystals. Accessory minerals are opaque, titanite and zircon.

Another set of felsic sills is represented by fine- to coarse-grained, white leucocratic pegmatite bodies, which mainly consists of plagioclase, K-feldspar and quartz, yellowish-green mica (phengite?) and scarce epidote. They generally are spatially closely associated with the Las Pirquitas thrust- related shear zones, locally cut the main foliation in the host amphibolite, which also overprints them, suggesting they intruded syntectonically during movements along the thrust-related shear zones.

Metasedimentary Rocks

The amphibolites and ultramafic rocks are locally intricately interleaved structurally on meso-and macro scale with metasedimentary rocks, particularly close to the Pirquitas thrust zone. The structural interleaving will be discussed in more detail in a forthcoming paper (van

Staal et al., in prep), but it involved at least two generations of isoclinal recumbent folds (F_2 and F_3), which probably refold an earlier thrust-related structural interleaving (see also below). The latter process produced a strong layering-parallel S_1 foliation but no folds (van Staal et al., 2002). This type of structural interleaving involved light greenish grey to reddish quartz-rich psammites (mainly feldspathic arenites) of the Caucete Group (but rarely, if ever, the calcareous rocks) and a dark grey, quartzofeldspathic muscovite-biotite-garnet schist, probably a metagreywacke. This lithology is absent in the part of the Caucete Group mapped in this study. The schist resembles rocks of the Difunta Correa sedimentary sequence described and dated with the SHRIMP by Casquet et al. (2001), and inferred to represent a cover sequence to the Pie de Palo Complex on the basis of Grenville-age (1032–1224 Ma) detrital zircons. We sampled a quartzofeldspathic mica schist (VVL 114) intercalated with mylonitic amphibolite, which we tentatively correlate with the Difunta Correa sedimentary sequence.

Geochemistry

Whole-rock chemical analyses were conducted on the dated mafic intrusive rocks (VVL 36/110, VVL37/38) together with a spatially associated partially layered (cumulate?) metagabbro (VVL87) and a younger tonalite or granodiorite sill (VVL 26), from the Quebrada del Gato. In addition, we analyzed a highly tectonized amphibolite (VVL31) interlayered with marble, interpreted as a metabasalt, from the same area. In Cerro Valdivia two mafic sills (V16 and V25) were sampled to further test correlations with rocks of the Pie de Palo Complex (Table 1). The rocks from Quebrada del Gato were analyzed by XRF and ICP-MS for major and trace elements at Memorial University of Newfoundland. The samples from Cerro Valdivia were analyzed at Activation Laboratories (Canada). XRF was used for determining major and some trace elements, and INAA for the majority of the trace and rare earth elements.

Given the evidence for strong deformation and metamorphism recorded in these rocks, we relied mainly on the more immobile elements, particularly rare earth elements (REE) and high field strength elements (HFSE) for petrological characterization.

Fig. 6. Tonalite dyke that has intruded metagabbro from Pie de Palo Complex in Quebrada del Gato. The tonalite dyke is folded into an open synform and locally slightly offset by a ductile-brittle fault. It appears to cut through a weakly developed, shallowly dipping foliation in the host gabbro.

Table 1. Chemical analyses of mafic to intermediate composition metaigneous rocks of Pie de Palo Complex (n.d.: no determinate).

Locality	Quebrada El Gato					Cerro Valdivia	
Rock type	Tonalite	Gabbro/diorite			Amphi-	Mafic	
Sample	sill				bolite	sills	
	VVL26	VVL36	VVL38	VVL87	VVL31	V16	V25
SiO_2	63.51	44.4	52.05	48.5	49.51	43.56	43.06
TiO_2	0.21	0.18	0.5	0.63	0.89	2.67	2.82
Al_2O_3	16.52	19.8	11.79	13.77	12.64	15.22	15.78
Fe_2O_3	2.63	7.04	5.37	9.17	10.6	15.27	15.14
MnO	0.03	0.11	0.12	0.2	0.19	0.22	0.31
MgO	2.01	12.2	10.7	10.03	10.04	6.87	6.84
CaO	2.34	3.27	12.18	9.98	7.81	8.39	8.51
Na_2O	8.0	3.87	3.3	2.99	3.44	3.01	3.26
K_2O	0.37	0.83	0.13	0.39	1.13	0.15	0.93
P_2O_5	0.08	0.02	0.01	0.01	0.32	0.37	0.4
Total	95.7	91.72	96.15	95.67	96.57	95.73	97.05
LOI	n.d.	n.d.	n.d.	n.d.	n.d.	1.6	1.18
Cr	3	251	112	97	430	90	89
Ni	0.2	18	6	6	57	90	84
Co	n.d.	n.d.	n.d.	n.d.	n.d.	60	61
Sc	3	18	42	41	30	36	31
V	33	209	236	274	244	270	280
Rb	8.5	11.9	1.3	9.0	19.4	11.0	7.0
Cs	0.34	0.44	0.05	0.19	0.5	0.3	0.4
Ba	132	187	18	78	506	45	64
Sr	137	211	211	292	373	298	195
Ta	0.24	0.04	0.07	0.07	0.22	0.5	0.5
Nb	2.9	0.2	0.7	0.9	2.9	6.0	8.0
Hf	3.2	0.42	1.78	1.0	1.0	3.5	3.6
Zr	91	9	19	11	38	140	156
Y	4.4	2.6	10.3	7.0	16.5	40	44
Th	2.18	0.07	0.10	0.07	0.17	0.5	0.5
U	1.12	0.07	0.06	0.07	0.12	0	0
La	7.82	1.27	1.50	0.344	12.57	9.5	9.9
Ce	16.29	2.42	4.38	1.41	28.73	25.0	25.0
Nd	6.23	1.76	4.2	2.04	19.7	17.0	19.0
Sm	1.153	0.507	1.428	0.772	4.745	5.0	5.4
Eu	0.433	0.313	0.736	0.831	1.493	1.82	2.04
Tb	0.148	0.089	0.298	0.194	0.683	1.1	1.1
Yb	0.399	0.235	0.911	0.893	1.769	3.75	3.91
Lu	0.049	0.041	0.11	0.102	0.229	0.52	0.58
Ratios							
Hf/Th	1.47	6.0	17.8	15.8	5.7	7.0	7.2
Ta/Hf	0.07	0.09	0.04	0.04	0.2	0.14	0.28
Th/Hf	0.68	0.17	0.06	0.06	0.17	0.143	0.14
Th/Ta	9.08	1.75	1.43	1.0	0.82	1.0	1.0
La/Ta	32.6	31.7	21.4	4.9	57.1	5.0	5.0
La/Yb	19.6	5.4	1.6	0.4	7.1	6.67	6.4

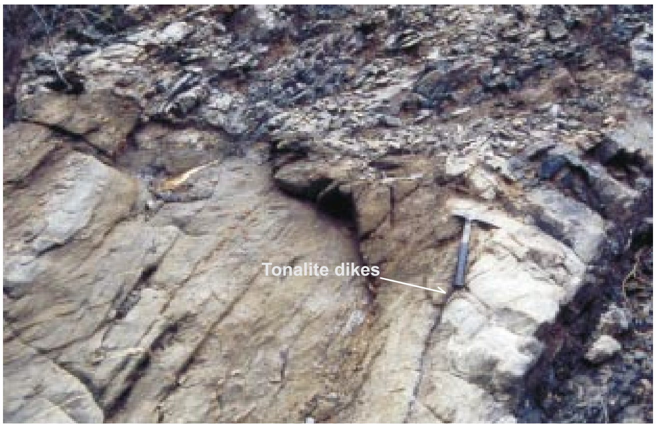

Fig. 7. Tonalite dyke in strongly foliated metagabbro of Quebrada del Gato. Dyke-gabbro contact makes a small angle with the main foliation, which is also well developed (and slightly refracted) in the tonalite.

