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Stratigraphy, age and correlation of Lepué Tephra: a widespread *c.* 11,000 cal. a BP marker horizon sourced from the Chaitén Sector of southern Chile

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ABSTRACT

We describe the stratigraphy, age and correlation of a prominent tephra marker, named Lepué Tephra, extensively distributed in northwestern Patagonia. Lepué Tephra is well-dated at *c.*11,000 cal. a BP from numerous lake and soil cover-bed sequences and its recognition is useful for assessing the rate and timing of deglaciation as well as associated environmental changes in this region during the last glacial termination and early Holocene. Lepué Tephra has attributes typical of a complex and compositionally zoned phreatomagmatic eruptive. While the initial rhyolitic phase can be readily distinguished from multiple eruptive products sourced from the adjacent Volcán Chaitén, the main erupted end member is of basaltic-andesite bulk composition - similar to younger tephras sourced from Holocene monogenetic cones adjacent to the Volcán Michimahuida massif (tMim).

Lepué Tephra can be correlated to an equivalent-aged pyroclastic flow deposit (Amarillo Ignimbrite) prominently distributed in the southeastern sector of tMim. The source vent for these co-eruptive events is obscured by an extensive ice field and is currently unknown. The widespread radially symmetrical distribution of Lepué Tephra centred on tMim cannot be attributed solely to volcanological considerations. Reduced Southern Hemisphere westerly wind influence interpreted from climate proxies at the time of eruption are also implicated.

[Words: 200]

Key Words: northwest Patagonia, tephrostratigraphy, Lepué Tephra, Volcán Michimahuida, Volcán Chaitén

INTRODUCTION

The ability to recognise, correlate and characterise tephra of mafic to intermediate-silicic compositions that have been subjected to intense post-depositional weathering and disturbance in temperate- to tropical-climate environments is a significant obstacle to tephra studies in many proximal to distal volcanic settings. For not only does the intense post-depositional pedogenic weathering effectively mask fine-grained and/or thin tephra inter-beds within soil-dominated cover-beds, it potentially compromises the morphological expression of the tephra as well as its constituent geochemistry and grain-size characteristics - all attributes of which are fundamental in tephra correlation. The characterisation of such tephra already susceptible to post-depositional alteration can be further complicated by compositional heterogeneity – that is, upward changes in tephra composition as an eruption progresses. Such changes may reflect sequential surface discharge of either a compositionally segregated magma body in the sub-volcanic system or a sudden magmatic recharge event into an already fractionating body.

The principal objective of this study is to describe the stratigraphy, distribution, age and geochemistry of a prominent tephra marker (here formally named Lepué Tephra) located in the hyper-humid and high-weathering andic environment of northwestern Patagonia (Fig. 1). The stratigraphy, age and chemistry of associated rhyolitic tephra sourced from Volcán Chaitén will be presented in a companion paper (see Alloway *et al.,* submitted). Lepué Tephra is regionally important for three reasons: First, it is one of the most widespread tephra marker beds to occur in this sector and is therefore ideal for assessing the timing and rate of deglaciation and associated environmental changes in this region during the Pleistocene-Holocene transition. Second, Lepué Tephra can be recognised in high resolution lacustrine and marine records and is therefore an important isochron potentially useful in assessing proxy record synchroneity between equivalent-aged offshore and onshore sequences. Third, Lepué Tephra is difficult to chemically characterise on account of the ubiquitous occurrence of microphenocrysts and compositional heterogeneity of glassy constituents. Hence, the application of a combination of grain discrete and bulk major and trace elemental techniques may be a useful template by which other similarly difficult tephra might be characterised, Finally, Lepué Tephra provides a unique insight into a compositionally zoned and complex phreatomagmatic eruption associated with a permanent Andean ice cap.

Setting

Northwestern Patagonia encompasses the Chilean Lake District and Chilotan Archipelago (40° to 44°S), and is bounded in the east by the Andes Cordillera and a lower lying coastal range in the west adjacent the Pacific Ocean (Fig. 1). This region frequently experiences intermittent eruptions of varying magnitude from compositionally diverse volcanoes situated within the Andean Southern Volcanic Zone (SVZ). At least 60 active or potentially active volcanoes in Chile and Argentina, as well as three caldera systems and numerous minor eruptive centres (Stern, 2004; Stern *et al.* 2007) occur within this zone. Volcanism results from the subduction of the Nazca Plate beneath the westward moving South American Plate (Stern, 2004), along a narrow volcanic arc that follows the Liquiñe-Ofqui fault system in Chile between 33°and 46°S. Several volcanoes within this zone have recently erupted - the most notable being Volcán Chaitén (VCha) in 2008, Puyehue-Cordon Caulle in 2011 and Calbuco in 2015.

Over the last two decades, there has been a number of studies detailing the late last glacial to Holocene tephrostratigraphy of northwestern Patagonia in order to develop an inventory of eruptive events, determine source as well as characterize size, composition and timing (i.e. Naranjo and Stern, 2004). While some eruptive histories of individual volcanic centres within the central portions of the SVZ have been described in detail (Lara *et al.* 2006; Singer *et al.* 2008), the eruptive histories of many centers particularly within the southern SVZ (SSVZ) are insufficiently known owing to their remote locations and inaccessibility (Watt *et al.* 2011). Tephra layers have been routinely recorded in lakes (i.e. Haberle and Lumley, 1998; Daga *et al.* 2010; Moreno *et al.* 2014) but in many studies the occurrence of tephra has been a subordinate focus in dominantly paleoecologically and paleoclimatically directed investigations (i.e. Abarzúa *et al.* 2004; Bertrand *et al.* 2008; Iglesias *et al.* 2012; Moreno and Videla, 2016). The need to better utilize tephra within sedimentary archives as an effective means to synchronize records was recently highlighted by Fontijn *et al.* (2016). Recent research efforts has also tended to focus on examining composite eruptive records in order to better assess region-wide hazards based on magnitude/frequency of historic and prehistoric eruptive events across large swaths of Patagonia (i.e. Watt *et al.* 2011; Fontijn *et al.* 2014; Rawson *et al.* 2015; Naranjo *et al.* 2017). Recent eruptions (i.e. Hudson, 1991; Chaitén, 2008; Puyehue Cordón-Caulle, 2011; Calbuco, 2015) have also served as a driver for renewed field-investigations so that eruptive histories and potential hazards posed to adjacent and downwind communities can be better clarified (i.e. Wilson *et al.* 2010, 2011; Amigo *et al.* 2013; Lara *et al.* 2013; Watt *et al.* 2013; Alloway *et al.* 2015, submitted).

Another dominant landscape feature is ubiquitous glacial landforms and ice-carved lake basins formed from Andean piedmont glaciers during episodes of cold (glacial) and/or temperate climate through the Quaternary. The configuration of these Andean piedmont ice lobes in northwestern Patagonia is well known largely based from the glacial morphologic mapping of moraines and outwash plains adjacent to lakes and ocean alongside the western margin of the Andes (Anderson *et al.* 1999; Denton *et al.* 1999). These seminal maps not only demarcated moraines and outwash plains deposited during the maximum phases of the last glaciation (locally referred to as Llanquihue glaciation) but also displayed older Casma and Colegual moraines and outwash plains first described by Mercer (1976). Radiocarbon dating of Llanquihue landforms show that the Andean ice lobes advanced into the moraine belt depicted in red in Fig. 1C numerous times during glacial and/or cool inter-stadial phases of Marine Isotope Stage (MIS) 4, 3 and 2, rather than simply being formed during the Last Glacial Maximum (LGM) in MIS 2. The chronology of the youngest advance is constrained by an extensive array of radiocarbon dates from sites tied to the former

Llanquihue, Reloncaví, Ancud and Golfo de Corcovado ice lobes (Denton *et al.* 1999; Moreno *et al.* 2015). Overall this chronology shows a culmination of the glacial readvance at 17,800 cal. a BP The advance of the two northern lobes (Llanquihue and Reloncaví) reached the inner margin of the LGM moraine belt whereas the two southern lobes (Ancud and Golfo de Corcovado) was either the most extensive, or close to the most extensive, of MIS 2.

Of particular relevance to this study are sites located in areas formerly occupied by ice lobes that overlie glacial deposits and contain the Lepué Tephra, as they can assist in constraining the recessional chronology of ice lobes as climate warmed abruptly during the Last Glacial Termination (LGT) (Moreno *et al.* 2015).

STRATIGRAPHY

In sections directly adjacent to the Volcán Michimahuida massif (tMim), Lepué Tephra is typically characterised by compact, dark grey to brownish-grey, poorly sorted, massive to weakly stratified, scoriaceous lapilli to lapilli-'tuff' (consolidated ash, Fisher and Schmincke, 1984) beds often containing accretionary lapilli. These textural and sorting characteristics, together with highly variable depositional architecture between adjacent sections, suggest 'molten fuel-coolant interactions' (MFCI; Zimanowski, 1998) resulting in a complex succession of magmatic and phreatomagmatic eruptive products (e.g. Cas and Wright, 1987; Ort and Carrasco-Núñez, 2009; Ngwa *et al.*, 2010; van Otterloo and Cas, 2016).

Proximal

Within sections in the vicinity of Chaitén and Santa Barbara and those sections further north towards Caleta Gonzalo (Fig. 2), a prominent decimetre(dm)-thick reddish-brown crudely stratified medium to coarse scoriaceous fall unit is directly overlain by a compact, dm-thick brownish-grey, crudely stratified, very poorly sorted ash with conspicuous dispersed accretionary and scoriaceous lapilli layers. At Section 9B (Fig. 3-F) the upper phreatomagmatic unit, clearly over-thickened at the base of a steeply inclined hillslope, infills an eroded lower scoriaceous fall unit suggesting a brief hiatus between these two syn-eruptive events. At all other sections in this sector both units appear conformable without any indication of an intervening break or soil development. At Section 9D (Fig. 3-E) the basal scoriaceous lapilli bed is itself underlain by a centimetre (cm)-thick surge deposit comprising compact, brownish-grey, low-angle cross-bedded fine to medium ash with few medium-scoriaceous lapilli dispersed randomly throughout. This surge deposit appears localised and most likely relates to its passage down an isolated stream tributary.

Further north, at Section 4 on the southern side of a formerly glaciated mountain pass (~264-m a.s.l) separating Lago Blanco (south) with Lago Negro (north) the stratigraphy of Lepué Tephra is well exposed (Fig. 4). Here, the stratigraphy reveals a prominent (metre-thick) rhyolitic pumiceous lapilli fall unit (Cha-1 *senso stricto* Naranjo and Stern, 2004; dated at *c.* 8700 ^{14}C a BP, Watt *et al.* 2011) sourced from an ancestral VCha, separated from a lower scoriaceous surge and fall couplet below by ~ 0.4 m of medial-ashy andic material (paleosol). This lower couplet is characterised by a basal fall sub-unit characterised by multiple, normal graded centimetre-thick beds of well-sorted coarse to very-fine sand textured scoriaceous ash, grading upwards to a more prominent fall sub-unit comprising weakly stratified, poorly sorted, scoriaceous coarse lapilli. This fall unit is unconformably overlain by a surge unit containing conspicuous, moderately sorted, inclined planar to low-angle cross-bedded, scoriaceous ash and lapilli beds. Charcoal fragments retrieved from within this upper surge unit were dated at 11483 ± 1034 cal. a BP (9960 ± 330 ^{14}C a BP; UCIAMS-145938) and are distinguishable from those radiocarbon ages acquired for Lepué Tephra correlatives elsewhere (see Age Section). At Section-4, Lepué Tephra (represented as a fall-flow couplet) is closely underlain by widespread and distinctive layers of banded rhyolite breccia and rhyolitic ashy material unconformably overlying basement bedrock. This layer of rhyolitic breccia underlying Lepué Tephra can be correlated to Section 6 (Lago Blanco) and Section 7 (within Chaitén township) (see Fig. 2) and likely represents explosive fragmental debris originating from a pre-Cha-1 lava dome (ancestral VCha). Such pre-Cha-1 rhyolitic sequences are rarely observed proximal to inferred source due to deep burial and/or pervasive Andean glaciation (Alloway *et al.* submitted).

Northwards along the continental coastline (see Fig. 5), Lepué Tephra can be reliably traced from Section 5 at Puente Águila to sections in the vicinity of Seno Reloncaví. In most sections, Lepué Tephra is subtly expressed within the andic soil material as laterally discontinuous cemented aggregates of olive-brown to reddish-brown fine to medium ash. Often Lepué Tephra is stratigraphically associated with Cha-1 tephra above (Fig. 5). At Puente Pichileufú on the Hualaihue Peninsula, Lepué Tephra is unconformably overlain by a scoriaceous coarse ash bed of presumed

Apagado-source (Ap-1? of Watt *et al.* 2011) whereas further north-eastwards (i.e. Chapo-S1) towards Ralún, Lepué Tephra is enveloped by a steadily increasing number of discontinuous weathered lapilli of presumed Calbuco-source dispersed in andic medial material.

Relationship with pyroclastic flow and surge deposits

In sections along road W-887 located directly adjacent to Río Michimahuida (i.e. Pumalín Section 1), a massive > 40 m-thick unconsolidated lithic-rich pyroclastic density current (PDC) deposit can be observed with metre-sized oriented lithic intra-clasts and rare, dispersed centimetre-sized charred wood fragments (Fig. 6A, B). At other sections along road W-887 (i.e. Pumalín-4), syn-eruptive fall deposits that overlie this PDC deposit can occasionally be observed. At these sections, the uppermost co-eruptive scoriaceous fall deposits are separated from Cha-1 above (i.e. Pum 4-T8) by a pervasive wedge of colluvial debris of mixed lithologies indicating widespread landscape instability in the devastating aftermath of this eruption. Northward from the W-887 road-end an extensive elevated sloping remnant valley-fill surface can be clearly observed within the confines of the glacially dissected Río Michimahuida valley and extending down to the Río Mallines–Michimahuida confluence (Fig. 6C). This same PDC-deposit and surface was recognised by Amigo *et al.* (2013) and named Amarillo Ignimbrite. Two radiocarbon samples acquired from within and just above the Amarillo Ignimbrite were dated at 9260 ± 50 and 9510 ± 50 ^{14}C a BP respectively and are broadly in accord with an age of 9785 ± 30 ^{14}C a BP (LLNL-122960) from our sample retrieved from Pumalín-1. These ages are also indistinguishable from a radiocarbon age associated with the prominent surge deposit occurring at Section 4 in the northwestern sector of Michimahuida (see Fig. 4). While the voluminous scoriaceous-rich PDC-deposit can be clearly identified in both the south-eastern and northwestern sectors of tMim, the precise location of the eruptive source vent is obscured by ice fields and is currently unknown.

Southern Sectors

At sections 1, 13 and 14 located on Ruta 7 between Amarillo and Puerto Cárdenas (see Figs. 7 and 8), Lepué Tephra (previously referred to as *Cor-1* by Naranjo and Stern, 2004) is enveloped by a sequence of at least six cm- to dm-thick, basaltic-andesite to andesitic ash and lapilli inter-beds within dominantly reddish-brown andic soil material that typically overlies glacial diamict (till) draping bedrock. While some of these enveloping tephra (i.e. Unk-2) can be reliably traced northwards towards Michimahuida, the eruptive origins of the majority (i.e. Yan-1, Cor-2 and Cor-3 named by Naranjo and Stern, 2004) have yet to be determined. In this sector, Lepué Tephra is typically characterised by a dm-thick weakly stratified, brownish-grey, very poorly sorted cemented ash with indistinct centimetre-sized accretionary lapilli and scoriaceous lapilli-rich ashy intrabeds. Cemented fine ash frequently contains open interstitial pore spaces, which are typically indicative of syn-depositional rain flushing (Fig. 8). Beneath this cemented grey ash are common, highly weathered reddish-brown scoriaceous fine to very fine lapilli dispersed within underlying medial andic material. Lepué Tephra can be traced south to the vicinity of Santa Lucía where it occurs as a laterally discontinuous, variably thick (8 to 13-cm) grey cemented fine ash intervening between Yan-1 and Cor-2 correlatives above clast-supported breccia (talus deposit).

Eastern Sectors

Lepué Tephra can be reliably correlated eastwards to distal sections in Chile (Lago Espejo, Futaleufú) and Argentina (Alerce-6 and La Zeta) (Fig. 9). Correlation is based on a combination of morphological expression, chronostratigraphic association and correspondence of glass shard major element compositions. The Lepué Tephra correlative at Lago Espejo, Alerce-6 and La Zeta is overlain by two prominent rhyolitic coarse ash beds that are be correlated with Cha-2 and Cha-1 tephras dated at *c.* 4950 and 9750 cal. a BP respectively (Watt *et al.* 2013). At La Zeta, a ~11-cm thick tephra is prominently expressed within a ~ 5-metre-thick lake sequence that contains numerous other mm- to cm-thick tephra inter-beds of basaltic through to rhyolitic compositions. A radiocarbon age (14,840 ± 70 ^{14}C a BP; UCIAMS-145920) from basal lake sediments directly overlying glacial diamict (till) establishes a maximum age of ~17,800 cal. a BP for the lake sequence. While the Lepué Tephra correlative at La Zeta is not directly dated, it is loosely constrained by radiocarbon dates obtained from enveloping tephra inter-beds within the lake sequence. Certainty of correlation is achieved by glass shard major element chemistry (see below).

At La Zeta, the Lepué Tephra correlative consists of three distinct fall units. The lowermost unit consists of dark gray well-sorted coarse ash (< 1-cm thick, layer a in

Fig. 9 photo inset). This unit is overlain by a compact, subtly bedded, pale gray, moderately sorted fine to very fine ash (~2-cm thick, layer b in photo inset) which in turn is overlain by a ~8-cm thick uppermost unit (layer c in photo inset) comprising loose, well-sorted, very coarse to fine, grey scoriaceous ash. The internal architecture of Lepué Tephra at this locality affirms the complex phreatomagmatic to magmatic origin of this deposit.

Western Sectors

Through most of Isla Grande de Chiloé and its adjacent islands, Lepué Tephra is the only macroscopic tephra that can be systematically observed within the late last glacial to post-glacial andic cover-beds. Stratigraphic columns show the correlation of Lepué Tephra along a western transect from south-central Isla Grande de Chiloé northwards towards Puerto Montt in southernmost continental Chile (Fig. 10). Typically in this sector, Lepué Tephra forms highly irregular, discontinuous pods of crudely bedded, cemented fine- to medium-ash enveloped by reddish-brown andic soil material and closely overlying late last glacial to Last Glacial Maximum (LGM)-aged colluvium, bedded fluvio-glacial gravels and sands, and glacial diamicts (till). The morphological expression of Lepué Tephra within andic cover-bed sections of Isla Grande de Chiloé can be highly variable depending on the thickness of encapsulating andic material and the permeability of the underlying substrate. Where Lepué Tephra occurs within thin andic soil material closely overlying impermeable glacial diamicts (which seasonally perches the local water table), tephra colour is strongly altered to strong brown chromas (i.e. Queilen and Chonchi sections, Fig. 11), whereas Lepué Tephra overlain by a thicker interval of free-draining andic soil material typically have grey to pale brown chromas (i.e. Lago Natri, Castro, Puente Puntra and Chacao sections, Fig. 11). In northern sections (i.e. Huelmo and along Ruta 5 connecting Pargua with Puerto Montt; Figs. 10 and 12) Lepué Tephra is closely underlain by intensely weathered andesitic ash and lapilli 'ghosts' that are most likely sourced from either Volcán Calbuco or Volcán Yate located eastwards along the Andean mountain divide. These highly weathered tephra have yet to be geochemically characterized.

Lake Records

A large number of cores over many years have been retrieved from bogs (Heusser *et al.* 2003) and shallow lakes throughout northwestern Patagonia in order to elucidate vegetation-climate change, fire regime shifts and volcanic disturbance (i.e. Moreno and León, 2003; Pesce and Moreno, 2014; Henríquez *et al.* 2015). A key priority for these ongoing investigations has been to disentangle the role of paleofires and explosive volcanism from climate drivers of past vegetation change. Until recently, the occurrence of Lepué Tephra has been a subordinate focus in dominantly paleoecologically directed investigations. However, there is growing appreciation of the utility this tephra is able to play in terms of vegetation-climate synchronization within equivalent-aged lake records of diverse latitude and elevation.

Lepué Tephra can be readily identified in most sediment cores as a macroscopic layer (centimetre-thick) showing primary fall deposition with minimal post-depositional reworking. However, in some lakes (i.e. Lago Lepué; Pesce and Moreno, 2014) Lepué Tephra shows evidence of reworking and is substantially overthickened compared with adjacent lake sequences. In all cases, Lepué Tephra can be readily identified as a very prominent down-core inorganic density (gr/cc) peak (Fig. 13). For cores throughout Isla Grande de Chiloé (i.e. Lago (L.) Quilque, L. Tarumán, L. Lepué, L. Melli and L. Tahui) this peak occurs at ~ 750-cm depth with a subordinate inorganic peak at ~650-cm likely representing a VCha-sourced tephra, which is not typically expressed macroscopically in adjacent andic soil cover-beds (Alloway *et al.* submitted). For continental cores south of Puerto Montt (i.e. L. Condorito, Huelmo mire, L. El Salto), Lepué Tephra occurs at ~650-cm depth whereas at L. Proschle and Puelche Section Lepué Tephra occurs at ~350-cm depth, and is associated with minor inorganic spikes likely representing tephra additions from Volcán (V.) Chaitén, V. Apagado and V. Calbuco. In all lake cores throughout the region, the ages of Lepué Tephra are well-constrained by numerous radiocarbon dates (see Age Section below).

So far the northern-most occurrence of Lepué Tephra within lake sediments is found at Lago Pichilaguna, located immediately west of Llanquihue township and ~178-km north-west of V. Michimahuida. Here, Lepué Tephra occurs at 382 to 390-cm depth within core 1402AT3 as a ~8-cm-thick dark olive-grey, normal graded coarse to very fine ash (see photo inset Fig. 10) and is chronologically constrained by bracketing radiocarbon dates of 8905 ± 35 ^{14}C a BP (CAMS-158137; 9989 ± 113 cal. a BP) above and 10,100 ± 25 ^{14}C a BP (UCIAMS-177595; 11,576 ± 109 cal. a BP) below. In this same vicinity, Lepué Tephra is not macroscopically preserved within the andic soil-forming environment.

In lakes close to its presumed Michimahuida source, only sediments and tephra post-dating Lepué Tephra have been retrieved since it forms a prominent hardpan and a significant obstacle for further core penetration. For example, at Lago Teo located near Chaitén (Moreno *et al.* 2014), no core penetration beyond 3.02 m depth was achieved. Lepué Tephra was not encountered despite being prominently expressed in all adjacent road sections. An age of 8925 ± 30 ^{14}C a BP of organic sediments from the base of the Lago Teo core provides a minimum age of 10,021 cal. a BP for Lepué Tephra in this sector.

Offshore Record

Site 1233 was drilled during ODP Leg 202 off southern continental Chile (41°0.01'S, 74°26.99'W; 40-km offshore; 838-m water depth) in a small basin on the upper continental slope away from the pathway of major turbidity currents. This offshore site is located at the northern margin of the Antarctic Circumpolar Current (ACC) and at the origin of the Perú-Chile Current (PCC), the most latitudinally extensive Eastern Boundary Current system in the world, driven by along-shore parallel winds along the Pacific coast of South America. This offshore core yielded high-resolution alkenone-based sea surface temperature (SST) and vegetation records extending over the last 50-70,000 years (Kaiser *et al.* 2005; 2008; Heusser *et al.* 2006; Lamy *et al.* 2007). A prominent macroscopic tephra layer was registered in core 1233D within clay and silty clays between 14.52-14.83 mcd and was accompanied by a prominent spike in magnetic susceptibility (916.8 m.mol^{-1} (SI)) (Fig. 14). Unfortunately, no radiocarbon dates were obtained directly associated with the upper and lower contacts of this tephra but bracketing radiocarbon samples from 12.94 and 17.01 mcd yielded calibrated ages of 10,040 and 12,260 cal. a BP, respectively.

