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# Forests, pastures, and furnaces in the south-eastern Alps: the Mid-Late Holocene palaeoenvironmental record of Lake Caldonazzo

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ABSTRACT

Drawing on the Lake Caldonazzo sedimentary record (Valsugana, Italy), this study reconstructs palaeoecological dynamics from the 6th to 1st millennium BCE, revealing the environmental imprint of pre-protohistoric copper mining in the south-eastern Alps. Integrating bio- and geochemical proxies (micro-botanical data, micro-charcoal, faecal biomarkers, and trace elements) we reconstruct the interplay between environmental dynamics and anthropogenic impacts from the Neolithic to the beginning of Iron Age. During the Middle Holocene, pristine silver fir-beech forests dominated the landscape, with incipient Neolithic human influence evidenced by pastoral indicators despite the absence of known settlements in the valley. Copper Age forest decline resulted from climate-induced cooling interacting with agropastoral activity expansion. During the Early and Middle Bronze Age, human impact on mountain ecosystems increased with the integrated development of farming, forest exploitation, and pastoral activities, while early geochemical signals raise the possibility of incipient local metallurgy during the advanced Middle Bronze Age. The Recent-Final Bronze Age marked a metallurgical apex, as evidenced by a surge in the heavy metal enrichment factor and micro-charcoal peaks, corroborating the current archaeological interpretative model. The latter saw the south-eastern Trentino as a continental-scale production hub before environmental degradation and resource depletion marked its end between the 2nd and 1st millennium BCE. Land use reactivation became evident during the subsequent territorial reorganisation of the Early Iron Age. Notably, the Löbben and Göschenen 1 climatic oscillation modulated but did not override anthropic pressures. The study demonstrates that pre-protohistoric communities triggered significant environmental impacts (e.g., deforestation, erosion, heavy metal pollution), underscoring the ecological consequences of resource exploitation within sensitive Alpine ecosystems.

## 1. Introduction

Among human activities with profound consequences on both climate and the environment (Ruddiman, 2003; Cremaschi, 2014; Stephens et al., 2019; Ellis, 2021), mining and metallurgy stand out for their role as drivers of technological progress (Tylecote, 1992; Diamond, 1997; Weeks, 2012), for their social implications (Knapp et al., 1998; Barca and Leonardi, 2016; Riofrancos, 2020), and for being agents of ecological transformation (Islam et al., 2022; Giljum et al., 2025). From the onset of metal production in prehistory, these practices have left

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permanent marks on landscapes, altering soil composition, accelerating deforestation, and reshaping hydrological systems. Their legacy persists in both palaeoenvironmental archives (Mighall et al., 2017; Py-Saragaglia et al., 2017; Becker et al., 2019; Szymczyk and Nita, 2021) and modern ecosystems (Meck et al., 2006; Nurcholis et al., 2017; Leogrande et al., 2019; Li et al., 2022), underscoring a continuum of anthropogenic impact that bridges millennia (Mercuri et al., 2025). The Alpine region, with its metal ore resources (Janković and Petrascheck, 1987; Pohl and Belocky, 1999; Artioli et al., 2013) and well-preserved natural geoarchives (e.g., lakes, peat bogs), offers an ideal laboratory to investigate these dynamics (Viehweider et al., 2015; Elbaz-Poulichet et al., 2020; Knierzinger et al., 2021; Furlanetto et al., 2025). Archaeological and palaeoecological studies reveal how mining and metallurgy brought about landscape modification (e.g., furnaces, mines, slag heaps; Šebesta, 2000; Stöllner, 2003), deforestation and wood consumption (Gobet et al., 2003; Heiss and Oeggl, 2008), farming and pastoral practices intensification (Breitenlechner et al., 2010, 2014), soil erosion increase (Rapuc et al., 2024), heavy metal contamination of atmosphere, hydrosphere, sediments, and soils (Shotyk et al., 2002; Preunkert et al., 2019; Carvalho and Schulte, 2021; Shah et al., 2024), as well as socio-economic stratification (Nikov et al., 2018; Heiss et al., 2021;).

This study employs a multi-proxy approach on the sediment sequence from Lake Caldonazzo to reconstruct the timing and interplay of climatic shift, environmental changes, and anthropogenic drivers in the subalpine area of Valsugana (south-eastern Trentino, Italy; Fig. 1). A suite of complementary proxies was integrated: pollen data to infer regional vegetation changes (Sugita, 1994; Pearsall, 2016); non-pollen palynomorphs (NPPs) to provide information on local habitats (van Geel et al., 1980; Marinova and Atassanova, 2006) and to serve as indirect proxies for anthropogenic activities (Florenzano et al., 2012; Lee et al., 2022); micro-charcoal to indicate fire activity (Whitlock and Larsen, 2002); faecal sterols and stanols to investigate biological inputs from humans and animals (Battistel et al., 2015; Bortolini et al., 2024); trace element analysis to track variations in heavy metal concentrations, potentially linked to metallurgical contamination (Shotyk, 1996; Kabata-Pendias, 2010).

Located in the core of the south-eastern Alps mining district (Avanzini et al., 2010; Artioli et al., 2013, 2016; Ferretti, 2020), Lake Caldonazzo offers a relevant archive to investigate these dynamics against the backdrop of two known phases of pre-protohistoric copper production: the 1st phase between the 26th-21st century BCE (Copper Age 2/3-first phases of the Early Bronze Age; Artioli et al., 2016, 2024; Pearce et al., 2022), while the 2nd phase between the 13th-10th century BCE (Recent-Final Bronze Age; Silvestri et al., 2019; Bellintani and Silvestri, 2021; Marzatico, 2022).