Amphibolites

The mafic rocks mainly have subalkaline basalt compositions, based on discrimination using the Zr/Ti- Nb/Y plot of Winchester and Floyd (1977), (Fig. 8). The Hf/Th ratios (see Table 1) of the mafic rocks (Hf/Th >3) are relatively high (Figs. 9a, 10), suggesting they are tholeiitic (Wood et al., 1979).

The gabbroic to dioritic samples (VVL87, VVL38 and VVL 36) all three contain less than 20% Al_2O_3, suggesting that plagioclase accumulation, if present, was minor (Pearce, 1996). VVL 87 and 38 have relatively high Sc–contents (41–42 ppm) and moderate Cr contents (97–112 ppm), suggesting that clinopyroxene accompanied plagioclase in the igneous assemblage. Potential accumulation of clinopyroxene and olivine is considered negligible for tectonic setting determination purposes, because Sc and Ni values remain below 50 ppm and 200 ppm respectively (Pearce, 1996).

VVL38 and VVL 36 display a negative Nb-anomaly with respect to Th and Ce (Fig. 9a), consistent with the earlier interpretation that they formed in a suprasubduction zone environment, although they do not show the Th-enrichment and HFSE-depletion with respect to N-MORB typical of arc-related magmas. LREE-enrichment, a high Al_20_3 content (19.8%) and its HFSE-characteristics indicate that VVL 36 has the strongest subduction component of the analyzed gabbros. A weaker subduction component in VVL 38 is consistent with a moderate La/Ta ratio of 21.4. Arc magmas typically have La/Ta > 25–30. The more arc-like VVL 36 on the other hand has a comparatively high La/Ta ratio of 31.7. VVL 87 has the lowest La/Ta ratio (4.9) and no negative Nb-anomaly, but the interpretation of this data is suspect, because the gabbro is layered and potentially has a composition influenced by cumulate processes. The relative differences in the subduction zone component between VVL 36 and VVL 38 are consistent with their position in the Th-Ta-Hf plot (Fig. 10) of Wood et al. (1979), which is particularly good in discriminating between volcanic arc basalts and mafic rocks formed in other tectonic settings: VVL 38 (and VVL 87) plots in the field of MORB or marginal basin basalts, whereas VVL 36 plots close to the boundary with the arc field. Our limited data thus suggest that VVL 37/38 were probably generated during the back-arc rather than the preceding arc phase in the model of Vujovich and Kay (1998). Indeed, the light REE and low Th composition and the overall chemical characteristics of VVL 38 are similar to some amphibolites that crop out in Quebrada Las Pirquitas previously assigned to the back-arc stage (Vujovich and Kay, 1998).

The metabasalt interlayered with marble (VVL31), which occurs in a tectonic sliver (Fig. 3) tectonically juxtaposed against the ultramafic cumulate rocks close to the sample location of VVL 37/38, is characterized by high Cr content (430 ppm), Sc content (30 ppm) and Ni content (57.3 ppm) suggesting that clinopyroxene and olivine were primary igneous mineral phases. It has no Eu anomaly (Fig. 9a) and displays light REE enrichment and low Th (0.18 ppm), U (0.12 ppm) and Ta (0.22 ppm) contents. Furthermore, it has no negative Nb-anomaly with respect to Th, shows no marked HFSE depletion in MORB-normalized plots and falls in the E-MORB/within plate field of the Th-Ta-Hf plot (Fig. 10). These characteristics suggest it belongs to the back-arc rather than the arc-phase. Thus, with the exception of the ultramafic cumulates at the base of the thrust sheets, most mafic rocks in Quebrada del Gato appear to be related to the rifted-arc/back-arc stage rather than the preceding (now remnant) arc stage.

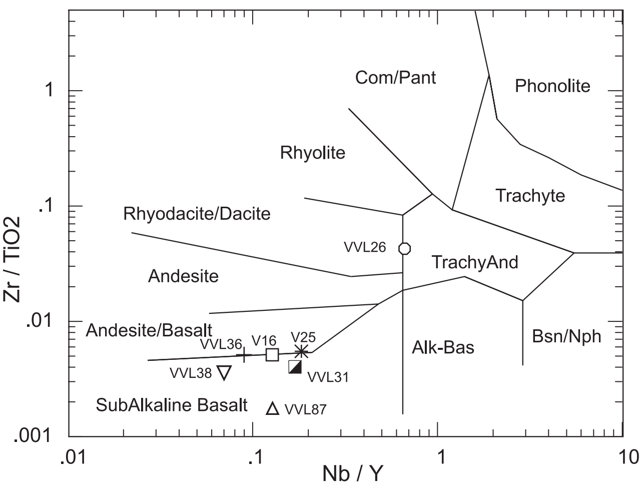

Fig. 8. Differentiation of the Pie de Palo Complex metaigneous rocks discussed in text in the Zr/TiO_2 and Nb/Y plot of Winchester and Floyd (1977).

The mafic sills from the central part of Cerro Valdivia (V16 and V25) are characterized by Th, Nb and La enrichment similar to E-MORB (Fig. 9 b) flat REE pattern (La/Yb = 2.5), and fall in the MORB/WPB field of the Th-Ta-Hf plot (Fig. 7) suggesting a non-arc environment. If these amphibolites are coeval and tectonically related to those in Sierra de Pie de Palo, they were probably generated during the oceanic back-arc spreading phase.

Intermediate composition sills

The tonalite sill (VVL26) shows an enrichment of Th, La and Ce relative to Nb and Ta on a N-MORB normalized plot (see Fig. 9c) characteristic of arc magmatic rocks. Such a setting is consistent with its relatively heavy REE depletion (La/Yb = 19.6), La/Ta ratio (31.6) and low La/Th ratio (3.6). Other tonalite sills (Vujovich and Kay, 1998; van Kleef and Lissenberg, 2001) exposed in Quebradas del Gato and Las Pirquitas display similar normalized patterns and suggest that they are consanguineous (see Fig. 9c).

In general, all these mafic to intermediate composition igneous rocks, display low high-field strength elements ratios: Th/Hf – 0.06–0.17, Ta/Hf – 0.04–0.28 and Th/Ta – 0.82–1.75 (Table 1), which are consistent with an oceanic rather than a continental setting.

Geochronology

Analytical techniques

Heavy mineral concentrates were prepared by standard techniques (crushing, grinding, Wilfley™ table, heavy liquids), and sorted by magnetic susceptibility using a Frantz™ isodynamic separator. All zircon fractions and selected titanite fractions (Table 2) were air abraded (Krogh, 1982). Analytical methods for U-Pb analyses of zircon are summarized in Roddick (1987) and Parrish et al. (1987), and for titanite in Davis et al. (1997). Analytical errors are determined based on error propagation methods of Roddick (1987). Analytical results are presented in table 2 and figures 11 and 12. A modified (York, 1969) regression method was used to calculate upper and lower concordia intercept ages (Table 2).

