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Detrital zircons U–Pb SHRIMP ages and provenance of La Modesta Formation, Patagonia Argentina

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A B S T R A C T

This paper summarizes the geology of the Paleozoic La Modesta Formation in Patagonia, Argentina, and presents new SHRIMP U–Pb dating of detrital zircons from muscovite-chlorite schist and tourmalinite. Also complementary geochemical and lead isotopic data are presented, indicating that the protoliths were formed from upper crustal rocks by the contribution of a large input from recycled (or felsic) sources. The maximum age of sedimentation of La Modesta Formation is about 446 ± 6 Ma. The basin closure (or eventually a paleocurrent shift) occurs at Lower Devonian before the exhumation of the Middle-Devonian granitoids of the Rio Deseado Complex (Deseado Massif). Many of the detrital zircons are igneous and record Ordovician ages, with a prominent Lower Ordovician-age peak at approximately 473 Ma. Most favourable candidates to provide the younger zircons in the basin would Ordovician granites of the Rio Deseado Complex (Deseado Massif) and Punta Sierra Plutonic Complex (Somun Cura Massif). Older zircons have peaks of different importance (including Brasiliano and Grenvillian ages) between 530 and 700, 750–1500, 1750–2000 and 2550–2700 Ma. La Modesta Formation is also a potential area of materials (detrital zircon) to the basin where the rocks of the Eastern Andean Metamorphic Complex and equivalent formations of the Andean region were generated.

R E S U M E N

Este trabajo resume las caracterisiticas geológicas de la Formación La Modesta de edad paleozoica en la Patagonia Argentina, y reporta nuevas edades SHRIMP U–Pb de circones detríticos procedentes de esquistos clorítico-muscovíticos y turmalinitas. Además se presentan los resultados geoquímicos y de isótopos de plomo, que indican que los protolitos se formaron a partir de rocas de la corteza superior por el aporte de variadas fuentes principalmente de rocas recicladas o félsicas. La edad máxima de sedimentación de la Formación La Modesta es de 446 ± 6 Ma. La colmatación de la cuenca (o un cambio en las paleocorrientes) tuvo lugar en el Devónico inferior, antes de la exumación de los granitoides del Devónico medio del Complejo Rio Deseado (Macizo del Deseado). Gran parte de los circones detríticos son de origen ígneo y muestran edades ordovícicas, con una edad pico predominante en el Ordovícico Inferior a aproximadamente los 473 Ma. La fuente de aporte probable de los circones más jóvenes fueron los granitoides ordovícicos del Complejo Río Deseado y del Complejo Plutónico Punta Sierra (Macizo de Somún Cura. Los circones más antiguos presentan picos de distinta importancia (que incluyen edades brasilianas y grenvillianas) entre 530–700, 750–1500, 1750–2000 y 2550–2700 Ma. Las rocas de la Formación La Modesta pueden haber aportado materiales a las cuencas donde se generaron las rocas del Complejo Metamórfico Andino Oriental y formaciones equivalentes de la región andina.

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1. Introduction

The Patagonia region occupies a wide area in southern South America from 39° to 40° S (Ramos et al., 2004), extending from the Andes to the Atlantic coast. According to Ramos (2010) it comprises the Patagonia terrane that includes the northern Patagonic Andes and the extra-Andean Patagonia, and the Southern Patagonia terrane comprising the Southern Andes and Cordillera Fueguina (Fig. 1). Since the late nineteenth century several ideas tried to explain some particular geologic and tectonic features of Patagonia. The autochthony, allochthony or para-autocthony respect to Gondwana and its internal evolution are under continuously reviewing (Ramos, 2008).

The extra-Andean Patagonia includes two blocks named Somun Cura Massif or Nordpatagonic Massif (at North) and Deseado Region (Giacosa et al., 2010) or Deseado Massif (in the south), separated by Jurassic to Tertiary basins (the Cañadón Asfalto and San Jorge basins). The southern boundary of the Deseado Massif is the Jurassic-Cretaceous Austral or Magallanes basin. Both massifs are characterized by an extensive volcanic/sedimentary cover of Mesozoic and pos-Mesozoic age. Pre-Mesozoic basement outcrops are more extensive and numerous in the Somun Cura Massif, but are rather scarce and isolated in the Deseado Massif, where only 8 exposures are known with maximum dimensions of the 6–8 km^2. In the latter, the basement rocks are grouped into the Río Deseado Complex (Viera and Pezzuchi, 1976) to the east whereas in the central-west they are termed La Modesta Formation (Di Persia, 1962), the aim of this study (Fig. 1).

This paper summarizes the geology of the La Modesta Formation and presents new SHRIMP U–Pb dating of detrital zircons. Complementary geochemical and Pb isotopic data are also presented. Even though the links of the La Modesta Formation with other Gondwana units on a global scale are beyond the scope of this research, the data are compared with others obtained from both the extra-Andean region and Andean region of Patagonia, with the aim of contributing to understanding its evolution during the Paleozoic times. The ages in the stratigraphic chart by Gradstein et al. (2004) are used.

2. Pre-Permian basement of the Deseado Massif

2.1. Rio Deseado Complex

In the eastern part of the Deseado Massif (Fig. 1), the basement rocks of the Rio Deseado Complex are composed of scarce, dispersed and small outcrops of metamorphic rocks (that is: phyllites, quartzites, schists, amphibolites, gneisses, and migmatites) and granitoid intrusions (Chebli and Ferello, 1974; Viera and Pezzuchi, 1976; Márquez and Panza, 1986; Panza et al., 1995; Giacosa et al., 1990). Earlier geochronological data yielded ages of 540 ± 20 Ma (K–Ar on amphibole) for an amphibolite rock from the Dos Hermanos outcrop (Pezzuchi, 1978) and 406 ± 10 Ma (Rb–Sr

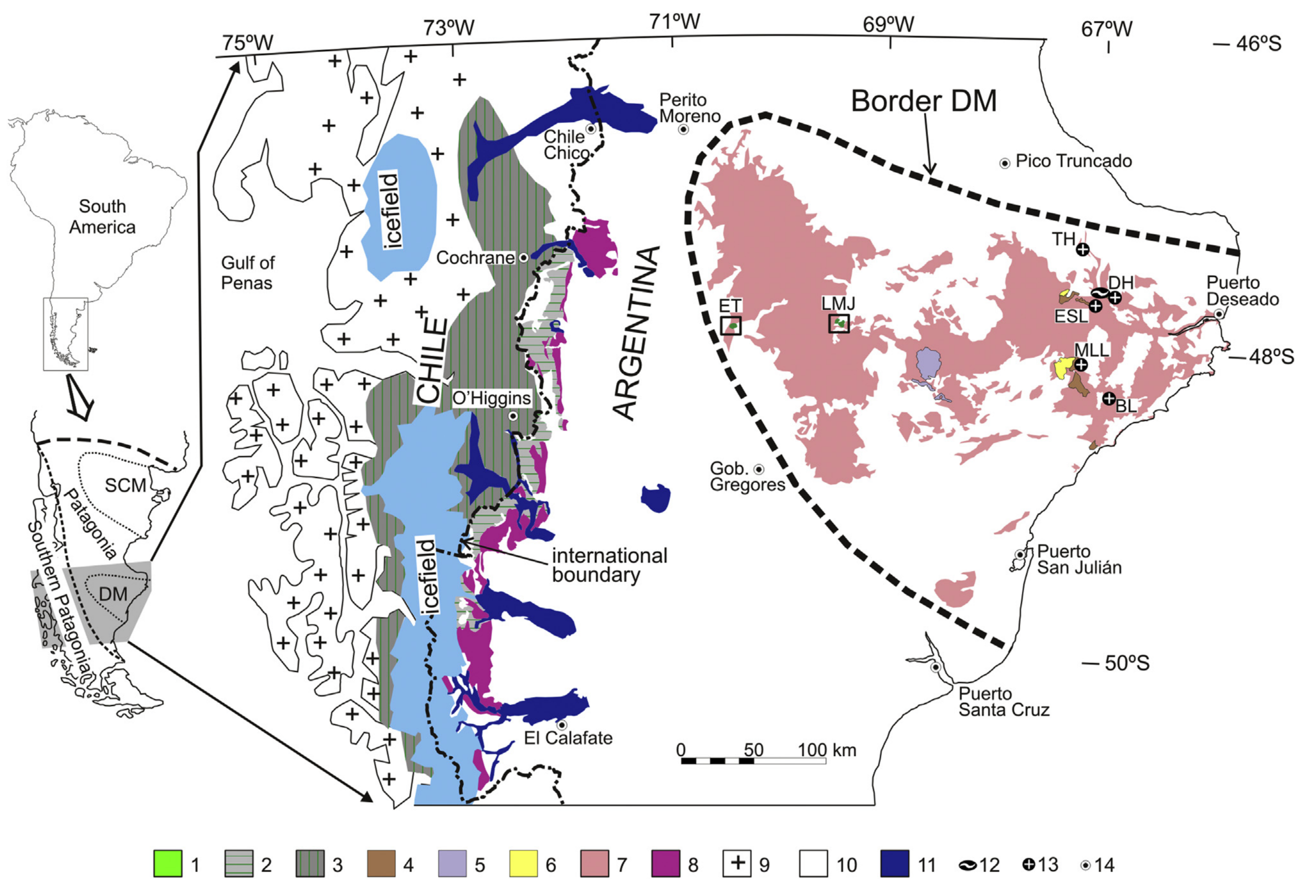

Fig. 1. Simplified map of the south Patagonia region (latitude of the La Modesta Formation outcrops). References in colour: 1) La Modesta formation, 2) Bahía La Lancha and Rio Lacteo formations, 3) Eastern Andean Metamorphic Complex, 4) La Golondrina formation (Permian), 5) Triassic-Lower Jurassic sedimentary and volcaniclastic rocks (El Tranquilo and Bajo Grande formations), 6) Upper Triassic-Lower Jurassic granitoids, 7) Middle-Upper Jurassic pyroclastic and volcanic rocks (Bajo Pobre and Chon Aike formations), 8) Upper Jurassic pyroclastic and volcanic rocks (El Quemado formation), 9) Patagonian batholit, 10) Cretaceous and younger sedimentary and volcanic rocks, 11) Lakes, 12) Metamorphic Rio Deseado Complex dated, 13) Magmatic Rio Deseado Complex dated, 14) Locality. Abbreviations BL: Bahia Laura area, DH: Dos Hermanos area, DM: Deseado Massif (insert), ESL: El Sacrificio-El Laurel area, ET: El Tranquilo-La Bajada area, LMJ: La Modesta-La Josefina area, MLL: Mina La Leona area, SCM: Somun Cura Massif (insert), TH: Tres Hermanas area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

whole rock) for a granite from the Tres Hermanas outcrop (Chebli and Ferello, 1974).

Guido et al. (2004) proposed that the Rio Deseado Complex rocks were regionally metamorphosed in the Pampean Cycle (Neoproterozoic–Paleozoic boundary) followed by an igneous intrusion stage of Famatinian age, represented by the Ordovician–Devonian granitoids (Famatinian magmatic arc), and finally affected by a post-Famatinian deformational event. Those authors proposed that the Río Deseado Complex is part of a Late Proterozoic-Mid Paleozoic orogenic belt.

The maximum metamorphic grade reached by this unit (epidote–amphibolite facies) could have occurred in the early Silurian, as suggested by Giacosa et al. (2002).

2.2. *La Modesta Formation*

The La Modesta Formation corresponds to the metamorphic basement in the center-west of the Deseado Massif and is known only in small outcrops in the areas La Modesta-La Josefina (main locality) and another 70 km away to the west, El Tranquilo-La Bajada (Figs. 1 and 2). These metamorphic rocks were first called "La Modesta Schists" by Di Persia (1962) and were tentatively assigned to the Precambrian. Pezzi (1970) formalized the name and proposed a pre-Devonian age on a stratigraphic basis.