AGE

A weighted mean age determination of 9588 ± 20 ^{14}C a BP (95% probability: 10,080 to 10,714 cal. a BP) was modeled for Lepué Tephra based on four R-combine-statistically grouped samples (UCIAMS-145938, LLNL-158290, LLNL-123032 and LLNL-12329) from Sections 4, 12A, Pichileufú and Puelche, respectively (Fig. 15; Table 1). Three sample outliers from Sections 9, 12A and Pumalín -1, (LLNL-158125, LLNL-158291 and LLNL-122960) were rejected. This modeled age of Lepué

Tephra compares closely with a similarly modeled age of 9725 ± 23 ^{14}C a BP based on samples retrieved from Huelmo (Moreno and Leon, 2003), Lago (L.) Condorito (Moreno, 2004), L. Tahui (Abarzúa *et al.* 2004), L. Melli (Abarzúa and Moreno, 2008) and L. Lepué (Pesce and Moreno, 2014) (Fig. 16; Table 1). The associated mean calendar age of 10,994 ± 124 cal. a BP collated from previous research is indistinguishable from a mean calendar age of 10,909 ± 228 cal. a BP determined for Lepué Tephra in this study from Chaitén (S-4, S-12A), Puelche and Pichileufú (see Fig. 5).

ISOPACH

Lepué Tephra is extensively distributed from the Chaitén Section of southern Chile in a wide arc from Isla Grande de Chiloé in the west to Esquel, Argentina across the Andes in the east (Fig. 17). Lepué Tephra can also be traced northwards to the vicinity of Seno Reloncaví and immediately south of Puerto Montt. In routinely measuring the thickness of Lepué Tephra two problems are encountered. Thicknesses recorded in the soil-forming (andic) environment bear little resemblance to those determined from lake/peat records. We consider that the most accurate thicknesses are likely to be derived from lakes and organic-rich lens, though bedding characteristics need to be carefully scrutinised to distinguish between primary and secondary depositional features. For example in L. Lepué (Pesce and Moreno, 2014) – Lepué Tephra is recorded as being ~ 44-cm thick with this thickness being significantly at odds with those from adjacent cored lakes (i.e. L. Melli, 11-cm; L. Tahui, 16-cm), with no mention of bedding characteristics that might distinguish primary airfall products from secondary redeposition and reworking.

Within the andic soil environment Lepué Tephra typically forms a highly irregular and laterally intermittent layer of well-cemented ashy material. This lateral distribution is presumably coincident with the density and distribution of vegetation that likely existed at the time of deposition with continued biological disturbance since (i.e. interference by roots, tree-throw). At any one particular section within the Chaitén sector, thickness values for Lepué Tephra are highly variable and are for the most part, interpreted as being over-thickened within the valleys and lower slopes adjacent the Andean range-front (along which most roads follow). This pervasive over-thickening certainly restricts the production of a reliable isopach map and by proxy - any accurate estimate of eruptive volume. However, these thickness measurement obstacles certainly do not diminish the utility of this tephra as one of the most important early Holocene stratigraphic markers in this sector.

GEOCHEMISTRY

We report major- and trace-element chemistry of pumice and matrix glass from Lepué Tephra utilising grain-discrete EMPA and LA-ICP-MS techniques (see Tables 2, 3 and SI Methods) as well as bulk solution nebulisation inductively coupled plasma mass spectrometry (SN-ICP-MS) analyses (see Table 4 and SI Methods). The key objective for this paper is to demonstrate its utility in supporting field correlations and is not intended to detail the genesis of the melt body (or melt bodies) involved. Thus, while a (micro)phenocryst assemblage dominated by plagioclase, with subordinate pyroxene and Fe-Ti oxide phases was noted, their routine analysis was not undertaken as mineral compositions, and their implications for petrogenesis of the deposit, were not considered central to this particular study. The grain specific major- and trace-element characterisation of the pure glass phase of the Lepué Tephra has proven to be difficult because of the progressive increase in the concentration of microphenocrysts (dominantly plagioclase) occurring within the tephra glass shards as the eruption proceeded.

Back-scatter electron (BSE) images of selected glass shards from Lepué Tephra correlatives indicate low microlite concentrations are observed within glassy grains at the base of the tephra sequence referred to as "microlite-poor glass" which are broadly rhyolitic in composition (onset of the Lepué eruption; Fig. 18-A to -C). Higher up in the tephra sequence, the microlite concentration within the glassy grains significantly increases (Fig. 18-D to -F) giving "intensely microlitic glass" which typically have a basaltic andesite composition. Analysing the intensely microlitic glass either by EMPA and/or LA-ICP-MS is highly problematic in that microlites are inevitably included in the material analysed (i.e. Fig. 18-G, -H), even when using a 10 μm diameter EMPA, or LA-ICP-MS, spot. However, with sufficient analyses, glass chemistry can be determined as an end-member to a trend of analyses contaminated by (dominantly) plagioclase phenocrysts, and in some cases "microlite-free" analyses can be produced, particularly so from the microlite-poor glass shards. Coinciding with the increase in microlite concentration, the proportion of well-formed oriented vesicles also decreases with a corresponding increase in irregular shaped (collapsed) and coalesced voids (Fig. 18-D, -F).

Selected major element compositions (weight percent SiO_2 *vs* Na_2O + K_2O and FeO *vs* K_2O and CaO) of glass shards from Lepué Tephra correlatives are presented in Fig. 19A to C. Two glass shard types can be clearly distinguished by differences in the major element analyses, viz. (i) the rhyolitic composition of glass from the microlite-poor shards and (ii) the broadly basaltic-andesite composition of the intensely microlitic shards, which represent analyses of mixed glass and phenocrysts, approximating to a "bulk" (modal) analyses of the glass shard, and not the glass phase only (*cf.* Platz *et al.* 2007). The insets on Fig. 19 show the tight compositional clustering of rhyolitic glass shards erupted at the onset of the Lepué eruption and these likely represent the initial magma withdrawal from the top of a melt body dominated by fractionated magma (~71 wt % SiO_2). Note that the rhyolitic end-member composition of Lepué Tephra can be clearly differentiated from all post 18,000 cal. a BP rhyolitic tephra sourced from V. Chaitén-sourced tephra (indicated in greyscale).

Selected trace element (Nd *vs* Th and Sr *vs* Y, Ho, Nd, Zr) compositions of glass shards from Lepué Tephra correlatives as determined by grain discrete LA-ICP-MS analyses are presented in Fig. 20. Data for glass shards from proximal sites at La Zeta, Puente Águila (S5) and Paso Lago Blanco (S4) sites are broadly coincident, showing strong linear relationships between the data in all plots. Samples from the more distal locations of Lago Lepué (020DT8-1804-cm) and ODP-1233D (14.68-m) plot slightly away from the trend displayed in the other Lepué samples, but the low Sr end-point of this compositional array is coincident, and the differences result from issues associated with the volume of material sampled during LA-ICP-MS microanalysis of microcryst-bearing glass shards.

All data display a range of compositions ranging from pure rhyolitic glass with a composition of ~ 72 to 113-ppm Sr (i.e. microlite-free analyses from microlite-poor glass shards) to high Sr compositions (~1000-ppm Sr) where the glasses become increasingly microlite-rich, with the highest Sr compositions coming from analyses which will have ablated almost entirely feldspar, with very little glass in the intensely microlitic shards. With increasing Sr, incompatible element concentrations decrease, associated with low incompatible element concentrations in feldspar. All analyses were calculated using the glass SiO_2 composition from the shards (determined by

EPMA) as the internal standard (I.S.). This will give accurate analyses for the pure glass component (i.e. low Sr analyses), but the change in glass composition by inclusion of feldspar in the analyses will mean that, as more feldspar is ablated, the true SiO_2 content of the ablated mixture (the I.S. composition) moves further from the pure glass composition and the analyses will become progressively less accurate (see Pearce, 2014). Incorporation of plagioclase in rhyolitic glass causes the SiO_2 content in the ablated mixture to drop, and thus, using the glass SiO_2 composition as I.S., analysed elements will are marginally overestimated. It is not possible to correct the internal standard concentration for this effect unless the amount of feldspar ablated with glass and the SiO_2 composition of feldspar and glass are both accurately known. The effect of ablation of feldspar increases the reported Sr (compatible in feldspar) considerably and decreases incompatible element concentrations (by dilution, as feldspar has very low incompatible element contents), and this dilution effect competes with the increase in concentration from the change in I.S. composition, with the overall effect depending strongly on exactly how much phenocryst has been ablated (see Pearce, 2014), however without knowing its composition, the amount cannot be calculated. The offset of the Sr-rich analyses of microcryst-bearing glasses from the distal sites at Lago Lepué and ODP-1233D when compared with data from the more proximal sites may relate to differences in glass composition and phenocryst assemblage/content associated with deposition at differ stages of the eruption, and the effects these variables may introduce into the LA-ICP-MS analyses described above. What is apparent though is that the microcryst-poor and microcryst-free glass analyses (i.e. where Sr <~ 150-ppm) from the more distal localities have the same glass composition as the microcryst-free glass analyses from the proximal localities, which establishes the correlation between these deposits (see Table 3) consistent with the well constrained chronologies at these sites. This microcryst-free glass composition (Sr 73 to 113-ppm) defines the composition (and compositional range) of the rhyolitic component of the Michimahuida magma at the onset of the eruption.

Solution-nebulisation-ICP-MS analyses were also conducted on bulk ash material and individual accretionary lapilli from a number of proximal- to distal-sites. Plots of the highly immobile elements (i.e. Th *vs* Zr) from Lepué Tephra correlatives from six proximal sites and sixteen distal sites located on Isla Grande de Chiloé and the coastal Chilean mainland are presented in Fig. 21A. These results are compared with individually analysed accretionary lapilli from seven proximal Lepué Tephra localities (Fig. 21B). While bulk ash analyses exhibit a wide elemental range (even between duplicate samples) and predominantly along a tightly clustered linear fractional crystallization pathway, accretionary lapilli samples exhibit a narrower elemental range positioned on the same linear pathway as the bulk ash samples. Lepué analyses were compared with similar analyses from Holocene-aged tephra beds (13) of tMim and its adjacent monogenetic satellite cones (here named Michimahuida Volcanic Complex, MimVC) (Fig. 21C). The elemental spread and orientation of tephra points are coincident along the Lepué Tephra linear evolutionary trend. These results indicate the limited utility of bulk analyses in the absence of associated chrono-stratigraphic contexts to be able to adequately differentiate MimVC-sourced eruptives. Results also indicate that all MimVC-sourced tephra irrespective of age, are fractionating under broadly similar phase equilibria constraints.

Confirming Michimahuida as the eruptive source

Glass shard major-element chemistry indicates that the initial eruptive phase of Lepué Tephra is rhyolitic in composition but distinguishable from all post-18,000 cal. a BP Chaitén-sourced tephra. As the Lepué eruption progresses the composition steadily becomes more basic and terminates in a compositional field that broadly straddles the Trachyte-andesite, Andesite, Basaltic-trachyte-andesite and Basaltic-andesite fields (see Fig. 19). This trend suggests a zoned magma body with a volatile-rich aphyric cap above a more mafic and phenocryst-rich magma. This more mafic end member of Lepué Tephra is similar to the composition (Basaltic-andesite) of proximal MimVC deposits exposed at Campo Grande, Pumalín-2 and Pumalín-4 (see Fig. 22). At these localities, dm-thick lapilli beds (CG-T3, Pum 2-T4, and Pum 4-T5) can be directly associated with adjacent MimVC monogenetic scoria cone complexes and lava flows. Two coarse-grained pumiceous lapilli and ash beds (Pum 2-T5 and Pum 4-T7) have distinct compositions that straddle the Trachyte and Dacite fields and on the same compositional trend as MimVC-sourced tephra (see Fig. 23). While these two tephra cannot be associated with an identifiable MimVC source vent - coarse grain-size and thickening characteristics would tend to indicate a putative MimVC-source. The three compositional groups identified from proximal MimVC-sites are similar to those identified from L. Teo (Moreno *et al.* 2014) and indicate a diverse range of discrete small-volumed silicic to mafic melt bodies resident at different levels within the MimVC sub-volcanic system and may reflect contributions from different upper mantle components (i.e. Hickey *et al.* 1986; Hickey-Vargas *et al.* 2002), differences in rates of crustal stagnation and differentiation as well as structural controls (i.e. Lopez-Escobar *et al.* 1995).

DISCUSSION

Relationship of Lepué Tephra to deglaciation

Lepué Tephra is one of the most widespread tephra marker beds to occur in this sector in the last 11,000 years and its early Holocene age is ideal for assessing the timing and rate of deglaciation and associated environmental changes as the climate ameliorated at the transition between the LGM and early Holocene.

Radiocarbon dates of organic material retrieved from the base of cores and sections through lacustrine and organic-rich sediments that overlie glacial deposits situated in areas formerly covered by ice lobes have been pivotal in terms of assessing the temporal-spatial extent of glaciers in this region and of relevance to this study, the timing of rapid ice lobe recession that followed the LGT advance into the LGM moraine belt. For example, a basal radiocarbon date from a low-elevation stratigraphic section containing Lepué Tephra at Puelche (see Fig. 5) indicates a minimum-limiting age of 14,070 ± 35 ^{14}C a BP (17,107 ± 99 cal. a BP) for recession of the Seno Reloncaví ice lobe. Similarly a radiocarbon date from a coastal roadside outcrop just north of Chaitén (section 12A, Fig. 2) (also containing Lepué Tephra) indicates a minimum-limiting age of 13,830 ± 50 ^{14}C a BP (16,737 ± 125 cal. a BP) for recession of the Golfo de Corcovado ice lobe. The persistence of ice lobes within low-elevation Cordilleran valley sites is indicated from minimum ages of *c.* 12,500 ^{14}C a BP (14,600 cal. a BP) from basal organic mud sequences overlying glacial till (i.e. Sta. Lucía, Fig. 7). Certainly, the spatial range of dates presented in this study support the findings of Moreno *et al.* (2015) that wholesale glacial recession in this region following the final advance of Andean ice lobes during a cold and wet LGT episode (17,700-18,100 cal. a BP) was very abrupt with diminished lobes recessed within the confines of continental Andean valleys in less than 1000 years.

Synchronisation of late last glacial to early post-glacial vegetation and climate records

Pollen percentage curves of selected key taxa from six sites (arranged south to north; L. Melli, L. Tahui, L. Lepué, L. El Salto, Huelmo mire and L. Condorito) between 8000 and 15,000 cal. a BP are shown in Fig. 24. While sediment cores from these sites have been individually described in the literature, the recognition of the widespread Lepué Tephra within these cores enable us to effectively time-slice and synchronise vegetation/climate records across a broad latitudinal swath of northwestern Patagonia and west of the Cordillera de los Andes. An intra-regional summary of these synchronised records is presented here.

Palynological studies of organic sediments from numerous lake cores and cover-bed sections that overlie glacial deposits or bedrock situated in areas formerly covered by ice lobes indicate that the interval preceding Lepué Tephra (11,700-15,000 cal. a BP) features dominance of closed-canopy temperate rainforests. Palynological records from lowlands sites indicate a prominent increase in the cold-resistant conifer *Podocarpus nubigena* starting at ~14,500 cal. a BP, concomitant with a decline in thermophilous rainforest trees (*Myrtaceae*) and vines (*Hydrangea*) (Moreno 1997, 2004; Moreno *et al.* 1997, 2004; Moreno *et al.* 1999, Moreno *et al.* 2001; Moreno and Leon, 2003). The species *P. nubigena* attained its maximum abundance between 12,700-13,000 cal. a BP, declined between 11,000-12,700 cal. a BP and then reached minimum abundance until 8000 cal. a BP These changes suggest a cooling trend and increase in precipitation between ~12,700-14,500 cal. a BP, followed by a decline in precipitation and/or enhanced precipitation seasonality with intense fire activity between ~11,000 -12,700 cal. a BP. Mainland sites show that fire disturbance promoted forest gaps and colonization of the opportunistic, shade-intolerant tree *Weinmannia trichosperma* over a cold and highly variable interval between ~11,000-12,700 cal. a BP. Over the same interval, sites in Isla Grande de Chiloé (Abarzúa and Moreno 2008; Abarzúa *et al.* 2004; Pesce and Moreno, 2014) show diversification of the forest canopy, lake-level lowering and encroachment of species of the myrtle family along the lake periphery. Deposition of the Lepué Tephra at ~11,000 cal. a BP occurred when *P. nubigena* had already reached low abundance in mainland palynological sites (L. Condorito, Huelmo mire), and at the culmination of a rapid decline of this conifer in Chilotan sites (L. Lepué, L. Melli, L. Tahui). Chilotan sites show abrupt increases in *W. trichosperma* following deposition of the Lepué Tephra; likewise, mainland sites exhibit a secondary expansion of this species. These changes have been interpreted as changes in temperature and precipitation, the latter associated with variation in intensity in the southern westerly winds (SWW) attributable to latitudinal shifts or intensity variations. Recent studies (Moreno *et al.* 2015; Moreno *et al.* 2010; Moreno *et al.* 2012) have proposed that the SWW intensified during the Antarctic Cold Reversal (~12,700-14,500 cal. a BP), shifted pole-ward during Younger Dryas time (~11,500-12,700 cal. a BP) and then weakened during the early Holocene (~7800-11,500 cal. a BP). These changes covaried with temperature and paleofires, with warm/dry conditions featuring enhanced fire activity and cold/wet climates inhibiting paleofires. Deposition of the Lepué Tephra occurred at the beginning of the warmest/driest interval of the last glacial-interglacial cycle, when the SWW attained their weakest condition and when SST's from core ODP-1233 reach a maximum of 15.6°C in the early Holocene (11,000 to 9000 cal. a BP) (Kaiser *et al.* 2005, 2008; Heusser *et al.* 2006).

Prevailing warm/dry climate conditions coupled with weak SWW flow might account for the broad distribution of Lepué Tephra west of Volcán Michimahuida at a time when zonal atmospheric flow did not impede its northwestward distribution toward the SE Pacific. However, the distribution of Lepué Tephra may have also been influenced by volcanological factors - in particular - a hybrid dry/wet plume that expands outward as a powerfully spreading umbrella cloud (see section below).

Eruption style and hazard implications

A schematic representation of the Lepué eruptive sequence centred at tMim is represented in Fig. 25. Dark grey, poorly-sorted, fine-grained sub-units of Lepué Tephra with accretionary lapilli and rain-flushed pore spaces within the ashy matrix clearly indicate the involvement of external water within the erupted mixture. The eruption comprising Lepué Tephra and its co-eruptive PDC (Amarillo Ignimbrite) is an excellent example of an early Holocene dominantly phreatomagmatic eruption derived from a volcanic massif presently mantled by an extensive area of permanent ice. Such eruptions are less usual compared with the more typical background of Strombolian to Plinian volcanism frequently experienced in this region during the Holocene. Thus, in the absence of proximal exposures on Volcán Michimahuida, it's not known if Lepué eruption was point-sourced and derived from a single magma reservoir, or alternatively, derived from a network of coalescing and/or discrete multiple co-genetic melt bodies (i.e. similar to the 2011 Puyehue-Cordón Caulle eruption, see Alloway *et al.*, 2015).

Within most sections adjacent to tMim, metre-thick accretionary lapilli bearing ash deposits with weak stratification between coarser and finer components can be observed and indicate fluctuating multilevel deposition – that is – coarse ash and lapilli transported farther during stable phases of the eruption (less water content with higher vertical velocities), yet deposited closer to source during periods of unstable water-rich plumes where moist convection simultaneously occurs both vertically and laterally away from the vent. If moist convection was a dominant feature of the Lepué plume, then a substantial portion of the initially erupted mass was likely ejected and maintained in the troposphere where temperature inversions inhibit the rise of the weaker, less stable portions of the eruption column. Under such circumstances, the ash plume would have had the tendency to spread outward as a broad, umbrella-shaped cloud. The combination of fluctuating multilevel transport/deposition and upwind/cross wind expansion at the troposphere would have likely favored the formation of a radially symmetrical ash cloud (see Houghton *et al.* 2015). Indeed, recorded thicknesses of Lepué Tephra over such an extensive area in all directions from source appear to support this scenario (see Fig. 17). While eruptive conditions were likely conducive to the broad radial distribution noted for Lepué Tephra, this distribution could also be attributed to the reduced SWW intensity interpreted from equivalent-aged environmental records.

In the advent of a future sustained eruption of similar magnitude to the Lepué eruption centred upon the ice-capped tMim, a centimetre-thick wet ash fall could be reasonably expected up to ~ 200-km from volcanic source and potentially affecting communities and critical infrastructure westward in Isla Grande de Chiloé, northwards towards the city of Puerto Montt and east and south-eastwards towards the communities of Futaleufú on the Chilean frontier and Esquel and Trevelin located in Argentina. Eruption-induced sub-glacial and surface melting of ice and snow on tMim is also likely to occur and lead to significant melt-water formation, jökulhlaups, and lahars extending down adjacent tributaries. Such events have already been shown to be a significant hazard in areas of Iceland (i.e. Katla, 1918; Eyjafjallajökull 2010), Alaska (i.e. Redoubt, 2009), Cascades (i.e. Mt. Rainier), Antarctica (i.e. Deception Island, 1969) and in parts of the Andes (i.e. Nevado del Ruiz, 1985). Although the area surrounding Volcán Michimahuida is sparsely populated with little critical infrastructure, melt-water floods and/or water-supported mass-flows would inundate picturesque and increasingly popular low-lying river-side tourist campgrounds within

Parque Pumalín and scattered farm dwellings farther down-stream. The community of Amarillo would likely be affected, though inundation is likely to be minimized by recent engineering works that have elevated and armored adjacent river-banks.

In summary, while Lepué Tephra is temporally associated with rhyolitic products from nearby Volcan Chaitén, it has physical and geochemical attributes are typical of a complex (zoned) phreatomagmatic eruption sourced from tMim. We propose that the eruption commenced with initial magma withdrawal from the top of a melt body dominated by fractionated Si-rich magma (~71 wt % SiO_2), which propagated downwards into the hosting crystalline-rich magma and ultimately resulted in the Si-rich magma being rapidly and almost entirely replaced by microphenocrysts with very minor interstitial melt (~55 wt % bulk SiO_2). Despite compositional heterogeneity, we were still able to characterise both the aphyric and microlitic glass of the Lepué Tephra by grain discrete and bulk analytical techniques to define a broad compositional array enabling us to distinguish and widely correlate this tephra marker in both terrestrial and marine realms of northwestern Patagonia. While discrete and bulk glass shard trace element analyses maybe of significant use in petrogenetic studies, this study also illustrates its utility in substantiating correlation beyond that already established from major element (EMP) analyses.

Lepué Tephra with its phreatomagmatic style and its compositional heterogeneity is exceptional in the context of other documented eruptions known from this Andean sector. We consider that our integrative approach of intensive mapping supported by multi-technique geochemical analysis is a useful template for the characterisation and correlation of such complex and compositionally variable tephra deposits elsewhere. Ultimately, our approach applied to weathered tephra in wet, hyper-humid environments, like that of northwestern Patagonia, will be of great assistance in the synchronisation of different equivalent-aged sedimentary archives.

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FIGURES

Fig. 1. A, B. The location of the study area in Llanquihue-Puerto Montt, Hornopirén, Chaitén, Isla Grande de Chiloé and Esquel Sectors of northwestern Patagonia. Coloured insets within Fig. 1B indicate the location of key transects presented in this paper that detail the stratigraphy of Lepué Tephra. **C**. Extent of ice lobes within the study area during the Last Glacial Maximum (LGM) (modified from Plates 1-4 *in* Denton *et al.* 1999). Moraine ridges or hills are indicated in red and areas of present-day permanent ice are indicated in black. The location of core ODP Site 1233

offshore of southern continental Chile is also indicated.

Fig. 2. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section 7 located within Chaitén township northward to Section 5 at Puente Águila on Ruta 7 ~ 8.2-km south of Caleta Gonzalo.

Fig. 3. Lepué Tephra at Sections 7 (A), 8 (B, C), 9 (D), 9D (E), 9B (F, G) and 5 (H) that illustrate the complex internal architecture of magmatic (LT-m) and phreatomagmatic (LT-phr-m) fall and flow (LT-sur) co-eruptive phases (see Fig. 2).

Fig. 4. The stratigraphy of Section 4 located on Ruta 7 on the southern side of the pass connecting Lago Blanco (south) with Lago Negro (north). The stratigraphy at this section reveals a prominent rhyolitic pumiceous lapilli (Cha-1 *sensu stricto*) dated at *c.* 8700 ^{14}C a BP and sourced from an ancestral Chaitén Volcano. Cha-1 tephra (now formally renamed Chana Tephra; Alloway *et al.* submitted) closely overlies a lower fall and surge co-eruptive couplet (Lepué Tephra) of presumed Michimahuida-source. The surge deposit is directly dated at 11,483 ± 1034 cal. a BP (9960 ± 330 ^{14}C a BP; UCIAMS-145938). The spade is 1-m length; (B) Low-angle cross-bedding and cross-cutting relationship of the surge across its co-eruptive fall deposit; (C) The entire sequence is underlain by a widespread and distinctive layer of banded rhyolite breccia (indicated by arrows) that likely represent an explosion of a pre-Cha-1/Chana Tephra lava dome (ancestral VCha).