SHRIMP analytical procedures followed those described by Stern (1997), with standards and U-Pb calibration methods following Stern and Amelin (2003). Zircons were cast in 2.5 cm diameter epoxy mounts along with fragments of the GSC laboratory standard zircon (z6266, with $^{206}Pb/^{238}U$ age = 559 Ma). The mid-sections of the zircons were exposed using 9, 6, and 1 μm diamond compound, and the internal features of the zircons (such as zoning, structures, alteration, etc.) were characterized with backscattered electrons (BSE) utilizing a Cambridge Instruments scanning electron microscope. Mount surfaces were evaporatively coated with 10 nm of high purity Au. Analyses were conducted using an $^{16}O^-$ primary beam, projected onto the zircons at 10 kV. Mass resolution was ~5000 (1%). Off-line data processing was accomplished

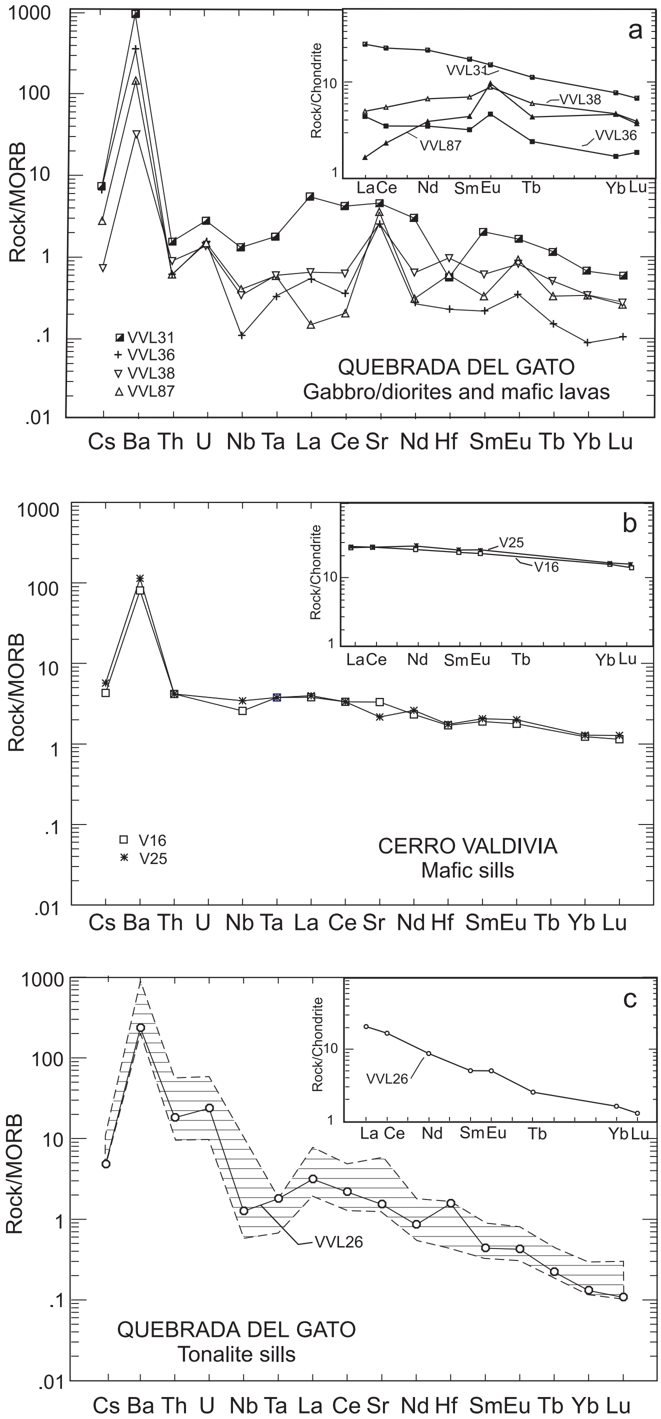

Fig. 9. a, b, c: N-MORB normalized extended trace element and Chondrite normalized REE patterns for mafic and intermediate igneous rocks of Pie de Palo Complex discussed in text (normalized values after Sun and McDonough, 1989).

Table 2. U-Pb data from Pie de Palo Complex.

Fraction[1]	#grains Description**	Wt. ug	U[a] ppm	Pb[a]* ppm	$^{206}Pb^{a}/^{204}Pb$	Pb[c] pg	$^{208}Pb^{c}/^{206}Pb$	$^{207}Pb^{2}/^{235}U$	±1 SE	$^{206}Pb^{2}/^{238}U$	±1 SE	Corr. Coeff.	$^{207}Pb^{2}/^{206}Pb$	±1 SE	Apparent Age (Ma)[3] $^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	+/-[3]	% Disc
VVL37																		
1 Z	3Z, cl, co, sub	9	221	24	935	14	0.0945	0.1065	0.0002	1.0230	0.0029	0.76089	0.06966	0.00016	652.3	918.3	9.6	30.4%
2 Z	11 Z, cl, co, sub	12	102	15	425	29	0.0577	0.1522	0.0002	1.5690	0.0060	0.78807	0.07473	0.00023	913.5	1061.4	12.5	15.0%
3 T	34 tur,pBr, fg	151	382	71	10735	63	0.0467	0.1935	0.0002	2.1160	0.0030	0.98857	0.07933	0.00003	1140.1	1180.3	1.7	3.7%
4 T	25 tur,pBr, fg	193	423	78	5559	168	0.0522	0.1893	0.0002	2.0620	0.0027	0.96259	0.07899	0.00004	1117.6	1172.0	2.0	5.1%
5 T	16 tur,pBr, fg	257	362	64	11044	93	0.0491	0.1823	0.0003	1.9700	0.0033	0.97920	0.07838	0.00004	1079.4	1156.6	1.8	7.2%
VVL-28																		
6 Z	23 cl,co,pr	14	90	15	821	16	0.045	0.1722	0.0005	1.8287	0.0110	0.72846	0.07700	0.00039	1024.6	1121.1	20.2	9.3%
7 Z	27 cl,co,el, pr	6	375	65	11175	2	0.0466	0.1797	0.0002	1.9186	0.0023	0.93095	0.07743	0.00005	1065.5	1132.2	2.3	6.4%
8 Z	29 cl,co,eu,pr	14	371	64	26617	2	0.0464	0.1798	0.0002	1.9212	0.0023	0.97468	0.07748	0.00003	1066.1	1133.7	1.7	6.5%
9 Z	17 cl,co,eu,pr	7	157	27	1509	8	0.0501	0.1766	0.0003	1.8751	0.0041	0.83485	0.07699	0.00012	1048.6	1120.9	6.5	7.0%
10 Z	17 cl,co,eu,pr	4	247	43	4014	3	0.0444	0.181	0.0002	1.9334	0.0031	0.90935	0.07744	0.00007	1072.8	1132.6	3.7	5.8%
VVL-114																		
11 Z	1 cl,co,el,pr,ro,ab	9	314	55	6175	5	0.0709	0.1781	0.0004	1.8380	0.0039	0.97895	0.07484	0.00004	1056.6	1064.2	2.5	0.8%
12 Z	3 cl,co,incl, pr,ab	14	58	11	2030	4	0.11	0.1821	0.0003	1.8930	0.0040	0.86755	0.07537	0.00011	1078.5	1078.4	5.4	0.0%
13 Z	1 cl,pBr,el,pr,ro	11	41	8	1910	3	0.2066	0.1828	0.0002	1.9090	0.0032	0.87905	0.07574	0.00008	1082.3	1088.2	4.4	0.6%
14 Z	1 cl,Br,pr	7	83	16	806	9	0.0633	0.1922	0.0004	2.0800	0.0056	0.88357	0.07850	0.00013	1133.3	1159.4	6.9	2.5%
15 Z	1 cl,pBr,eu,pr	9	53	10	311	18	0.0966	0.1833	0.0008	1.9160	0.0146	0.79738	0.07583	0.00045	1084.8	1090.6	23.5	0.6%
16 Z	1 cl,Br,el,pr,ro,ab	20	68	8	2730	3	0.1249	0.1094	0.0001	0.9310	0.0019	0.88388	0.06174	0.00008	669.2	665.2	5.8	–0.6%
17 Z	4 cl,co,el,pr,ro,ab	15	150	28	5028	5	0.0868	0.183	0.0003	1.9190	0.0031	0.93063	0.07605	0.00006	1083.6	1096.3	3.2	1.3%
18 Z	1 cl,co,incl, pr,ab	7	90	11	1510	3	0.267	0.1098	0.0002	0.9320	0.0034	0.71443	0.06154	0.00019	671.6	658.2	13.3	–2.1%
19 Z	3 cl,co,el,pr,ro,ab	12	160	32	337	73	0.1172	0.1943	0.0003	2.0860	0.0108	0.81711	0.07785	0.00033	1144.6	1143.1	16.9	–0.1%