The main outcrop at La Modesta-La Josefina (Fig. 2 A) is composed of alternating pelitic and psammitic muscovite-chlorite schists and meta-quarzites, with minor calc–silicate rocks, basic metavolcanics and exhalative rocks (graphitic tourmalinites, tourmaline-bearing schists and Fe–Mn horizons). The metamorphic grade is very low to low, from prehnite-pumpellyite to greenschist facies. Moreira et al. (2005) suggests a sedimentation age for La Modesta Formation of older than 413 ± 17 Ma on the basis of a Rb–Sr whole rock errorchron. More recent SHRIMP U–Pb detrital zircons data reported in abstract by Moreira et al. (2007) suggests a maximum age of sedimentation of approximately 473 Ma.

At the El Tranquilo-La Bajada outcrop (Fig. 2 B) basement rocks are composed of a homogeneous sequence of pelitic and psammitic quartz-muscovite-chlorite schists, with blastesis of biotite and variable amounts of carbonate, feldspar, garnet, epidote and tourmaline. The metamorphic grade corresponds to biotite-garnet grade greenschist facies (Moreira et al., 2012).

The main protolith of these rocks has been interpreted to be a pelitic and psamo-pelitic marine sedimentary succession. It has a regional metamorphic foliation, S_1, subparallel to the sedimentary stratification S_0. The schistosity S_1 was deformed by a second deformational event, generating a non penetrative S_2/L_2, best evidenced in the El Tranquilo-La Bajada outcrops (Moreira et al., 2012).

There is no evidence to establish the relationship between La Modesta Formation and the igneous-metamorphic Rio Deseado Complex whose nearest exposures are located around 200 km to the east. Based on seismic information, Homovc and Constantini (2001) interpreted the entire Deseado Massif and its offshore extension (San Julian Basin) to be a single metamorphic basement (pre-Carboniferous) upon which, during periods of Permian rifting and Triassic-Jurassic sag, large thicknesses (up to 2500 m) of continental clastic sediments, usually fossiliferous, were deposited, followed by widespread deposits of Jurassic pyroclastic and volcanic rocks and Cretaceous sedimentary rocks. Moreira et al. (2005) proposed that the Rio Deseado Complex and the La Modesta Formation should be considered as independent entities on the basis of their different metamorphic grade and the (minimum) sedimentation age of the last unit (413 ± 17 Ma). These authors also interpreted the Rio Deseado Complex provide detritus to the La Modesta Formation basin. While there is no evidence as to the

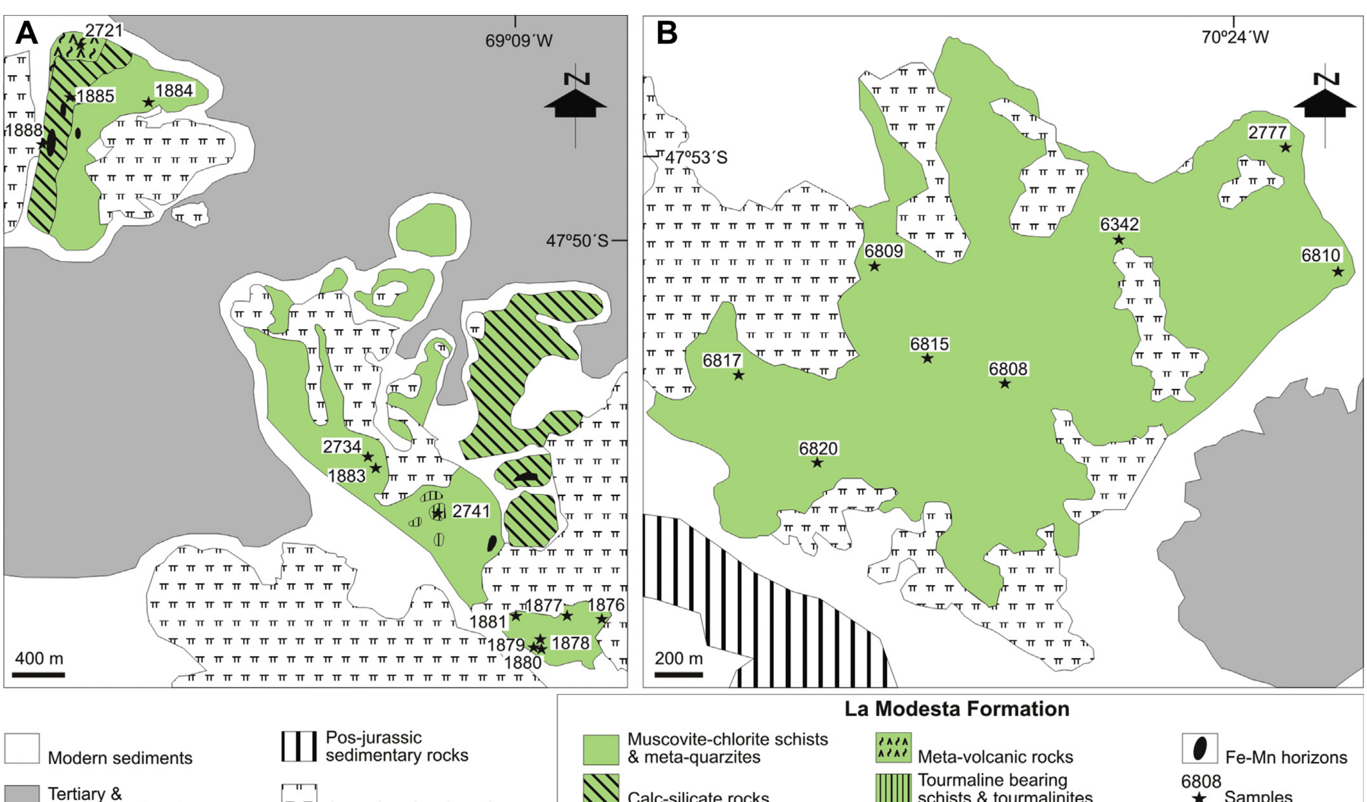

Fig. 2. Geological maps of the La Modesta Formation main outcrops. A: Geological map of La Modesta-LaJosefina outcrops adapted after Moreira et al. (2005). B: Geological map of El Tranquilo outcrops adapted after Moreira et al. (2012).

nature of the rocks underlying the La Modesta basin, Moreira et al. (2005) have interpreted that their protoliths filled a forearc Pacific basin, that later became part of the accretionary prism of SW Gondwana. Further, they have correlated La Modesta Formation with sedimentary or low-grade metamorphic diachronic units recognized west of the Deseado Massif, such as the Bahia La Lancha and Rio Lacteo Formations (Argentina) and the Eastern Andean Metamorphic Complex (Chile).

The age of La Modesta Formation has no precise stratigraphic control, although it is covered or cut by Upper Jurassic pyroclastic and volcanic rocks (Chon Aike Formation). However following the seismic interpretation by Homovc and Constantini (2001) it has been interpreted to be part of a rigid basement possibly since before the Carboniferous. The block in the La Modesta-La Josefina area constituted a horst that probably was not covered at least by the Permian deposits (Fig. 16 from Homovc and Constantini, 2001).

3. Sampling and analytical methods

Three samples were taken from La Modesta Formation units corresponding to a metasedimentary rock which is the dominant lithology (sample 2734), a tourmalinite (sample 2741) and a meta-volcanic rock (sample 2721). The metasedimentary rock and tourmalinite were selected for U–Pb zircon dating by SHRIMP and tourmalinite and meta-volcanic rock were selected for Pb isotopic studies.

Sample 2734 (47°50′57″S and 69°26′36″W) is a grey muscovite-chlorite schist with folded quartz veins and segregations, concordant to schistosity. It is composed of quartz and plagioclase, and scattered crystals of carbonate, tourmaline and zoisite that typically are developed in a granoblastic texture. The schist is characterized by grano-lepidoblastic to lepidoblastic texture with chlorite and muscovite and minor zoisite, quartz, plagioclase, opaque minerals and pre-graphite/graphite (±apatite ± tourmaline). Some detrital quartz and feldspar (plagioclase and microcline) grains up to 400 μm and scarce muscovite (200 μm) are present. Quartz crystals show undulate extinction and form incipient deformation sheets and microfractures. Feldspars also have microfractures and twins are shading and lightly deformed. Sub-round zircon grains, 20 a 175 μm in length and round to sub-rectangular monazite (25 a 150 μm in diameter) are present as accessory minerals.

Sample 2741 (47°51′13″S and 69°26′10″W) is a black graphitic tourmalinite with one well-developed thin cleavage. It is composed of quartz and plagioclase sheets with a granoblastic texture between domains rich in tourmaline crystals from 50 to 300 μm in length (up to 40%) with minor chlorite. Tourmaline crystals are colourless, brown to green blue with fibrous to prismatic forms, oriented and occasionally zoned. In addition abundant granular aggregates of sub-rectangular to hexagonal apatite crystals from 50 to 500 μm are present. Other accessory minerals are rutile, oriented graphite sheets (25 μm) and opaque minerals (diagenetic pyrite with small crystals of magnetite, hematite, ilmenite, chalcopyrite and pirrotine). It also contains detrital grains of quartz, feldspar (plagioclase and microcline) and sub-round zircon, 40–100 μm in length.

Sample 2721 (47°49′15″S and 69°28′34″W) is a brownish black to green schistose meta-volcanic rock. It is composed of quartz and plagioclase that are developed in a granoblastic texture with prehnite, chlorite and zoisite. Hematite and ilmenite with minor chalcopyrite (<200 μm) are abundant and aligned in what appears to be a relictic volcanic fluidal texture. Pilotaxitic volcanic texture is partially conserved and is composed of a disordered subhedral tabular and altered plagioclase aggregate. Deformed twins are present in some relict plagioclase grains.

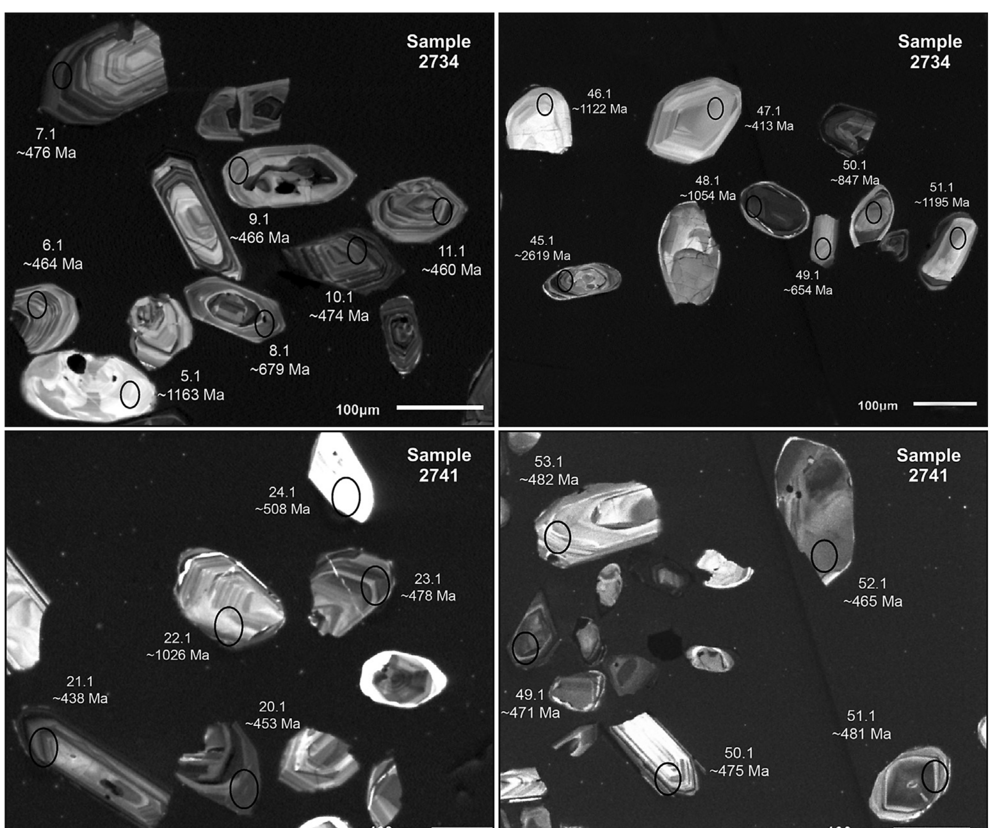

Fig. 3. Representative CL images of grains analysed from samples 2734 and 2741 of the La Modesta Formation showing the location of the SHRIMP analysis and the radiogenic age.