Fig. 5. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section 5 at Puente Águila northwards to sections located in the vicinity of Seno Reloncaví and Ralún. Note the closely overlying occurrence of Cha-1 (now formally named Chana Tephra, see Alloway *et al.* submitted) sourced from VCha.

Fig. 6. A. Massive > 40-m thick pyroclastic density current (PDC) deposit exposed at Pumalín-1 (Pum-1) section along road W-887 located directly adjacent to Río Michimahuida. This PDC-deposit correlates with Amarillo Ignimbrite of Amigo *et al.* (2013) and is considered contemporaneous with Lepué Tephra on the basis of its equivalent stratigraphic position and age. Arrow indicates oriented, metre-sized, lithic

clast transported within this PDC; **B.** Typical PDC-internal architecture with dispersed poorly sorted, angular, lithic clasts and rare charcoal fragments that are dated at 11,190 ± 88 cal. a BP (9785 ± 30 ^{14}C a BP; LLNL-122960); **C.** Remnant Amarillo Ignimbrite valley-infill surface viewed northwest from W-887 roadside lookout (42° 55'18.33" S; 72° 23' 46.99" W); ~ 436-m asl). Note that this surface is clearly inclined towards the Michimahuida massif (tMim).

Fig. 7. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section Pumalín-3 southward to Santa Lucía-3 ~ 2.4-km north of the Sta. Lucía-Futaleufú junction. Note the occurrence of a diamict (1.82 to 2.68-m below surface) within Sta. Lucía-1 containing fragmental rock clasts, wood and organic rip-up clasts (dated at *c.* 9400 ^{14}C a BP; *c.* 10,600 cal. a BP). The internal architecture strongly suggests deposition from a debris avalanche event. Although the erosional base of this debris avalanche deposit is associated with a prominent tephra, the two events do not appear to be chronologically related. On this basis it seems more likely that this catastrophic avalanche event was probably triggered by tectonic seismicity.

Fig. 8. Lepué Tephra at Sections 1 (A), 13 (B) and 14 (C, D, E) of the southern transect (see Fig. 7). Here, Lepué Tephra is dominated by compact grey, poorly-sorted and crudely stratified 'lapilli-tuff' deposits (phreatomagmatic phase) containing dispersed centimetre-sized accretionary lapilli (D) and obvious open interstitial pore spaces (E) indicative of rain flushing. No co-eruptive magmatic phase was identified.

Fig. 9. Stratigraphic columns showing the correlation of Lepué Tephra and enveloping tephra beds from Section Pumalín-2 eastwards to La Zeta 3-km west of Esquel in Argentina. A lake record from Lago Espejo, Futaleufú, Chile is also included to show correlation of Lepué Tephra as well as rhyolitic tephra sourced from an ancestral Volcan Chaitén. The inset photo shows Lepué Tephra as preserved enveloped by paleolake sediments at La Zeta. Note the well-defined shower bedding with a thin, well-sorted coarse ash base (initial magmatic phase) overlain by compact, grey-coloured poorly-sorted massive structured very fine ash (phreatomagmatic phase) followed by proportionally thicker normal-graded moderately well sorted very coarse to fine ash (magmatic phase). This eruptive architecture is in accord with

features from more proximal localities that similarly indicate a complex phreatomagmatic-magmatic eruption style for Lepué Tephra.

Fig. 10. Stratigraphic columns showing the correlation of Lepué Tephra along the western transect from south-central Isla Grande de Chiloé northward towards Puerto Montt in southernmost continental Chile. In northern sections (i.e. Huelmo and along Ruta 5 connecting Pargua with Puerto Montt) Lepué Tephra is closely underlain by intensely weathered andesitic ash and lapilli 'ghosts' that are most likely derived from either Volcanes Calbuco or Yate located to the eastward along the Andean mountain divide. These weathered tephra have yet to be geochemically characterized. At the La Paloma site located between Puerto Montt and Alerce, Lepué Tephra forms a continuous layer ~12-cm thick within peat and is closely overlain (~20-cm) by discontinuous and irregularly thick (< 1-cm) of Cha-1 (Chana Tephra). The other photo inset shows the Lepué Tephra at its northernmost occurrence within Lago Pichilaguna, immediately west of Llanquihue township and 180-km northwest of Volcán Michimahuida. Here, Lepué Tephra occurs within core 1402AT3 at 382 to 390-cm depth as a ~8-cm thick dark olive-grey, normal graded coarse to very fine ash. In this same vicinity, Lepué Tephra is not recognized macroscopically within the andic soil-forming environment.

Fig. 11. The variable morphological expression of Lepué Tephra within cover-bed sections (Queilen, Lago Natri, Chonchi, Castro, Puente Puntra and Chacao) in Isla Grande de Chiloé (see Fig. 10). The position of Lepué Tephra is indicated by yellow arrows. At all sections in this sector Lepué Tephra is the only macroscopic tephra observable within the cover-bed sequence and forms highly irregular, discontinuous pods of cemented fine ash. Typically in this sector, Lepué Tephra is enveloped by andic soil material and closely overlies colluvium, bedded fluvio-glacial gravels and sands and glacial diamictons (till). In cases where Lepué Tephra closely overlies impermeable glacial diamictons which seasonally perch the local water table, tephra colour is strongly altered to strong brown chromas, whereas Lepué Tephra enveloped by thicker successions of free-draining andic soil material typically have grey to pale brown chromas.

Fig. 12. Lepué Tephra occurring within cover-bed sections in southernmost

1021 continental Chile (San Augustin, Huelmo and Ruta 5 connecting Pargua with Puerto Montt). Sections (Caleta La Arena, 13-S7, 13-S8, Chapo S1) in the vicinity of Seno Reloncaví are also shown (see Figs. 5 and 10). Note that Cha-1 is now formally renamed Chana Tephra (Alloway *et al.*, submitted).

1026 **Fig. 13.** Down-core inorganic densities (gr/cc) of lake sediments retrieved from Isla Grande de Chiloé (i.e. Quilque, Tarumán, Lepué, Melli and Tahui), coastal continental lakes and mires east of Golfo de Ancud (Lago Proschle and Puelche), south (i.e. Condorito, Huelmo, El Salto) and north (i.e. Pichilaguna) of Puerto Montt. The occurrence of Lepué Tephra is strongly indicated in all records and is closely overlain by a subordinate peak. This lesser peak (i.e. Isla Grande de Chiloé sites) likely coincides with a c. 8 cal. ka Chaitén-sourced rhyolitic cryptotephra (Puma Verde Tephra, see Alloway *et al.*, submitted), which unlike Lepué Tephra is not typically expressed macroscopically in adjacent andic soil cover-beds.

1036 **Fig. 14.** Magnetic susceptibility (SI units; indicated in green) and alkenone-based Sea Surface Temperature estimates (°C) of ODP-202 Site-1233 (indicated in red). The position of calibrated radiocarbon ages are indicated on the right. The inset shows a prominent macroscopic tephra encapsulated within clay and silty clays between 14.52 and 14.83-mcd and is accompanied by a prominent spike in magnetic susceptibility (916.8-m.mol^{-1} (SI)). Unfortunately, no radiocarbon dates were obtained directly associated with the upper and lower contacts of this tephra but bracketing radiocarbon samples from 12.94 and 17.01-mcd yielded calibrated ages of 10,040 and 12,260 cal. a BP, respectively.

1046 **Fig. 15.** Weighted mean modeled age determination (9588 ± 20 ^{14}C a BP) for Lepué Tephra based on four R-combine-statistically grouped samples (UCIAMS-145938, LLNL-158290, LLNL-123032 and LLNL-12329) from Sections 4, 12A, Pichileufú and Puelche, respectively. Three ^{14}C sample outliers from Sections 9, 12A and Pumalín -1, (LLNL-158125, LLNL-158291 and LLNL-122960) were rejected. The Southern Hemisphere terrestrial calibration curve (SHCal13) and OxCal Program (v.4.2.4) were used for all samples radiocarbon dated in this study.

1054 **Fig. 16.** Modeled ages determinations of Lepué Tephra from Huelmo mire (Moreno and Leon, 2003), L. Condorito (Moreno, 2004), L. Tahui (Abarzúa *et al.*, 2004), L. Melli (Abarzúa and Moreno, 2008) and L. Lepué (Pesce and Moreno, 2014). Modelled ages are arranged according to intervals (cm) sampled with respect to the basal contact of Lepué Tephra. Error bars represent ± 2 σ. A weighted mean modeled age determination of 9725 ± 23 ^{14}C a BP for Lepué Tephra is based on eight R-combine-statistically grouped samples from Huelmo mire (ETH-20386), L. Condorito (A8069), L. Tahui (NSRL-12473 and GX28215), L. Melli (ETH-25249) and L. Lepué (CAMS-125915 and ETH-25451). The associated mean age of 10,994 ± 124 cal. a BP is indistinguishable from a mean age of 10,909 ± 228 cal. a BP determined for Lepué Tephra from Chaitén (S-4, S-12A), Puelche and Pichileufú (this study; Fig. 5).

Fig. 17. Map of the study area indicating the maximum-recorded thicknesses (in centimetres) of Lepué Tephra occurring within andic soil cover-bed sections. At any one site, it is usually very difficult to derive a representative thickness for the pocketed, highly irregular and variably thick Lepué Tephra. Thickness values from lake cores are also shown and indicate considerable thickness differences between adjacent soil and lacustrine depositional environments. Large thickness variations were also noted between closely situated closed basin lakes suggesting that either tephra thickness measurements made from previous studies may not have distinguished between primary and secondarily tephric inputs or perhaps, the existence of more complex sedimentary inputs to these lake systems.

Fig. 18. Selected back-scatter electron (BSE) images of glass shards from Lepué Tephra correlatives showing the varying concentration of dominantly plagioclase microlites within their glassy matrix (**A, B** – lowermost Lepué, Section 4; **C** – lowermost Lepué, Section 5; **D** – uppermost Lepué, Section 5; **E** - 1819-1821 cm, L. Lepué; **F** - 1831-1838 cm, L. Lepué; **G** – Lepué Tephra, Puente Puntra, Isla Grande de Chiloé; **H** – 14.68 m, ODP-1233D). Low microlite concentrations were observed within glassy grains at base of the tephra (onset of the Lepué eruption; **A, B, C**), however, the microlite concentration within the matrix of glassy grains significantly increases (**D, E, F**) progressively upwards within the tephra deposit. In distal localities, the overwhelming dominance of glass grains containing profuse microlites made it very difficult and in many cases, impossible for 10-20 μm diameter electron

and laser beams to be positioned on glass and without any obvious microlite contamination (i.e. **G, H**). Note that as the microlite concentration increases, the proportion of well-formed oriented vesicles decrease with a corresponding increase in irregular shaped (collapsed) and coalesced voids (**D, F**).

Fig. 19. Selected major element compositions (weight percent SiO_2 *vs* Na_2O + K_2O and FeO *vs* K_2O and CaO) of glass shards from Lepué Tephra correlatives. Two glass end members, microlite-poor and microlitic, are plotted to show compositional and elemental concentration differences occurring between these two end members. All post-18,000 cal. a BP Chaitén-sourced tephra are plotted for comparison.

Fig. 20. Nd *vs* Th and Sr *vs* Y, Ho, Nd, Zr compositions of glass shards from Lepué Tephra correlatives determined by grain discrete LA-ICP-MS analysis. Microlite-poor and microlitic glass data are plotted and show significant concentration differences between these two glass types associated with the ablation of (dominantly) plagioclase with glass. The microlite-poor glass compositions occur between 73 -113 ppm Sr, and these analyses are indicated on the plot of Nd *vs* Th. See text for explanation.

Fig. 21. Th *vs* Zr (ppm) plots as determined by bulk sample solution-ICP-MS analysis showing Lepué Tephra correlatives from proximal and distal (continental Chile and Isla Grande de Chiloé). These results are compared with individually analysed accretionary lapilli from seven proximal Lepué Tephra localities. Tephra beds of presumed MimVC-source stratigraphically associated with Lepué Tephra are plotted for comparison.

Fig. 22. Sections containing analysed proximal tephra beds sourced from satellite MimVC monogenetic scoria cones. Inset map shows the location of associated satellite MimVC monogenetic scoria cone complexes and lava flows, sections containing analysed Lepué Tephra and Amarillo Ignimbrite and its remnant valley-fill surface.

Fig. 23. SiO_2 *vs* Na_2O + K_2O (wt. %) compositions of glass shards from **A.** proximal-distal Lepué Tephra compared with proximal tephra beds sourced from satellite

MimVC monogenetic scoria cones, and **B.** post-11,000 cal. a BP tephra beds from L. Teo (Moreno *et al.,* 2014). All tephra beds (except Pum 4-T7) as well as Group 2 and 3 tephra inter-beds from L. Teo occur on the same fractional crystallisation pathway as analysed Lepué Tephra. The compositions of all post-18,000 cal. a BP. Chaitén-sourced tephra are indicated for comparison.

Fig. 24. Pollen percentage curves of key taxa from 6 sites (arranged south to north; L. Melli, L. Tahui, L. Lepué, L. El Salto, Huelmo mire and L. Condorito; see Fig. 17) between 8000 and 15,000 cal. a BP Background blue represents an interval of interpreted cold/wet climate, green - an interval of cold and seasonally dry climate, and pink – an interval of warm and dry climate. Lepué Tephra occurs at all sites and its position within each record is indicated (LT).

Fig. 25. A schematic model for Lepué Tephra and its co-eruptive PDC (Amarillo Ignimbrite). **A.** A zoned magma body within the MimVC sub-volcanic system comprising a volatile-rich cap of dominantly fractionated glass occurring on top of a more mafic phenocryst-rich magma; **B.** Explosive phreatomagmatic eruption involving snow and ice from tMim and dominantly upward thrust of volatile-rich fractionated magma forming a stable column with associated fall dominated by aphyric glass; Episodic moist convection generates flanking PDC deposits; **C.** As the eruption continues, magma withdrawal steadily propagates downwards into the underlying crystal-rich magma and results in a fall increasingly dominated by microphenocrysts with very minor interstitial melt; Intensified water vaporisation results in heightened convection and plume instability; **D.** Continued oscillations between buoyant (dry) and wet eruptive phases leads to the development of a multilevel plume; Continued sustained moist convection and climactic plume collapse generates the Amarillo Ignimbrite.

Table Captions

Table 1. Radiocarbon dates and ages associated with Lepué Tephra and its distal correlatives. The Southern Hemisphere terrestrial calibration curve (SHCal13) and OxCal Program (v.4.2.4) were used for all radiocarbon samples dated in this study.

Table 2. Summary of individual glass shard major-element compositions (normalised to an anhydrous basis) of proximal to distal Lepué Tephra in the Chaitén, Isla Grande de Chiloé and Esquel Sectors of NW Patagonia.

Table 3. Summary of individual glass shard trace-element compositions of proximal to distal Lepué Tephra in the Chaitén, Isla Grande de Chiloé and Esquel Sectors of NW Patagonia obtained by LA-ICP-MS at Aberystwyth. All concentrations in ppm unless otherwise stated.

Table 4. All trace-element concentrations from bulk Lepué Tephra correlative samples obtained by Solution-nebulisation-ICP-MS at Aberystwyth University, Wales. All concentrations in ppm unless otherwise stated.

SUPPLEMENTARY INFORMATION

METHODS

Electron Microprobe (EMP) technique

Major-element determinations were made on a JEOL Superprobe (JXA-8230) housed at Victoria University of Wellington, using the ZAF correction method. Analyses were performed with 15 kV accelerating voltage, 8 nA beam current, and an electron beam defocused to between 20 to 10 µm. Standardization was achieved by means of mineral and glass standards. A rhyolitic glass standard (ATHO-G) was routinely used to monitor calibration in all analytical runs, and used to evaluate any day-to-day differences in the calibration. The large number of samples precluded conducting all analyses in a single batch. All analyses are normalized to 100 wt. % anhydrous, with H_2O by difference being given, and total Fe is reported as FeO. Glass shard major-element analyses are presented in Table 2. All analyses are available upon request to the corresponding author.

Laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) technique

Trace-element analyses on individual glass shards were performed by laser ablation (LA) ICP-MS in the Department of Geography and Earth Sciences, Aberystwyth University, using a Coherent GeoLas ArF 193 nm Excimer LA system coupled to a Thermo Finnegan Element 2 sector field ICP-MS. Trace element data were collected for individual shards with the majority of analyses performed using 20 µm ablation craters. Laser fluence was 10 Jcm^{-2} at a repetition rate of 5 Hz for a 24 second acquisition. The minor ^{29}Si isotope was used as the internal standard, with SiO_2 (determined by EMPA) used to calibrate each analysis, after normalization to an anhydrous basis. The NIST 612 reference glass was used for calibration, taking concentrations from Pearce *et al.* (1997). A fractionation factor was applied to the data to account for analytical bias related to the different matrices of the reference standard and the sample. For this factor as well as ICP-MS and laser operating conditions see Pearce *et al.* (2011), and references therein. The MPI-DING reference glass ATHO-G (Jochum *et al.* 2006) was analysed as an unknown under the same operating conditions at the same time. Analytical precision is typically between ± 5-10%, and accuracy is typically around ± 5%, when compared with the published GeoReM concentrations for ATHO-G. Glass shard trace-element analyses are presented in Table 3.

Solution nebulisation inductively coupled plasma mass spectrometry (ICP-MS) technique

Dried bulk samples were crushed and homogenised using an agate mortar and pestle to a fine powder and bagged. To ensure no sample cross-contamination occurred, all crushing equipment was washed with 18.2 MΩ deionised H_2O (MilliQ®), 5% HCl (hydrochloric acid) and 5% HNO_3 (nitric acid) between the each sample. Subsequently, 0.25 g of each homogenised sample was weighed into polytetraflouroethylene (PTFE) beakers ready for standard HF/$HClO_4$ acid digestion (performed by Andy Brown in the Geochemistry Laboratory, DGES). Initially samples were treated with 5 mL concentrated HCl and evaporated to dryness, followed by an open HF/$HClO_4$ digestion (15 mL/4 mL) which was left cold overnight before evaporation to dryness at about 170°C. A second HF/$HClO_4$ digestion was used if needed. Once dry, 4 mL of $HClO_4$ was added to each sample and evaporated to dryness to remove any residual HF, and the samples were then taken up to a final volume of 250 ml in 2.5% HCl and stored in Nalgene™ sample bottles ready for analysis by solution nebulisation Inductively Coupled Plasma – Mass spectrometry (SN-ICP-MS) to determine their trace-element content in the

Department of Geography and Earth Sciences, Aberystwyth University. All acids were AnalaR grade or better, and blanks were prepared with all batches of samples. Analyses were performed on and Agilent 7700 ICP-MS, which determined a range of trace elements, with low masses (<52) determined using He as a collision gas to reduce polyatomic interferences (He-mode). Calibration was achieved against multi-element synthetic standards produced from stock single element standard solutions, and Te was used as the internal standard for analyses. Some samples were prepared in triplicate and dispersed through the analytical run, and indicate analytical precision is better than 4% on average (although this varies with within element concentration etc., see Pearce *et al.* 2004). Two reference materials (USGS QLO-1 Quartz Latite and GSJ JA-3 Andesite) were routinely analysed to check accuracy. Analyses are presented in Table 4.