[1] Fractions are number sequentially through the entire manuscript; [2]errors on atomic ratios are 1 s; corrected for fractionation, spike, blank common Pb (At% 208:207:206=50.97:21.36:25.29) and initial common Pb (Cumming and Richards, 1975) *=Radiogenic Pb; a=Include sample weight error of 0.001 mg in concentration uncertainty; c=Common Pb in analysis; [3] $^{206}Pb/^{238}U$ age and $^{207}Pb/^{206}Pb$ age with 2 s absolute error in Ma. 207Pb/206Pb age is 2 standard error in Ma; ** Fraction description abreviations: Mineral type: Z, zircon; T, titanite; Colour: co=colourless; Br=brown; pBr=pale brown; Clarity: Clr=clear; tur=turbid; incl=inclusions; Morphology: Eu=euhedral; El=elongate; Fg=fragment; Pr=prismatic; Sub=subhedral; ro=rounded

Table 3. ion probe data from VVL110 sample, foliated plagiogranite, of Pie de Palo Complex.

Spot name	U (ppm)	Th (ppm)	Th/U	Pb* ppm	^{204}Pb ppb	$^{204}Pb/^{206}Pb$	$\pm\, ^{204}Pb/^{206}Pb$	$f(206)^{204}$	$^{208*}Pb/^{206*}Pb$	$\pm\, ^{208}Pb/^{206}Pb$	$^{207*}Pb/^{235}U$	$\pm\, ^{207}Pb/^{235}U$	$^{206*}Pb/^{238}U$	$\pm\, ^{206}Pb/^{238}U$	Corr. Coeff.	$^{207*}Pb/^{206*}Pb$	$\pm\, ^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$\pm\, ^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	$\pm\, ^{207}Pb/^{206}Pb$	Disc. (%)
7223-1.1	405.9	46.9	0.119	78	1	0.00001843	0.00001286	0.00032	0.0364	0.0007	2.237	0.027	0.2012	0.0021	0.9162	0.08064	0.00040	1182	11	1213	10	97.4
7223-5.1	123.0	31.2	0.262	23	2	0.0001169	0.00005791	0.00203	0.0796	0.0030	2.027	0.038	0.1907	0.0021	0.6767	0.07712	0.00107	1125	11	1124	28	100
7223-8.1	153.9	59.3	0.398	30	2	0.00008836	0.00003555	0.00153	0.1265	0.0035	2.001	0.038	0.1857	0.0020	0.6674	0.07812	0.00111	1098	11	1150	28	95.5
7223-12.1	311.9	54.7	0.181	55	4	0.00007975	0.00001873	0.00138	0.0537	0.0012	1.893	0.028	0.1812	0.0021	0.8526	0.07576	0.00059	1074	11	1089	16	98.6
7223-7.1	133.4	56.4	0.436	25	1	0.00005696	0.00008088	0.00099	0.1355	0.0047	1.871	0.047	0.1792	0.0025	0.6393	0.07572	0.00149	1063	14	1088	40	97.7
7223-2.1	25.4	8.5	0.343	5	1	0.00028886	0.00028574	0.00501	0.1012	0.0111	1.889	0.121	0.1780	0.0027	0.3576	0.07696	0.00463	1056	15	1120	125	94.3
7223-11.1	283.4	55.1	0.201	49	3	0.00006566	0.00004129	0.00114	0.0581	0.0019	1.844	0.040	0.1772	0.0020	0.6305	0.07548	0.00128	1052	11	1081	34	97.3
7223-6.1	217.9	75.8	0.360	39	3	0.00007756	0.00005196	0.00134	0.1094	0.0024	1.848	0.038	0.1750	0.0021	0.6841	0.07659	0.00116	1040	12	1110	31	93.6
7223-9.2	54.6	15.8	0.299	9	2	0.00019917	0.00017063	0.00345	0.0930	0.0070	1.754	0.072	0.1669	0.0022	0.4338	0.07623	0.00284	995	12	1101	77	90.4
7223-9.1	88.6	29.1	0.340	14	4	0.00029146	0.0000951	0.00505	0.1067	0.0042	1.588	0.051	0.1612	0.0020	0.4995	0.07147	0.00202	963	11	971	59	99.2
7223-3.1	275.7	1.2	0.005	19	1	0.00007361	0.00006028	0.00128	0.0022	0.0024	0.598	0.016	0.0756	0.0011	0.6253	0.05736	0.00120	470	6	505	47	92.9
7223-4.1	234.9	0.7	0.003	15	3	0.00023123	0.00007225	0.00401	-0.0033	0.0027	0.539	0.015	0.0714	0.0009	0.5575	0.05473	0.00131	444	6	401	55	110.7

Notes (see Stern, 1997; Stern and Amelin, 2003 for analytical details) Uncertainties reported at 1s (absolute) and are calculated by numerical propagation of all known sources of error. Calibration standard: BR266 - Age 559.0 Ma; 206Pb/238U = 0.09059; error 1.0% F206204 refers to mole fraction of total 206Pb that is due to common Pb, calculated using the 204Pb-method; common Pb composition used is the surface blank: 4/6: 0.05770; 7/6: 0.89500; 8/6: 2.13840 Concordance relative to origin = 100 * (1-(206Pb/238U age)/(207Pb/206Pb age) using customized in-house software. The 1σ external errors of $^{206}Pb/^{238}U$ ratios reported in table 3 incorporates a $\pm$1.0 % error in calibrating the standard zircon (see Stern and Amelin, 2003). No fractionation correction was applied to the Pb-isotope data; common Pb correction utilized the measured $^{204}Pb/^{206}Pb$ compositions of surface Au. Isoplot v. 2.49 (Ludwig, 2001) was used to generate concordia plot and regression.

Sample VVL37: gabbroic pegmatite

Sample VVL37 is a 1.5 m wide coarse-grained plagioclase-hornblende gabbro pegmatite in a finer grained isotropic gabbro (VVL 38) described above.

Zircon and titanite were recovered from this sample. Five analyses of zircon and titanite are discordant with $^{207}Pb/^{206}Pb$ ages ranging from 1180 to 918 Ma. Zircon is generally of poor optical quality and is more discordant than titanite. The titanites have low common Pb contents and range from 4 to 7% discordant. Regression of the three-titanite fractions yields an upper intercept age of 1202 $^{+5.3}/_{-4.7}$ Ma and a lower intercept of 488$\pm$43 Ma (MSWD = 0.01). The lower intercept is within error of the age estimate for Ordovician metamorphism in the area (see below) and the discordia is interpreted to indicate Pb-loss or recrystallization during the Ordovician. One of the zircon analyses plots on the same regression and when regressed together with the titanite gives an age of 1204 $^{+4.3}/_{-3.9}$ Ma (Fig. 11); whereas the most discordant analyses plots below the discordia, probably due to a component of recent Pb-loss. The 1204 $^{+4.3}/_{-3.9}$ Ma is interpreted as the best estimate for the igneous crystallization age of the gabbro pegmatite.