Zircon grains were separated from samples 2734 and 2741 using standard crushing, washing, heavy liquid (Sp. Gr. 2.96 and 3.3) and paramagnetic procedures. The zircon-rich heavy mineral concentrates were poured onto double-sided tape, mounted in epoxy together with chips of the reference zircons (FC1 Duluth Gabbro), sectioned approximately in half, and polished. Reflected and transmitted light photomicrographs were prepared for all zircons. Cathodoluminescence (CL) Scanning Electron Microscope (SEM) images were prepared for all zircon grains. The CL images were used to decipher the internal structures of the sectioned grains and to ensure that the ~20–30 μm SHRIMP spot was wholly within a single age component (usually the youngest) within the sectioned grains. Representative CL images are given in Fig. 3. The U–Th–Pb analyses were made using SHRIMP I at the Research School of Earth Sciences, The Australian National University, Canberra, Australia. For each sample, zircons on the mount were analysed sequentially and randomly until a total of at least 60 grains for each sample was reached. Each analysis consisted of 4 scans through the mass range, with the FC1 reference zircon analysed for every five unknown zircon analyses; SHRIMP analytical method follows Williams (1998, and references therein). The data have been reduced using the SQUID Excel Macro of Ludwig (2001).

The U/Pb ratios have been normalized relative to a value of 0.01859 for the FC1 reference zircon, equivalent to an age of 1099 Ma (see Paces and Miller, 1993). Uncertainties given for individual analyses (ratios and ages) are at the one sigma level (Tables 2 and 3). Correction for common Pb was either made using the measured $^{204}Pb/^{206}Pb$ ratio in the normal manner, or for grains younger than say 800 Ma (or those low in U and so radiogenic Pb) the ^{207}Pb correction method has been used (see Williams, 1998). When the ^{207}Pb correction is applied it is not possible to determine radiogenic $^{207}Pb/^{206}Pb$ ratios or ages. In general, for grains younger than 800 Ma the radiogenic $^{206}Pb/^{238}U$ age has been used for the probability density plots (and for areas that are areas low in U and therefore radiogenic Pb). The $^{207}Pb/^{206}Pb$ age is used for grains older than say 800 Ma, or for those enriched in U. Tera and Wasserburg (1972) concordia plots, probability density plots with stacked histograms and weighted mean $^{206}Pb/^{238}U$ age calculations were carried out using ISOPLOT/EX (Ludwig, 2003).

Samples 2741 and 2721 were selected for Pb isotopes at the Pará-Iso Laboratory, Instituto de Geociencias, do Pará Federal University (Belém, Brazil). Pb was analysed in total rock. Bi-distilled acids and four times distilled water were used for chemical separation. The silicates were dissolved in HF (48%) and HBr (9 N). Lead was subsequently extracted and purified using conventional HBr–ClH resin ion exchange techniques. The samples were loaded with silica gel in dilute phosphoric acid on single rhenium filaments. Mass spectrometry of Pb isotopes was determinate on a VG mass-spectrometer with static multi-channel collector.

4. Results

4.1. Detrital zircon data

Sixty and 62 zircon grains were analysed respectively from samples 2741 and 2734 (Tables 2 and 3). For each sample, it can be

Table 1
Geochemical results from La Modesta Formation samples modified from Moreira et al. (2005) and Moreira et al. (2012). n.a.: not analyzed, n.d.: not detected.

Lithology	La Josefina – La Modesta											El Tranquilo – La Bajada							
	Muscovitic–chlorite schists and metaquartzites								Calc–silicate rocks		Meta volc.	Muscovitic–chlorite schists (±biotite ± garnet)							
	1876	1877	1878	1879	1880	1881	1883	1884	1885	1888	2721	6817	6342	6809	6810	6820	2777	6808	6815
SiO_2	78.80	72.85	68.44	86.80	74.43	67.97	69.34	81.68	45.66	42.66	48.23	70.35	57.22	61.7	72.5	81.84	60.57	56.12	55.93
TiO_2	0.47	0.75	0.70	0.19	0.51	0.66	0.72	0.20	2.00	2.62	2.38	0.57	1.02	0.76	0.62	0.36	0.86	1.37	1.18
Al2O3	8.14	13.51	12.76	5.83	10.65	13.49	12.54	5.56	13.65	16.84	16.11	14.3	15.27	18.26	12.4	6.84	13.51	14.22	15.71
FeO	3.49	3.41	3.95	2.25	4.04	4.00	3.76	1.76	5.55	10.63	4.63	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fe_2O_3	1.26	2.57	0.92	0.04	0.81	0.65	1.32	2.25	5.72	4.25	8.97	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fe_2O_3 t	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.78	8.34	7.59	6.05	4.74	6.73	10.11	9.25
MnO	0.06	0.03	0.09	0.03	0.10	0.07	0.08	0.12	0.20	0.31	0.22	0.11	0.16	0.1	0.06	0.13	0.13	0.18	0.14
MgO	1.13	2.49	2.38	0.58	1.65	2.03	2.21	0.61	4.35	4.50	4.62	0.94	2.37	2.09	1.63	0.83	2.62	3.97	3.54
CaO	0.83	0.60	1.95	0.23	0.58	1.85	1.29	2.19	10.21	8.05	4.25	1.13	5.83	0.29	0.45	0.15	4.64	4.94	2.56
Na_2O	1.37	1.00	3.06	2.34	2.03	3.88	2.76	0.99	3.27	2.32	5.36	3.44	3.61	0.32	0.19	0.08	4.35	3.09	2.82
K_2O	0.99	0.13	1.91	0.09	1.55	1.79	2.17	0.76	0.07	0.07	0.20	2.07	1.09	4.32	2.73	1.32	0.46	0.72	1.83
P_2O_5	0.17	0.18	0.15	0.11	0.11	0.16	0.16	0.15	0.22	0.30	0.25	0.14	0.23	0.14	0.15	0.12	0.12	0.2	0.21
L.O.I.	2.78	1.94	2.99	0.89	2.94	2.81	3.01	3.24	8.53	6.79	4.14	3.24	4.78	4.68	3.18	3.31	5.96	5.62	5.68
Tot	99.48	99.45	99.28	99.38	99.40	99.35	99.36	99.51	99.44	99.35	99.36	100.07	99.92	100.25	99.96	99.72	99.95	100.54	98.85
Sr	59	81	133	50	90	92	105	42	203	521	203	94	281	94	94	94	187.2	280.8	93.6
Ba	201	84	548	24	302	678	656	243	34	85	96	575	383	1054	671	287	191.6	287.4	479
Cr	118	332	160	212	141	137	148	181	158	259	218	68	68	137	68	n.d.	68	68	68
Sc	16	21	19	19	19	19	21	16	17	24	59	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
V	55	116	110	24	84	102	115	39	329	453	391	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	11	7	16	6	14	11	13	6	36	57	48	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	28	34	40	14	33	36	36	19	55	93	80	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	15	25	7	12	22	11	16	37	57	54	129	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	46	66	53	30	78	71	49	54	89	136	115	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ga	1	16	7	n.d.	n.d.	11	4	5	n.d.	12	19	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	43	4	70	5	72	75	84	36	6	5	12	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	21	23	27	10	26	24	29	13	35	55	51	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	168	164	176	42	133	166	184	44	136	166	193	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	9	14	10	6	10	10	12	6	7	6	7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
La	17	26	18	13	16	46	39	13	3	6	n.d.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ce	16	29	63	11	36	57	55	16	30	34	33	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nd	8	30	28	11	22	23	24	5	19	18	13	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pb	n.d	10	30	n.d.	10	28	37	n.d.	93	53	7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Th	12	16	14	9	14	15	14	8	n.d.	n.d.	2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
U	1	n.d.	2	n.d.	3	3	3	1	n.d.	n.d.	n.d.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 2
Summary of SHRIMP U–Pb zircon results for sample 2734.