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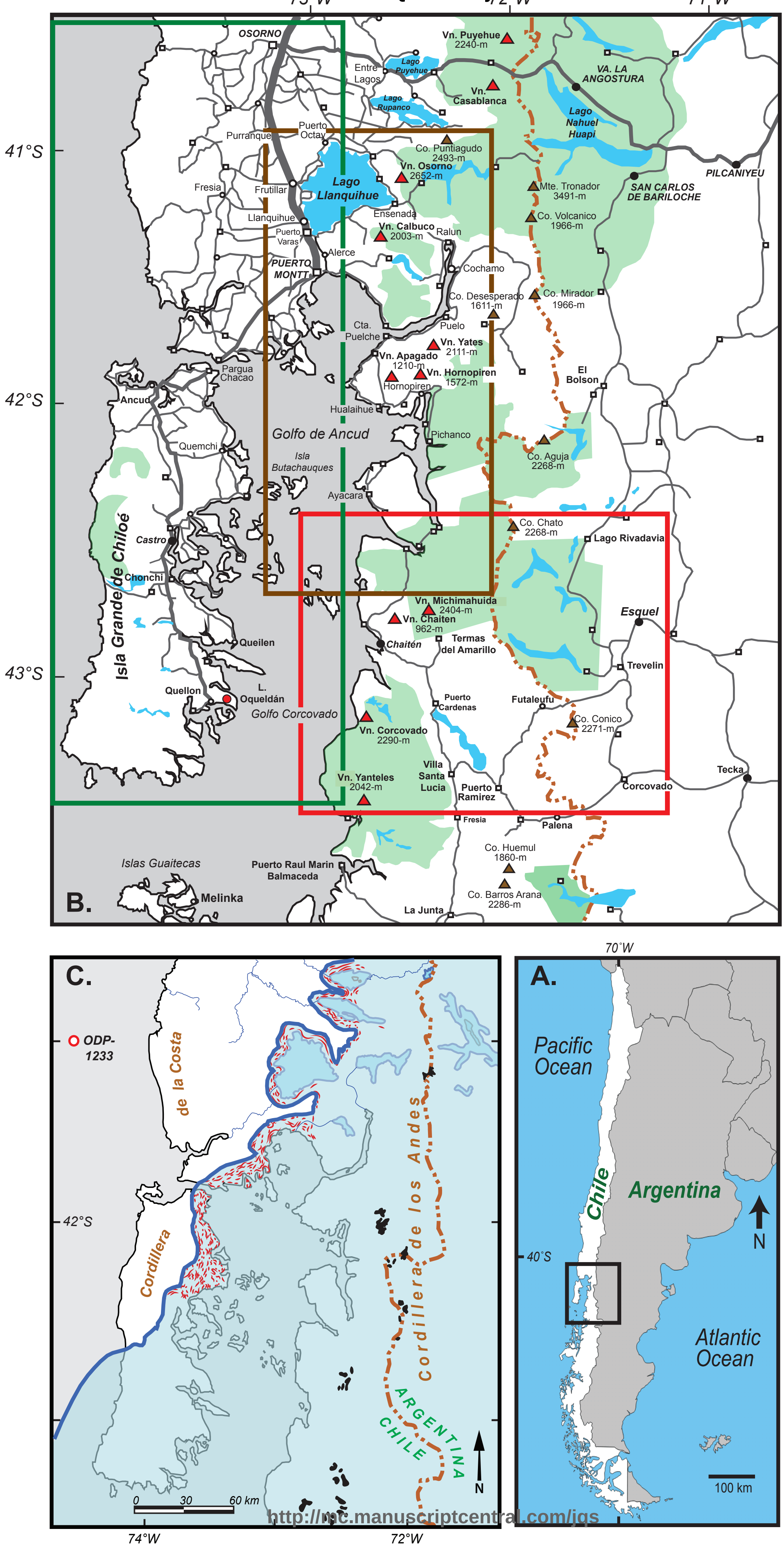
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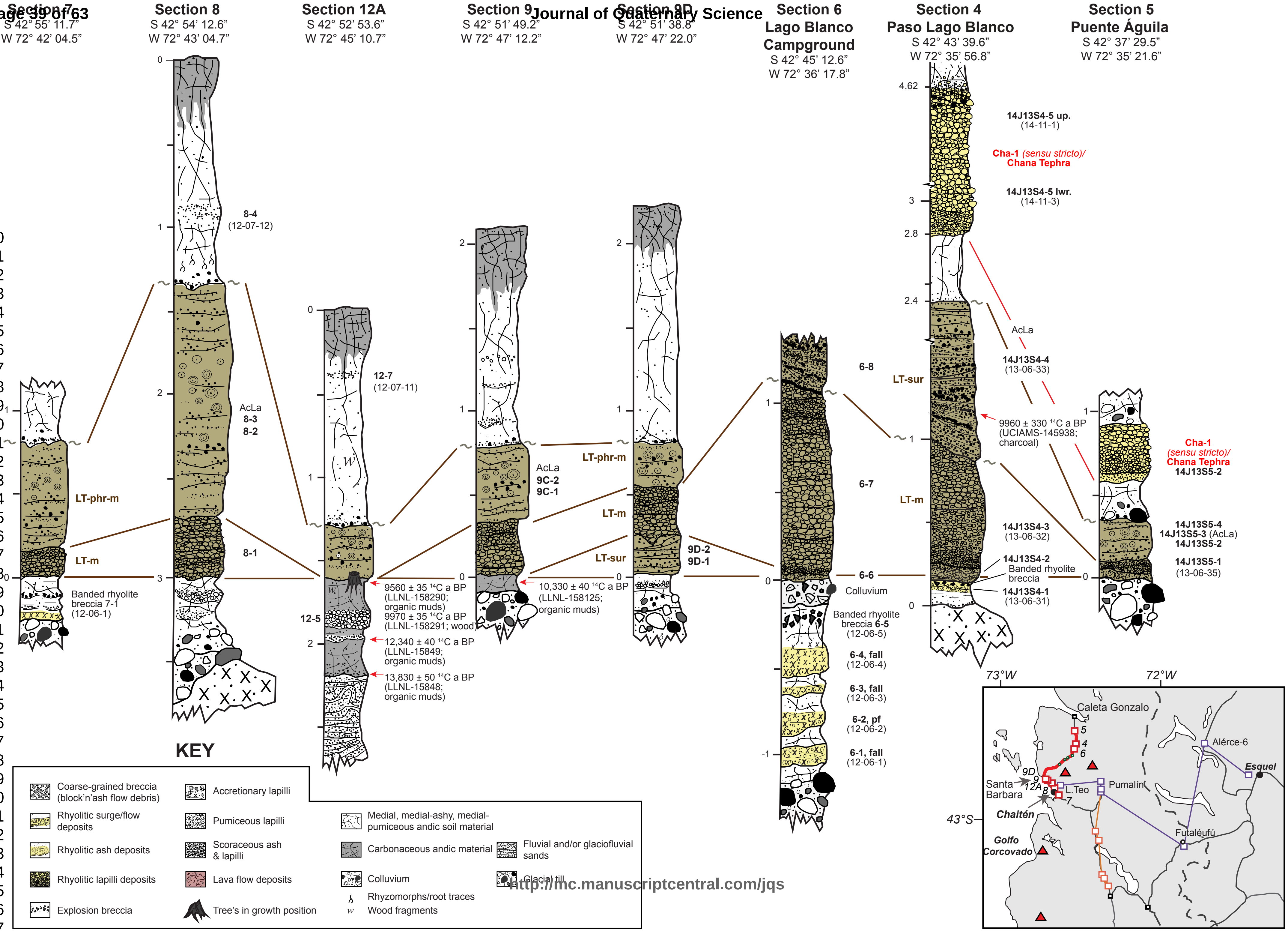
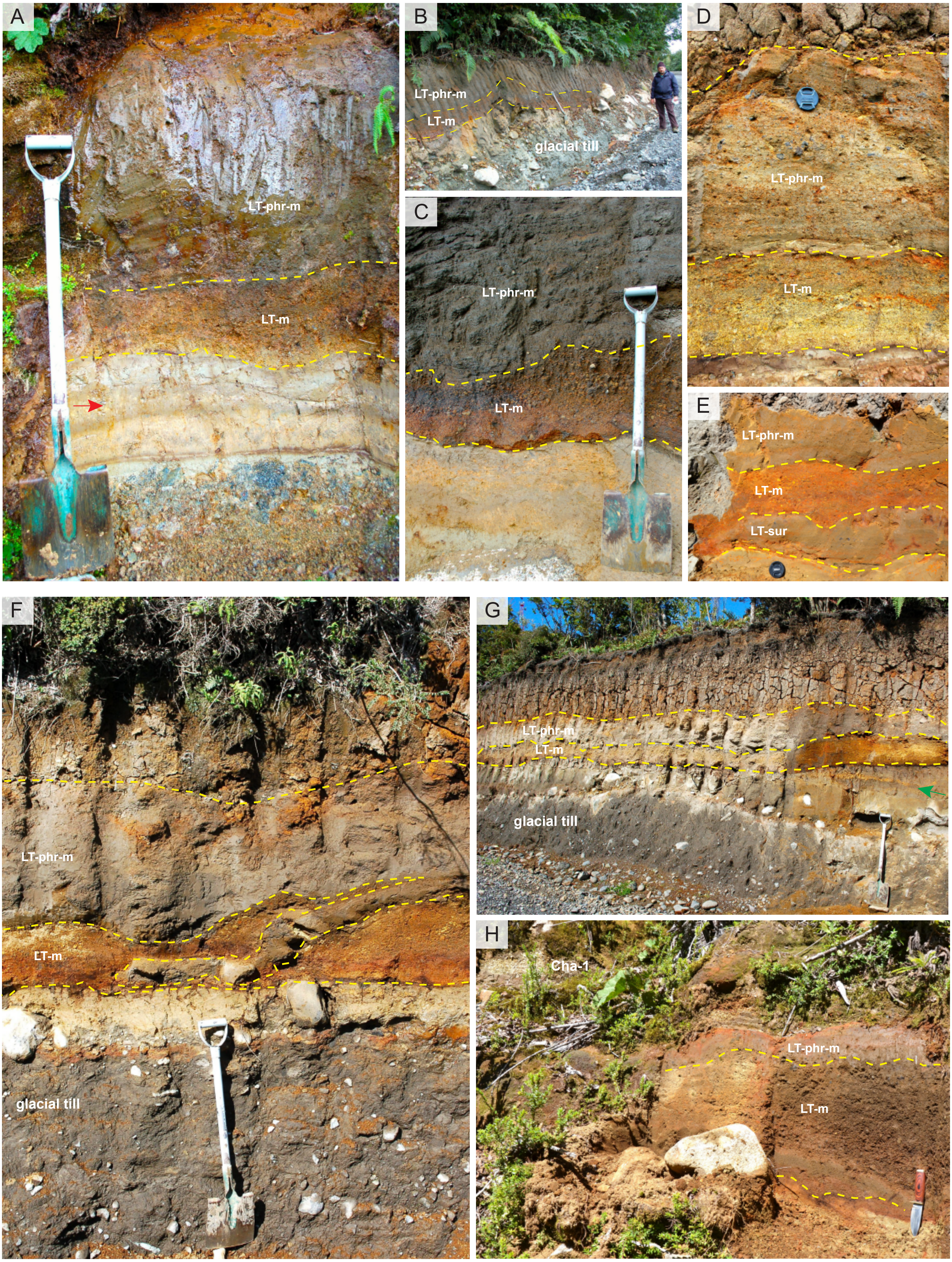
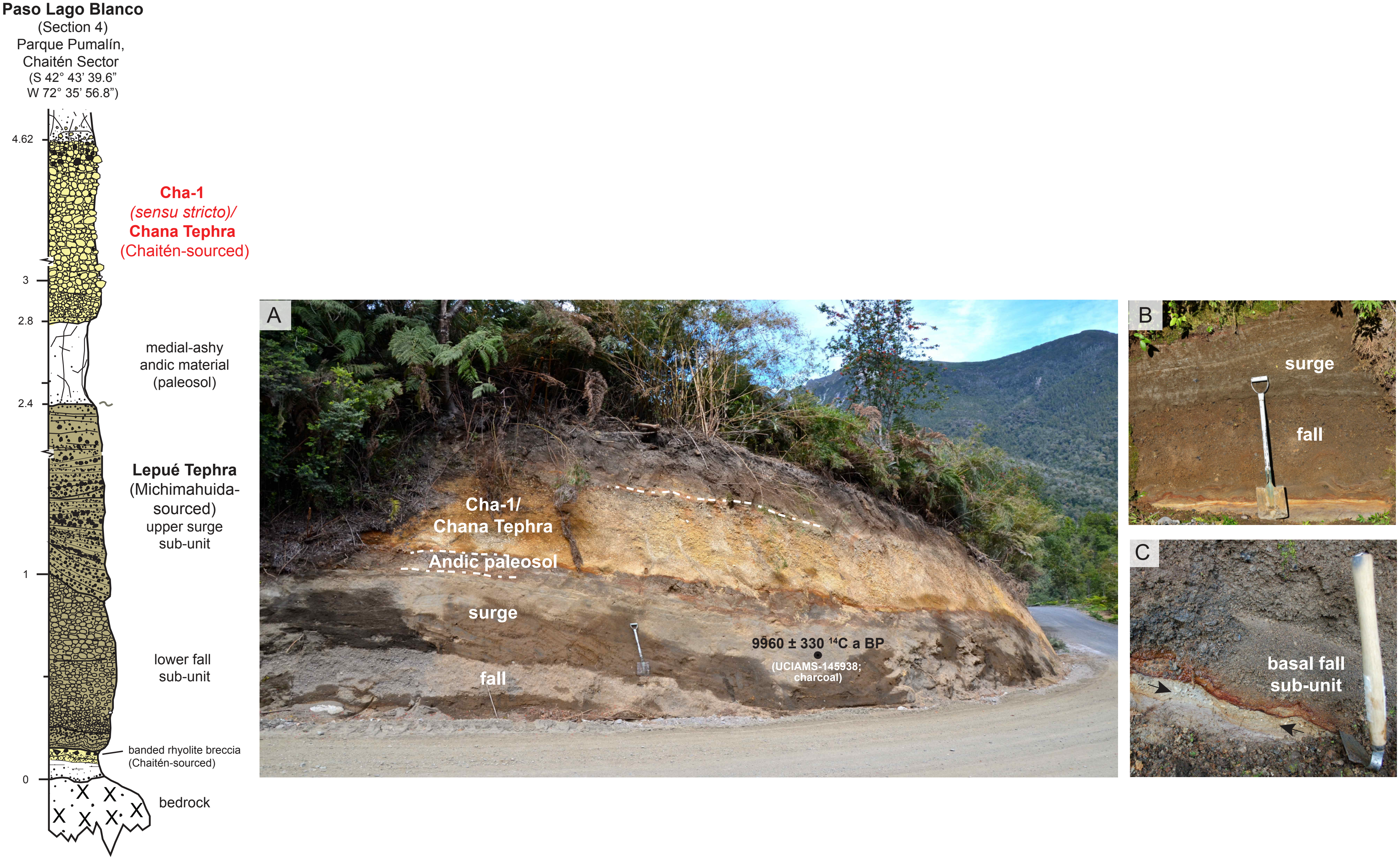
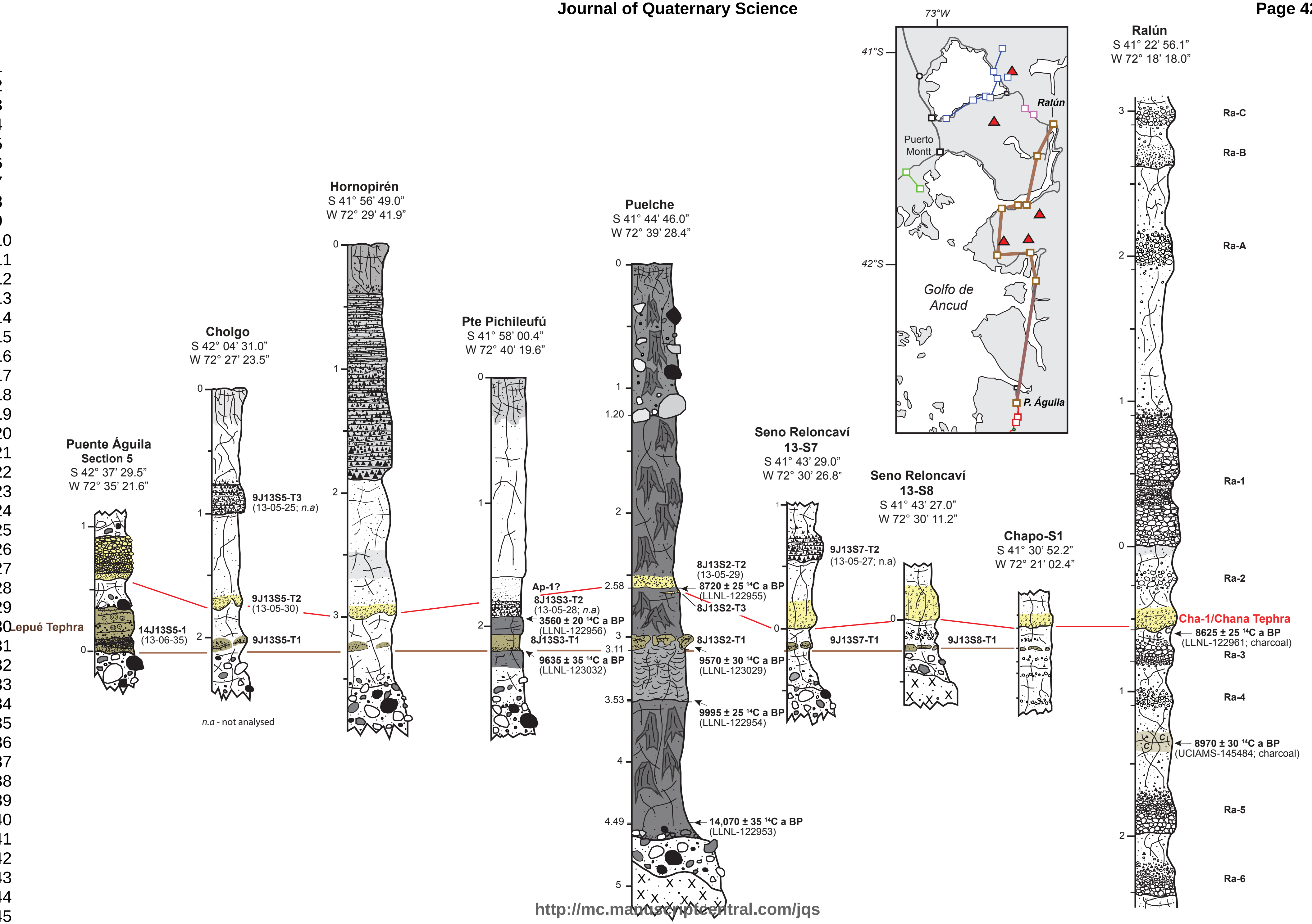
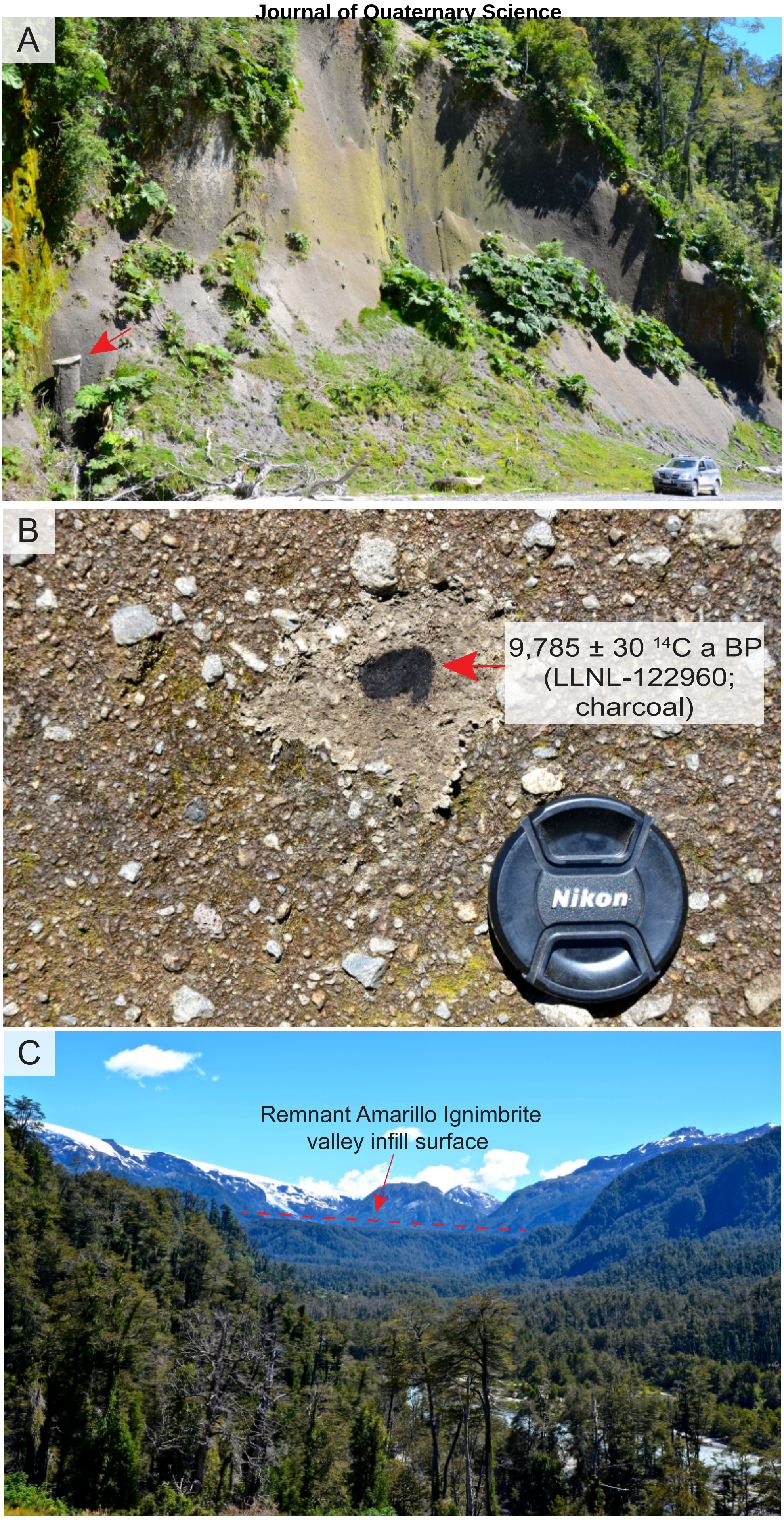
41°S
42°S
43°S
OSORNO
Vn. Puyehue 2240-m
Lago Puyehue
Entre Lagos
VA. LA ANGOSTURA
Vn. Casablanca
Lago Rupanco
Lago Nahuel Huapi
Puerto Octay
Purranque
Co. Puntiagudo 2493-m
Vn. Osorno 2652-m
Lago Llanquihue
PILCANIYEU
Fresia
Frutillar
Mte. Tronador 3491-m
SAN CARLOS DE BARILOCHE
Llanquihue
Ensenada
Co. Volcanico 1966-m
Puerto Varas
Vn. Calbuco 2003-m
Ralun
Alerce
PUERTO MONTT
Cochamo
Co. Desesperado 1611-m
Co. Mirador 1966-m
Puelo
Cta. Puelche
Vn. Yates 2111-m
Vn. Apagado 1210-m
Vn. Hornopiren 1572-m
Hornopiren
El Bolson
Pargua Chacao
Ancud
Hualaihue
Golfo de Ancud
Pichanco
Quemchi
Co. Aguja 2268-m
Isla Butachauques
Ayacara
Co. Chato 2268-m
Lago Rivadavia
Castro
Isla Grande de Chiloé
Chonchi
Vn. Michimahuida 2404-m
Vn. Chaiten 962-m
Esquel
Chaitén
Termas del Amarillo
Queilen
Trevelin
Quellon
L. Oqueldán
Golfo Corcovado
Puerto Cardenas
Futaleufu
Co. Conico 2271-m
Vn. Corcovado 2290-m
Villa Santa Lucia
Tecka
Vn. Yanteles 2042-m
Puerto Ramirez
Corcovado
Fresia
Palena
Co. Huemul 1860-m
Islas Guaitecas
Puerto Raul Marin Balmaceda
Melinka
Co. Barros Arana 2286-m
La Junta
B.
C.
ODP-1233
Cordillera de la Costa
42°S
Cordillera de los Andes
ARGENTINA
CHILE
N
0 30 60 km
74°W
72°W
A.
70°W
Pacific Ocean
Chile
Argentina
40°S
N
Atlantic Ocean
100 km

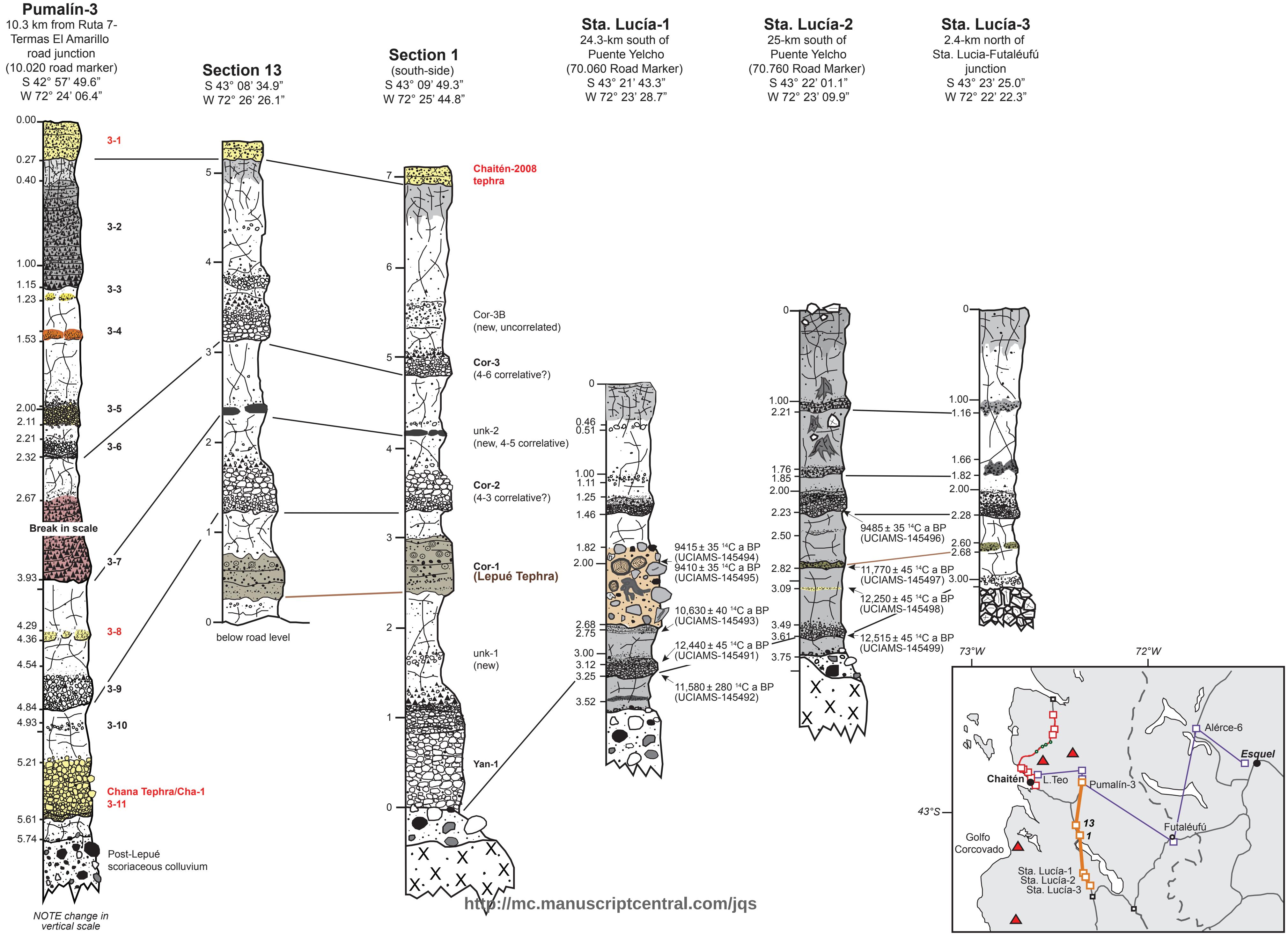

Section 7
S 42° 55' 11.7"
W 72° 42' 04.5"
Section 8
S 42° 54' 12.6"
W 72° 43' 04.7"
Section 12A
S 42° 52' 53.6"
W 72° 45' 10.7"
Section 9
S 42° 51' 49.2"
W 72° 47' 12.2"
Section 9D
S 42° 51' 38.8"
W 72° 47' 22.0"
Section 6
Lago Blanco
Campground
S 42° 45' 12.6"
W 72° 36' 17.8"
Section 4
Paso Lago Blanco
S 42° 43' 39.6"
W 72° 35' 56.8"
Section 5
Puente Águila
S 42° 37' 29.5"
W 72° 35' 21.6"
8-4
(12-07-12)
AcLa
8-3
8-2
8-1
LT-phr-m
LT-m
Banded rhyolite
breccia 7-1
(12-06-1)
12-7
(12-07-11)
12-5
9560 ± 35 ¹⁴C a BP
(LLNL-158290;
organic muds)
9970 ± 35 ¹⁴C a BP
(LLNL-158291; wood)
12,340 ± 40 ¹⁴C a BP
(LLNL-15849;
organic muds)
13,830 ± 50 ¹⁴C a BP
(LLNL-15848;
organic muds)
AcLa
9C-2
9C-1
10,330 ± 40 ¹⁴C a BP
(LLNL-158125;
organic muds)
LT-phr-m
LT-m
LT-sur
9D-2
9D-1
6-8
6-7
6-6
Colluvium
Banded rhyolite
breccia 6-5
(12-06-5)
6-4, fall
(12-06-4)
6-3, fall
(12-06-3)
6-2, pf
(12-06-2)
6-1, fall
(12-06-1)
LT-sur
LT-m
14J13S4-5 up.
(14-11-1)
Cha-1 (sensu stricto)/
Chana Tephra
14J13S4-5 lwr.
(14-11-3)
AcLa
14J13S4-4
(13-06-33)
9960 ± 330 ¹⁴C a BP
(UCIAMS-145938;
charcoal)
14J13S4-3
(13-06-32)
14J13S4-2
Banded rhyolite
breccia
14J13S4-1
(13-06-31)
Cha-1
(sensu stricto)/
Chana Tephra
14J13S5-2
14J13S5-4
14J13S5-3 (AcLa)
14J13S5-2
14J13S5-1
(13-06-35)
KEY
Coarse-grained breccia
(block'n'ash flow debris)
Rhyolitic surge/flow
deposits
Rhyolitic ash deposits
Rhyolitic lapilli deposits
Explosion breccia
Accretionary lapilli
Pumiceous lapilli
Scoraceous ash
& lapilli
Lava flow deposits
Tree's in growth position
Medial, medial-ashy, medial-
pumiceous andic soil material
Carbonaceous andic material
Fluvial and/or glaciofluvial
sands
Colluvium
Glacial till
Rhyzomorphs/root traces
Wood fragments
73°W
72°W
43°S
Caleta Gonzalo
Alérce-6
Esquel
Santa
Barbara
L.Teo
Pumalín
Chaitén
Golfo
Corcovado
Futaléufú