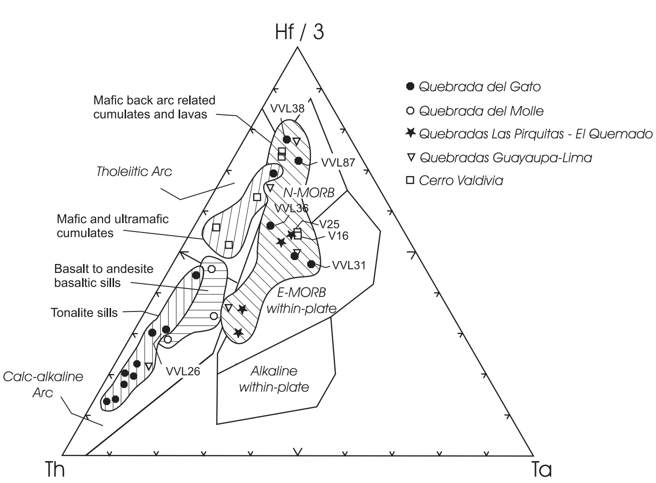

Fig. 10. Th-Hf/3-Ta plot (Wood et al., 1979) showing distribution of igneous rocks of Pie de Palo Complex. Points labeled with sample numbers are mentionated in text. Data from Vujovich and Kay (1998) are included for comparison.

Sample VVL 110: foliated leucogabbro/diorite

Sample VVL110 is a medium-grained foliated leucogabbro/diorite that occurs as a sheet-like body in gabbro correlated with VVL 38. The main minerals are plagioclase, light green hornblende and very scarce quartz. Titanite and zircon are accessory minerals. Albite, epidote, chlorite, and white mica are secondary minerals replacing the igneous plagioclase.

Zircons consist of euhedral to subhedral crystals some of which have discrete rims. Owing to the small number of zircons recovered and to the presence of overgrowths, U-Pb analytical work was carried out using the SHRIMP II ion microprobe. Analyses of igneous cores exhibit a range of $^{207}Pb/^{206}Pb$ ages between 950 and 1200 Ma. Two analyses of recrystallized outer zones that truncate internal growth zoning yield a weighted mean $^{206}Pb/^{238}U$ age of 455$\pm$10 Ma. These two analyses have very low Th/U ratios typical of recrystallization under metamorphic conditions. The data define a linear regression with an upper intercept of 1174$\pm$43 Ma and a lower intercept of 469$\pm$65 Ma (Fig. 11). The upper intercept is interpreted as the igneous crystallization age of the leucogabbro/diorite; with a metamorphic overprint at circa 455 Ma. The two dates are within error of each other; the 455 age is preferred as it is more precise and likely more accurate as it is a direct measurement of the rims.

VVL28: tonalite sill

The tonalite mainly contains quartz, epidote and albite pseudomorphs after primary plagioclase and small biotite crystals. Accessory minerals are opaque, titanite and zircon.

Five, multi-grain fractions of euhedral, prismatic zircons yield variably discordant results between 6 and 9% discordant. The data define a five point linear regression with an upper intercept of 1172 $^{+96}/_{-32}$ Ma and a lower intercept of 481 Ma (MSWD 1.9). The lower intercept is interpreted to reflect partial Pb-loss during Ordovician metamorphism. A more precise age estimate of 1169 $^{+8}/_{-7}$ Ma is obtained if the lower intercept is fixed at 460$\pm$50 Ma; a reasonable estimate for the time of the metamorphic disturbance (MSWD=1.43;) given our 455$\pm$10 Ma age on the metamorphic zircon rims, and a previous estimate of circa 460 Ma given by Casquet et al. (2001).

VVL114: biotite-muscovite-garnet schist

The biotite-garnet schist was sampled in Quebrada del Molle (Fig. 2) and occurs as a few meters thick, isolated lense interleaved with Pie de Palo amphibolites in mylonites associated with the Las Pirquitas thrust system.

The schist contains large zircon grains of diverse morphological types that range from euhedral grains with sharp terminations (#15) to rounded and pitted grains

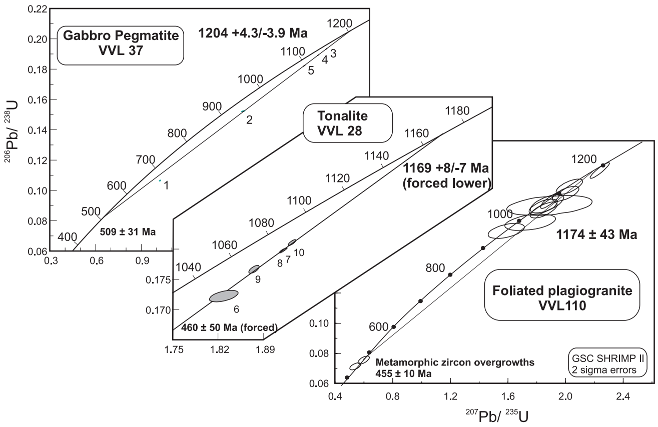

Fig. 11. Concordia plots of U-Pb isotopic data (TIMS and SHRIMP) from mafic rocks and tonalite sills of Pie de Palo Complex.

indicating a high degree of mechanical rounding and pitting (#16). Six single grain analyses range in age from 1160 Ma to 670 Ma (Fig. 12). The youngest grains are slightly reversely discordant and give a weighted mean $^{207}Pb/^{206}Pb$ age of 664±5 Ma. Three multi-grain analyses (#12,17,19) have composite ages of c. 1100 Ma, consistent with the single grain analyses. Although the dataset is limited there is no apparent correlation between age and degree of rounding as both younger and older grains show variable rounding. The youngest detrital grain in the sample provides a maximum depositional age of ~670 Ma, and demands that intercalation of the schists and Pie de Palo amphibolites is tectonic, consistent with field-evidence for tectonic imbrication.

Interpretation of the Ages

Pie de Palo igneous rocks

The U-Pb ages presented above provide age constraints on the life span of the Pie de Palo Complex and have implications for its tectonic evolution. The highly tectonized ultramafic-mafic arc cumulate sequence exposed in Quebrada del Gato, previously interpreted to represent the remnant arc after back-arc spreading and retreat of the active arc (Tofua stage) towards the trench, could not be dated due to a lack of suitable rocks. Instead, we investigated rocks in the adjacent, in part less deformed sequence of homogeneous and layered gabbroic rocks and associated metabasalt in Quebrada del Gato in the hope that they would comprise a mixed sequence. The composition of the oldest gabbro phases and associated metabasalts of this sequence, however, suggest they are all related to the rifted-arc/back-arc phase of Vujovich and Kay (1998) rather than the remnant arc phase. Hence, in this tectonic scenario, the 1204 $^{+5.3}/_{-4.7}$ Ma crystallization age of VVL 37 constraints the timing of back-arc rifting and provides a minimum age of the early arc stage of the Pie de Palo Complex. The tonalite/granodiorite sills and dykes are constrained by the 1169 $^{+8}/_{-7}$ Ma age of VVL 28. Chemistry and field relationships suggest that the more arc-like leucogabbro/diorite (VVL 110), which has an age of 1174±43 Ma, also belongs to this arc stage. Both ages have large error ranges and at least in part overlap with the age of the back-arc gabbro. Hence, they do not help discriminate whether these felsic intrusives represent part of a younger, unrelated arc erupted through thickened crust following a collision between the oceanic Pie de Palo Complex and the Mesoproterozoic basement of the Precordillera terrane as speculated by Vujovich and Kay (1998), or form part of a more mature stage in the evolution of the active arc (Tofua arc stage) after initial back-arc spreading. Field relationships are also ambiguous in this matter, because the evidence for ductile Mesoproterozoic deformation in the Pie de Palo Complex before intrusion of the tonalite and granodiorite sills and dykes is at present weak or absent.