Total ratios																		Age (Ma)				
Grain spot	U ppm	Th ppm	Th/U	^{206}Pb ppm	^{204}Pb/^{206}Pb	f_{206} %	^{238}U/^{206}Pb	±	^{207}Pb/^{206}Pb	±	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	ρ	^{206}Pb/^{238}U	±	^{207}Pb/^{206}Pb	±	% Disc
1.1	116	103	0.88	11.0	0.000366	1.08	9.068	0.115	0.0707	0.0010	0.1091	0.0014						667	8			
2.1	742	202	0.27	213.1	0.000022	0.03	2.993	0.032	0.1127	0.0003	0.3340	0.0036	5.176	0.057	0.1124	0.0003	0.962	1858	17	1838	5	−1
3.1	337	7	0.02	31.9	0.000044	0.43	9.079	0.114	0.0654	0.0008	0.1097	0.0014						671	8			
4.1	205	129	0.63	13.3	0.000486	0.52	13.195	0.157	0.0606	0.0008	0.0754	0.0009						469	5			
5.1	43	41	0.96	7.3	0.000529	0.89	5.016	0.077	0.0857	0.0015	0.1978	0.0036	2.154	0.154	0.0790	0.0046	0.774	1163	19	1172	116	1
6.1	213	177	0.83	13.9	0.000655	1.35	13.221	0.157	0.0673	0.0009	0.0746	0.0009						464	5			
7.1	824	165	0.20	54.4	0.000305	0.26	13.010	0.141	0.0587	0.0004	0.0767	0.0008						476	5			
8.1	585	79	0.13	55.9	0.000169	0.08	9.001	0.097	0.0628	0.0004	0.1110	0.0012						679	7			
9.1	199	70	0.35	12.9	0.000716	1.05	13.189	0.164	0.0649	0.0009	0.0750	0.0010						466	6			
10.1	409	195	0.48	26.9	0.000266	0.43	13.063	0.146	0.0601	0.0006	0.0762	0.0009						474	5			
11.1	329	155	0.47	21.0	0.000449	0.54	13.446	0.153	0.0606	0.0007	0.0740	0.0009						460	5			
12.1	496	566	1.14	33.4	0.000146	0.18	12.757	0.143	0.0583	0.0005	0.0782	0.0009						486	5			
13.1	489	58	0.12	31.8	0.000437	0.81	13.201	0.145	0.0630	0.0009	0.0751	0.0008						467	5			
14.1	78	77	0.99	22.5	0.000281	0.43	2.975	0.039	0.1186	0.0010	0.3347	0.0044	5.297	0.104	0.1148	0.0017	0.675	1861	21	1877	26	1
15.1	80	59	0.73	5.3	0.001195	2.00	13.091	0.201	0.0725	0.0016	0.0749	0.0012						465	7			
16.1	33	18	0.55	3.3	0.002630	3.92	8.565	0.152	0.0945	0.0024	0.1122	0.0021						685	12			
17.1	120	10	0.09	10.8	0.000642	0.98	9.568	0.122	0.0689	0.0010	0.1035	0.0014						635	8			
18.1	446	46	0.10	48.0	0.000577	1.83	7.974	0.087	0.0793	0.0007	0.1231	0.0014						748	8			
19.1	190	16	0.08	11.7	0.000792	0.74	13.884	0.176	0.0618	0.0010	0.0715	0.0009						445	6			
20.1	110	161	1.46	32.5	0.000163	0.25	2.909	0.036	0.1160	0.0008	0.3443	0.0053	5.567	0.260	0.1173	0.0040	0.868	1907	25	1915	61	0
21.1	113	62	0.54	50.1	0.000153	0.21	1.941	0.024	0.1814	0.0009	0.5149	0.0067	12.848	0.237	0.1810	0.0015	0.921	2678	28	2662	14	−1
22.1	531	42	0.08	32.9	0.000188	0.22	13.846	0.152	0.0577	0.0006	0.0721	0.0008						449	5			
23.1	53	90	1.69	25.2	0.000108	0.14	1.823	0.026	0.1851	0.0013	0.5478	0.0077	13.885	0.232	0.1838	0.0016	0.845	2816	32	2688	15	−5
24.1	173	46	0.27	10.7	0.000556	0.75	13.964	0.174	0.0619	0.0010	0.0711	0.0009						443	5			
25.1	579	92	0.16	233.7	0.000142	0.20	2.130	0.023	0.1764	0.0004	0.4685	0.0050	11.282	0.125	0.1746	0.0005	0.965	2477	22	2603	5	5
26.1	203	64	0.32	15.5	0.000266	0.69	11.263	0.173	0.0641	0.0009	0.0882	0.0014						545	8			
27.1	496	158	0.32	36.6	0.000239	0.67	11.645	0.128	0.0634	0.0006	0.0853	0.0010						528	6			
28.1	913	68	0.07	138.7	0.000036	0.06	5.654	0.060	0.0748	0.0005	0.1768	0.0019	1.812	0.024	0.0743	0.0006	0.819	1049	10	1051	15	0
29.1	688	160	0.23	61.7	0.000092	0.22	9.573	0.103	0.0628	0.0004	0.1042	0.0011						639	7			
30.1	282	49	0.17	19.5	0.001764	3.35	12.447	0.144	0.0840	0.0020	0.0776	0.0009						482	6			
31.1	184	20	0.11	18.8	0.001100	1.45	8.388	0.100	0.0752	0.0009	0.1175	0.0014						716	8			
32.1	264	358	1.35	78.5	0.000051	0.08	2.892	0.036	0.1154	0.0005	0.3456	0.0043	5.468	0.075	0.1148	0.0007	0.907	1913	21	1876	10	−2
33.1	29	77	2.63	8.0	0.000366	0.57	3.144	0.054	0.1137	0.0016	0.3163	0.0055	4.742	0.154	0.1087	0.0030	0.531	1771	27	1778	50	0
34.1	142	205	1.44	42.5	0.000204	0.31	2.873	0.034	0.1168	0.0007	0.3470	0.0042	5.454	0.089	0.1140	0.0013	0.738	1920	20	1864	20	−3
35.1	328	94	0.29	30.4	0.000320	0.83	9.283	0.104	0.0682	0.0007	0.1068	0.0012						654	7			
36.1	889	228	0.26	56.4	0.000113	0.16	13.533	0.147	0.0575	0.0004	0.0738	0.0008						459	5			
37.1	55	229	4.12	17.7	0.000530	0.80	2.690	0.038	0.1301	0.0012	0.3688	0.0053	6.256	0.144	0.1230	0.0022	0.620	2024	25	2001	32	−1
38.1	28	12	0.42	12.9	0.000518	0.70	1.888	0.031	0.1884	0.0022	0.5259	0.0088	13.207	0.319	0.1821	0.0032	0.695	2724	37	2672	29	−2
39.1	108	30	0.28	17.6	0.000634	1.07	5.269	0.067	0.0828	0.0009	0.1877	0.0024	1.910	0.058	0.0738	0.0020	0.426	1109	13	1036	55	−7
40.1	429	117	0.27	62.6	0.000256	0.44	5.886	0.065	0.0764	0.0004	0.1695	0.0020	1.735	0.035	0.0743	0.0009	0.863	1009	11	1049	24	4
41.1	148	65	0.44	23.0	0.000279	0.47	5.519	0.067	0.0774	0.0008	0.1805	0.0023	1.851	0.057	0.0743	0.0016	0.785	1070	13	1051	44	−2
42.1	306	14	0.05	19.8	0.000276	0.23	13.300	0.176	0.0582	0.0007	0.0750	0.0010						466	6			
43.1	49	14	0.28	29.0	0.000244	0.29	1.441	0.033	0.2719	0.0015	0.6944	0.0162	26.072	0.679	0.2723	0.0017	0.972	3399	62	3319	10	−2
44.1	217	72	0.33	99.3	0.000005	0.01	1.882	0.029	0.1870	0.0006	0.5314	0.0083	13.698	0.219	0.1869	0.0006	0.977	2747	35	2716	6	−1
45.1	230	48	0.21	91.8	0.000028	0.04	2.150	0.024	0.1767	0.0006	0.4649	0.0052	11.302	0.134	0.1763	0.0007	0.945	2461	23	2619	6	6
46.1	42	0	0.00	7.0	0.001460	2.46	5.179	0.080	0.0886	0.0015	0.1902	0.0030	1.990	0.075	0.0759	0.0024	0.576	1122	16	1092	63	−3
47.1	63	45	0.72	3.7	0.002646	2.76	14.682	0.225	0.0773	0.0021	0.0662	0.0010						413	6			
48.1	446	124	0.28	68.1	0.000116	0.20	5.619	0.062	0.0748	0.0007	0.1776	0.0020	1.793	0.030	0.0732	0.0009	0.653	1054	11	1019	26	−3
49.1	103	32	0.31	9.5	0.000431	0.33	9.337	0.128	0.0641	0.0011	0.1068	0.0015						654	9			
50.1	162	122	0.75	19.7	0.000449	0.78	7.069	0.085	0.0707	0.0008	0.1404	0.0017	1.243	0.037	0.0643	0.0018	0.403	847	10	750	58	−13
51.1	96	70	0.73	16.8	0.000444	0.74	4.900	0.063	0.0803	0.0009	0.2036	0.0029	2.199	0.096	0.0783	0.0026	0.786	1195	16	1156	66	−3
52.1	128	19	0.1	17.9	0.000690	1.18	6.144	0.075	0.0791	0.0009	0.1615	0.0020	1.621	0.039	0.0728	0.0013	0.727	965	11	1008	35	4
53.1	416	260	0.62	144.3	0.006719	10.21	2.480	0.027	0.2881	0.0099	0.3621	0.0069	10.337	0.805	0.2071	0.0156	0.245	1992	33	2883	123	31
54.1	270	186	0.69	18.0	0.000446	1.18	12.846	0.148	0.0662	0.0008	0.0769	0.0009						478	5			

(*continued on next page*)

Table 2 (*continued*)

Total ratios																		Age (Ma)				
Grain spot	U ppm	Th ppm	Th/U	^{206}Pb ppm	^{204}Pb/^{206}Pb	f_{206} %	^{238}U/^{206}Pb	±	^{207}Pb/^{206}Pb	±	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	ρ	^{206}Pb/^{238}U	±	^{207}Pb/^{206}Pb	±	% Disc
55.1	226	42	0.19	14.9	0.000697	0.72	12.983	0.158	0.0624	0.0010	0.0765	0.0010						475	6			
56.1	245	211	0.86	23.1	0.000262	0.87	9.114	0.108	0.0689	0.0011	0.1088	0.0013						666	8			
57.1	194	43	0.22	17.0	0.000630	0.53	9.765	0.120	0.0650	0.0008	0.1019	0.0013						625	7			
58.1	127	44	0.34	14.0	0.000344	0.60	7.812	0.097	0.0710	0.0009	0.1272	0.0016	1.159	0.047	0.0661	0.0025	0.314	772	9	808	80	4
59.1	360	40	0.11	30.5	0.000265	0.94	10.144	0.113	0.0676	0.0006	0.0977	0.0011						601	7			
60.1	241	76	0.31	47.1	0.000175	0.29	4.402	0.050	0.0863	0.0006	0.2265	0.0026	2.617	0.045	0.0838	0.0011	0.656	1316	13	1288	25	−2
61.1	440	133	0.30	29.2	0.000154	0.05	12.977	0.143	0.0571	0.0006	0.0770	0.0009						478	5			
62.1	477	237	0.50	31.9	0.000390	0.50	12.852	0.144	0.0608	0.0006	0.0774	0.0009						481	5			

1. Uncertainties given at the one sigma level.
2. Error in FC1 reference zircon calibration was 0.34% for the analytical session. (not included in above errors but required when comparing ^{206}Pb/^{238}U data from different mounts).
3. f206% denotes the percentage of ^{206}Pb that is common Pb.
4. For areas older than ~800 Ma correction for common Pb made using the measured ^{204}Pb/^{206}Pb ratio.
5. For areas younger than ~800 Ma correction for common Pb made using the measured ^{238}U/^{206}Pb and ^{207}Pb/^{206}Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).
6. For % Disc, 0% denotes a concordant analysis.

clearly seen from the CL images that the majority of the grains are zoned igneous zircon (Fig. 3). Rare metamorphic grains are present, as are complexly structured zircons, although often the latter have rims that are too narrow to be analysed by the ∼20 μm SHRIMP spot size.

The analytical data are plotted on Tera-Wasserburg diagrams as total ratios, uncorrected for common Pb (Fig. 4). Whilst some of the data plot close to the concordia curve and so the areas analysed are dominated by radiogenic Pb, many of the areas analysed are variably enriched in common Pb, and so the total ratios plotted on Fig. 4 are above the concordia curve. This does not indicate that the areas analysed are discordant, only that they are enriched in common Pb.

Probability density plots, with stacked histograms of the detrital zircon radiogenic ages are presented in Fig. 5. The results for both samples are remarkably similar consistent with a dominant age peak between 450 and 490 Ma, and a secondary peak or array between 560 and 680 Ma in sample 2741, and 630 to 680 Ma in sample 2734 sample. There are scattered smaller peaks or single analyses between 750 and 1300/1500 Ma, 1750 and 2000 Ma and 2550 to 2700 Ma in both samples (Fig. 5). The youngest single grain analysis in sample 2734 has a ^{206}Pb/^{238}U age of ∼413 Ma, whilst the next youngest ^{206}Pb/^{238}U ages are ∼443 Ma, ∼445 Ma and 449 Ma. Little geological significance can be placed on the analysis of a single zircon grain and so the grouping of the three zoned igneous zircon grains with a weighted mean age of 446 ± 6 Ma (MSWD = 0.34) constrains the maximum time of sedimentation (Fig. 5, Table 1). The most prominent age peak in this sample, comprising 15 analyses has a weighted mean ^{206}Pb/^{238}U age of ∼473 Ma (Fig. 5, Table 1). For sample 2741 the youngest grain has a ^{206}Pb/^{238}U age of ∼438 Ma (Fig. 5, Table 2). However the youngest group of analyses is the major peak comprising 13 single grain analyses with a mean ^{206}Pb/^{238}U age of ∼473 Ma. Once again these youngest zircons grains can be seen from the CL images to be zoned igneous zircon. One exception is grain 38 which has a low Th/U ration of ∼0.01 (cf. Rubatto, 2002) and the area analysed is interpreted to be metamorphic in origin. The metamorphic grade of the La Modesta Formation has not exceeded the greenschist facies and it is unlikely that metamorphic zircon would have crystallized under these conditions. Thus the time of deposition of sample 2741 can be no older than ∼470 Ma; ie the age for grain 38.

4.2. Pb isotope results

The present day isotopic Pb compositions (whole rock data) from the La Modesta Formation meta-volcanic and tourmalinic rocks exhibit a restricted range from 18.59 to 18.83 for the ^{206}Pb/^{204}Pb ratio, 15.62–15.75 for the ^{207}Pb/^{204}Pb and 38.37–38.86 for the ^{208}Pb/^{204}Pb (Table 4). This suggests a possible genetic connection with a common Pb isotope source from volcanic and exhalative processes, such as was envisaged by Moreira et al. (2005) on the basis of field mapping, detailed mineral and textural analysis and whole rock geochemistry. The lead isotope composition of the tourmalinites are slightly more radiogenic than the meta-volcanic rocks and suggests a significant upper crustal influence for the exhalative rocks, in accordance with the shallow origin (Moreira et al., 2006).

