Characterizing the continental basement of the Central Andes: constraints from Bolivian crustal xenoliths

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ABSTRACT

Critical to understanding the development of active continental margins is knowledge of the crustal basement on which magmatic arcs are built. This study reports results from a whole rock geochemical and zircon U-Pb geochronological study of a suite of crustal xenoliths from the Bolivian Altiplano, Central Andes that provide new insight into the evolution and composition of the continental basement beneath the region. The xenoliths are hosted in Plio-Pleistocene trachyandesitic/dacitic lavas which erupted from monogenetic volcanic centres in the Andean back-arc region and comprise both igneous and metamorphic lithologies including diorites, microgranites, gneisses, garnet-

mica schists, granulites, quartzites, and dacites. The xenolith suite exhibits significant Sr-isotopic heterogeneity with values extending from 0.7105 to 0.7368. Pb isotopic signatures reflect the crustal domains previously constrained from scattered exposures of basement rocks throughout the region. Ion microprobe U-Pb dating of cores and rims from zircon separates from two of the sampled xenoliths reveal predominant Early Phanerozoic age peaks (*c*. 500 Ma; population 1), Late Mesoproterozoic (1.0-1.2 Ga; population 2) and Palaeoproterozoic (1.7-1.9 Ga; population 3). Populations 1 and 2 are well-documented throughout the Andes and correspond to periods of supercontinent formation (e.g. Rodinia at *c*. 1.0 Ga) and break-up. Population 3, poorly represented in the zircon record of the Andes as a whole, may record geological events during the construction of the Palaeoproterozoic Amazonian craton. The presence of the three age peaks in the zircon record of a single crustal xenolith demonstrates the important role of crustal recycling in the construction of the modern day Andean margin. The character of the xenoliths and their detrital zircon record is also inconsistent with current understanding of the eastern extent of the Arequipa-Antofalla Basement (AAB) block beneath the Bolivian Altiplano.

INTRODUCTION

The basement to continental arcs deserves study for two principal reasons; 1) its composition and structure dictate the potential effects on continental arc magmas as they ascend through, and differentiate within, the crust, e.g. enriched LILE, depleted HFSE, Davidson et al. 2005), and 2) the composition, ages and structures are key to determining the geological and plate tectonic development of an active continental margin.

Although it is generally recognized that the western margin of South America has been the type example of an active continental margin for most of the Phanerozoic at least, to date, incomplete knowledge of the continental crust in the Central Andes, hampers our efforts to constrain and refine both palaeo-plate reconstruction models (e.g. Dalziel, 1997; Loewy et al., 2004) and the extent of crust-mantle interaction in Central Andean magmas (e.g. Sørensen and Holm, 2008; Mamani et al., 2010). Current tectonic models for the Neoproterozoic and early Palaeozoic history of the western margin of the South American continent have proposed a collision between the eastern Laurentian Craton and the western margin of Gondwana, of which modern-day South America was a part (Cordani et al., 2005). Fundamental to refining these models and associated terrane maps is knowledge of the continental crust, yet surface exposures of the Central Andean basement are rare due to the lack of tectonically-driven exhumation of basement rocks across the Altiplano region and the extensive Tertiary sedimentary sequences that blanket the region today. Many geochemical studies of volcanic rocks throughout the Central Andes have invoked the variable role of the continental crust during the petrogenesis of magmatic rocks across the region in order to account for the geochemical differences observed within and between magmas erupted/emplaced along and across strike of the active arc (Davidson et al., 1991; Wörner et al., 1992; Aitcheson et al., 1995; Davidson and de Silva, 1995; Caffe et al., 2002). The compositions of potential crustal contaminants however remain poorly constrained.

Studies of crustal xenoliths brought to the surface by ascending magmas during the most recent phase of volcanism (Plio-Pleistocene) have the potential to provide a unique cross section of the continental basement that will provide additional constraints to regional tectonic models and offer new insights to the composition of the Central Andean crust. The crustal xenoliths that are the focus of this research represent a region of the Central Andes where the continental basement has not previously been sampled through studies of surface exposures and/or drill cores. Thus, the objectives of this study are threefold; (1) to present long sought after compositions for the crustal components in Central Andean magmas; (2) to contribute geochronological constraints on the evolution of the western margin of the South American continent to explore the roles of crustal recycling in construction of the Central Andean basement; and (3) to help constrain existing basement terrane models for this region of the Andes.

GEOLOGIC SETTING AND PREVIOUS WORK

This study focuses on a suite of entrained crustal xenoliths hosted in Plio-Pleistocene lavas which have erupted from two monogenetic centres at Pampas Aullagas (PA; 19^{o}S, 67^{o}W) and Quillacas (QL; 19^{o}S, 66^{o}W) on the Bolivian Altiplano (Fig 1a, b). Both centres consist of several lava flows which have erupted along NW-SE trending faults and form part of a lineament of minor volcanic centres which runs subparallel to the volcanic front (Davidson and de Silva, 1995).