Metasedimentary rocks

The youngest detrital grain in the garnet-mica schist (VVL 114) provides a maximum Neoproterozoic depositional age of 665±6 Ma. This demands that intercalation of the schists and the much older Pie de Palo amphibolites is tectonic, probably a result of D_1 thrust-imbrication (van Staal et al., 2002) because both rocks were intercalated prior to being folded by F_2. Thus, the bulk of the penetrative, polyphase ductile deformation recorded by rocks of the Pie de Palo Complex is Paleozoic, probably Middle Ordovician on the basis of our metamorphic zircon rims (VVL 110) and lower intercept ages. The main

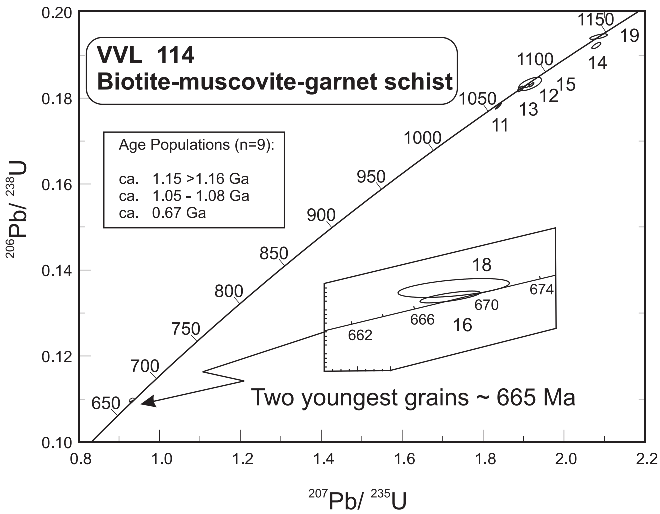

Fig. 12. Concordia plots of U-Pb isotopic data (TIMS) for detrital zircons from foliated quartzite (Difunta Correa Unit?) structurally interleaved with Pie de Palo Complex.

population of detrital zircon grains has Mesoproterozoic ages; the oldest age is c. 1160 Ma. Although the number of grains analyzed is not high, the Mesoproterozoic detrital zircon ages are consistent with predominantly sourcing the calc-alkaline felsic members of the Pie de Palo Complex and younger felsic plutons dated by McDonough et al. (1993). The greywacke protolith of the schists could thus have been deposited on part of the Pie de Palo Complex as proposed by Casquet et al. (2001) for correlative rocks of the Difunta Correa metasedimentary sequence. The similar age range of the detrital zircons in the Difunta Correa metasedimentary sequence (1032–1224) lends weight to such an interpretation.

The overall age range of the detrital grains is also consistent with a Laurentian provenance. The ~665 Ma of the youngest detrital grain in VVL 114 is rare in Late Neoproterozoic-Early Paleozoic Laurentian clastic sediments, but both Cawood and Nemchin (2001) and McLennan et al. (2001) have found within error range similar detrital zircons in late Neoproterozoic-Cambrian Laurentian passive margin sediments of the New England and Newfoundland Appalachians. Rift-induced magmatism related to the break-up of Rodinia and the opening of Iapetus lasted from circa 770 to 550 Ma in Laurentia (Cawood et al., 2001; Su et al., 1994, Aleinikoff et al., 1995) and, involved at least two major pulses. The earliest pulse of rift-related magmatism include the 680±4 Ma Suck Mountain granite in the Southern Appalachians (Tollo et al., 2004), which is nearly coeval with the youngest detrital zircon grain in VVL 114. As yet unidentified correlative igneous rocks elsewhere in Laurentia could have been the source of these detrital zircons.

Conclusions

The new Mesoproterozoic U-Pb ages presented for the Pie de Palo Complex, Pie de Palo terrane (Cuyania) in west-central Argentina indicate that an oceanic arc/backarc complex existed by at least 1204 Ma. Following the model of Vujovich and Kay (1998), this age constraints the timing of arc rifting and back-arc spreading with an active, dominantly calc-alkaline arc migrating trenchward. The c. 1170 Ma tonalitic-granodioritic sills and dykes may represent an evolved part of the active arc (Tofua) stage formed during and after back-arc spreading or a tectonically unrelated arc as suggested by Vujovich and Kay (1998).

Metamorphic zircon rims on igneous zircon grains and lower intercept of both zircon and titanite indicate that a major thermal event took place during the Middle Ordovician (455–470 Ma), probably as a result of the Famatinian collision between the Gondwanan Pampia terrane and Cuyania. No evidence has been found in our Pie de Palo Complex samples for a Grenville tectonothermal event, contrary to previous inferences by Casquet et al. (2001) and Vujovich and Kay (1998). Such an event was invoked to explain amalgamation with Mesoproterozoic continental crust of the future Precordillera terrane. The Grenville and late Neoproterozoic (~665 Ma) detrital zircon ages of the Difunta Correa sedimentary sequence are compatible with a Laurentian provenance, consistent with other evidence that indicates that Cuyania represents an exotic Laurentian fragment in South America.

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References

Abbruzzi, J.M. (1994) The chemistry, Pb isotopic signature, and age of the Central Andean Precordillera Basement: implications for "flat-slab" volcanic rocks and Laurentia-Gondwana connections. M. Thesis., Cornell Univ., (unpub.), Ithaca, 113p.

Abbruzzi, J.M., Kay, S.M. and Bickford, S.M. (1993) Implications for the nature of the Precordilleran basement from the geochemistry and age of Precambrian xenoliths in Miocene volcanic rocks, San Juan province. 12° Cong. Geol. Argentino and 2° Cong. Explorac. Hidrocarburos, Actas, 3, pp. 331-339.

Aceñolaza, F.G., Miller, H. and Toselli, A.J. (2002) Proterozoic-Early Paleozoic evolution in western South America: a discussion. Tectonophys., v. 354, pp. 121-137.

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T. and Burton, W.C. (1995) U-Pb ages of metarhyolites of the Catoctin and Mount Rogers Formations, central and southern Appalachians: evidence for two pulses of Iapetan rifting. Amer. J. Sci., v. 295, pp. 428-454.

Astini, R.A. and Thomas, W.S. (1999). Origin and evolution of the Precordillera terrane of western Argentina: a drifted Laurentian orphan. In: Ramos, V.A. and Keppie, J.D. (Eds.), Laurentia-Gondwana connections before Pangea. Geol. Soc. Amer., Spec. Paper, v. 336, pp. 1-20.

Astini, R.A., Benedetto, J.L. and Vaccari, N.E. (1995) The Early Paleozoic evolution of the Argentine Precordillera as a Laurentian rifted, drifted and collided terrane: A geodynamic model. Geol. Soc. Amer., Bull., v. 107, pp. 235-273.

Astini, R., Ramos, V.A., Benedetto, J.L., Vaccari, N.E. and Cañas, F.L. (1996) La Precordillera: un terreno exótico a Gondwana. 13° Cong. Geol. Argentino and 3° Cong. Explorac. Hidrocarburos, Actas, 5, pp. 293-324.

Baldo, E., Casquet, C. and Galindo C. (1998) Datos preliminares sobre el metamorfismo de la Sierra de Pie de Palo, Sierras Pampeanas Occidentales (Argentina). Geogaceta, v. 24, pp. 39-42.

Borrello, A.V. (1969) Los geosinclinales de la Argentina. Direc. Nac. Geología y Minería, Buenos Aires, Anales 14, pp. 1-188.

Casquet, C., Baldo, E., Pankhurst, R.J., Rapela, C.W., Galindo, C., Fanning, C.M. and Saavedra, J. (2001) Involvement of the Argentine Precordillera terrane in the Famatinian mobile belt: U-Pb SHRIMP and metamorphic evidence from the Sierra de Pie de Palo. Geology, v. 29, pp. 703-706.

Castro de Machuca, B. (1981) Génesis de la mina de talco "Don León", sierra de Pie de Palo, provincia de San Juan. 8° Cong. Geol. Argentino, Actas, 4, pp. 535-555.

Castro de Machuca, B., Meissl, E. and Conte-Grand, A. (1995) Las serpentinitas de la sierra de Pie de Palo y su mineralización, provincia de San Juan, Argentina. 5° Cong. Nac. Geol. Económica, Actas 1, pp. 1-11.