The Pb isotopic system has been used in the southwestern part of South America to discriminate between different basement domains (Schwartz and Gromet, 2004; Loewy et al., 2004 and references there in cited) and to assess the provenance of metasedimentary rocks (Bock et al., 2000; Drobe et al., 2009). For these purposes Pb isotopes are plotted in uranogenic (^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb) and thorogenic (^{208}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb) diagrams (Fig. 6). Samples selected from La Modesta Formation

Table 3
Summary of SHRIMP U–Pb zircon results for sample 2741.

Total ratios																		Age (Ma)				
Grain spot	U ppm	Th ppm	Th/U	^{206}Pb ppm	$^{204}Pb/^{206}Pb$	f_{206} %	$^{238}U/^{206}Pb$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	ρ	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{206}Pb$	±	% Disc
1.1	171	44	0.26	13.1	0.000256	0.77	11.251	0.137	0.0646	0.0009	0.0882	0.0011						545	7			
2.1	209	86	0.41	79.2	0.000109	0.16	2.264	0.026	0.1719	0.0007	0.4411	0.0051	10.375	0.130	0.1706	0.0008	0.928	2356	23	2563	8	8
3.1	73	22	0.30	12.9	0.000951	1.59	4.853	0.066	0.0942	0.0011	0.2028	0.0028	2.259	0.093	0.0808	0.0031	0.340	1190	15	1216	76	2
4.1	51	38	0.75	10.2	0.000613	1.01	4.293	0.063	0.0978	0.0013	0.2306	0.0035	2.837	0.130	0.0892	0.0039	0.333	1338	18	1409	83	5
5.1	547	113	0.21	53.0	0.000343	1.04	8.873	0.096	0.0707	0.0006	0.1115	0.0012						682	7			
6.1	118	49	0.42	7.8	0.000908	1.63	13.017	0.170	0.0697	0.0012	0.0756	0.0010						470	6			
7.1	159	24	0.15	13.0	0.000783	0.73	10.504	0.132	0.0653	0.0009	0.0945	0.0012						582	7			
8.1	151	137	0.91	43.1	0.000149	0.23	3.006	0.035	0.1170	0.0007	0.3319	0.0039	5.261	0.079	0.1150	0.0011	0.786	1847	19	1879	17	2
9.1	605	30	0.05	50.0	0.000085	0.20	10.407	0.122	0.0613	0.0004	0.0959	0.0011						590	7			
10.1	248	26	0.10	41.6	0.000185	0.31	5.129	0.058	0.0781	0.0006	0.1950	0.0022	2.109	0.033	0.0784	0.0007	0.841	1149	12	1158	17	1
11.1	342	160	0.47	27.1	0.000627	1.36	10.859	0.124	0.0699	0.0006	0.0908	0.0011						560	6			
12.1	83	29	0.35	13.8	0.000247	0.42	5.170	0.067	0.0831	0.0010	0.1926	0.0025	2.114	0.057	0.0796	0.0019	0.486	1136	14	1187	47	4
13.1	177	91	0.52	11.9	0.000547	0.77	12.716	0.153	0.0631	0.0009	0.0780	0.0010						484	6			
14.1	182	43	0.24	11.9	0.000402	0.71	13.189	0.246	0.0622	0.0009	0.0753	0.0014						468	9			
15.1	360	83	0.23	32.3	0.000301	0.48	9.563	0.108	0.0649	0.0006	0.1041	0.0012						638	7			
16.1	89	55	0.62	14.1	0.000196	0.33	5.461	0.070	0.0798	0.0010	0.1825	0.0024	1.939	0.049	0.0771	0.0017	0.510	1081	13	1123	44	4
17.1	222	90	0.41	20.7	0.000264	0.70	9.215	0.106	0.0673	0.0008	0.1078	0.0013						660	7			
18.1	246	75	0.30	101.8	0.000073	0.10	2.077	0.023	0.1778	0.0006	0.4811	0.0053	11.734	0.137	0.1769	0.0007	0.947	2532	23	2624	6	4
19.1	99	35	0.36	14.9	0.000155	0.26	5.705	0.072	0.0781	0.0009	0.1748	0.0022	1.829	0.048	0.0759	0.0017	0.488	1039	12	1092	46	5
20.1	759	21	0.03	47.5	0.000277	0.21	13.721	0.149	0.0577	0.0006	0.0727	0.0008						453	5			
21.1	703	331	0.47	50.5	0.006275	15.97	11.954	0.129	0.1850	0.0056	0.0703	0.0010						438	6			
22.1	282	90	0.32	42.0	0.000234	0.40	5.774	0.073	0.0771	0.0005	0.1725	0.0022	1.753	0.031	0.0737	0.0009	0.714	1026	12	1034	25	1
23.1	546	88	0.16	40.6	0.003935	11.19	11.543	0.127	0.1475	0.0215	0.0769	0.0025						478	15			
24.1	38	36	0.96	5.4	0.025378	51.05	5.965	1.343	0.4743	0.0795	0.0821	0.0251						508	149			
25.1	757	158	0.21	70.0	0.002408	5.53	9.298	0.098	0.1058	0.0016	0.1016	0.0011						624	7			
26.1	423	202	0.48	53.8	0.000471	0.81	6.760	0.074	0.0804	0.0005	0.1459	0.0018	1.387	0.044	0.0690	0.0016	0.818	878	10	897	47	2
27.1	51	33	0.64	4.0	0.002684	3.02	11.132	0.169	0.0828	0.0018	0.0871	0.0014						538	8			
28.1	37	49	1.31	7.0	0.001324	2.20	4.577	0.070	0.1031	0.0015	0.2137	0.0035	2.487	0.151	0.0844	0.0049	0.268	1248	18	1303	114	4
29.1	127	47	0.37	22.2	0.000313	0.52	4.929	0.059	0.0847	0.0008	0.2018	0.0024	2.233	0.054	0.0802	0.0017	0.504	1185	13	1203	41	1
30.1	86	45	0.52	17.8	0.000488	0.80	4.164	0.053	0.0950	0.0009	0.2382	0.0031	2.897	0.074	0.0882	0.0019	0.506	1377	16	1387	42	1
31.1	95	12	0.13	13.9	0.000449	0.77	5.894	0.074	0.0795	0.0010	0.1684	0.0022	1.696	0.062	0.0731	0.0025	0.354	1003	12	1016	69	1
32.1	481	164	0.34	30.9	0.000739	1.20	13.364	0.146	0.0659	0.0006	0.0739	0.0008						460	5			
33.1	141	71	0.51	12.7	0.000479	0.85	9.530	0.116	0.0679	0.0014	0.1040	0.0013						638	8			
34.1	380	184	0.49	36.1	0.000075	0.13	9.034	0.118	0.0631	0.0005	0.1105	0.0015						676	9			
35.1	262	162	0.62	29.6	0.000344	0.60	7.605	0.087	0.0717	0.0006	0.1307	0.0015	1.202	0.027	0.0667	0.0013	0.520	792	9	829	40	4
36.1	123	66	0.53	8.0	0.000425	0.21	13.114	0.200	0.0582	0.0010	0.0761	0.0012						473	7			
37.1	40	17	0.42	3.6	0.002036	1.65	9.488	0.150	0.0744	0.0017	0.1037	0.0017						636	10			
38.1	333	3	0.01	21.6	0.000188	0.24	13.256	0.148	0.0584	0.0006	0.0753	0.0009						468	5			
39.1	135	126	0.93	31.8	0.001759	2.84	3.659	0.043	0.1386	0.0009	0.2656	0.0032	4.203	0.100	0.1148	0.0023	0.512	1518	16	1877	37	19
40.1	132	76	0.58	61.0	0.000088	0.12	1.862	0.022	0.1853	0.0008	0.5365	0.0062	13.627	0.169	0.1842	0.0008	0.936	2769	26	2691	7	−3
41.1	219	60	0.27	15.6	0.000486	0.26	12.117	0.163	0.0596	0.0008	0.0823	0.0011						510	7			
42.1	106	48	0.46	10.2	0.001965	2.51	8.872	0.113	0.0826	0.0012	0.1099	0.0014						672	8			
43.1	552	33	0.06	59.9	0.000080	0.14	7.913	0.137	0.0694	0.0004	0.1262	0.0022	1.187	0.025	0.0682	0.0008	0.837	766	13	875	24	12
44.1	135	48	0.36	26.2	0.000785	1.30	4.432	0.054	0.0973	0.0008	0.2227	0.0028	2.650	0.079	0.0863	0.0023	0.423	1296	15	1345	52	4
45.1	37	18	0.49	5.2	0.001275	2.19	6.120	0.095	0.0958	0.0017	0.1590	0.0028	1.614	0.104	0.0736	0.0039	0.701	951	16	1030	108	8
46.1	53	27	0.52	10.2	0.001065	1.76	4.450	0.061	0.1068	0.0050	0.2207	0.0032	2.798	0.199	0.0919	0.0064	0.205	1286	17	1466	132	12
47.1	117	327	2.78	10.0	0.000523	0.87	10.078	0.124	0.0672	0.0010	0.0984	0.0012						605	7			
48.1	179	86	0.48	43.4	0.000995	1.59	3.548	0.040	0.1280	0.0011	0.2774	0.0034	4.379	0.160	0.1145	0.0039	0.334	1578	17	1872	62	16
49.1	308	116	0.38	20.3	0.000691	1.17	13.024	0.145	0.0660	0.0006	0.0759	0.0009						471	5			
50.1	212	160	0.75	14.0	0.000682	0.54	12.993	0.150	0.0609	0.0007	0.0765	0.0009						475	5			
51.1	260	211	0.81	17.3	0.000137	0.19	12.893	0.146	0.0582	0.0007	0.0774	0.0009						481	5			
52.1	194	52	0.3	12.5	0.000413	0.47	13.320	0.156	0.0602	0.0008	0.0747	0.0009						465	5			
53.1	91	48	0.52	6.6	0.003323	7.87	11.858	0.155	0.1207	0.0125	0.0777	0.0017						482	10			
54.1	77	81	1.05	16.9	0.000410	0.67	3.899	0.049	0.0956	0.0009	0.2555	0.0038	3.255	0.157	0.0924	0.0034	0.825	1467	20	1475	70	1

(*continued on next page*)

Table 3 (*continued*)

	Total ratios																	Age (Ma)				
Grain spot	U ppm	Th ppm	Th/U	^{206}Pb ppm	^{204}Pb/^{206}Pb	$f_{206\ \%}$	^{238}U/^{206}Pb	±	^{207}Pb/^{206}Pb	±	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	ρ	^{206}Pb/^{238}U	±	^{207}Pb/^{206}Pb	±	% Disc
55.1	430	139	0.32	33.8	0.000244	0.21	10.920	0.143	0.0606	0.0005	0.0914	0.0012						564	7			
56.1	356	79	0.22	39.9	0.000167	0.29	7.649	0.085	0.0676	0.0005	0.1304	0.0014	1.172	0.020	0.0652	0.0008	0.652	790	8	780	27	−1
57.1	159	112	0.71	10.9	0.000774	1.16	12.519	0.149	0.0663	0.0009	0.0790	0.0010						490	6			
58.1	84	25	0.30	7.0	0.001785	1.56	10.338	0.135	0.0723	0.0012	0.0952	0.0013						586	7			
59.1	284	180	0.64	27.7	0.000064	0.33	8.794	0.099	0.0652	0.0008	0.1133	0.0013						692	8			
60.1	338	45	0.13	28.7	0.000334	0.28	10.124	0.113	0.0624	0.0006	0.0985	0.0011						606	7			

1. Uncertainties given at the one sigma level.
2. Error in FC1 reference zircon calibration was 0.34% for the analytical session.(not included in above errors but required when comparing ^{206}Pb/^{238}U data from different mounts).
3. f206% denotes the percentage of ^{206}Pb that is common Pb.
4. For areas older than ~800 Ma correction for common Pb made using the measured ^{204}Pb/^{206}Pb ratio.
5. For areas younger than ~800 Ma correction for common Pb made using the measured ^{238}U/^{206}Pb and ^{207}Pb/^{206}Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).
6. For % Disc, 0% denotes a concordant analysis.