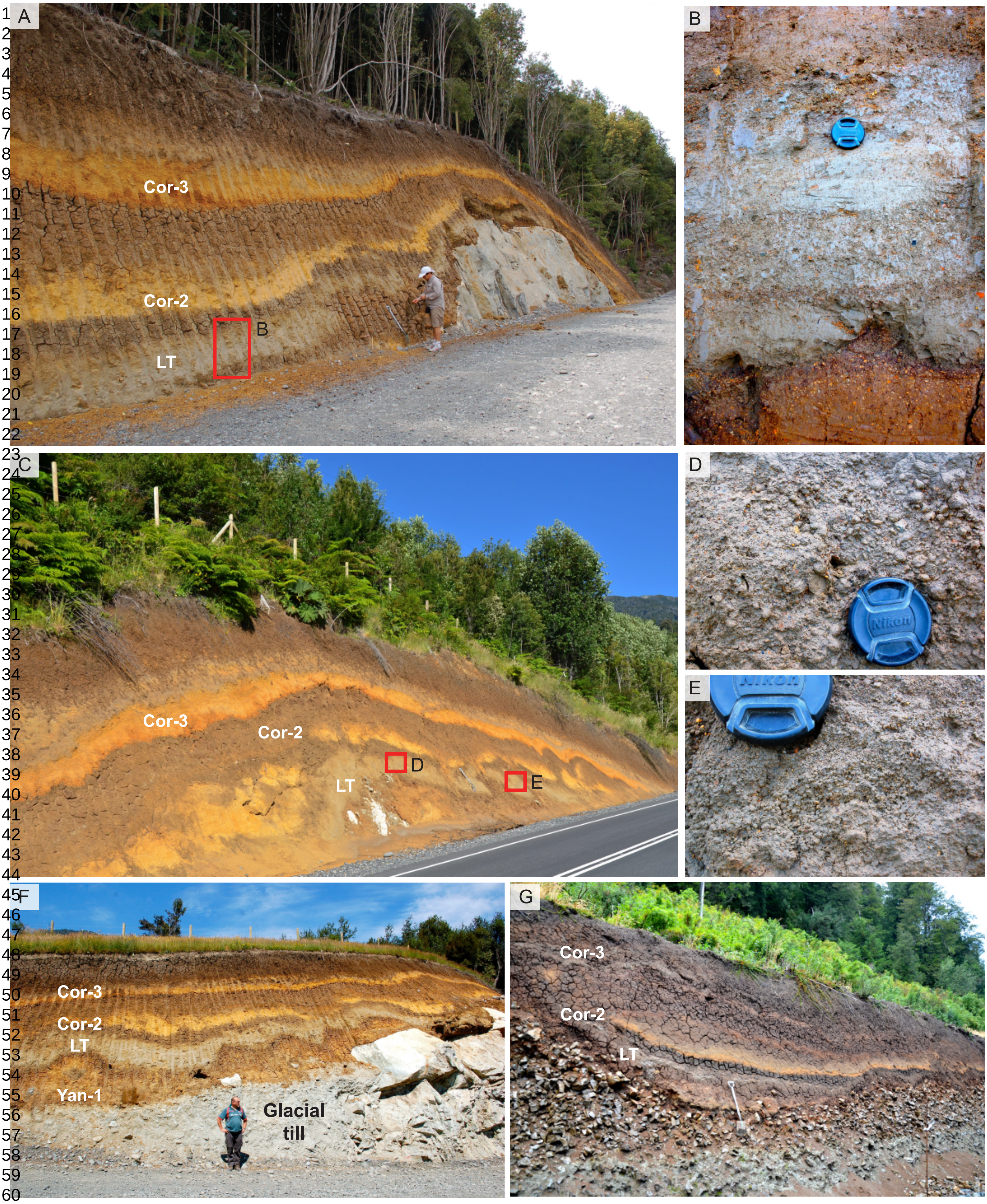

A
LT-phr-m
LT-m
B
LT-phr-m
LT-m
glacial till
C
LT-phr-m
LT-m
D
LT-phr-m
LT-m
E
LT-phr-m
LT-m
LT-sur
F
LT-phr-m
LT-m
glacial till
G
LT-phr-m
LT-m
glacial till
H
Cha-1
LT-phr-m
LT-m

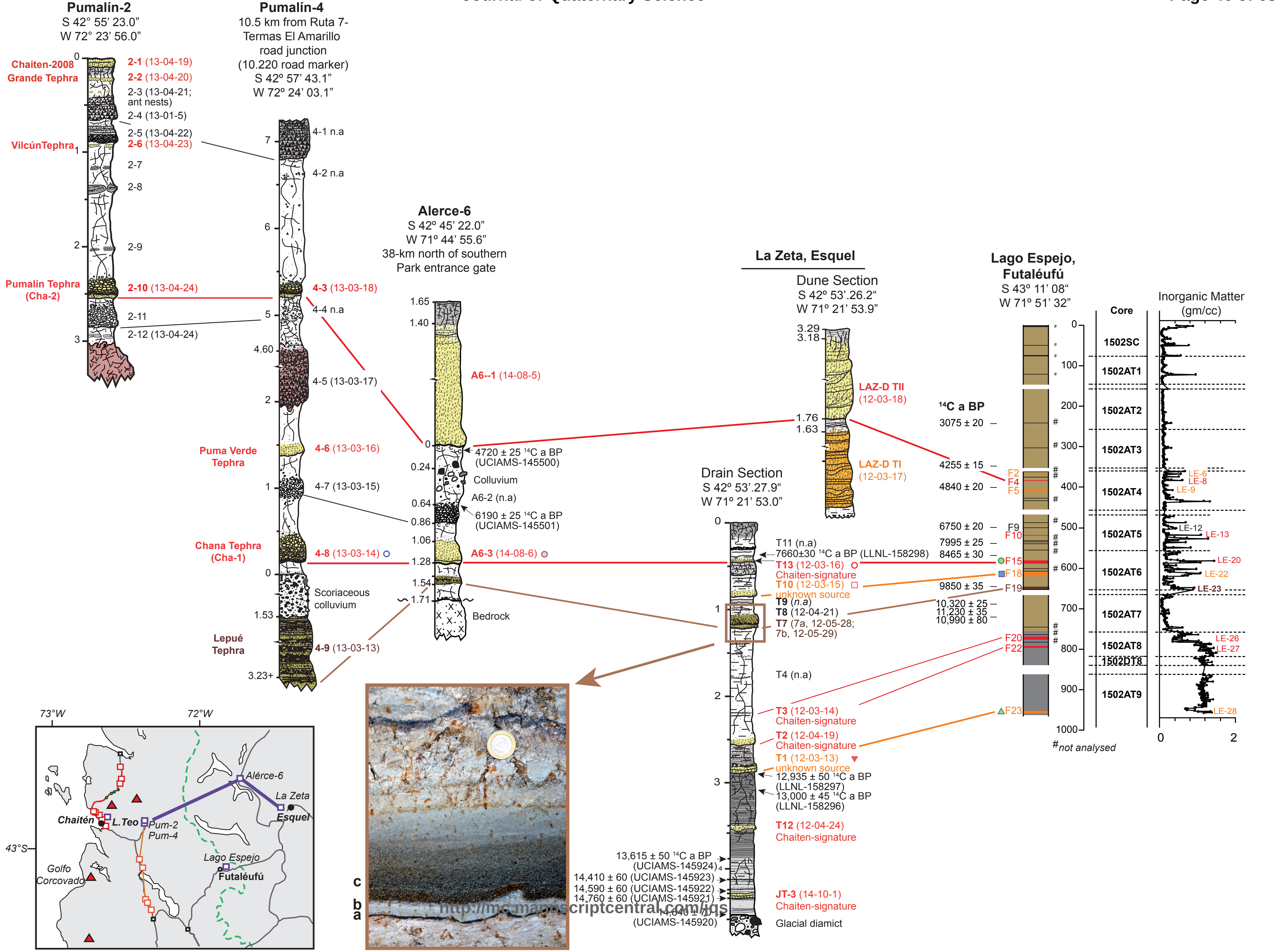

Paso Lago Blanco
(Section 4)
Parque Pumalín,
Chaitén Sector
(S 42° 43' 39.6"
W 72° 35' 56.8")
4.62
3
2.8
2.4
1
0
Cha-1
(sensu stricto)/
Chana Tephra
(Chaitén-sourced)
medial-ashy
andic material
(paleosol)
Lepué Tephra
(Michimahuida-
sourced)
upper surge
sub-unit
lower fall
sub-unit
banded rhyolite breccia
(Chaitén-sourced)
bedrock
A
Cha-1/
Chana Tephra
Andic paleosol
surge
fall
9960 ± 330 14C a BP
(UCIAMS-145938;
charcoal)
B
surge
fall
C
basal fall
sub-unit

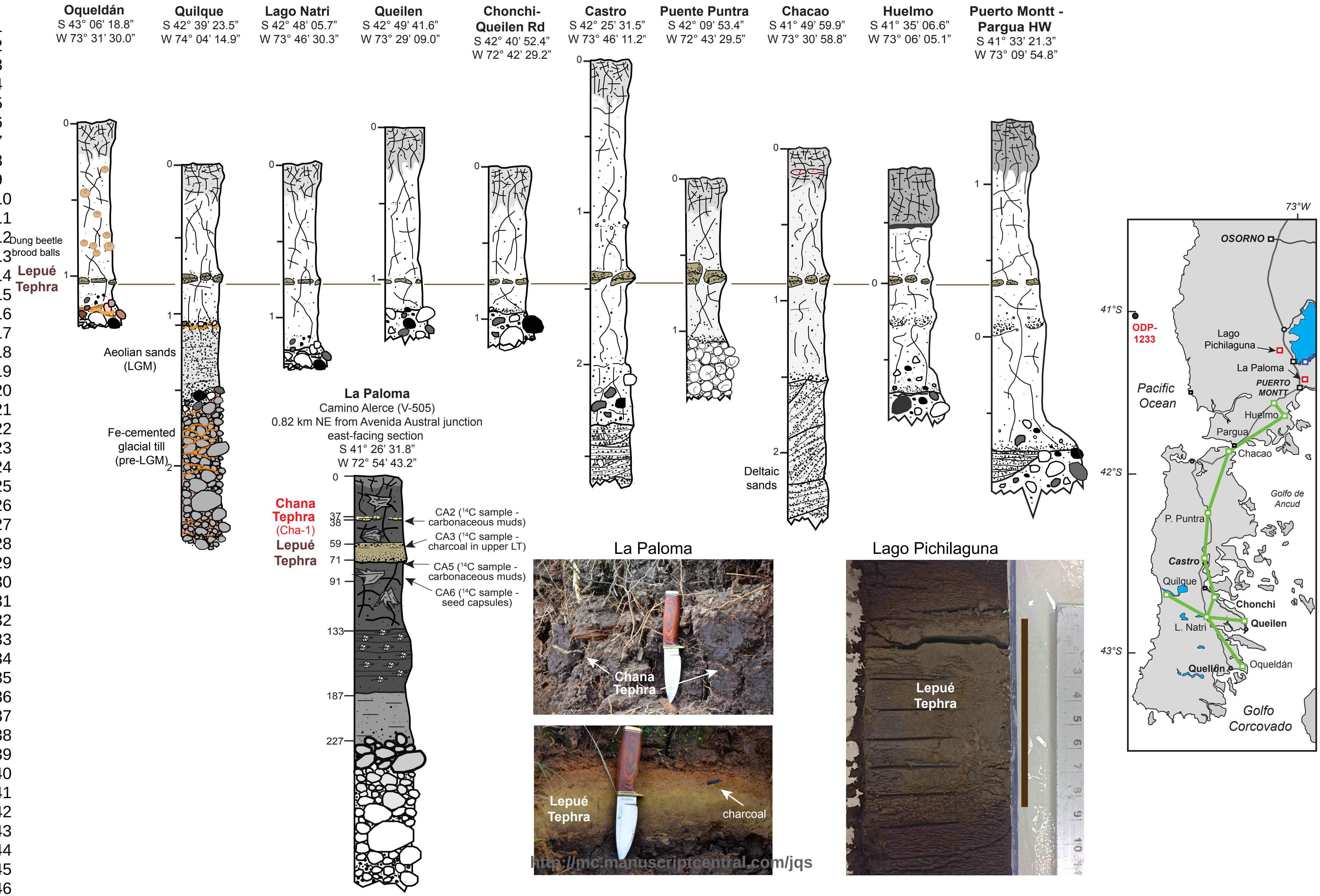

73°W
41°S
42°S
Ralún
Puerto Montt
Golfo de Ancud
P. Águila
Puente Águila Section 5
S 42° 37' 29.5"
W 72° 35' 21.6"
Lepué Tephra
14J13S5-1
(13-06-35)
Cholgo
S 42° 04' 31.0"
W 72° 27' 23.5"
9J13S5-T3
(13-05-25; n.a)
9J13S5-T2
(13-05-30)
9J13S5-T1
n.a - not analysed
Hornopirén
S 41° 56' 49.0"
W 72° 29' 41.9"
Pte Pichileufú
S 41° 58' 00.4"
W 72° 40' 19.6"
Ap-1?
8J13S3-T2
(13-05-28; n.a)
3560 ± 20 14C a BP
(LLNL-122956)
8J13S3-T1
9635 ± 35 14C a BP
(LLNL-123032)
Puelche
S 41° 44' 46.0"
W 72° 39' 28.4"
8J13S2-T2
(13-05-29)
8720 ± 25 14C a BP
(LLNL-122955)
8J13S2-T3
8J13S2-T1
9570 ± 30 14C a BP
(LLNL-123029)
9995 ± 25 14C a BP
(LLNL-122954)
14,070 ± 35 14C a BP
(LLNL-122953)
Seno Reloncaví 13-S7
S 41° 43' 29.0"
W 72° 30' 26.8"
9J13S7-T2
(13-05-27; n.a)
9J13S7-T1
Seno Reloncaví 13-S8
S 41° 43' 27.0"
W 72° 30' 11.2"
9J13S8-T1
Chapo-S1
S 41° 30' 52.2"
W 72° 21' 02.4"
Ralún
S 41° 22' 56.1"
W 72° 18' 18.0"
Ra-C
Ra-B
Ra-A
Ra-1
Ra-2
Cha-1/Chana Tephra
8625 ± 25 14C a BP
(LLNL-122961; charcoal)
Ra-3
Ra-4
8970 ± 30 14C a BP
(UCIAMS-145484; charcoal)
Ra-5
Ra-6

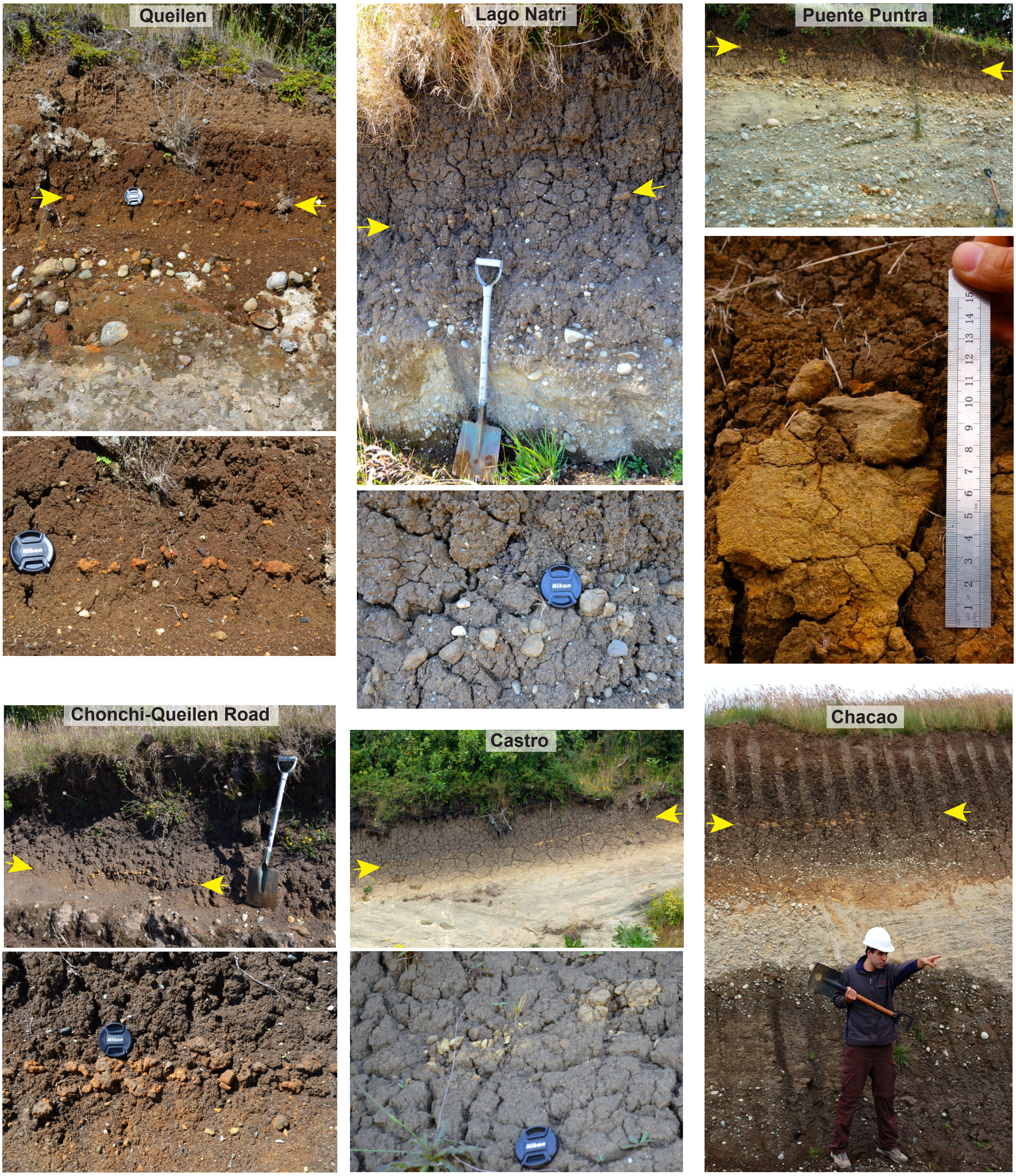

A
B
9,785 ± 30 ^{14}C a BP
(LLNL-122960;
charcoal)
Nikon
C
Remnant Amarillo Ignimbrite
valley infill surface

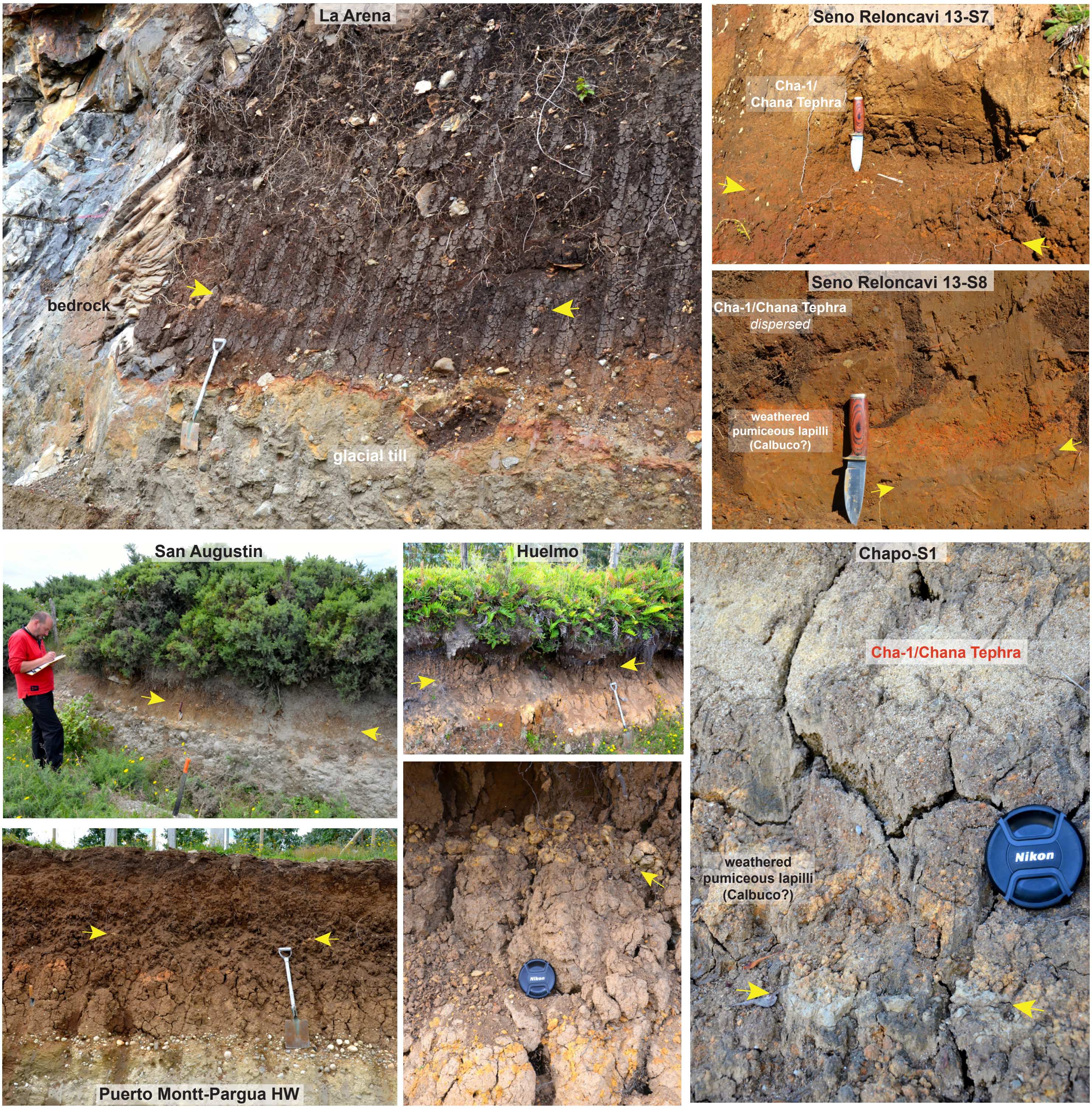

Pumalín-3
10.3 km from Ruta 7-Termas El Amarillo road junction
(10.020 road marker)
S 42° 57' 49.6"
W 72° 24' 06.4"
Section 13
S 43° 08' 34.9"
W 72° 26' 26.1"
Section 1
(south-side)
S 43° 09' 49.3"
W 72° 25' 44.8"
Sta. Lucía-1
24.3-km south of Puente Yelcho
(70.060 Road Marker)
S 43° 21' 43.3"
W 72° 23' 28.7"
Sta. Lucía-2
25-km south of Puente Yelcho
(70.760 Road Marker)
S 43° 22' 01.1"
W 72° 23' 09.9"
Sta. Lucía-3
2.4-km north of Sta. Lucia-Futaléufú junction
S 43° 23' 25.0"
W 72° 22' 22.3"
3-1
3-2
3-3
3-4
3-5
3-6
Break in scale
3-7
3-8
3-9
3-10
Chana Tephra/Cha-1
3-11
Post-Lepué scoriaceous colluvium
NOTE change in vertical scale
below road level
Chaitén-2008 tephra
Cor-3B (new, uncorrelated)
Cor-3 (4-6 correlative?)
unk-2 (new, 4-5 correlative)
Cor-2 (4-3 correlative?)
Cor-1 (Lepué Tephra)
unk-1 (new)
Yan-1
9415 ± 35 ¹⁴C a BP (UCIAMS-145494)
9410 ± 35 ¹⁴C a BP (UCIAMS-145495)
10,630 ± 40 ¹⁴C a BP (UCIAMS-145493)
12,440 ± 45 ¹⁴C a BP (UCIAMS-145491)
11,580 ± 280 ¹⁴C a BP (UCIAMS-145492)
9485 ± 35 ¹⁴C a BP (UCIAMS-145496)
11,770 ± 45 ¹⁴C a BP (UCIAMS-145497)
12,250 ± 45 ¹⁴C a BP (UCIAMS-145498)
12,515 ± 45 ¹⁴C a BP (UCIAMS-145499)
73°W
72°W
43°S
Alérce-6
Esquel
Chaitén
L.Teo
Pumalín-3
13
1
Futaléufú
Golfo Corcovado
Sta. Lucía-1
Sta. Lucía-2
Sta. Lucía-3