Cawood, P.A. and Nemchin, A.A. (2001) Paleogeographic development of the east Laurentian margin: constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians. Geol. Soc. Amer., Bull., v. 113, pp. 1234-1246.

Cawood, P.A., McCausland, P.J.A., Dunning, G.R. (2001) Opening Iapetus: constraints from the Laurentian margin in Newfoundland. Geol. Soc. Amer., Bull., v. 113, pp. 443-453.

Cingolani, C.A. and Varela, R. (1999) Rb-Sr isotopic age of basement rocks of the San Rafael Block, Mendoza, Argentina. 2° S. Amer. Symp. Isotope Geol., Actas, pp. 23-26.

Cumming, G.L. and Richards, J.R. (1975) Ore lead in a continuously changing Earth. Earth Planet. Sci. Lett., v. 28, pp. 155-171.

Dalla Salda, L. and Varela, R. (1984) El metamorfismo en el tercio sur de la sierra de Pie de Palo, San Juan. Revista Asoc. Geol. Argentina, v. 39, pp. 68-93.

Dalla Salda, L., Cingolani, C. and Varela, R. (1992a) Early Paleozoic orogenic belt of the Andes in southwestern South America: result of Laurentia-Gondwana collision? Geology, v. 20, pp. 617-620.

Dalla Salda, L., Dalziel, I.W., Cingolani, C. and Varela, R. (1992b) Did the Taconic Appalachians continue into southern South America? Geology, v. 20, pp. 1059-1062.

Dalziel, I.W.D. (1997) Overview. Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol. Soc. Amer., Bull., v.109, pp.16-42.

Davis, W.J., McNicoll, V.J., Bellerive, D.R., Santowski, K. and Scott, D.J. (1997) Modified chemical procedures for the extraction and purification of uranium from titanite, allanite and rutile in the Geochronology Laboratory, Geological Survey of Canada. Radiogenic age and isotopic studies: Report 10, Geol. Surv. Canada, Current Res. 97-F: 33-35.

Finney, S., Gleason, J., Gehrels, G. and Peralta, S. (2003) Early Gondwanan connection for Argentine Precordillera. Earth Planet. Sci. Lett., v. 205, pp. 349-359.

Finney, S.C., Gleason, J.D., Gehrels, G.E., Peralta, S. and Aceñolaza, G. (2004) Corrigendum to "Early Gondwanan connection for the Argentine Precordillera terrane". Earth Planet. Sci. Lett., v. 219, p. 413.

Hawkins, Jr., J.W. (1995) The geology of the Lau Basin. In: Taylor B. (Ed.), Backarc basins: tectonics and magmatism. Plenum Press, New York, pp. 497-517.

Kay, S.M., Orrel, S. and Abbruzzi, J.M. (1996) Zircon and whole rock Nd-Pb isotopic evidence for a Greenville age and Laurentian origin for the basement of the Precordillera terrane in Argentina. J. Geol., v. 104, pp. 637-648.

Kilmurray, J.O. and Dalla Salda, L. (1971) Las fases de deformación y metamorfismo en el área del cerro Valdivia, provincia de San Juan, República Argentina Revista Asoc. Geol. Argen., v. 26, pp. 25-39.

Krogh, T.E. (1982) Improved accuracy of U-Pb ages by the creation of more concordant systems using an air abrasion technique. Geochim. Cosmochim. Acta, v. 46, pp. 637-649.

Leal, P.R., Hartmann, L.A., Santos, J.O.S., Miró, R.C. y Ramos, V.A. (2003) Volcanismo postorogénico en el extremo norte de las Sierras Pampeanas Orientales: Nuevos datos geocronológicos y sus implicancias tectónicas. In: Ramos, V.A. (Ed.), Geología de las Sierras Pampeanas. Revista Asoc. Geol. Argentina, v. 58, pp. 593-607.

Leveratto, M.A. (1968) Geología de la zona al oeste de Ullún-Zonda, borde oriental de la Precordillera de San Juan, eruptividad subvolcánica y estructura. Revista Asoc. Geol. Argentina, v. 23, pp. 129-157.

Ludwig, K.R. (2001) User's manual for Isoplot/Ex rev. 2.49: a Geochronological Toolkit for Microsoft Excel. Spec. Pub., 1a, Berkeley Geochronology Center, Berkeley, 55p.

McDonough, M.R., Ramos, V.A., Isachsen, C.E., Bowring, S.A. and Vujovich, G.I. (1993) Nuevas edades de circones del basamento de la sierra de Pie de Palo, Sierras Pampeanas Occidentales de San Juan: sus implicancias para los modelos del supercontinente proterozoico de Rodinia. 12° Cong. Geol. Argentino and 2° Cong. Explor. Hidrocarburos, Actas, 3, pp. 340-342.

McLennan, S.M., Bock, B., Compston, W, Hemming, S.R.and McDaniel, D.K. (2001) Detrital circón geochronology of Taconian and Acadian foreland sedimentary rocks in New England. J. Sediment. Res., v. 71, pp. 305-317.

Pankhurst, R.J. and Rapela, C.W. (1998) The proto-Andean margin of Gondwana. An introduction. Pankhrust, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc. London, Spec. Pub., v. 142, pp. 1-9.

Pankhurst, R.J., Rapela, C.W. and Fanning C.M. (2000) Age and origin of coeval TTG, I- and S-type granites in the Famatinian belt of NW Argentina. Trans. R. Soc. Edinburgh: Earth Sci., v. 91, pp. 151-168.

Pankhurst, R.J., Rapela, C.W., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I. and Fanning, C.M. (1998) The Famatian magmatic arc in the central Sierras Pampeanas: an Early to Mid-Ordovician continental arc on the Gondwana margin. In: Pankhurst, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc., London, Spec. Pub., v. 142, pp. 343-367.

Parrish, R.R., Roddick, J.C., Loveridge, W.D., and Sullivan, R.W. (1987) Uranium-lead analytical techniques at the geochronology laboratory, Geological Survey of Canada. Radiogenic age and isotopic studies: Report 1, Geol. Surv. Canada, Paper 87-2, pp. 3-7.

Pearce, J.A. (1996) A user's guide to basalt discrimination diagrams. In: Wyman, D.A. (Ed.), Trace element Geochemistry of volcanic rocks: Application for Massive Sulphide exploration: Geol. Assoc. Canada, Short Course Notes, v. 12, pp. 79-113.

Quenardelle, S. and Ramos, V.A. (1999) Ordovician western Sierras Pampeanas magmatic belt: Record of Precordillera accretion in Argentina. In: Ramos, V.A. and Keppie, J.D. (Eds.), Laurentia-Gondwana connections before Pangea. Geol. Soc. Amer., Spec. Paper, v. 336, pp. 63-86.

Ramos, V.A. (2004) Cuyania, an exotic block to Gondwana: review of a historical success and the present problems. Gondwana Res. v. 7, pp. 1009-1026.

Ramos, V.A. and Vujovich, G.I. (2000) Hoja Geológica 3169-IV, San Juan, Provincia de San Juan. Subsec. Minería Nación, Serv. Geol. Minero Argentino, Buenos Aires, Boletín, v. 243, 82p.

Ramos, V.A., Cristallini, E.O. and Pérez, D.J. (2002) The Pampean flat-slab of the Centra Andes. J. S. Amer. Earth Sci., v. 15, pp. 59-78.

Ramos, V.A., Dallmeyer, D. and Vujovich, G.I. (1998) Ar/Ar constraints in the age of deformation of the Pie de Palo basement: implications for the docking of Precordillera and Chilenia. In: Pankhrust, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc., London, Spec. Pub., v. 142, pp. 143-158.