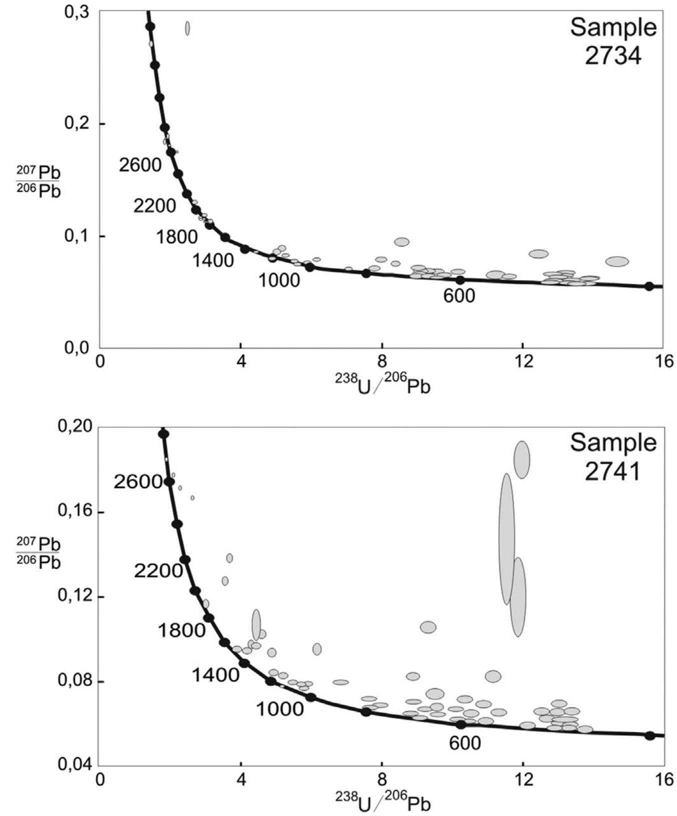

Fig. 4. Tera-Wasserburg U–Pb Concordia diagrams for SHRIMP analyses of zircons from samples 2734 and 2741 of the La Modesta Formation.

present a mean and homogenized isotopic composition of the rocks from which they were derived. It can be clearly seen that the whole rock Pb isotopic compositions overlap with the compositional data for a variety of basement rocks from western Gondwana (Fig. 6).

4.3. Whole rock geochemical composition

Table 1 shows the whole-rock element compositions of meta-sedimentary, calc–silicatic and meta-volcanic rocks from the La Modesta Formation. The metasediments from the La Modesta-La Josefina area show a felsic bulk composition with SiO_2 contents in the range 68–86 wt % (the higher in meta-sandstone). Values for Al_2O_3: 5.5–13.5 and Fe_2O_3 total (Table 1 recalculated) could be expected in recycled mature (Augustsson and Balbhurg, 2008) or moderately immature sediments. The calc–silicatic and meta-volcanic rocks show similarities in chemical composition, with lower SiO_2 and higher Al_2O_3, Fe_2O_3 (total), MgO and CaO compared to metasediments, which could represent the influence of volcanic contributions, consistent with their high TiO_2, Co, Ni, V, Cu and Zn contents. The meta-sedimentary rocks from El Tranquilo-La Bajada area show a more variable composition, which may indicate a higher variability of sources.

Selected metasedimentary rock samples (excluding those containing calcite) were plotted on the discriminant plot of Roser and Korsch (1988), as shown in Fig. 7 A. The major element composition of the La Modesta metasedimentary rocks is compatible with a large input from recycled (or felsic) sources for most samples. The distributions shown in this plot indicates higher variability in source contributions than the metasedimentary rocks studied by Augustsson and Balbhurg (2008) in the northern Eastern Andes Metamorphic Complex (EAMC).

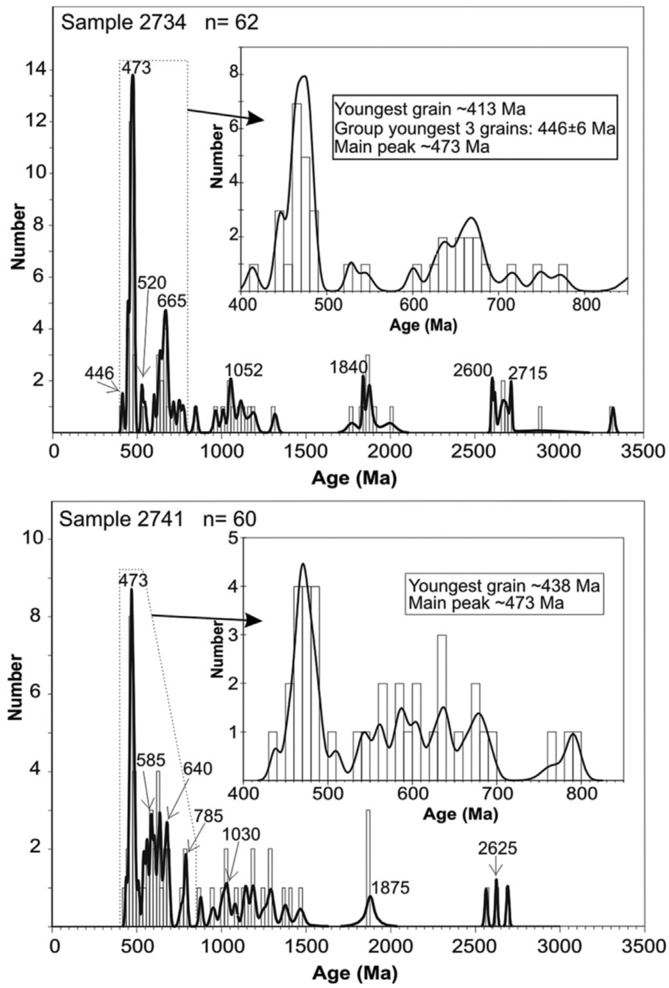

Fig. 5. Relative probability spectra of the detrital zircon radiogenic ages from samples 2734 and 2741 of the La Modesta Formation.

Provenance-indicative element ratios for La Modesta Formation such as Th/Sc (0.50–0.79) and La/Sc (0.45–1.89) are lower than the upper continental crust (UCC) as determined by McLennan (2001): Th/Sc ~ 0.8 and La/Sc ~ 2.2. While the Th/Co ratio (0.94–2.3) is higher (UCC ~ 0.6). Moreover the Zr/Sc ratio (2.3–10.2) is significantly lower than that of the UCC (~ 14). This may reflect the immaturity of sedimentary protoliths for La Modesta Formation, regarding the recycled, selected and mature sediments of the UCC. Plotted in ternary diagrams for discrimination between greywackes from different tectonic environments (Bhatia and Crook, 1986), some samples of La Modesta Formation overlap the Continental Island Arc field (Fig. 7B), while others are scattered outside the fields established by these authors. They also show a different composition of the Northern EAMC samples studied by Augustsson and Balbhurg (2008) that largely overlap the Continental Island Arc field.

Table 4
Pb isotope composition of the La Modesta Formation samples.

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
2721	18,593	15,648	38,371
2741-01	18,635	15,621	38,597
2741-02	18,697	15,676	38,502
2741-03	18,830	15,746	38,857

5. Discussion

U–Pb zircon ages (SHRIMP) have been obtained in the last years from several metamorphic and magmatic rocks in Patagonia advancing the knowledge of its evolution. Fig. 8 schematically shows the location of the areas where the detrital and magmatic Pre-Permian zircons were obtained and their spatial relationship with the La Modesta Formation (extended) as discussed in this paper.

In the Deseado Massif, metamorphic rocks from the Rio Deseado Complex have been dated (SHRIMP U–Pb) by Pankhurst et al. (2003). The Dos Hermanos phyllite, that is cross-cut by amphibolites dated at 540 ± 20 Ma (K–Ar on amphibole, Pezzuchi, 1978), contains detrital zircons with age groupings at ~565, ~590 and ~630 Ma. The oldest detrital zircons show age peaks at ~865 and ~1000–1060 Ma ("Grenvillian" cycle). The latter are of similar age to those obtained by K–Ar and Rb–Sr methods at Cabo Belgrano (Cape Meredith) in the Malvinas (Falkland) Islands by Cingolani and Varela (1976) and confirmed by Jacobs et al. (1999) with SHRIMP U–Pb zircon and $^{40}Ar/^{39}Ar$ minerals ages from Cape Meredith Complex pre- and postectonic granitoids.

The magmatic rocks from the Rio Deseado Complex yielded ages between Lower Ordovician and Carboniferous (Mississippian). The oldest SHRIMP U–Pb zircon ages recorded by Pankhurst et al. (2003) were 476 ± 5 Ma and 472 ± 5 Ma for granitoid cobbles within a conglomerate of the Permian La Golondrina Formation, overlying metamorphic rocks in the Dos Hermanos area. Pankhurst et al. (2003) interpreted that the large size of the cobbles indicates that the source area cannot have been very far away. These authors also proposed a minimum age of 450 Ma for the Dos Hermanos leucogranite on the basis of conventional and SHRIMP U–Pb data. A late Silurian SHRIMP U–Pb zircon crystallization age of 425 ± 4 Ma has been reported for the El Sacrificio granite, with inherited zircon cores at ~540, ~590, ~890, ~1060 and ~1320 Ma. A similar conventional U–Pb age of 423 ± 3 Ma was obtained for the Tres Hermanas granite (Pankhurst et al., 2003). A middle Devonian SHRIMP U–Pb zircon crystallization age of 395 ± 4 Ma has been published for the El Laurel tonalite (Pankhurst et al., 2003) and an age of 393 ± 2 Ma for the Bahia Laura granite (Guido et al., 2005). The youngest granite (Mississippian) known from the Rio Deseado Complex is exposed in Bajo de La Leona, with SHRIMP U–Pb zircon age of 344 ± 4 Ma (Pankhurst et al., 2003).

There are no surface exposures of basement rocks south of the Deseado Massif, but in Tierra del Fuego, Söllner et al. (2000) found a foliated granodiorite basement in the Magallanes basin (oil well) of Cambrian age based on U–Pb zircons (529 ± 7.5 Ma). This granodiorite was re-analysed by Pankhurst et al. (2003) giving a similar age of 523 ± 4 Ma. Further, in core drill holes into the basement of the Magallanes basin Hervé et al. (2010) report Lower Cambrian crystallization ages for orthogneisses (U–Pb SHRIMP in zircon): 522 ± 6, 523 ± 7 and 538 ± 6 Ma, and a Cambrian migmatite with inherited zircon of 550–650 ("Brasiliano"-cycle) and 950–1100 Ma ("Grenvillian"-cycle).

In the northeastern region of the Somun Cura Massif there is a larger geochronological data-base than for the Deseado Massif and this permits enhanced age constraints for the Lower Paleozoic metamorphic rocks (the El Jaguelito and Nahuel Niyeu Formations and the Mina Gonzalito Complex), magmatic rocks (Punta Sierra Magmatic Complex) and sedimentary rocks (Sierra Grande Formation).