Based on previous studies, the PA and QL centres are located on the Arequipa-Antofalla Basement (AAB) block (Fig. 1c; Loewy et al., 2004; Ramos, 2008; Chew et al., 2011). This crustal block can be divided into the northern Arequipa Massif, described as the best-preserved basement inlier throughout the central Andes (Ramos, 2008), and the southern Antofalla basement block. Collectively they are comprised of three distinct domains based Pb-isotopic signatures (after Loewy et al., 2004) the Northern (Arequipa) and the Central and Southern (Antofalla) Domains. These domains young to the south and are exposed intermittently along the Arica embayment (Fig. 1c). Western Bolivia and southern Peru are underlain by the Northern Domain that consists of Palaeoproterozoic (2.02-1.79 Ga) intrusions that were later metamorphosed between 1.82 and 1.79 Ga (Loewy et al., 2004). The oldest rocks in the Central Domain are constrained to Mesoproterozoic age with crystallisation of migmatites and orthogneisses at ~1.25 Ga and ~1.21 Ga respectively. The Central and Northern Domains subsequently underwent metamorphism between 1.20 and

0.94 Ga, whereas the Southern Domain in northern Chile and north-western Argentina is composed of Ordovician rocks and experienced metamorphism at 440 Ma (Loewy et al., 2004). To the east of the AAB lies the cratonic nucleus of South America, the Amazonian Craton which consists of several Archaean and Proterozoic domains (Chew et al., 2011). Several workers inferred an allochthonous origin for the AAB and have suggested that it accreted to the South American margin at the time of the Sunsás Orogeny during assembly of Rodinia (1.2-1 Ga: Loewy et al., 2004; Chew et al., 2007a; Ramos, 2008). The continental basement between the AAB and Amazonian Craton is poorly characterised at this latitude in the Central Andes (Fig. 1c) due to limited tectonic activity and recent sedimentation (identified as "metamorphic basement and Ordovician clastic platform deposits" by Ramos, 2008). Volcano-sedimentary sequences deposited after 320 Ma, and which were subsequently metamorphosed (310 Ma), have been identified to the north of the study area in the Eastern Peruvian Andes (Cardona et al. 2009).

Basement surface exposure in Bolivia is constrained to a single outcrop at Cerro Uyarani on the Western Altiplano (18^{o}30'S, 68^{o}40'W, Fig. 1c) where granulites, charnockites and rare amphibolites with early Proterozoic protoliths have been identified (Wörner et al., 2000). Evernden et al. (1977) reported clasts of red gneiss (K-Ar age of 647 Ma) and granite within the Azurita Conglomerate ~200 km south of La Paz which are inferred to have been derived from western Bolivia. These clasts, in addition to those found in the Mauri formation near Berenguela, western Bolivia, were found to be Mesoproterozoic in age and characteristic of the northern part of the AAB (Loewy et al., 2004). The location of the PA and QL centres and the entrained xenoliths within erupted lavas will therefore allow characterisation of the continental basement in a region of the Central Andes where surface exposure is rare and will provide constraints on the eastward extent of the AAB basement block.

ANALYTICAL PROCEDURES

Rock powders were produced from rock chips free of weathered material. Sr-Nd isotopic analyses were determined on a multicollector VG mass spectrometer (TIMS) at the University of Califorrnia, Los Angeles (UCLA, see Davidson and de Silva, 1995). Additional Sr, Nd and also Pb isotopic compostions were measured on a plasma ionization multicollector mass spectrometer (PIMMS) using the ThermoElectron Neptune instrument at the Arthur Holmes Isotope Geology Laboratory (AHIGL), part of NCIET, at Durham University, UK. Electron microprobe analyses of biotites and garnets were undertaken at the School of Geosciences, University of Edinburgh using the CAMECA SX100 instrument. Secondary ionization mass spectrometry (SIMS) analyses for U-Pb ages in zircons were performed at the UCLA Department of Earth and Space Sciences using a CAMECA ims1270 ion microprobe (SIMS). Sample preparation for each of the analytical techniques, details of standards run throughout this study and all whole rock sample data are provided in the supplementary material. Results from SIMS analyses are presented in Tables 1 and 2.

Corresponding major and trace element data are presented in the supplementary material. Major element and selected trace element abundances were determined by XRF at the University of Edinburgh using the Panalytical PW2404 wavelength-dispersive sequential X-ray spectrometer. Additional trace element concentrations were measured at NCIET (Northern Centre of Isotopic and Elemental Tracing) at Durham University, UK by inductively coupled plasma mass spectrometry (ICPMS) on a Perkin Elmer-Sciex Elan 6000. Where reported, Zr (ppm) data is XRF data due to the difficulty of dissolving zircon encountered during dissolution of whole rocks powders for ICPMS analysis. For this reason, no Hf data are reported

GEOCHEMISTRY

The xenolith suite consists of eight lithologies of which average modal mineralogical abundances are presented in Fig. 2 and key characteristics are described here.