Ramos, V.A., Vujovich, G.I. and Dallmeyer, D. (1996) Los klippes y ventanas tectónicas de la estructura preándica de la sierra de Pie de Palo (San Juan): Edad e implicancias tectónicas. 13° Cong. Geol. Argentino and 3° Cong. Explorac. Hidrocarburos, Actas, 5, pp. 377-391.

Ramos, V.A., Escayola, M., Mutti, D.I. and Vujovich, G.I. (2000) Proterozoic-early Paleozoic ophiolites of the Andean basement of southern South America. In: Dilek, Y., Moores, E.M., Elthon, D. and Nicolas, A. (Eds.), Ophiolites and Oceanic crust: new insigths from field studies and the ocean drilling program. Geol. Soc. Amer., Spec. Paper, v. 349, pp. 331-349.

Ramos, V.A., Vujovich, G.I., Kay, S.M. and McDonough, M.R. (1993) La orogénesis de Grenville en las Sierras Pampeanas Occidentales: Pie de Palo un sistema de acreción de arcos isląndicos. 12° Cong. Geol. Argentino and 2° Cong. Explor. Hidrocarburos, Actas, 3, pp. 343-357.

Ramos, V.A., Jordan, T.E., Allmendinger, R.W., Mpodozis, C., Kay, S.M., Cortés, J.M. and Palma, M.A. (1986) Paleozoic terranes of the central Argentine-Chilean Andes. Tectonics, v. 5, pp. 855-880.

Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Saavedra, J. and Galindo, C. (1998) Early evolution of the proto-Andean margin of South America. Geology, v. 26, pp. 707-710.

Roddick, J.C. (1987) Generalized numerical error analysis with applications to geochronology and thermodynamics. Geochem. Cosmoch. Acta, v. 51, pp. 2129-2135.

Sato, A.M., Tickjy, H., Llambías, E.J. and Sato, K. (2000) The Las Matras tonalitic-trondhjemitic pluton, central Argentina: Grenvillian-age constraints, geochemical characteristics, and regional implications. J. S. Amer. Earth Sci., v. 13, pp. 587-610.

Sato, A.M., Tickyj, H., Llambías, E.J., Basei, M.A.S. and González, P.D. (2004) Las Matras Block, Central Argentina (37°S - 67°W): The southernmost Cuyania terrane and its relationship with the Famatinian orogeny. Gondwana Res., v. 7, pp. 1077-1087.

Stern, R.A. (1997) The GSC Sensitive High Resolution Ion Microprobe (SHRIMP): analytical techniques of zircon U-Th-Pb age determinations and performance evaluation In: Radiogenic age and isotopic studies, Report 10, Geol. Surv. Canada, Current Res. 1997-F, pp. 1-31.

Stern, R.A. and Amelin, Y. (2003) Assessment of errors in SIMS zircon U-Pb geochronology using a natural zircon standard and NIST SRM 610 glass. Chem. Geol., v. 197, pp. 111-146.

Su, Q., Goldberg, S.A. and Fullagar, P.D. (1994) Precise U-Pb zircon ages of Neoproterozoic plutons in the southern Appalachian Blue Ridge and their implications for the initial rifting of Laurentia. Precambrian Res., v. 68, pp. 81-95.

Sun, S-S. and McDonough, W.F. (1989) Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes. In: Saunders, A.D. and Norry, M.J. (Eds.), Magmatism in the ocean basins. Geol. Soc. London, Spec. Pub., v. 42, pp. 313-345.

Thomas, W.A. and Astini, R.A. (2003) Ordovician accretion of the Argentine Precordillera terrane to Gondwana: a review. J. S. Amer. Earth Sci., v. 16, pp. 67-79.

Thomas, W.A., Astini, R.A. and Bayona, G. (2002) Ordovician collision of the Argentine Precordillera with Gondwana, independent of Laurentian Taconic orogeny. Tectonophys., v. 345, pp. 131-152.

Tollo, R.P., Aleinikoff, J.N., Bartolomew, M.J. and Rankin, D.W. (2004) Neoproterozoic A-type granitoids of the central and southern Appalachians: intraplate magmatism associated with episodic rifting of the Rodinian supercontinent. Precambrian Res., v. 128, pp. 3-38.

Van Kleef, G.K.M. and Lissenberg, C.J. (2001) Geochemistry of the Mesoproterozoic mafic-ultramafic belt (Pie de Palo Complex, Sierra de Pie de Palo, Argentina); support for an arc-back arc setting. Bach. Thesis (unpub.) Vrije Univ., Amsterdam, 18p.

Van Staal, C.R., Vujovich, G.I. and Davis, W. (2002) Tectonostratigraphic relationships and structural evolution of the western margin of the Sierra de Pie de Palo, Cuyania (Precordillera) terrane, Argentina. GSA, Ann. Meeting, Denver. Abst., Paper No. 223-7.

Varela, R. and Dalla Salda, L. (1993) Geocronología Rb-Sr de metamorfitas y granitoides del extremo sur de la Sierra de Pie de Palo, San Juan. Revista Asoc. Geol. Argentina, v. 47, pp. 271-276.

Villar, L. (1985) Las fajas ultrabásicas argentinas, tipos de ultramáficas. Metalogenia. 4° Cong. Geol. Chileno, Actas, 2, pp. 610-633.

Vujovich, G.I. (1993) Arcos magmáticos isląndicos en el sector occidental del terreno Pampeano. 12° Cong. Geol. Argentino and 2° Cong. Explorac. Hidrocarburos, Actas, 4, pp. 17-22.

Vujovich, G.I. (1994) Reinterpretación geoquímica de las anfibolitas del Cerro Valdivia, provincia de San Juan. II Jorn. Mineral. Petrol. y Metalogénesis de Rocas Ultrabásicas, IRM, UNLP, La Plata, v. 3, pp. 653-662.

Vujovich, G.I. (2003) Metasedimentos siliciclásticos proterozoicos en la sierra de Pie de Palo, San Juan: procedencia y ambiente tectónico. Revista Asoc. Geol. Argentina, v. 58, pp. 608-622.

Vujovich, G.I. and Kay, S.M. (1996) Evidencias geoquímicas del origen y ambiente geológico de las rocas metamórficas de composición máfica a intermedia de las Sierras Pampeanas

Occidentales. 13° Cong. Geol. Argentino and 3° Cong. Explorac. Hidrocarburos, Actas , 5, pp. 273-291.

Vujovich, G.I. and Kay, S.M. (1998) A Laurentian? Grenville-age oceanic arc/back-arc terrane in the Sierra de Pie de Palo, Western Sierras Pampeanas, Argentina. In: Pankhrust, R.J. and Rapela, C.W. (Eds.), The Proto-Andean margin of Gondwana. Geol. Soc., London, Spec. Pub., v. 142, pp. 159-180.

Vujovich, G.I. and Ramos, V.A. (1994) La faja de Angaco y su relación con las Sierras Pampeanas Occidentales. 7° Cong. Geol. Chileno, Actas 1, pp. 215-219.

Vujovich, G.I. and Ramos, V.A. (1999) Mapa geotectónico de la República Argentina (1: 2.500.000), Subsec. Minería Nación, Buenos Aires, Serv. Geol. Minero Argentino.

Vujovich, G., Miller, H. and Ramos, V.A. (1994) Proterozoic metavolcanics from western Sierras Pampeanas Terrane, Argentine. J. S. Amer. Earth Sci., v. 7, pp. 309-323.

Winchester, J.A. and Floyd, P.A. (1977) Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chem. Geol., v. 20, pp. 325-343.

Wood, D.A., Joron, J.L. and Trevil, M. (1979) A re-appraisal of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings. Earth Planet. Sci. Lett., v. 45, pp. 326-336.

York, D. (1969) Least squares fitting of a straight line with correlated errors. Earth Planet. Sci. Lett., v. 5, pp. 320-324.