The protholits of the low grade metamorphic El Jaguelito Formation were deposited between the Cambrian and lower Ordovician (González et al., 2002). A maximum age constraint of middle Early Cambrian is based on archaeocyath identified in limestone blocks from a meta-conglomerate intercalated in the sequence (González et al., 2011). These authors also reported the affinities of

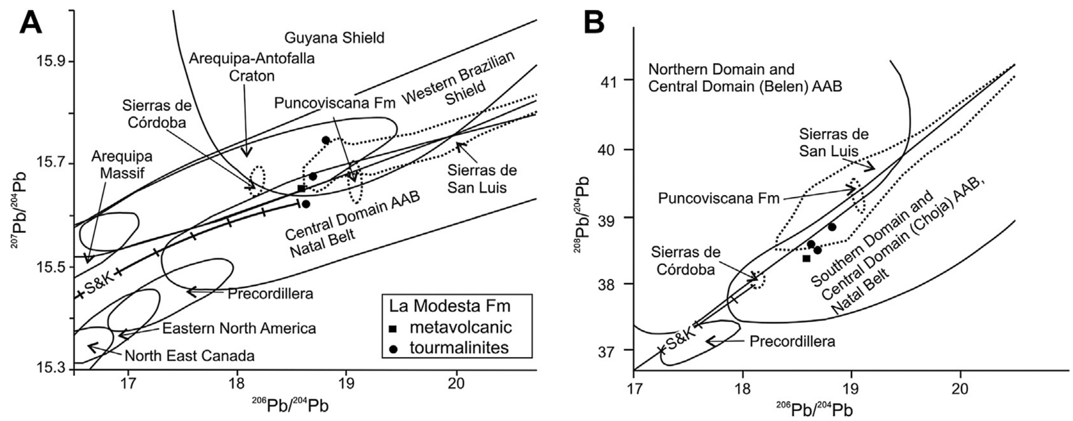

Fig. 6. Pb isotopic values from La Modesta Formation metavolcanic and tourmalinic rocks. A: $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ present day ratios. B: $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ present day ratios. Fields in solid lines were taken from Schwartz and Gromet (2004) and Drobe et al. (2009). Fields in dotted lines: Eastern Sierras Pampeanas granitoids (Schwartz and Gromet, 2004); Metasedimentary rocks of the Puncoviscana Formation (Bock et al. (2000); Eastern Sierras Pampeanas metamorphic rocks (Drobe et al., 2009). S&K: Stacey and Kramer (1975) line as reference.

the fossils with the paleobiogeographic Antartic-Australia province. The youngest detrital zircons ages from the El Jaguelito Formation are grouped between ~503 and ~574 Ma in the meta-conglomerate with limestone blocks and ~523 to ~644 Ma in meta-wackes with maximum age peaks at ~523 and ~580 Ma respectively (Naipauer et al., 2010; U–Pb LA-ICP-MS). Pankhurst et al. (2006) found a dominant detrital zircon peak age at ~535 Ma (U–Pb SHRIMP). The low-grade meta-sedimentary Nahuel Niyeu Formation contains detrital zircons with a main age peak at ~515 Ma (Pankhurst et al., 2006; U–Pb SHRIMP). Although the ages of the youngest single zircon grains found by these authors were reinterpreted by Chernicoff et al. (2013) who proposed a maximum sedimentation age at 482 Ma for this Formation. From the high-grade metamorphic Mina Gonzalito Complex Pankhurst et al. (2006) have obtained a main detrital zircon age peak at ~540 Ma; the zircon grains have metamorphic rims at ~472 Ma (U–Pb SHRIMP). A SHRIMP U–Pb zircon crystallization age of 492 ± 6 Ma has been reported by Varela et al. (2011) for an orthogneiss from this Complex.

In addition to the above mentioned youngest detrital zircons all these metamorphic rocks have consistently older inherited zircons with secondary age peaks in the Neopotrerozoic ("Brasiliano"-cycle) and Late Mesoproterozoic ("Grenvillian"-cycle), with scarce older grains (Pankhurst et al., 2006; Naipauer et al., 2010).

The magmatic rocks exposed near the town of Sierra Grande have been included in the Punta Sierra Plutonic Complex by Busteros et al. (1998). SHRIMP U–Pb zircon ages of 476 ± 4 Ma (Playas Doradas granite), 475 ± 6 Ma (Arroyo Salado granite) and 476 ± 6 Ma (Sierra Grande granite) were obtained by Pankhurst et al. (2006). Additionally Gonzalez et al. (2008) report a crystallization age of 472 ± 5 Ma for the El Molino pre-orogenic pluton that intrudes the El Jaguelito Formation. Further to the northwest leucogranites from the Valcheta Pluton has an $^{39}Ar/^{40}Ar$ age of 470 ± 5 Ma (Gozalvez, 2009).

The Sierra Grande Formation is composed of quartz-rich sandstones, shales and iron horizons overlying the El Jaguelito Formation and the Punta Sierra Plutonic Complex. From base to top it has been subdivided into the Polke, San Carlos and Herrada Members respectively (Zanettini, 1999). Based on marine fossil recordings the sediments are interpreted to have been deposited between the Middle Silurian and Lower Devonian (Manceñido and Domborenea, 1984; Limarino et al., 1999). SHRIMP U–Pb detrital zircon data reported by Pankhurst et al. (2006) show a maximum concentration between ~500 and ~700 Ma, a secondary peak about ~1000 Ma and Paleoproterozoic single grains. Detrital zircons from the Polke Member show the main age peaks at ~500, ~570 and ~1035 Ma (Naipauer et al., 2011; U–Pb LA-MS-ICP ages). The latter authors proposed to separate this unit from de Sierra Grande

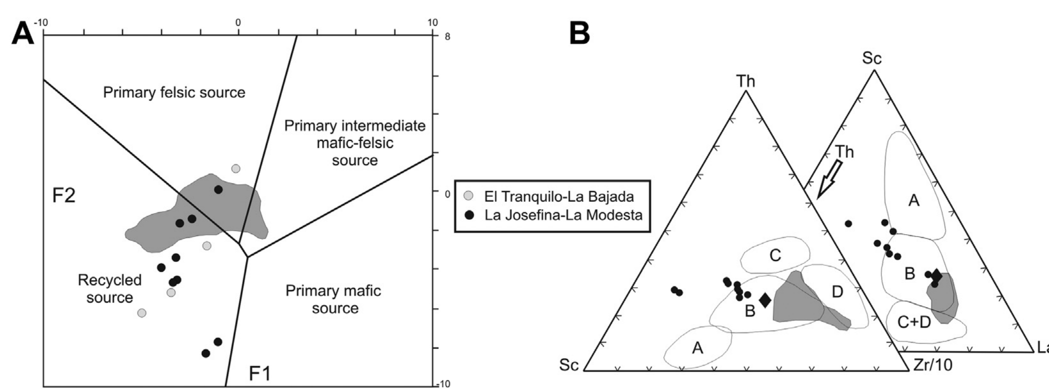

Fig. 7. A: Major element discrimination scheme for the La Modesta Formation samples (excluded those containing calcite). Diagram after Roser and Korsch (1988). *Grey field*: Bahia La Lancha and Rio Lacteo Formations and Cochrane Unit from Augustsson and Balbhurg (2008). B: La Josefina-La Modesta samples in trace elements ternary diagrams for discrimination between greywackes from different tectonic environments (Bhatia and Crook, 1986). A: Ocean island arc, B: Continental island arc, C: Active continental margen, D: Passive margen. *Diamonds*: Upper Continental Crust (McLennan, 2001). *Grey field*: Bahia La Lancha and Rio Lacteo Formations and Cochrane Unit from Augustsson and Balbhurg (2008).

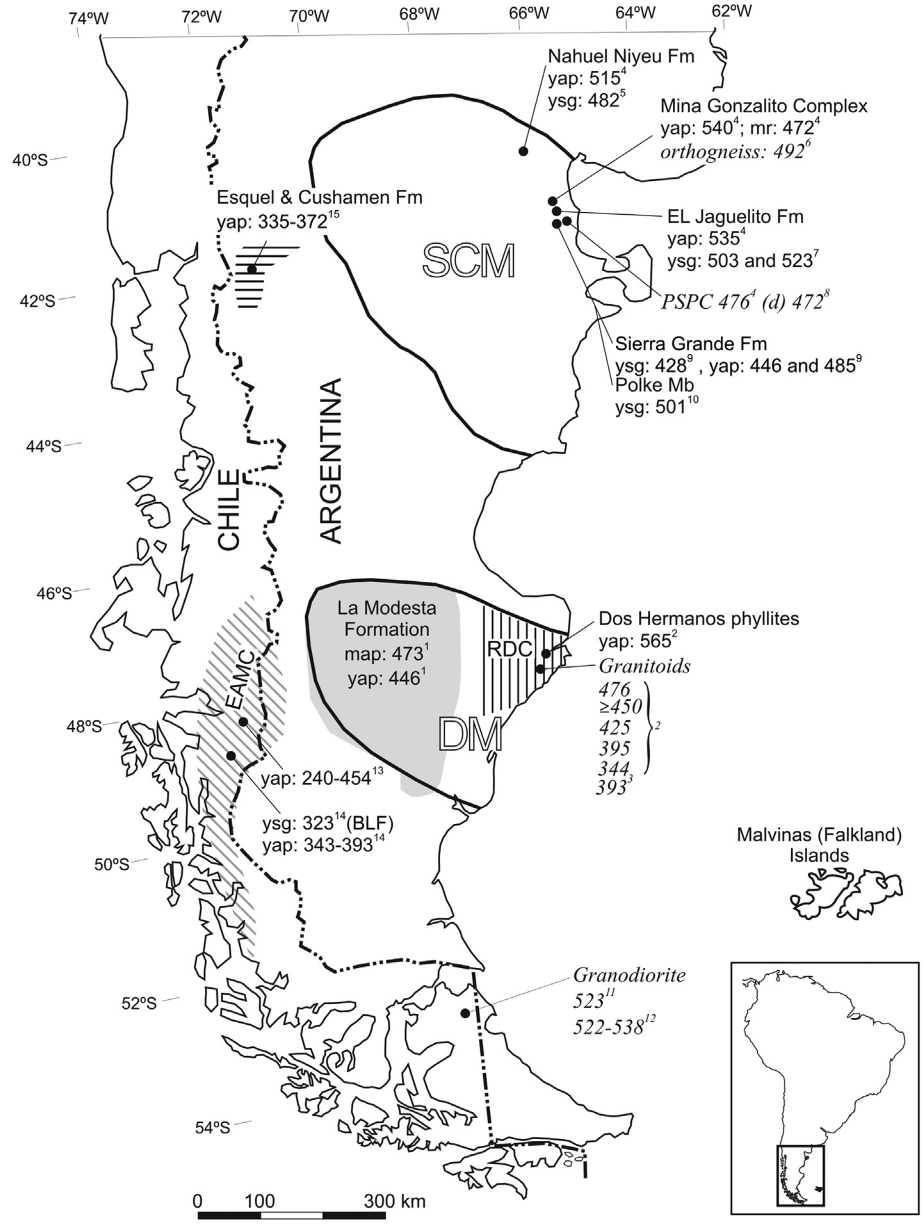

Fig. 8. Schematic distribution of younger zircon ages from granitoids, metamorphic and sedimentary rocks of Patagonia, possibly related to La Modesta Formation as proposed in this paper. Abbreviations: DM Deseado Massif, SCM Somun Cura Massif, EAMC Eastern Andes Metamorphic Complex, RDC Río Deseado Complex, BLF Bahia La Lancha Formation, PSPC Punta Sierra Plutonic Complex; mr: metamorphic rim, map: main age peak, yap: youngest detrital zircon age peak, ysg: youngest single detrital zircon grain. Letters in italica: age of crystallization. Data from: [1] this paper, [2] Pankhurst et al. (2003), [3] Guido et al. (2005), [4] Pankhurst et al. (2006), [5] Chernicoff et al. (2013), [6] Varela et al. (2011), [7] Naipauer et al. (2010), [8] González et al. (2008), [9] Uriz et al. (2011), [10] Naipauer et al. (2011),[11] Söllner et al. (2000), [12] Hervé et al. (2010), [13] Hervé et al. (2003), [14] Augustsson et al. (2006), [15] Hervé et al. (2005). All ages in Ma (±omitted).