Major and trace elements

Sampled diorites are the most mafic of the sampled suite ranging from 52.7 to 57.7 SiO_2 at higher MgO (2.8-5.7); Fe_2O_3 (7.2-8.4) and K_2O (2.6-6.9) than the majority of the other xenoliths. These samples also exhibit some of the highest Cr and Ni abundances. They are characterised by abundant hornblende, plagioclase and biotite with biotite displaying alteration to orthopyroxene, consistent with biotite breakdown (plus melt). Microgranitic and dacitic xenoliths are characterised by plagioclase, biotite ± alkali feldspar and up to 60% quartz. Samples consistently display very similar major element chemical signatures over a restricted range of SiO_2 (66.7 to 69.3) and high Na_2O + K_2O at ~8 wt. %. The remaining xenoliths show high Al_2O_3 contents which, coupled with the high abundance of aluminous minerals (garnet, sillimanite, biotite) indicate the aluminous nature of the probable pelitic protoliths. Specifically, gneisses and garnet-mica schists are characterised by regular alternating layers of biotite-sillimanite ± garnet melanosomes and quartzofeldspathic leucosomes. Sampled garnets in the mica-schists are almandine ($Py_{15}Alm_{70}Gr_5Sp_{10}$-$Py_{16}Alm_{76}Gr_4Sp_4$) as would be expected of garnet produced during regional metamorphism of argillaceous sediments (i.e. a pelitic protolith, Deer et al., 1992). A few of the sampled granulites and gneisses show evidence for partial melting in the form of quenched glass (estimated at ≤2 vol. % where present), which is interpreted as having formed during entrainment of the xenoliths within their host lavas. Within the glass phase, very fine grained (<200 µm) acicular crystals of anatase (TiO_2) are present (McLeod et al., 2012). Subsequent (partial) extraction of this melt phase during entrainment is likely to have contributed to the high percentage of residual quartz and high bulk SiO_2 contents (up to 88 wt. %) observed in these particular samples.

Dacites and microgranites display LILE enrichment (e.g. Rb, Ba) and exhibit broadly similar enrichment signatures from Ba through to Sm. There are notable peaks at U, K and Pb and troughs at Nb-Ta and Sr. The majority of xenoliths have Sm/Nd ~0.2 (see supplementary information, Fig. i.) similar to that of the upper (and middle) continental crust (Rudnick and Gao, 2003). The majority of samples, to a greater or lesser degree, exhibit a negative Eu anomaly which is again, akin to REE patterns of the upper (and middle) continental crust (Rudnick and Fountain, 1995; Rudnick and Gao, 2003).

Sr-Nd-Pb isotopes

18 xenoliths were chosen for Sr-Nd isotopic analysis. Fig. 3a shows the xenoliths and the Sr-Nd isotope compositional fields for sampled crustal basement rocks in neighbouring Chile and Argentina. The xenoliths overlap compositions from previous basement studies, exhibit slightly higher $^{87}Sr/^{86}Sr$ at lower $^{143}Nd/^{144}Nd$ but do not extend to the extreme $^{87}Sr/^{86}Sr$ values of Palaeozoic Argentinian gneisses. Fig. 3b shows the variation in $^{87}Sr/^{86}Sr$ signatures of recent (<60 Ma) volcanic rocks erupted along the Andean Cordillera. Regional variation is attributed to the difference in continental crustal composition, age and thickness: Mafic, Cretaceous and younger between 50 km (recent mapping of the Moho by the European Space Agency) and 70 km (from gravity data; Feininger and Seguin, 1983) thick in the NVZ; Palaeozoic with mafic and felsic components and up to 40 km thick in the SVZ (Hildreth and Moorbath,1988); Proterozoic and younger, predominantly felsic and thick, up to 80 km (e.g. Thorpe and Francis, 1979; Zandt et al., 1994) in the CVZ. Volcanic rocks in the Central Andes extend to more crust-like $^{87}Sr/^{86}Sr$ compositions than in the northern and southern zones but not to the extremely high $^{87}Sr/^{86}Sr$ of the crustal xenoliths of this study or those of

crustal rocks from the Central Andes previously investigated (Fig. 3). 20 xenoliths were chosen for Pb isotopic analysis. The microgranites are relatively non-radiogenic with characteristically low Pb isotopic ratios at $^{206}Pb/^{204}Pb$ <17.77; $^{207}Pb/^{204}Pb$ <15.61; and $^{208}Pb/^{204}Pb$ <38.49 (Fig. 4a, b). The remaining xenoliths exhibit $^{206}Pb/^{204}Pb$ values from 18.17 to 18.93; $^{207}Pb/^{204}Pb$ values from 15.64 to 15.69; $^{208}Pb/^{204}Pb$ values from 38.66-39.46, which fall near upper crustal evolution trends. Aside from adding to the limited knowledge on the compositions of the rock types which comprise the Central Andean continental basement, the geochemical database presented here offers much needed constraints on the crustal component(s) involved during petrogenesis of Central Andean magmas, a process which has been, and is currently, extensively investigated and modelled (Davidson and de Silva, 1992; 1995; Sørensen and Holm, 2008; Mamani et al., 2010; Kay et al., 2010; Caffe et al., 2012).

Geochronology

Zircon is a useful mineral for U-Pb geochronology as it has a closure temperature in excess of typical zircon dissolution temperatures for continental crustal compositions (Cherniak and Watson, 2001), and it is physically and chemically robust, incorporating U and Th but little (if any) common Pb. $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ion microprobe data on U-Pb concordia plots for 64 interior and rim analyses from 31 zircon crystals derived from two xenoliths of this study are presented on figures 5a and b and in Tables 1 and 2.