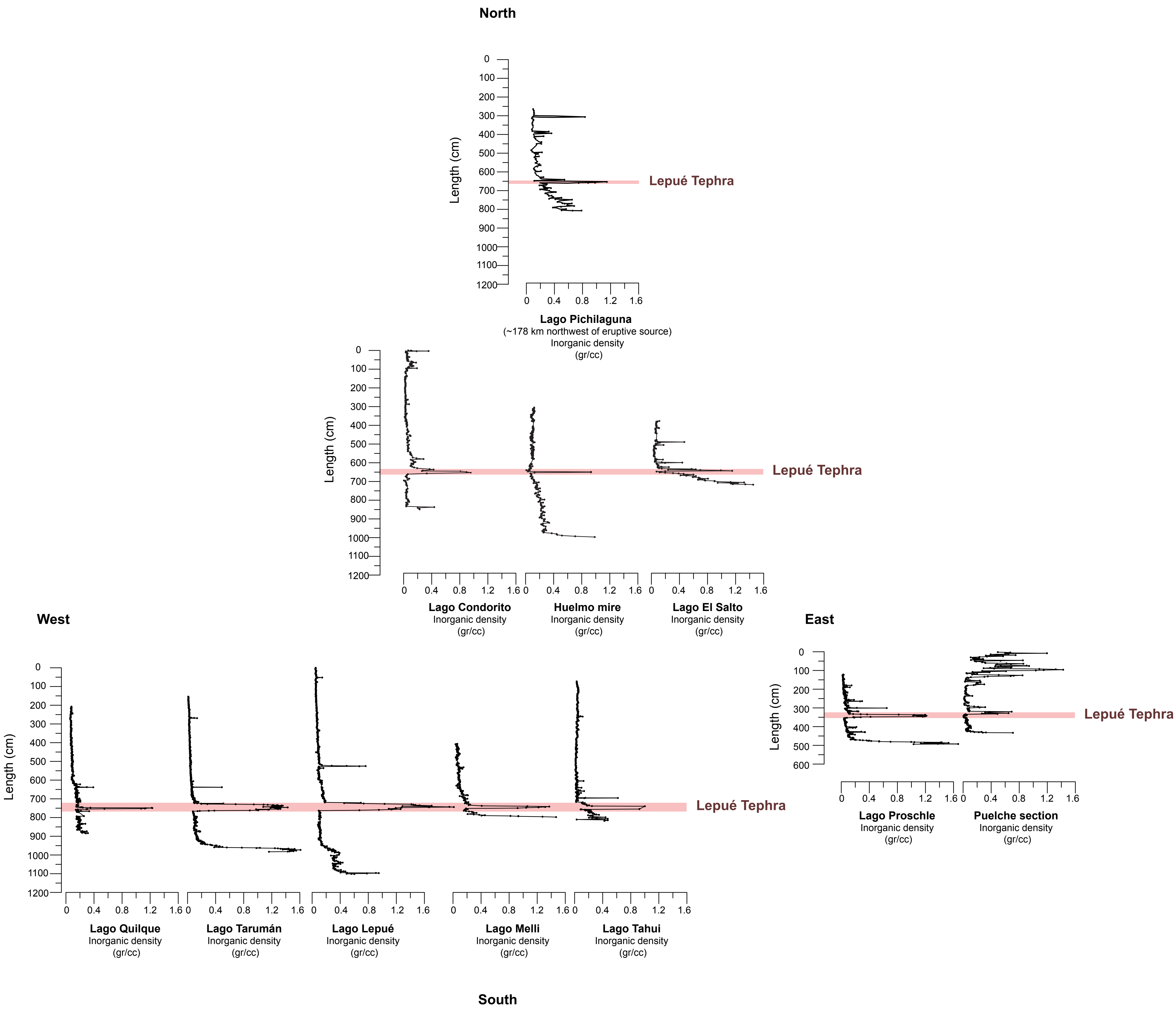

A
Cor-3
Cor-2
B
LT
B
C
Cor-3
Cor-2
D
LT
E
D
Nikon
E
F
Cor-3
Cor-2
LT
Yan-1
Glacial
till
G
Cor-3
Cor-2
LT

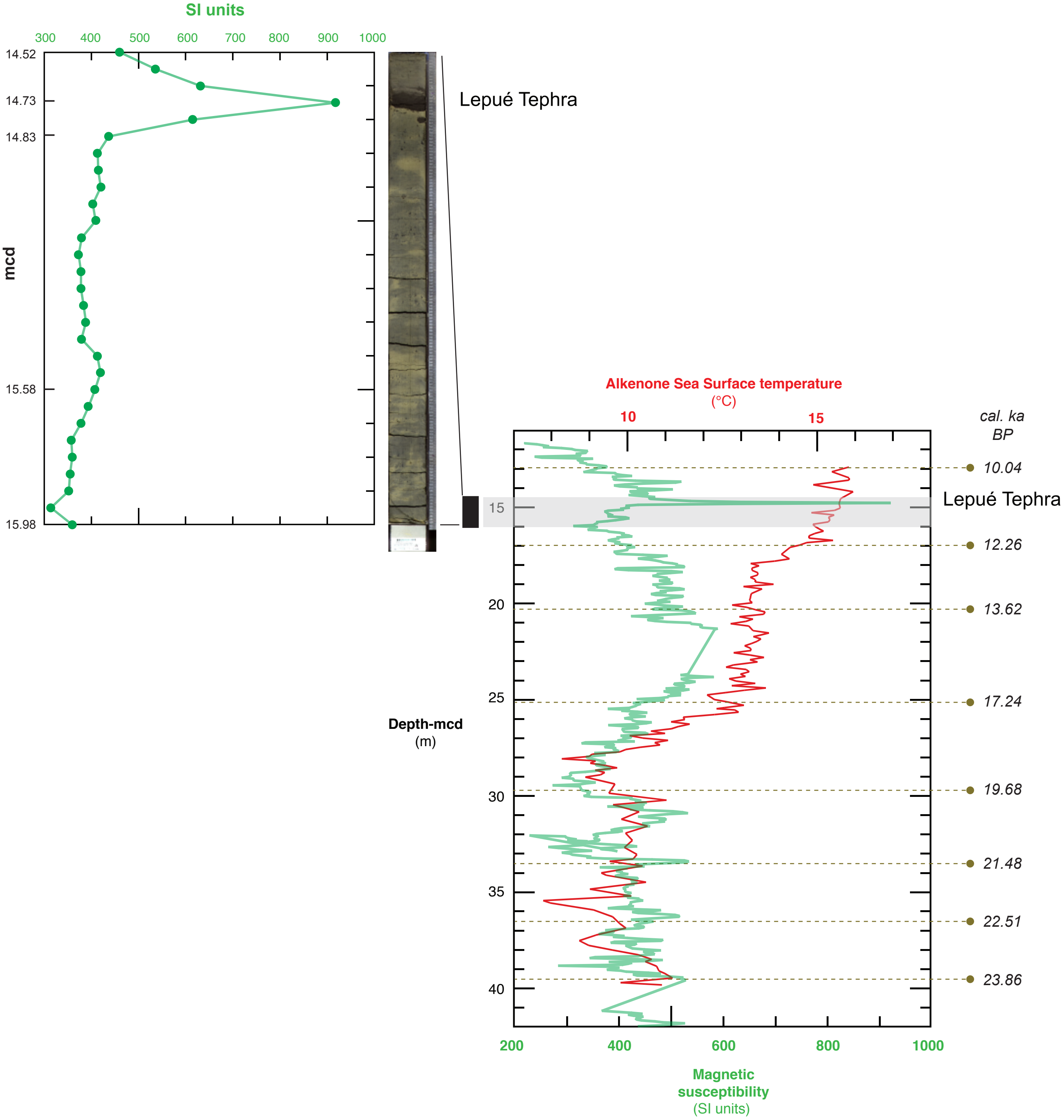

Pumalín-2
S 42° 55' 23.0"
W 72° 23' 56.0"
Chaiten-2008 Grande Tephra
2-1 (13-04-19)
2-2 (13-04-20)
2-3 (13-04-21; ant nests)
2-4 (13-01-5)
2-5 (13-04-22)
VilcúnTephra
2-6 (13-04-23)
2-7
2-8
2-9
Pumalín Tephra (Cha-2)
2-10 (13-04-24)
2-11
2-12 (13-04-24)
Pumalín-4
10.5 km from Ruta 7-Termas El Amarillo road junction (10.220 road marker)
S 42° 57' 43.1"
W 72° 24' 03.1"
4-1 n.a
4-2 n.a
4-3 (13-03-18)
4-4 n.a
4-5 (13-03-17)
Puma Verde Tephra
4-6 (13-03-16)
4-7 (13-03-15)
Chana Tephra (Cha-1)
4-8 (13-03-14)
Lepué Tephra
4-9 (13-03-13)
Alerce-6
S 42° 45' 22.0"
W 71° 44' 55.6"
38-km north of southern Park entrance gate
A6--1 (14-08-5)
4720 ± 25 ¹⁴C a BP (UCIAMS-145500)
Colluvium
A6-2 (n.a)
6190 ± 25 ¹⁴C a BP (UCIAMS-145501)
A6-3 (14-08-6)
Scoriaceous colluvium
Bedrock
La Zeta, Esquel
Dune Section
S 42° 53'.26.2"
W 71° 21' 53.9"
LAZ-D TII (12-03-18)
LAZ-D TI (12-03-17)
Drain Section
S 42° 53'.27.9"
W 71° 21' 53.0"
T11 (n.a)
7660±30 ¹⁴C a BP (LLNL-158298)
T13 (12-03-16) Chaiten-signature
T10 (12-03-15) unknown source
T9 (n.a)
T8 (12-04-21)
T7 (7a, 12-05-28; 7b, 12-05-29)
T4 (n.a)
T3 (12-03-14) Chaiten-signature
T2 (12-04-19) Chaiten-signature
T1 (12-03-13) unknown source
12,935 ± 50 ¹⁴C a BP (LLNL-158297)
13,000 ± 45 ¹⁴C a BP (LLNL-158296)
T12 (12-04-24) Chaiten-signature
13,615 ± 50 ¹⁴C a BP (UCIAMS-145924)
14,410 ± 60 (UCIAMS-145923)
14,590 ± 60 (UCIAMS-145922)
14,760 ± 60 (UCIAMS-145921)
(UCIAMS-145920)
JT-3 (14-10-1) Chaiten-signature
Glacial diamict
Lago Espejo, Futaléufú
S 43° 11' 08"
W 71° 51' 32"
¹⁴C a BP
3075 ± 20
4255 ± 15
4840 ± 20
6750 ± 20
7995 ± 25
8465 ± 30
9850 ± 35
10,320 ± 25
11,230 ± 35
10,990 ± 80
F2 F4 F5 F9 F10 F15 F18 F19 F20 F22 F23
Core
1502SC 1502AT1 1502AT2 1502AT3 1502AT4 1502AT5 1502AT6 1502AT7 1502AT8 1502DT8 1502AT9
Inorganic Matter (gm/cc)
LE-6 LE-8 LE-9 LE-12 LE-13 LE-20 LE-22 LE-23 LE-26 LE-27 LE-28
#not analysed
73°W
72°W
43°S
Alérce-6
La Zeta
Esquel
Chaitén
L.Teo
Pum-2
Pum-4
Golfo Corcovado
Lago Espejo
Futaléufú
c
b
a

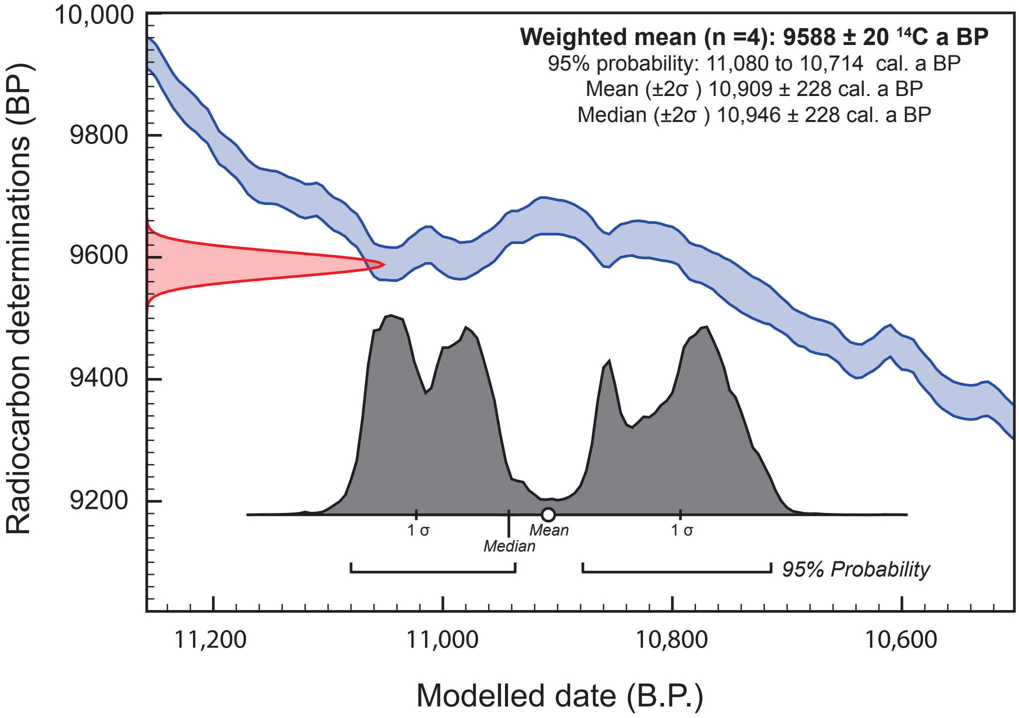

Oqueldán
S 43° 06' 18.8"
W 73° 31' 30.0"
Quilque
S 42° 39' 23.5"
W 74° 04' 14.9"
Lago Natri
S 42° 48' 05.7"
W 73° 46' 30.3"
Queilen
S 42° 49' 41.6"
W 73° 29' 09.0"
Chonchi-Queilen Rd
S 42° 40' 52.4"
W 72° 42' 29.2"
Castro
S 42° 25' 31.5"
W 73° 46' 11.2"
Puente Puntra
S 42° 09' 53.4"
W 72° 43' 29.5"
Chacao
S 41° 49' 59.9"
W 73° 30' 58.8"
Huelmo
S 41° 35' 06.6"
W 73° 06' 05.1"
Puerto Montt - Pargua HW
S 41° 33' 21.3"
W 73° 09' 54.8"
Dung beetle brood balls
Lepué Tephra
Aeolian sands (LGM)
Fe-cemented glacial till (pre-LGM)
Deltaic sands
La Paloma
Camino Alerce (V-505)
0.82 km NE from Avenida Austral junction
east-facing section
S 41° 26' 31.8"
W 72° 54' 43.2"
Chana Tephra (Cha-1)
Lepué Tephra
CA2 (14C sample - carbonaceous muds)
CA3 (14C sample - charcoal in upper LT)
CA5 (14C sample - carbonaceous muds)
CA6 (14C sample - seed capsules)
37
38
59
71
91
133
187
227
La Paloma
Chana Tephra
Lepué Tephra
charcoal
Lago Pichilaguna
Lepué Tephra
73°W
41°S
42°S
43°S
OSORNO
ODP-1233
Lago Pichilaguna
La Paloma
PUERTO MONTT
Pacific Ocean
Huelmo
Pargua
Chacao
Golfo de Ancud
P. Puntra
Castro
Quilque
Chonchi
Queilen
L. Natri
Quellón
Oqueldán
Golfo Corcovado

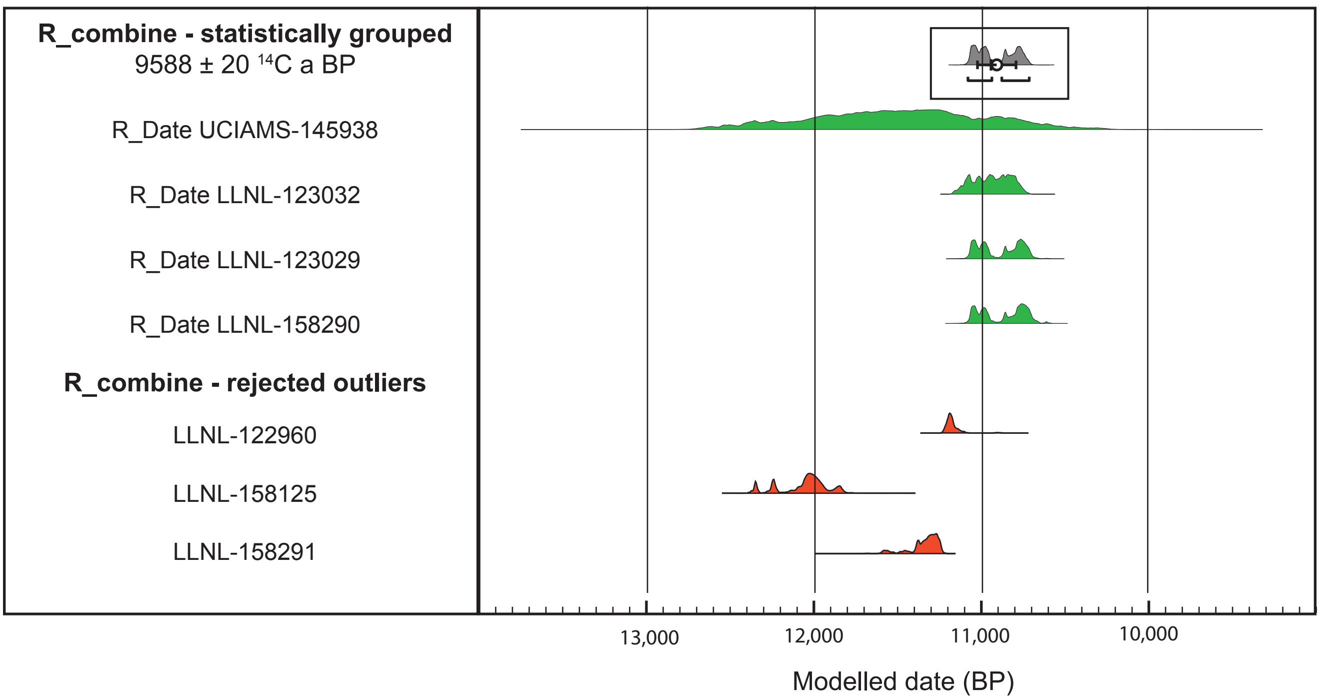

Queilen
Lago Natri
Puente Puntra
Chonchi-Queilen Road
Castro
Chacao

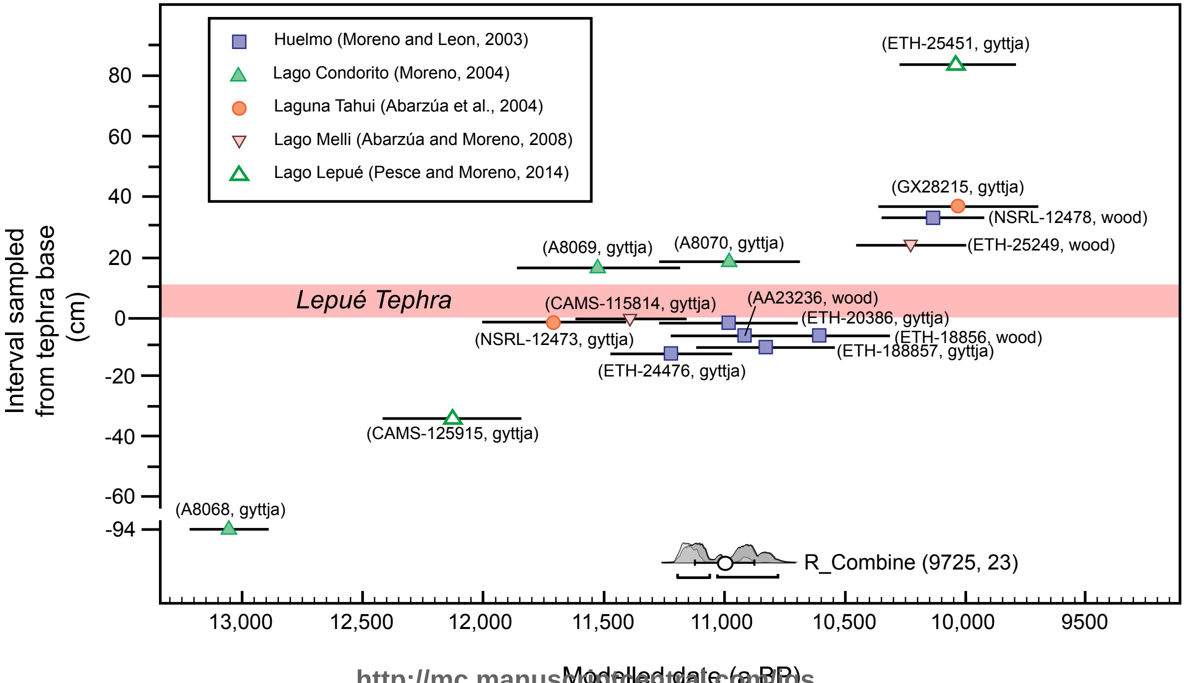

La Arena
bedrock
glacial till
Seno Reloncavi 13-S7
Cha-1/
Chana Tephra
Seno Reloncavi 13-S8
Cha-1/Chana Tephra
dispersed
weathered
pumiceous lapilli
(Calbuco?)
San Augustin
Huelmo
Chapo-S1
Cha-1/Chana Tephra
Nikon
weathered
pumiceous lapilli
(Calbuco?)
Puerto Montt-Pargua HW