Formation and suggested that the detrital zircons from Pankhurst et al. (2006) would belong to the Polke Member. The youngest detrital zircons found by Uriz et al. (2011) in the Sierra Grande Formation are Ordovician with main peaks at ~446 and ~485 Ma (SHRIMP U–Pb and LA-MS-ICP). There are also Lower Cambrian-Neoproterozoic ("Brasilian" cycle) and late Mesoproterozoic ("Grenvillian" cycle) peaks, and scarce older grains. From a single detrital zircon grain these authors proposed that maximum sedimentation age of the Sierra Grande Formation is ~428 Ma, in agreement with the biostratigraphic age.

Using the youngest single detrital zircon age (Dickinson and Gehrels, 2009) interpreted the maximum depositional age of La Modesta Formation to be 413 ± 6 Ma. This age is consistent broadly with 413 ± 17 Ma previously obtained for this Formation (whole rock Rb–Sr errorchron) although it was interpreted as resulting from a mixture of detrital and metamorphic minerals (Moreira et al., 2005). There are no rocks known in Patagonia that could have contributed the youngest zircons recorded in the La Modesta Formation: early Lower Devonian (c. 413 Ma) and Ordovician-Silurian boundary (c. 438–445 Ma). Due to the low abundance of zircons of this age (only 4 single grains) it can be interpreted that Lower Devonian rocks could have only been of minor importance as a source of the detrital zircon in the metasediments.

A high proportion of detrital zircons (~26%) found in the La Modesta Formation record Ordovician ages, with a prominent Lower Ordovician peak at ~ 473 Ma. The most favourable candidates to provide these zircons in the basin would be magmatic rocks from the Rio Deseado Complex represented by the Lower-

Ordovician (dated in cobbles from Permian conglomerate) and Middle-Upper Ordovician granites. The Silurian (Wenlock) El Sacrificio and Tres Hermanas granites (Pankhurst et al., 2003) might have been available, but there is no record of zircons of this age in the La Modesta Formation. Further, the Lower Ordovician Punta Sierra Plutonic Complex in the Somun Cura Massif could also have been a source for those zircons. These rocks also contributed zircons to the basin of the Silurian–Devonian Sierra Grande Formation (Uriz et al., 2011) excluding the underlying Polke Member.

The oldest detrital zircons found in the La Modesta Formation show a wide range of ages with the highest proportions in the Early Cambrian-Neoproterozoic (Ediacaran-Early Cambrian: ∼ 12% and Cryogenian: ∼ 20%) and Mesoproterozoic (Stenian: ∼ 13%) reflecting affinities with sources of "Brasiliano"-age cycle and "Grenvillian"-age cycle, respectively. Zircons of these ages were recorded in neighbouring metamorphic rocks to east in the Rio Deseado Complex (Dos Hermanos phyllites, Pankhurst et al., 2003) and are also widely represented in the pre-Silurian metamorphic and sedimentary rocks located in the northeastern of the Somun Cura Massif (El Jaguelito and Nahuel Niyeu Formations, the Mina Gonzalito Complex and the Polke Member). These detrital zircons ages may indicate that the basin of the La Modesta Formation, in addition Ordovician granites, could have received detritus from the metamorphic rocks of the Rio Deseado Complex and from the pre-Silurian metamorphic and sedimentary rocks of the Somun Cura Massif. Another potential source of detritus for the La Modesta Formation could have been the orthogneiss and migmatites from the basement at Magallanes Basin. Other more distant sources of supply with "Brasiliano" and "Grenvillian" zircons from SW Gondwana cannot be ruled out.

The remaining older detrital zircons of the La Modesta Formation are Mesoproterozoic (Ectasian-Calymmian: 6%), late Paleoproterozoic (Statherian-Orosinian: 8%) and Neoarchean (7.5%), in addition to two Meso- and Paleoarchean single grains. Zircons of these ages were not recorded in the Rio Deseado Complex, but these age ranges except Meso- and Paleoarchean, were found in zircons from pre-Silurian formations of the Somun Cura Massif: El Jaguelito and Nahuel Niyeu Formations (Pankhurst et al., 2006), metawackes of the El Jaguelito Formation (Naipauer et al., 2010), Polke Member (Naipauer et al., 2011), and the Silurian–Devonian Sierra Grande Formation (Uriz et al., 2011). The ages of the oldest detrital zircons suggest a common source with the La Modesta Formation protholits.

Paleoproterozoic and Neoarchean inherited zircons have been recorded in a Permian (or younger) tonalitic orthogneiss from the Yaminue Complex (Chernicoff et al., 2013) and Paleoproterozoic, Neo-, Meso- and Paleoarchean inherited zircons were founded in the Lower Jurassic to Lower Cretaceous granites from the Mesozoic Patagonian Batholith near 45° S (Rolando et al., 2002, 2004). The latter authors suggested the assimilation of old crust during the generation of these magmas. This old crust could be present in "Southern Patagonia terrane" (as in Ramos, 2010) but according to the tectonic evolution proposed by Chernicoff et al. (2013) this "terrane" would not be available as input area during the La Modesta Formation sedimentation. Scattered Paleoproterozoic and Neoarchean zircons are common along the Pacific margin of Gondwana and so it is more likely these oldest zircons are recycled or transported from other areas; that is they are second or third order derivations.

Whilst sedimentation of La Modesta Formation may have been as young as Lower Devonian (Lochkovian), the absence of Middle-Devonian (El Laurel tonalite and Bahia Laura granite) and Carboniferous-Mississippian (Mina La Leona granite) zircons (cf. Pankhurst et al., 2003; Guido et al., 2005) means that basin closure or a change in paleocurrent occurred before exhumation of the Middle-Devonian granitoids (395–393 Ma). This is particularly the case as the Rio Deseado Complex rocks are likely to have been an important source of Ordovician detritus. The age of closure of that basin in the Lower Devonian as indicated by Moreira et al. (2005) on the basis of a Rb–Sr errorchron (413 ± 17 Ma) is consistent with pre-Upper Devonian exhumation of the Rio Deseado Complex as proposed by Giacosa et al. (2002).

To the west of the La Modesta Formation, the Eastern Andes Metamorphic Complex (EAMC) crops out, including the Cochrane, Lago General Carreras (Chile), Bahía La Lancha and Río Lácteo formations. Their protoliths (easternmost rocks) were deposited during the Devonian-Carboniferous (Hervé et al., 2003) in a passive continental margin (Hervé et al., 1988; Faúndez et al., 2002; Augustsson and Balbourgh, 2008) and were metamorphosed before the late Permian at approximately 267 Ma (Thomson and Hervé, 2002. Fission-track zircon ages). The maximum sedimentation ages (SHRIMP U–Pb) indicated by detrital zircons (youngest peaks), excluding the younger analyses that were probably affected by metamorphism or radiogenic Pb-loss, range between ∼454 and ∼240 Ma (Hervé et al., 2003). The older age corresponds to the easternmost sample. These authors also reported a wide range of ages of provenance with prominent peaks in the Cambrian, Neoproterozoic ("Brasilian"-cycle), Mesoproterozoic ("Grenvillian"-cycle) and scarce Paleoproterozoic and Archean grains. The maximum sedimentation ages obtained from Cochrane and Bahía La Lancha formations are between ∼330 and ∼385 Ma (Augustsson et al., 2006; SHRIMP U–Pb detrital zircon). The samples studied by these authors are dominated by broad series of age peaks in the range 350–700 Ma and minor peaks between 900 and 1500 Ma, with a few Archean zircons.

According to the age of the youngest zircons determined by Hervé et al. (2003) in the eastern sample EAMC (VS11A: 457 Ma) that area could correspond to La Modesta Formation rocks incorporated in EAMC by tectonic effects. The rest of the rocks sampled from EAMC (Hervé et al., 2003; Augustsson et al., 2006) have zircon age peaks significantly younger than those for the La Modesta presented in this paper. These young zircons may have been derived from Devonian-Carboniferous granites of northern Patagonia (Varela et al., 2005; Pankhurst et al., 2006) and the Deseado Massif (Western Magmatic Arc of Ramos, 2008). The oldest detrital zircons of EAMC may have had contributions from the same areas as those identified for the La Modesta Formation and may even have come from the same formation.

The generation of diachronic basins on continental crust that begins in the east with the La Modesta Formation and continuing to the west with the units that form the EAMC (partly on the ocean floor) was suggested by Moreira et al. (2005).

Detrital zircon ages of metamorphic rocks of Esquel and Cushamen formations (about 400 km north – present day – of EAMC) have ranges between 350–520 and 330–500 Ma respectively Hervé et al. (2005). The Cushamen Formation has a higher proportion of Proterozoic zircons, particularly Grenvillian, and scattered Archaean grains, indicating a widespread source area for this formation. The younger zircon ages are consistent with igneous rocks of the Devonian to Early Carboniferous in Somun Cura Massif (Varela et al., 2005; Pankhurst et al., 2006) and also with the Middle Devonian to Mississippian granitoids of Río Deseado Complex in the Deseado Massif. In addition, young zircons of Cushamen and Esquel formations agree in age with those of Bahia La Lancha and Cochrane formations. This may indicate a common source area. While the spectrum of ages of old zircons is comparable with that of Dos Hermanos phyllite, in the Deseado Massif, which also may have been part of the source area (Hervé et al., 2005). La Modesta Formation is also a potential area of materials (detrital zircon) for these formations in the North Patagonian Cordillera.

This work has not obtained any evidence for the age of metamorphism of the La Modesta Formation, but it must have happened at least before the Permian, which is the age of metamorphism assigned to EAMC by Thomson and Hervé (2002). The probable age of metamorphism could be prior to 300 Ma (Late Carboniferous) that proposed by Augustsson et al. (2006) for the initiation of subduction in the southern Patagonia.

6. Conclusions

The youngest single zircon analysed has a $^{206}Pb/^{238}U$ age of $\sim$413 $\pm$ 6 Ma age (post-Lower Devonian). Whilst this single analysis may constrain the time of deposition, it is clear that on the basis of three grains the time of sedimentation of La Modesta Formation can be no older than 446 $\pm$ 6 Ma (youngest grouping in sample 2734). Moreover it has been interpreted that the basin closure or eventually a paleocurrent shift occurs during the Lower Devonian before exhumation of the Middle-Devonian granitoids of the Rio Deseado Complex. The precise metamorphic age of La Modesta Formation is not known but it must have happened before the Permian and could be prior to 300 Ma (Late Carboniferous).

Many of the detrital zircons in the La Modesta Formation are igneous and record Ordovician ages, with a prominent Lower Ordovician-age peak at approximately 473 Ma. On the basis of existing regional geochronological data the favourable candidates to provide detrital zircons to the basin are the Ordovician granites of the Rio Deseado Complex (Deseado Massif) and Punta Sierra Plutonic Complex (Somun Cura Massif).

Older ages (including Brasiliano and Grenvillian) of detrital zircons may indicate that the basin could have received inherited igneous zircons mainly from the metamorphic rocks of the Rio Deseado Complex, from the pre-Silurian metamorphic and sedimentary rocks of the Somun Cura Massif, from the basement of the Magellan basin and other sources.

Silurian–Devonian sedimentary rocks of the Somun Cura Massif have detrital zircon ages that are similar to those recorded from La Modesta Formation suggesting a common source for the protholits.

Also the La Modesta Formation could have potentially provided detrital zircon to the Eastern Andean Metamorphic Complex and equivalent formations of the Andean region.

Complementary geochemical and lead isotopic results provide evidence that the protoliths of La Modesta Formation were formed from upper crustal rocks with the contribution of a large input from recycled (or felsic) sources.

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