From sample BC93PAX14 (garnet-sillimanite granulite), three ages were discordant, likely reflecting Pb loss from the system. From 34 concordant ages, the oldest ages cluster at 1857 ± 17 Ma and the youngest at 380 ± 14 Ma. The oldest ages define a small peak from ~1.7 to ~1.9 Ga with one age at 1611 ± 21 Ma. A prominent age population is present between ~1.0 and ~1.2 Ga and the most significant population of Ordovician ages (11) is present between 439 ± 13 Ma and 487 ± 14 Ma (see inset graph in Fig. 5a). Additionally, two analyses yielded upper Devonian ages of 385 ± 11 Ma and 380 ± 14 Ma ($^{206}Pb/^{238}U$). The zircons analysed from sample BC10QSX107 (garnet granulite) yield predominantly concordant ages with significant age peaks from approximately 1.7 to 1.9 Ga and 1.0 to 1.2 Ga (see inset graph in Fig. 5b). A third clustering of ages is present between 417 ± 17 Ma and 495 ± 17 Ma. Five ages fall outside these populations with three showing late Neoproterozoic ages (average 653 ± 56 Ma) and two normally discordant analyses exhibiting early Palaeoproterozoic ages (2178 ± 7 Ma and 2503 ± 10 Ma). Thus, of the 64 ages yielded from the two chosen samples, 59 are concordant from which three age peaks at *c*. 500 (population 1), 1.0-1.2 (population 2) and 1.7-1.9 Ga (population 3) can be identified.

There is no systematic age relationship between the sampled zircons as rim ages differ between grains hosted in the same crustal xenolith. Age data constrains a minimum age of *c*. 420 Ma and *c*. 380 Ma for the garnet granulite and the garnet-sillimanite granulite respectively. This clearly demonstrates the detrital origin of the zircons and indicates that the sampled xenoliths may have originally been post Devonian sediments. Core-rim age relationships also vary between grains within the same xenolith implying that the zircon population may represent derivation from numerous source regions (see Tables 1 and 2).

DISCUSSION

Insight into basement domains as inferred from bulk Pb isotopes and Nd model ages

From previous work, the location of the volcanic centres at PA and QL are inferred to have erupted through the Arequipa-Antofalla basement (AAB) block (Fig. 1c; e.g. Ramos, 1988; 2008). The evolutionary history of this basement block will be discussed in detail later. In relation to three previously identified crustal domains within the AAB block (after Loewy et al., 2004), the Pb-isotopic compositions of the xenoliths plot mainly in the Central Domain which stretches from ~18^{o}S to ~22^{o}S consistent with the location of PA and QL (figures 6a and b). A subset of samples display relatively radiogenic $^{208}Pb/^{204}Pb$ signatures akin to those of the Northern Domain present north of ~18°S to ~14°S and that incorporates the Precambrian Arequipa Massif. This suggests one of several possibilities; 1) local compositional heterogeneity with respect to $^{208}Pb/^{204}Pb$ within the Central Domain, 2) involvement of crustal basement to the east of the Arequipa-Antofalla basement where the continental crust is uncharacterised, or 3) the domain boundary between the Northern and Central Domain is much more complex and extends further south than thought. Previous work on the Pb-isotopic composition of the continental basement in this region supports a complex transition between the northern and central domains (Wörner et al., 1992; de Silva et al., 1993; Davidson and de Silva, 1995); a shallow southward-dipping, complexly interleaved inter-crustal domain boundary has been suggested to exist beneath the PA and QL centres thus both domains may be sampled by vertical conduits.

In terms of $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ all samples are distinct from the Southern Domain which is present south of ~22°S in Chile and Argentina. Fig. 6c shows Pb isotopic data from this study combined with data from previous Central Andean studies on basement rocks (Tosdal, 1996; Wörner et al., 2000; Loewy et al., 2004). All sampled xenoliths follow the Arequipa-Brazilian Shield trend, above the Stacey and Kramers (1975) bulk crustal evolution curve and just above the Pb isotopic evolution curve at μ=10. All sampled basement rocks from the Central Andes, including the xenoliths of this study, fall distinctly outside the Pb isotopic domain of Laurentian crust at μ=9.3 to which Argentinian Precordillera rocks have been found to show affinity (Thomas et al., 2002). This excludes the role of any Laurentian crust (either as reworked crustal material or as protoliths) in the genesis of the continental crust in this region of the Central Andes.

Calculated xenolith εNd values range from -7.5 to -15.8. Calculated T_{DM} ages for the sampled xenolith suite form a continuous range from 2.6 to 1.0 Ga, with a peak at *c*. 1.9 Ga (with the exception of the garnet mica schist at *c*. 4.0 Ga and one diorite at *c*. 2.9 Ga). This is comparable with the range exhibited by Central Andean basement rocks (1.7-2.0 Ga, see compilation by Becchio et al., 2011). T_{DM} ages are broadly comparable to T_{DM} ages of the Northern and Central Domains of the Arequipa-Antofalla basement that range from 2.3 to 1.9 Ga and 2.2 to 1.3 Ga respectively (Loewy et al., 2004). T_{DM} ages in the younger Southern Domain range widely from 1.9 to 0.5 Ga. Sample BC93PAX14 (garnet-sillimanite granulite) has a T_{DM} age of 2.34 Ga however; multiple analyses for the U-Pb ages in its zircons reveal events at *c*. 1.8, 1.0 and 0.5 Ga. The crystallisation age of these zircons range from the Late Palaeoproterozoic to Early Devonian and clearly demonstrate the role of extensive crustal reworking. Given that the (proto) Andean margin has been an active site of orogenesis and magmatism since at least the mid-Proterozoic (see discussion below) calculated T_{DM} ages are likely an average age derived from both crustal and mantle sources and thus highlight the role of crustal recycling throughout the history of the western South American margin.