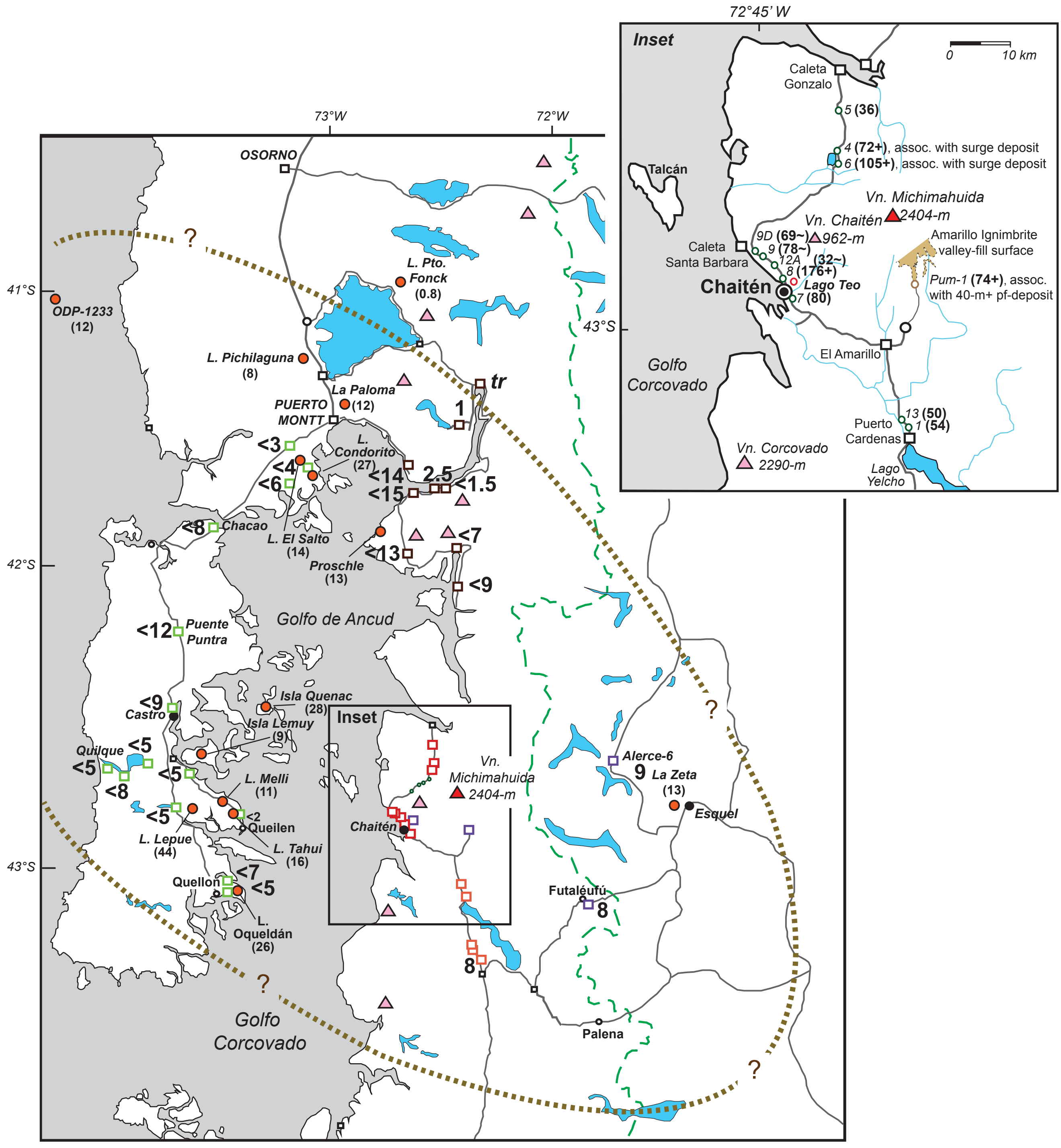

North
Lepué Tephra
Length (cm)
Lago Pichilaguna
(~178 km northwest of eruptive source)
Inorganic density
(gr/cc)
Lago Condorito
Huelmo mire
Lago El Salto
West
East
Lago Quilque
Lago Tarumán
Lago Lepué
Lago Melli
Lago Tahui
Lago Proschle
Puelche section
South

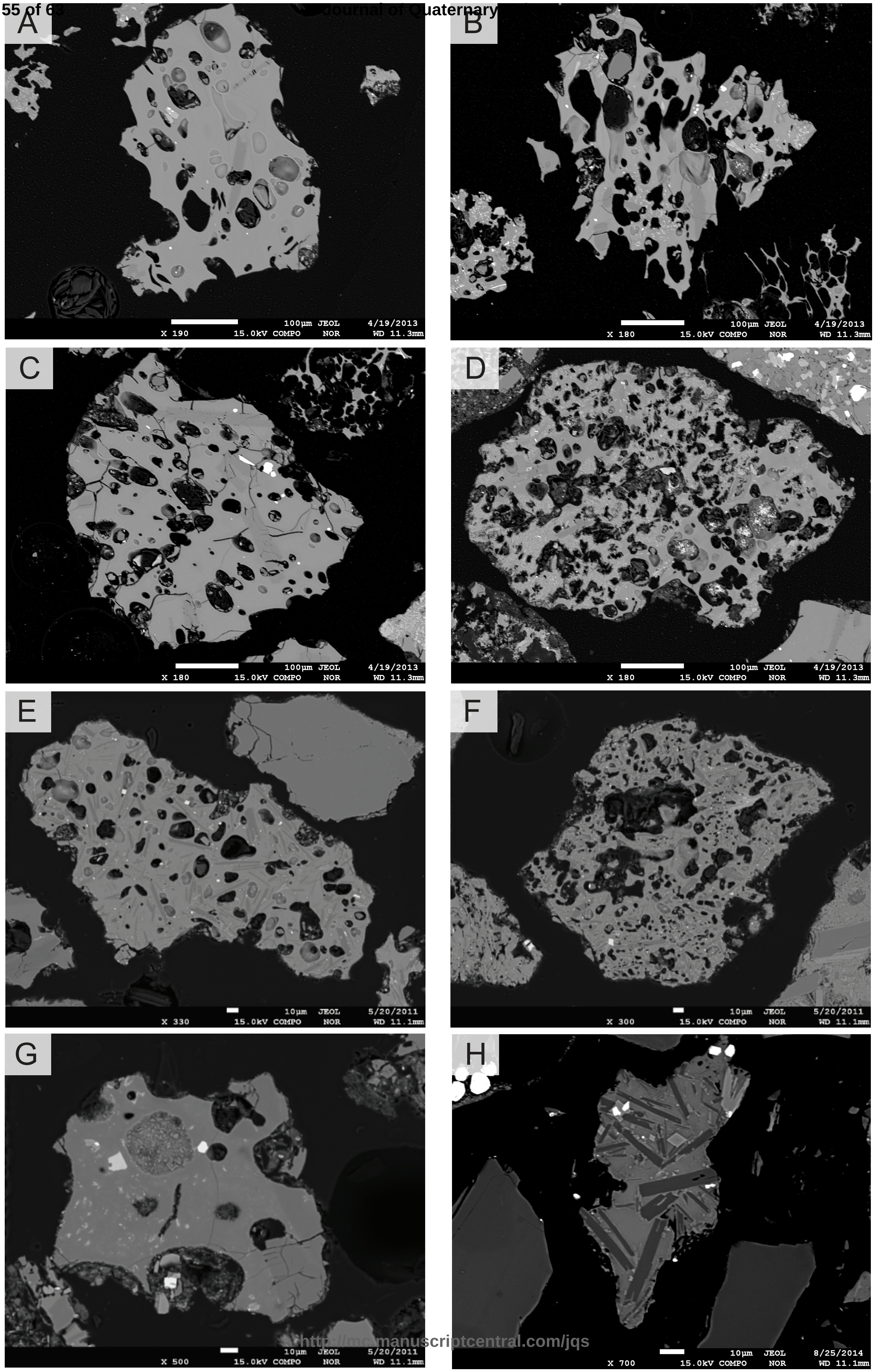

SI units
300
400
500
600
700
800
900
1000
14.52
14.73
14.83
15.58
15.98
mcd
Lepué Tephra
Alkenone Sea Surface temperature
(°C)
10
15
cal. ka
BP
10.04
Lepué Tephra
12.26
13.62
17.24
19.68
21.48
22.51
23.86
15
20
25
30
35
40
Depth-mcd
(m)
200
400
600
800
1000
Magnetic
susceptibility
(SI units)

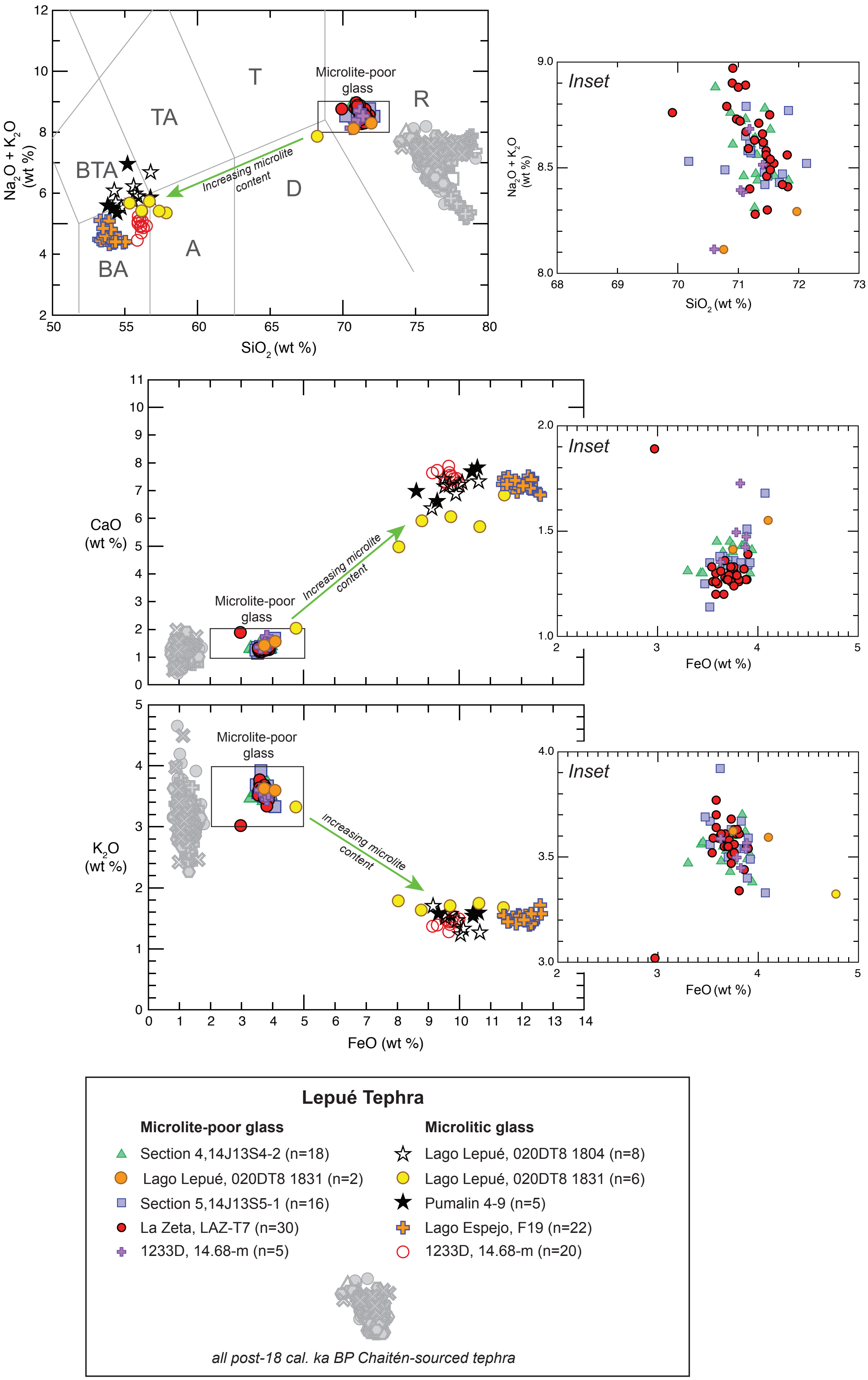

Weighted mean (n =4): 9588 ± 20 14C a BP
95% probability: 11,080 to 10,714 cal. a BP
Mean (±2σ) 10,909 ± 228 cal. a BP
Median (±2σ) 10,946 ± 228 cal. a BP
Radiocarbon determinations (BP)
10,000
9800
9600
9400
9200
1 σ
Median
Mean
1 σ
95% Probability
11,200
11,000
10,800
10,600
Modelled date (B.P.)

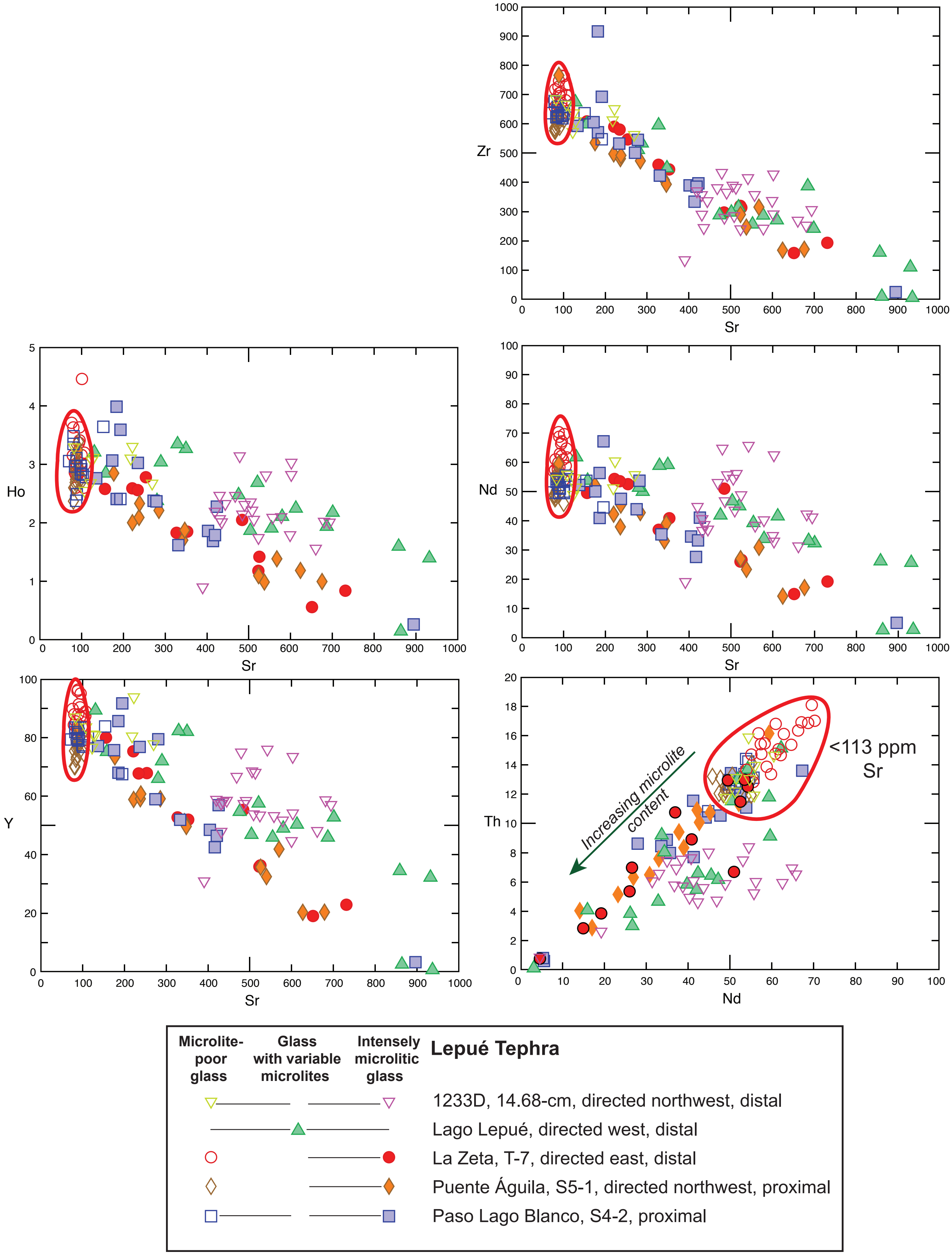

R_combine - statistically grouped
9588 ± 20 14C a BP
R_Date UCIAMS-145938
R_Date LLNL-123032
R_Date LLNL-123029
R_Date LLNL-158290
R_combine - rejected outliers
LLNL-122960
LLNL-158125
LLNL-158291
13,000
12,000
11,000
10,000
Modelled date (BP)

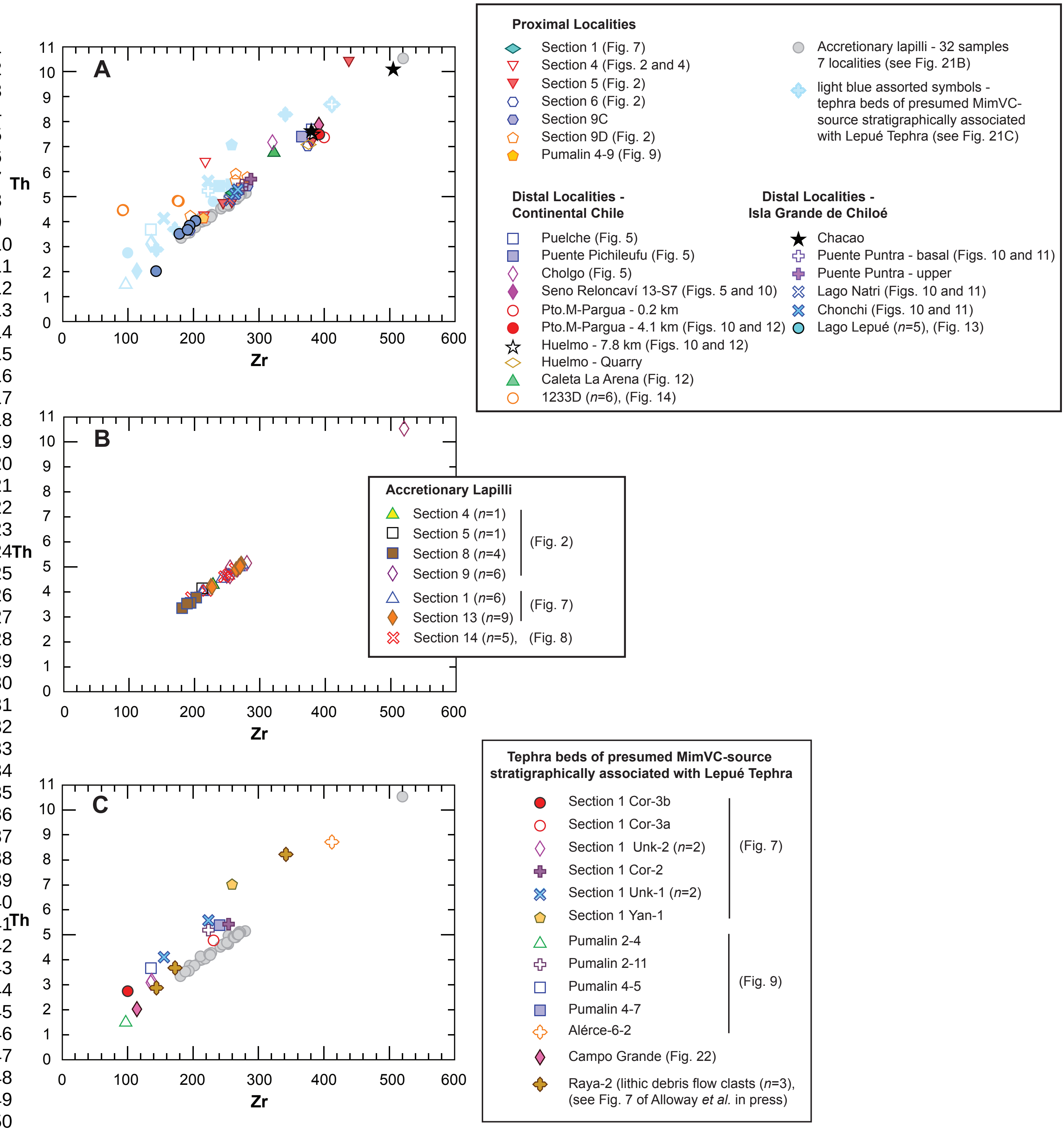

Huelmo (Moreno and Leon, 2003)
Lago Condorito (Moreno, 2004)
Laguna Tahui (Abarzúa et al., 2004)
Lago Melli (Abarzúa and Moreno, 2008)
Lago Lepué (Pesce and Moreno, 2014)
(ETH-25451, gyttja)
(GX28215, gyttja)
(NSRL-12478, wood)
(ETH-25249, wood)
(A8069, gyttja)
(A8070, gyttja)
Lepué Tephra
(CAMS-115814, gyttja)
(AA23236, wood)
(ETH-20386, gyttja)
(NSRL-12473, gyttja)
(ETH-18856, wood)
(ETH-188857, gyttja)
(ETH-24476, gyttja)
(CAMS-125915, gyttja)
(A8068, gyttja)
R_Combine (9725, 23)
Interval sampled from tephra base (cm)
80
60
40
20
0
-20
-40
-60
-94
13,000
12,500
12,000
11,500
11,000
10,500
10,000
9500
Modelled date (a BP)

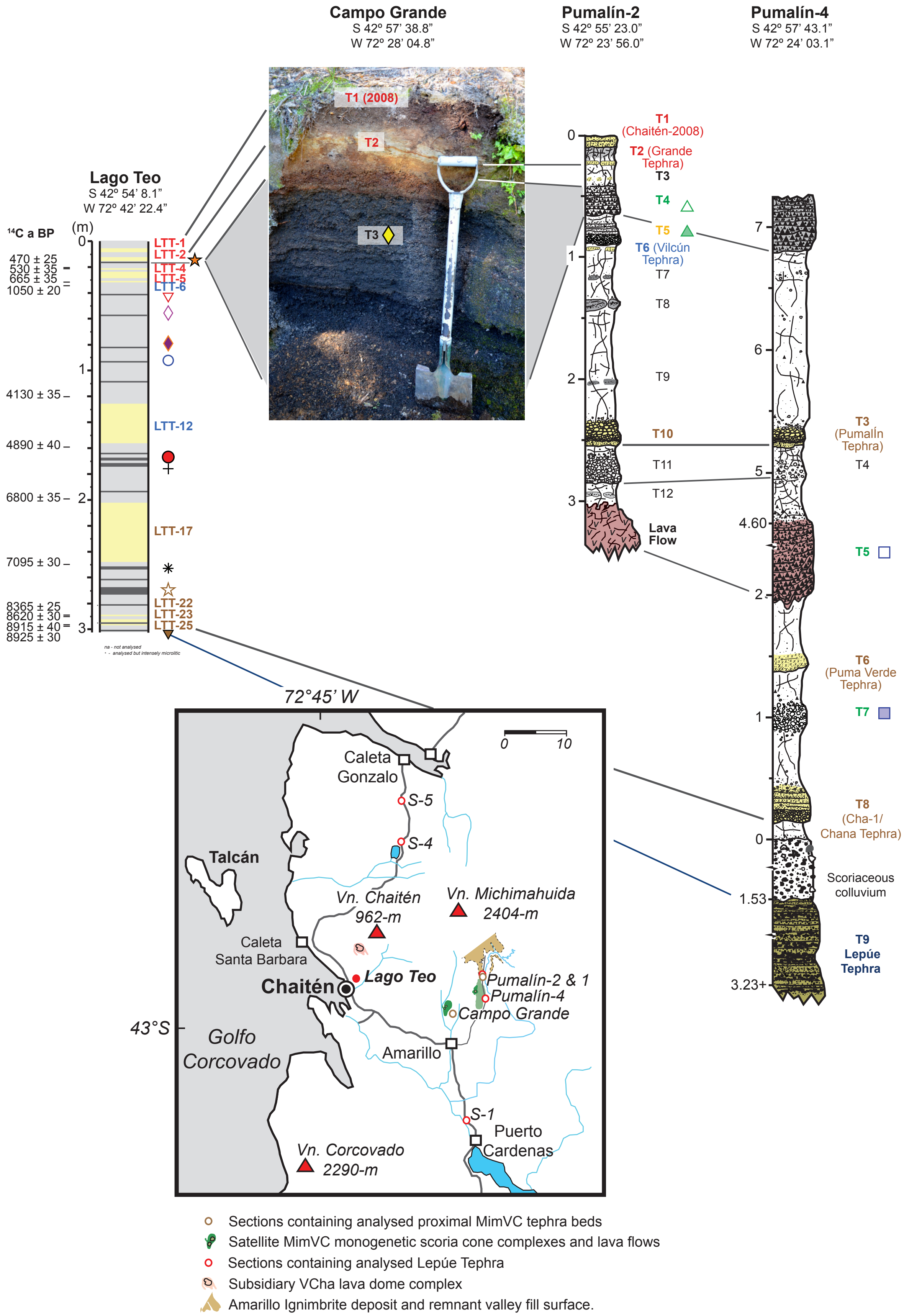

OSORNO
73°W
72°W
41°S
42°S
43°S
ODP-1233 (12)
L. Pto. Fonck (0.8)
L. Pichilaguna (8)
La Paloma (12)
PUERTO MONTT
L. Condorito (27)
L. El Salto (14)
Proschle (13)
Chacao
Golfo de Ancud
Puente Puntra
Isla Quenac (28)
Isla Lemuy (9)
Castro
Quilque
L. Melli (11)
Queilen
L. Lepue (44)
L. Tahui (16)
Quellon
L. Oqueldán (26)
Golfo Corcovado
Chaitén
Vn. Michimahuida 2404-m
Alerce-6
La Zeta (13)
Esquel
Futaléufú
Palena
Inset
72°45' W
0 10 km
Caleta Gonzalo
5 (36)
4 (72+), assoc. with surge deposit
6 (105+), assoc. with surge deposit
Talcán
Vn. Michimahuida 2404-m
Vn. Chaitén 962-m
9D (69~)
9 (78~)
12A (32~)
8 (176+)
7 (80)
Caleta Santa Barbara
Chaitén
Lago Teo
Amarillo Ignimbrite valley-fill surface
Pum-1 (74+), assoc. with 40-m+ pf-deposit
El Amarillo
Golfo Corcovado
Vn. Corcovado 2290-m
Puerto Cardenas
13 (50)
1 (54)
Lago Yelcho