Insight into basement domain models from Zircon U-Pb ages

Constraining the evolution of the Central Andean continental basement is challenging due to 1) the accretion of several allochthonous and autochthonous tectonic blocks to the South American margin, 2) the fact that each of these blocks has a unique geological history and 3) that each will have experienced multiple orogenic events throughout the Phanerozoic. Perhaps more importantly however, is the lack of exposure of Precambrian age basement rocks throughout the modern Central Andean Cordillera. As shown previously, concordant U-Pb zircon ages of this study exhibit three prominent age populations at the late Palaeoproterozoic (population 3) late Mesoproterozoic (population 2) and early Phanerozoic (population 1, Fig. 7a). Fig. 7b and c show concordant U-Pb zircon ages from provenance and basement studies across the Central Andes and throughout the Andean Cordillera where prominent age peaks are identified at *c*. 500 Ma (population 1 of this study) and *c*. 1.1 Ga (population 2) and a scattering of ages exists throughout the Palaeoproterozoic and into the Archean (e.g. Beccio et al., 2011). Despite the comparatively small sample size of this study, it is significant that the overall age pattern previously identified throughout the entire Central Andes is imprinted in the zircon record of the two xenoliths selected for analysis. This further attests to extensive crustal recycling, but also speaks to the refractory and reliable nature of zircon as a recorder of crustal evolution. Below we examine the implications of our data for current models of basement domains in the Central Andes.

Palaeoproterozoic ages (Population 3)

Material older than ~1.7 Ga is typically lacking from Central Andean U-Pb zircon data sets which has led to the suggestion that the Sunsás orogen (1.2 to 0.9 Ga; Grenville age) acted as a topographic barrier preventing the supply of material from the Amazonian craton, which forms the continental "nucleus" of South America (Chew et al., 2007b; 2011). A similar scenario has been invoked for the evolution of Newfoundland and the Appalachian mountain chains (Cawood et al., 2007). The craton is comprised of two Archean and five Proterozoic crustal provinces with crustal growth patterns suggesting that domains young with distance from the cratonic interior, the youngest being the Sunsás (1.28-0.95 Ga) exposed in Eastern Bolivia (see Fig. 1c; Chew et al. 2011).

Palaeoproterozoic ages from this study range predominantly from 1.9 to 1.7 Ga with late to mid Mesoproterozoic data (1.7-1.2 Ga) almost completely absent. Similar zircon ages have been identified elsewhere throughout the Andean Cordillera (e.g. Peru, Loewy et al., 2004; Chew et al., 2008). During the mid Palaeoproterozoic, the Trans-Amazonian Belt developed from northern Amazonia to Argentina as a tectonic collage and is understood to have been established by ~1.8 Ga. Following this, a series of tectonic events dominated by post-orogenic granitic plutonism, explosive and extrusive volcanism, crustal-scale shearing and rifting associated with the formation of volcano-sedimentary basins occurred from 1.8 to 1.6 Ga (de Almeida et al., 2000). These events could potentially account for the >1600 Ma Palaeoproterozoic ages detected in our study and others, and implies that pre-Mesoproterozoic Amazonian cratonic material was available during the development of the Andean margin. This requires re-examination of the Sunsás orogeny topographic barrier hypothesis.

Mesoproterozoic ages (Population 2)

At approximately 1 Ga a single supercontinental mass, Rodinia, is hypothesised to have existed (McMenamin and McMenamin, 1990). Grenvillian aged belts produced during the Mesoproterozoic and hence prior to supercontinent formation exist as scattered fragments across the continents on earth today and have been used to reconstruct the paleogeography of Rodinia (e.g. Hoffman, 1991). This reconstruction, alongside more recent efforts, juxtapose the western margin of the Amazonian craton (Palaeoproterozoic to Archean in age) against Laurentia's eastern (Appalachian) margin (e.g. Torsvik, 2003). The Arequipa-Antofalla Basement (AAB) block of the Central Andes (after Loewy et al., 2004) is considered to represent a fragment of a Mesoproterozoic, Grenvillian-aged, orogenic belt which is allochthonous to Amazonia (Ramos, 1988; Dalziel, 1994; Fuck et al., 2008). Its accretion to the proto-Andean margin has been proposed at 1000-1300 Ma during the Sunsás orogenic episode and the building of the Rodinian supercontinent implying a major crustal domain boundary separates the two (Wörner et al., 2000; Loewy et al., 2004)). The prominent age peak between 1 and 1.2 Ga observed within the sampled zircon suite of this study, and others (Fig, 7) is therefore attributable to the Grenville-aged Sunsás orogenic source associated with the construction of Rodinia and is consistent with an AAB origin. Syn and post tectonic

Sunsás related deformation and orogenesis has recently been identified between 1105 and 1014 Ma in zircons derived from intrusive rocks within the Sunsás belt (Chew et al., 2011 and references therein). This age peak coincides extremely well with age peaks derived from numerous other U-Pb detrital zircon studies aimed at reconstructing Rodinia e.g. California, Arizona and the Mojave Province, north-western Mexico (Stewart et al., 2001; Farmer et al., 2005); south-western Africa and Uruguay (Basei et al. 2005); Mongolia (LaiCheng et al., 2007); Scotland, Newfoundland and the Appalachians (Cawood et al., 2007).

Neoproterozoic and Early Phanerozoic ages (Population 1)

Rifting of the Rodinian supercontinent is understood to have been multi-stage and may have occurred as early as ~850 Ma (Torsvik, 2008) with the eventual formation of the Iapetus Ocean as Laurentia separated from western Gondwana (Fig. 8). Paleontological evidence for the link between the proto-Andean margin and the Iapetus Ocean is provided by brachiopods in Argentina, Bolivia and Peru (Benedetto, 1998). Remnant basement blocks from the Sierra Pampeanas, Argentina, indicate active arc magmatism between 650 and 530 Ma on the western margin of Gondwana during Iapetus times, which is considerably earlier than that recorded on Laurentia (~500 Ma and younger, Chew et al., 2008). Mid-Late Neoproterozoic U-Pb ages from our detrital zircon study (and those of the (Central) Andean record) can be inferred to record the Pampean-Brasiliano orogenic cycle during which a magmatic arc is understood to have developed on the proto-Andean margin (0.5-0.7 Ga, Loewy et al., 2004; Chew et al., 2008; Wotzlaw et al., 2011). This orogenic belt is understood to have developed during the assembly of western Gondwana as allochthonous terranes converged on the Amazonian craton (Fig. 8). However, the present day expression of this orogeny in Bolivia (the Tucavaca Belt at ~16^{o}S, 65^{o}W, see Fig. 1c) is composed of deformed sedimentary sequences and not oceanic lithosphere (Pimentel et al., 1999). A potential source for the Mid-

Late Neoproterozoic ages in the detrital zircon record of this study may therefore be the Brasília Belt that lies to the northeast of the Tucavaca Belt where syn-collisional and arc-related (granitoid) magmatism has been dated between 0.9 to 0.63 Ga (Chew et al., 2008).

At the onset of the Phanerozoic, the western margin of Gondwana was active (Fig. 8) but the number and associated ages of orogenic events throughout the Palaeozoic is poorly constrained (Chew et al., 2007b). A subduction regime is thought to have been established along the western Gondwana margin during the Cambrian, which defined a convergent tectonic regime between the margins of eastern Laurentia and western Gondwana. At this time, rifted fragments of Laurentian crust are thought to have accreted to the western Gondwana margin as recorded by the Laurentian Precordillera terrane in northwest Argentina, (Fig. 6c, Kay et al., 1996; Thomas et al., 2002). However, involvement of Laurentian crust is not recorded in the Pb-isotopic compositions of sampled xenoliths (Fig. 5a, b) suggesting there was limited, if any, accretion of Laurentian derived material to the continental basement of the western South American margin at modern-day latitudes (based on data currently available).

Mid Palaeozoic ages recorded in the detrital zircon record of this study (495-380 Ma) could reflect magmatism related to the Famatinian orogeny (*c*. 480 Ma) during which the Iapetus Ocean closed. However, the southern Laurentian margin is thought to have eventually collided with the northern margin of South America meaning that the western margin has remained active since early Palaeozoic times (Thomas and Astini, 2003).

In summary, U-Pb zircon data from crustal xenoliths hosted in Quaternary lavas from the Bolivian Altiplano, supports previous work by indicating the presence of Grenville-aged crustal basement in the Central Andes and the potential derivation of material from the Amazonian craton, Grenville-aged (Sunsás) and Famatinian-aged peaks in the analysed zircon populations implies the availability of these sources to supply material to Palaeozoic strata. Today these belts may form, at least part of, the crust on which the modern day Andean mountain chain is built and may have been buried as recently as the Eocene-Oligocene (Chew et al., 2008). The presence of all three age populations within the detrital U-Pb zircon record from the same crustal xenolith clearly indicates the important role of crustal recycling during the evolution of the (Central) Andean continental margin. Furthermore, given the lack of a systematic age relationship between the detrital grains sampled by this study and the age constraints emplaced by the youngest observed ages (*c.* 420 and 320 Ma), the host xenoliths likely represent post Silurian and/or post Devonian sediments. On a separate note, the prominent age peaks of zircon population 2 and 3 found in this study and throughout the Andean Cordillera can also be attributed to significant periods of continental crustal growth at 1.9 and 1.2 Ga (c.f. Condie, 1998).

Implications for the Arequipa-Antofalla Basement block of the Central Andes.