A
100μm JEOL 4/19/2013
X 190 15.0kV COMPO NOR WD 11.3mm
B
100μm JEOL 4/19/2013
X 180 15.0kV COMPO NOR WD 11.3mm
C
100μm JEOL 4/19/2013
X 180 15.0kV COMPO NOR WD 11.3mm
D
100μm JEOL 4/19/2013
X 180 15.0kV COMPO NOR WD 11.3mm
E
10μm JEOL 5/20/2011
X 330 15.0kV COMPO NOR WD 11.1mm
F
10μm JEOL 5/20/2011
X 300 15.0kV COMPO NOR WD 11.1mm
G
10μm JEOL 5/20/2011
X 500 15.0kV COMPO NOR WD 11.1mm
H
10μm JEOL 8/25/2014
X 700 15.0kV COMPO NOR WD 11.1mm

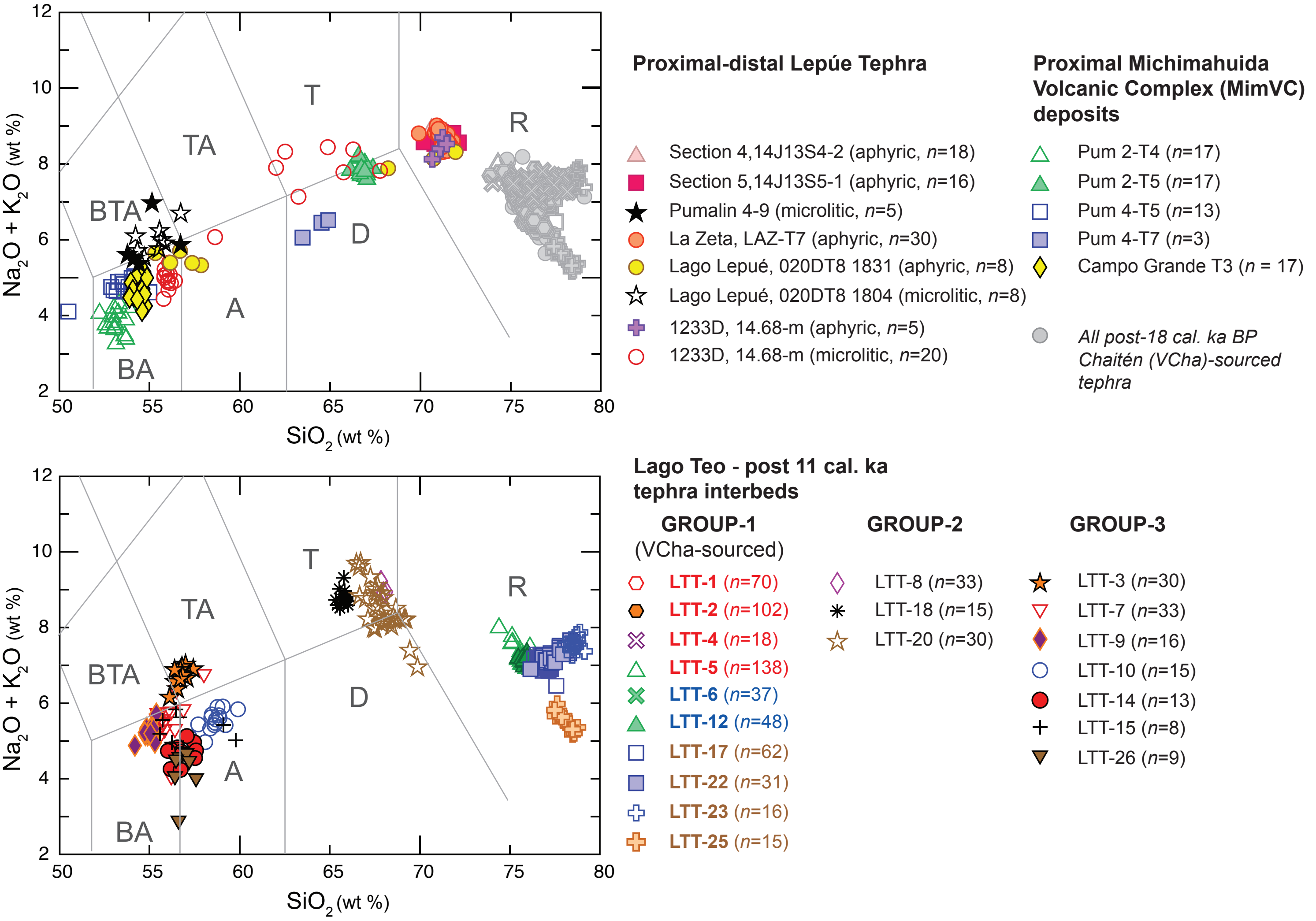

Microlite-poor glass
T
R
TA
BTA
D
A
BA
Increasing microlite content
$Na_2O + K_2O$ (wt %)
SiO_2 (wt %)
Inset
CaO (wt %)
FeO (wt %)
K_2O (wt %)
Lepué Tephra
Microlite-poor glass
Section 4,14J13S4-2 (n=18)
Lago Lepué, 020DT8 1831 (n=2)
Section 5,14J13S5-1 (n=16)
La Zeta, LAZ-T7 (n=30)
1233D, 14.68-m (n=5)
Microlitic glass
Lago Lepué, 020DT8 1804 (n=8)
Lago Lepué, 020DT8 1831 (n=6)
Pumalin 4-9 (n=5)
Lago Espejo, F19 (n=22)
1233D, 14.68-m (n=20)
all post-18 cal. ka BP Chaitén-sourced tephra

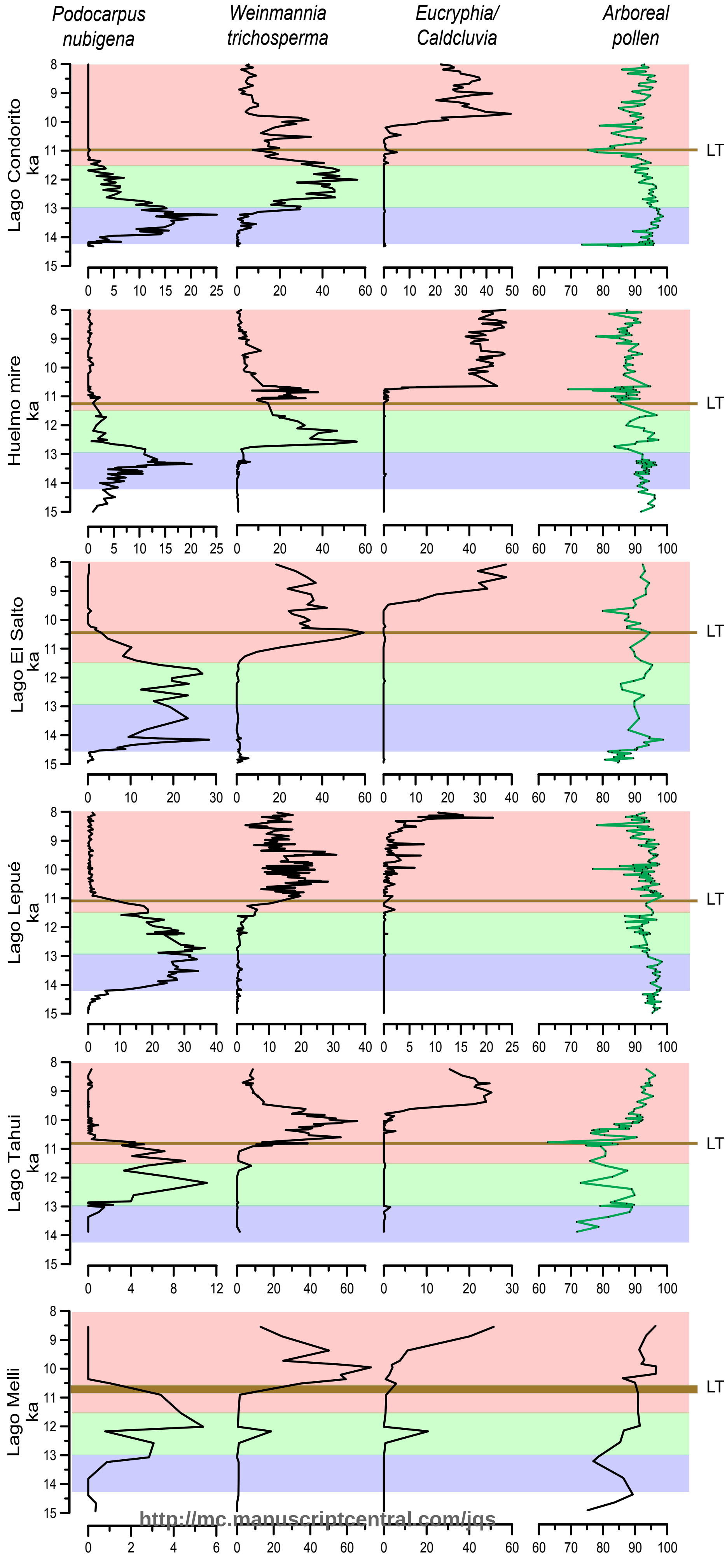

Zr
Sr
Ho
Sr
Nd
Sr
Y
Sr
Th
Nd
Increasing microlite content
<113 ppm Sr
Microlite-poor glass
Glass with variable microlites
Intensely microlitic glass
Lepué Tephra
1233D, 14.68-cm, directed northwest, distal
Lago Lepué, directed west, distal
La Zeta, T-7, directed east, distal
Puente Águila, S5-1, directed northwest, proximal
Paso Lago Blanco, S4-2, proximal

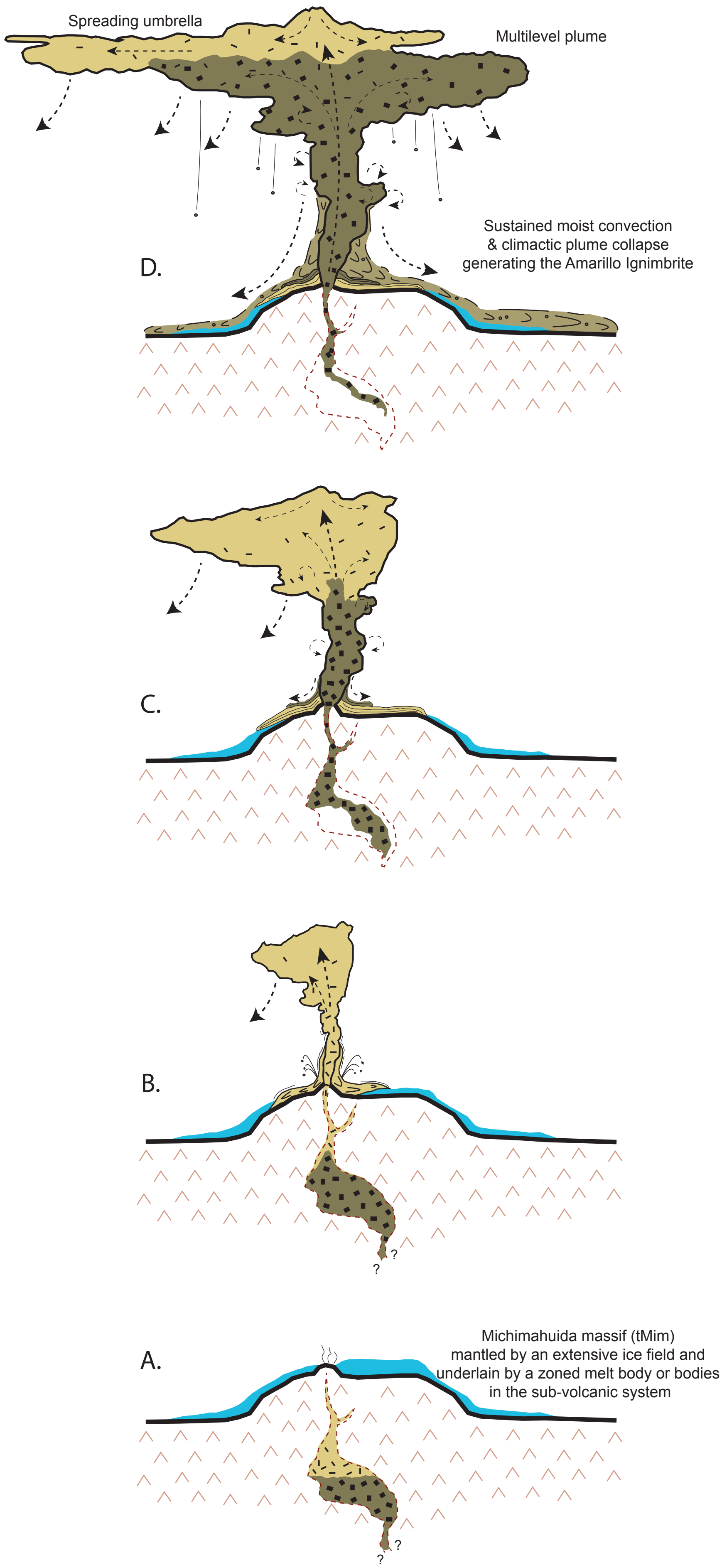

A
B
C
Th
Zr
Proximal Localities
Section 1 (Fig. 7)
Section 4 (Figs. 2 and 4)
Section 5 (Fig. 2)
Section 6 (Fig. 2)
Section 9C
Section 9D (Fig. 2)
Pumalin 4-9 (Fig. 9)
Accretionary lapilli - 32 samples 7 localities (see Fig. 21B)
light blue assorted symbols - tephra beds of presumed MimVC-source stratigraphically associated with Lepué Tephra (see Fig. 21C)
Distal Localities - Continental Chile
Puelche (Fig. 5)
Puente Pichileufu (Fig. 5)
Cholgo (Fig. 5)
Seno Reloncaví 13-S7 (Figs. 5 and 10)
Pto.M-Pargua - 0.2 km
Pto.M-Pargua - 4.1 km (Figs. 10 and 12)
Huelmo - 7.8 km (Figs. 10 and 12)
Huelmo - Quarry
Caleta La Arena (Fig. 12)
1233D (n=6), (Fig. 14)
Distal Localities - Isla Grande de Chiloé
Chacao
Puente Puntra - basal (Figs. 10 and 11)
Puente Puntra - upper
Lago Natri (Figs. 10 and 11)
Chonchi (Figs. 10 and 11)
Lago Lepué (n=5), (Fig. 13)
Accretionary Lapilli
Section 4 (n=1)
Section 5 (n=1)
Section 8 (n=4)
Section 9 (n=6)
(Fig. 2)
Section 1 (n=6)
Section 13 (n=9)
(Fig. 7)
Section 14 (n=5), (Fig. 8)
Tephra beds of presumed MimVC-source stratigraphically associated with Lepué Tephra
Section 1 Cor-3b
Section 1 Cor-3a
Section 1 Unk-2 (n=2)
Section 1 Cor-2
Section 1 Unk-1 (n=2)
Section 1 Yan-1
(Fig. 7)
Pumalin 2-4
Pumalin 2-11
Pumalin 4-5
Pumalin 4-7
Alérce-6-2
(Fig. 9)
Campo Grande (Fig. 22)
Raya-2 (lithic debris flow clasts (n=3), (see Fig. 7 of Alloway et al. in press)



Campo Grande
S 42° 57' 38.8"
W 72° 28' 04.8"
Pumalín-2
S 42° 55' 23.0"
W 72° 23' 56.0"
Pumalín-4
S 42° 57' 43.1"
W 72° 24' 03.1"
T1 (2008)
T2
T3
Lago Teo
S 42° 54' 8.1"
W 72° 42' 22.4"
¹⁴C a BP
(m)
470 ± 25
530 ± 35
665 ± 35
1050 ± 20
4130 ± 35
4890 ± 40
6800 ± 35
7095 ± 30
8365 ± 25
8620 ± 30
8915 ± 40
8925 ± 30
LTT-1
LTT-2
LTT-4
LTT-5
LTT-6
LTT-12
LTT-17
LTT-22
LTT-23
LTT-25
T1
(Chaitén-2008)
T2 (Grande
Tephra)
T3
T4
T5
T6 (Vilcún
Tephra)
T7
T8
T9
T10
T11
T12
Lava
Flow
T3
(Pumalín
Tephra)
T4
4.60
T5
T6
(Puma Verde
Tephra)
T7
T8
(Cha-1/
Chana Tephra)
Scoriaceous
colluvium
1.53
T9
Lepúe
Tephra
3.23+
72°45' W
43°S
0
10
Caleta
Gonzalo
S-5
S-4
Talcán
Vn. Chaitén
962-m
Vn. Michimahuida
2404-m
Caleta
Santa Barbara
Lago Teo
Chaitén
Pumalín-2 & 1
Pumalín-4
Campo Grande
Golfo
Corcovado
Amarillo
S-1
Puerto
Cardenas
Vn. Corcovado
2290-m
Sections containing analysed proximal MimVC tephra beds
Satellite MimVC monogenetic scoria cone complexes and lava flows
Sections containing analysed Lepúe Tephra
Subsidiary VCha lava dome complex
Amarillo Ignimbrite deposit and remnant valley fill surface.


$Na_2O + K_2O$ (wt %)
SiO_2 (wt %)
T
TA
BTA
BA
A
D
R
Proximal-distal Lepúe Tephra
Section 4,14J13S4-2 (aphyric, n=18)
Section 5,14J13S5-1 (aphyric, n=16)
Pumalin 4-9 (microlitic, n=5)
La Zeta, LAZ-T7 (aphyric, n=30)
Lago Lepué, 020DT8 1831 (aphyric, n=8)
Lago Lepué, 020DT8 1804 (microlitic, n=8)
1233D, 14.68-m (aphyric, n=5)
1233D, 14.68-m (microlitic, n=20)
Proximal Michimahuida Volcanic Complex (MimVC) deposits
Pum 2-T4 (n=17)
Pum 2-T5 (n=17)
Pum 4-T5 (n=13)
Pum 4-T7 (n=3)
Campo Grande T3 (n = 17)
All post-18 cal. ka BP Chaitén (VCha)-sourced tephra
Lago Teo - post 11 cal. ka tephra interbeds
GROUP-1
(VCha-sourced)
LTT-1 (n=70)
LTT-2 (n=102)
LTT-4 (n=18)
LTT-5 (n=138)
LTT-6 (n=37)
LTT-12 (n=48)
LTT-17 (n=62)
LTT-22 (n=31)
LTT-23 (n=16)
LTT-25 (n=15)
GROUP-2
LTT-8 (n=33)
LTT-18 (n=15)
LTT-20 (n=30)
GROUP-3
LTT-3 (n=30)
LTT-7 (n=33)
LTT-9 (n=16)
LTT-10 (n=15)
LTT-14 (n=13)
LTT-15 (n=8)
LTT-26 (n=9)


Podocarpus nubigena
Weinmannia trichosperma
Eucryphia/ Caldcluvia
Arboreal pollen
Lago Condorito
ka
Huelmo mire
ka
Lago El Salto
ka
Lago Lepué
ka
Lago Tahui
ka
Lago Melli
ka
LT
LT
LT
LT
LT
LT


Spreading umbrella
Multilevel plume
Sustained moist convection
& climactic plume collapse
generating the Amarillo Ignimbrite
D.
C.
B.
A.
?
?
?
?
Michimahuida massif (tMim)
mantled by an extensive ice field and
underlain by a zoned melt body or bodies
in the sub-volcanic system

Location	Lab ID	Sample type	Sample position	^{14}C AMS age (^{14}C a BP)	Calibrated ‡ Age (± 2σ) (cal. a BP)	95% HPDF * (cal. a BP)
Onshore *(this study)*						
S-4, Chaitén *	UCIAMS-145938	Charcoal (twig)	Within surge deposit (co-eruptive correlative)	9,960 ± 330	11,483 ± 1,034	10,561-12,552
Pumalín-1, Chaitén	LLNL-122960	Charcoal (outer small tree)	Within pyroclastic deposit (co-eruptive correlative)	9,785 ± 30	11,190 ± 88	11,108-11,237
Pte Pichileufú *	LLNL-123032	Bulk carbonac. muds	Immediately below lower contact	9,635 ± 35	10,934 ± 118	10,753-11,134
Puelche *	LLNL-123029	Bulk highly carbonac. muds	Immediately below lower contact	9,570 ± 30	10,862 ± 250	10,595-11,080
S- 9, Chaitén	LLNL-158125	Bulk carbonac. muds	Immediately below lower contact	10,330 ± 40	12,033 ± 280	11,825-12,383
S-12A, Chaitén *	LLNL-158290	Bulk carbonac. muds	Immediately below lower contact	9,560 ± 35	10.841 ± 262	10,563-11,081
	LLNL-158291	Wood in growth position	Immediately below lower contact	9,970 ± 35	11,321 ± 170	11,234-11,500
R_combine modelled age (n=4 *)				**9,588 ± 20**	**10,909 ± 228**	**10,714-11,080**
(Previous studies) **Huelmo** (Moreno & Leon, 2003)	NSRL-12478	Wood	901B-601A, 666.5-cm	9,030± 60	10,139 ± 214	9,914-10,246
	Lepúe tephra correlative (10-cm thick), 700-cm depth (basal contact)					
	ETH-20386	Bulk gyttja	901B-601A, 702-cm	9,695± 90	10,982 ± 290	10,735-11,225
	ETH-18856	Wood	901B-601A, 706-cm	9,415± 80	10,595 ± 286	10,289-11,063
	AA23236	Wood	901B-601A, 706-cm	9,635± 85	10,938 ± 284	10,696-11,196
	ETH-188857	Bulk gyttja	901B-601A, 710-cm	9,545± 70	10,820 ± 308	10,580-11,100
	ETH-24476	Bulk gyttja	901B-601A, 712-cm	9,830± 75	11,208 ± 244	10,800-11,399
Lago Condorito (Moreno, 2004)	A8070	Bulk gyttja	PM10, 685-688-cm	9,680± 85	10,967 ± 282	10,732-11,211
	A8069	Bulk gyttja	PM10, 710-713-cm	10,060± 80	11,527 ± 328	11,245-11,917
	Lepúe tephra correlative (27-cm thick), 726-cm depth (basal contact)					
	A8068	Bulk gyttja	PM10, 821-824-cm	11,265 ± 65	13,090 ± 148	12,928-13,258
Laguna Tahui (Abarzúa et al., 2004)	GX28215		004D, 891-895-cm	8,990 ± 110	10,029 ± 332	9,635-10,367
	Lepúe tephra correlative (16-cm thick), 932-cm depth (basal contact)					
	NSRL-12473	Bulk gyttja	004D, 934-936-cm	10,150± 50	11,703 ± 296	11,403-11,960
Lago Meli (Abarzúa and Moreno, 2008)		Terrestrial macrofossil	818-819-cm	9,105 ± 70	10,227 ± 218	9,930-10,479
	Lepúe tephra correlative (11-cm thick), 843-cm depth (basal contact)					
	CAMS-115814	Bulk gyttja	844-cm	10,000± 40	11,377 ± 218	11,247-11,610
Lago Lepúe (Pesce & Moreno, 2014)	ETH-25451	Bulk gyttja	0201 DT8, 786-cm	8,965 ± 65	10,033 ± 234	9,781-10,227
	Lepúe Tephra (44-cm thick), 870-cm depth (basal contact)					
	CAMS-125915	Bulk gyttja	0201 DT9, 904-cm	10,360 ± 40	12,123 ± 272	11,948-12,401
Offshore						
ODP Site 1233D (Lamy et al. 2004)	KIA 21451	Mixed planktonic foraminifera	12.94 mcd	9, 340 ± 80	10,175 ± 288	9,916-10,387
	Lepúe Tephra (12-cm thick), 14.80 mcd (basal contact)					
	KIA21473	Mixed planktonic foraminifera	17.01 mcd	10,800 ±70	12,276 ± 280	12,019-12,534

‡ The Southern Hemisphere terrestrial calibration curve (SHCal13) and OxCal Program (v. 4.2.4) were used for all samples; * Highest Probability Density Function Radiocarbon laboratories used in this study: UCIAMS - University of California at Irving AMS Facility; LLNL – Lawrence Livermore National Laboratory.