The U-Pb zircon record of the (Central) Andes in this study complements and enhances previous work that demonstrates the development of the Andean margin from pre-Grenville times to the establishment of the modern-day tectonic regime through a sequence of supercontinent construction, subsequent break up, the docking of exotic crustal terrane blocks and the important role of crustal recycling. Below we evaluate the implications of our work for the Arequipa-Antofalla Basement (AAB) block – the putative local basement to the study area on the Bolivian Altiplano.

From previous work, the AAB block is inferred to underlie the volcanic centres at PA and QL (see Fig. 1c). Early studies of basement inliers in this region suggested the AAB was one coherent basement domain (Ramos, 1988) but more recent work has indicated that the Antofalla Basement is distinct from the northern, nonradiogenic Precambrian Arequipa Massif (Ramos, 2008) despite both exhibiting similar Palaeoproterozoic protoliths ages (c.

1900 Ma; Loewy et al., 2004). The Arequipa Massif is characterised by granulites, gneisses, dioritic gneisses, foliated migmatites, mylonites and meta-igneous basic rocks (Ramos, 2008). The Antofalla Basement is comparatively radiogenic (Fig. 6a, b) but like the Arequipa Massif, exhibits similar high-grade Mesoproterozoic metamorphic ages (e.g. Wasteneys et al., 1995) indicating that the two blocks, at least in part, share a common history. Antofalla rock types preserved in the scattered surface outcrops are dominated by Proterozoic gneisses (orthogneisses, quartz-biotite paragneisses granodioritic orthogneisses, migmatitic gneisses) muscovite schists and amphibolites (Wörner et al., 2000; Loewy et al., 2004). Rifting associated with the break-up of Rodinia is inferred to have partially detached the AAB from the Amazonian margin (Fig. 9a in Ramos, 2008) and established a passive margin regime during the Neoproterozoic (the Puncoviscana Basin, see Fig. 1c; Cawood et al., 2001). During the Cambrian and preceding the assembly of Gondwana, the tectonic regime changed to one of subduction during which the AAB was re-accreted to Amazonia during the Famatinian orogeny (Ramos, 2008). The distinct Pb isotopic composition of the southern Antofalla (Southern Domain after Loewy et al., 2004) has been attributed to the counterclockwise separation from Gondwana following early Cambrian re-accretion such that, although dominated by an extensional regime, oceanic crust did not develop in the northern Antofalla (Central Domain after Loewy et al., 2004). Ramos (2008) inferred that following cessation of continental rifting, the Antofalla was reaccreted to the continental margin again.

Cardona et al. (2009) recently studied the Maranón Complex in the Eastern Cordillera of the Peruvian Andes. This complex encompasses all the metamorphic basement rocks of the Eastern Cordillera and is characterised by low to middle-grade metamorphic units in two basins of volcano-sedimentary origin, which are inferred to have developed in an arc-related tectonic regime during the late Palaeozoic. From detrital zircons and stratigraphic age relationships, sedimentation was constrained to 318-300 Ma for the western basin (450-420 Ma in the east). Metamorphism of these deposited sequences, attributed to terrane accretion or a change in the subduction regime, has been constrained to 300-310 Ma in exposed schists with evidence for younger granitoid intrusions during the Triassic (Cardona et al., 2009).

From our perspective, the youngest detrital zircon age obtained by this study is 380 Ma. This constrains the age of the host garnet-sillimanite granulite xenolith to < *c*. 380 Ma (< *c*. 420 Ma for the garnet granulite). The high wt. % Al_2O_3 contents in the majority of the sampled xenoliths and the high abundance of aluminous minerals present (garnet, sillimanite, biotite) are indicative of the aluminous nature of potential pelitic protolith(s). Furthermore, the almandine-rich nature of sampled garnets (schists only) can be used to infer garnet growth during regional metamorphism of argillaceous sediments (Deer et al., 1992). These observations and constraints present difficulty when attempting to reconcile these xenoliths within the evolutionary history of the AAB given that our observations indicate that 1) the Central Domain is predominantly characterised by gneissose lithologies (Loewy et al, 2004) and 2) source regions to the detrital zircons must have been available until at least 380 Ma. This is in contrast to current thinking about the AAB, which is composed predominantly of Proterozoic gneisses (and thus devoid of Phanerozoic material) and only affected by magmatism during the Early Palaeozoic (Loewy et al., 2004). Thus, whilst the sampled zircon suite shares a similar U-Pb age record as that observed in the AAB (Fig, 7b), we suggest that the sampled xenoliths of this study are not derived from the continental basement of the AAB. Instead, we infer that the sampled crustal suite represents the meta volcano-sedimentary continental basement of the Eastern Bolivian Cordillera, the composition of which may be similar to that identified in the Peruvian Eastern Cordillera by Cardona et al.

(2009). The eastern terrane boundary of the AAB may therefore be further west than inferred by previous studies (Fig, 1c).

CONCLUSIONS

The crustal xenoliths from the back-arc region of the modern-day active Central Andean margin reveal significant lithological heterogeneity exists within the continental basement. Measured major and trace element concentrations and Sr-Nd-Pb isotopic compositions place important constraints on the characteristics of the Central Andean crust. The data presented provides an absolute, comprehensive geochemical dataset of potential crustal contaminants for studies of crustal contamination which aim to evaluate the role of the continental crust during petrogenesis of Central Andean magmas.

The sampled xenoliths are entrained within *c*. 2 Ma lavas which erupted from two monogenetic volcanic centres on the Bolivian Altiplano beneath which, based on previous work, the Central Domain of the Precambrian Arequipa-Antofalla Basement (AAB) block is thought to exist. The Pb isotopic characteristics of the xenolith suite overlap the Pb compositions of the Central (and Northern) AAB Domain and are compositionally distinct from Laurentian crust, thus suggesting a limited contribution from Laurentian-derived material, at least in this region of the Central Andes, to the continental basement.

The detrital U-Pb zircon record from two of the xenoliths reveal three populations with age peaks at *c*. 1.8 Ga, *c*. 1.1 Ga and *c*. 0.5 Ga and demonstrate the important role of crustal recycling during the growth of the Central Andean margin. These ages can be reconciled with periods of supercontinent formation, subsequent break-up and active margin magmatism. The core-rim age relationships vary between grains implying numerous sources contributed to the detrital record. The age constraints implied by the detrital record and the aluminous nature of inferred pelitic protoliths indicate that these xenoliths represent post Silurian and/or post

Devonian sediments. This interpretation is difficult to reconcile within the evolutionary history of the AAB and suggests these xenoliths are sampling the meta volcano-sedimentary continental basement of the Bolivian Eastern Cordillera. This further implies that the eastern extent of the Proterozoic AAB Central Domain is further west than previously thought.

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FIGURE CAPTIONS

Fig. 1a. The four volcanic zones of the Andean Cordillera: NVZ (Northern Volcanic Zone); CVZ (Central); SVZ (Southern) and AVZ (Austral). Modified from de Silva (1989). b. Monogenetic volcanic centres on the Bolivian Altiplano (grey circles). Volcanoes of the Andean arc are represented by black triangles. Modified from Davidson and de Silva (1995). c. Map showing the three domains, Northern, Central and Southern, of the Arequipa-Antofalla Basement (AAB) block of the Central Andes. Field locality at Pampas Aullagas and Quillacas, indicated by the star symbol, is located at the eastern extent of the Central Domain. Map is modified from Loewy et al. (2004).

Fig. 2. Average modal mineralogy of the sampled xenolith lithologies.

Fig. 3a. Sr-Nd isotopic compositions of Bolivian xenoliths. Compositional fields for previously studied outcrops of crustal basement throughout the central Andes are also shown. Data sources: James (1982); Lucassen et al. (1999); Lucassen et al. (2001). The Precambrian Charcani Gneiss of Peru (Arequipa Massif, Fig. 1c) plots outwith the compositional field shown at significantly lower $^{143}Nd/^{144}Nd$ (0.5115) and $^{87}Sr/^{86}Sr$ of 0.740 (James, 1982). b. Variation of $^{87}Sr/^{86}Sr$ between Cenozoic (<60 Ma) volcanic rocks of the NVZ, CVZ and SVZ (in 5^{o} latitude bins). Data were compiled from GEOROC, Map is modified from de Silva (1989). Values for MORB after Kelemen et al. (2004); BSE (Bulk Silicate Earth) after DePaolo and Wasserburg (1979).

Fig. 4a**.** $^{207}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ for crustal xenoliths. b. $^{208}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ for crustal xenoliths. Geochron and upper crustal evolution lines (each tick at 100 Ma intervals) after Zartman and Haines (1988); Rollinson (1993) respectively.

Fig. 5a, b. U-Pb concordia plots for sampled cores and rims of zircons within BC10QSX107 and BC93PAX14. Age shown on inset graph is U-Pb age with the smallest error (see supplementary information).

Fig. 6a, b. Pb isotopic composition of sampled xenoliths plotted alongside the Northern, Central and Southern crustal domains of the Arequipa-Antofalla basement block of Fig. 1c.

Domains are redrawn from Loewy et al. (2004). c. $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ for crustal xenoliths of this study and from previous studies of continental basement rocks in the Central Andes. All samples are distinct from the Laurentian crustal trend at μ of ~9.3 along which basement rocks from the Argentinian Precordillera (Southern Andes), plot. Compositional fields redrawn from Wörner et al. (2000).

Fig. 7a-c. U-Pb ages from analyses of zircon grains across the Andean Cordillera. Data sources: Tosdal, R. M. (1996); Goldstein, S. L. (1997); Restrepo-Pace, P. A., et al. (1997); Rapela, C. W., et al. (1998); Wörner, G., et al., (2000); Cordani, U. G., et al., (2005); Rapela, C. W., et al., (2007); Chew, D. M., et al. (2008); Collo, G., et al. (2009); Folkes, C. B., et al. (2011). See also Becchio et al. (2011).

Fig. 8. Map showing the separation of Laurentia and Gondwana by the Iapetus Ocean at 550 Ma. AAB: Arequipa-Antofalla Basement; AC: Amazonian Craton; AN: Arabian-Nubian Shield; ANT: Antarctica; AU: Australia; C-SF: Congo-San-Francisco; C: Colombian basement; Cu: Cuyania; IN: India; K: Kalahari; LA: Laurentia; RP: Rio de la Plata (see Fig. 1c); U-N: Uweinat-Nile; WA: Western Africa. (Map modified from Cordani et al., 2005).

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