This study aims to address the following research questions:

- What is the sequence and timing of major vegetation and land use changes in the Valsugana area during the Middle and Late Holocene, and how do they correlate with known climatic events and archaeological evidence for human activity?
- What is the specific palaeoecological signature of the known pre-protohistoric mining and smelting phases in the local ecosystem, particularly in terms of heavy metal deposition, erosion, and forest management?

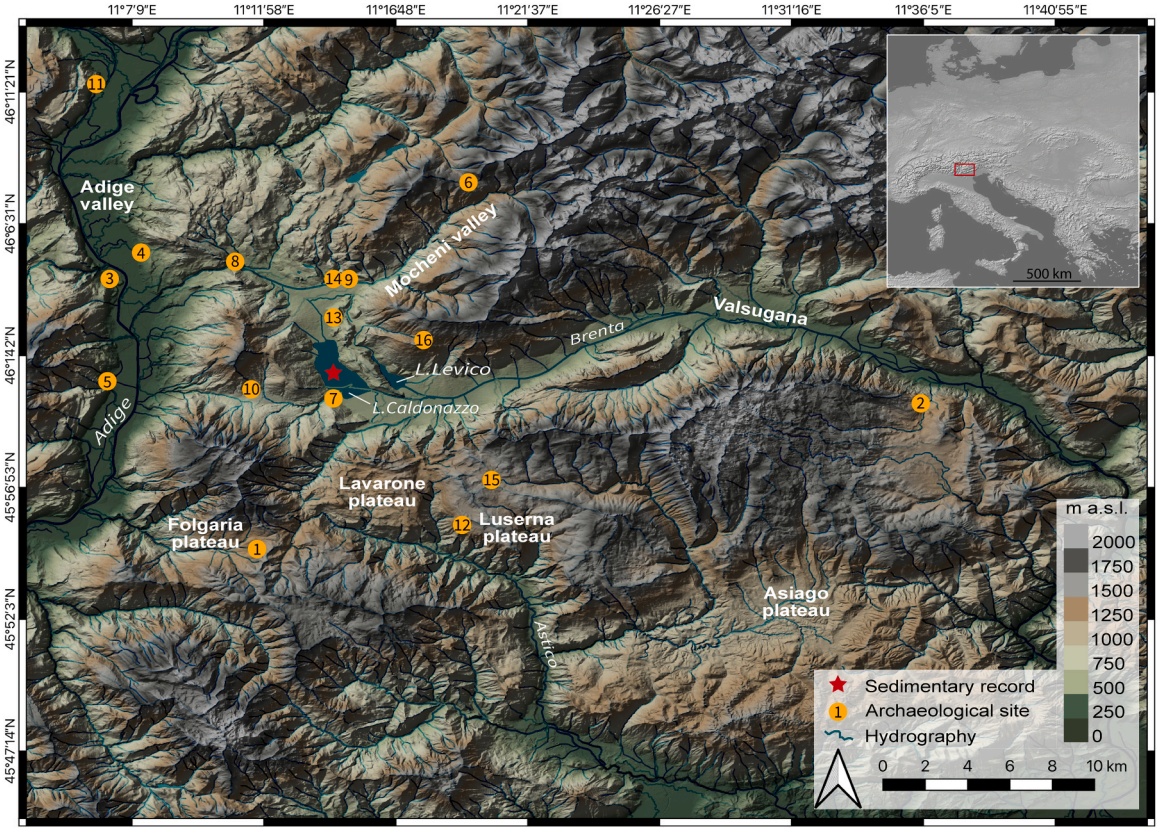


**Fig. 1.** Geographical setting of the study area. Lake Caldonazzo (red star) is located in the western sector of Valsugana. Main archaeological sites are as follows (UP=Upper Palaeolithic; M=Mesolithic; N = Neolithic; CA=Copper Age; BA=Bronze Age; IA= Iron Age): 1. Palù Echen (UP), 2. Riparo Dalmeri (UP), 3. La Vela (M, N, CA, BA), 4. Riparo Gaban (M, N, CA, BA), 5. Romagnano (M, N, CA, BA, IA), 6. Acqua Fredda-Passo del Redebus (BA), 7. Calceranica (BA), 8. Civezzano (BA, IA), 9. Croz del Cius (BA), 10. Dossi di Vigolo Vattaro (BA), 11. Fai della Paganella (BA), 12. Luserna Platz von Motze (BA), 13. Masetti di Pergine Valsugana (BA), 14. Montesi di Serso (BA, IA), 15. Passo Vezzena (BA), 16. Vetriolo (BA) (base map by Tarquini et al. 2007, 2023, by https://www.eea.europa.eu EU-Hydro River Network Database 2006–2012 (vector), Europe - version 1.3, Nov. 2020, and by https://www.naturalearthdata.com 1:10 m Gray Earth).

– Based on our multi-proxy record, which indicators are most effective for detecting different types of anthropogenic impact, from agro-pastoralism to metallurgy?

## 2. Study area

### 2.1. Valsugana and Lake Caldonazzo

The Valsugana valley extends approximately 50 km through south-eastern Trentino with three morphologically distinct sectors (Fig. 1). The western sector follows a North/North-West - South/South-East orientation and is hydrographically dominated by the Fersina torrent system. The central sector undergoes a significant physiographic transition to an East-West alignment along the Brenta River corridor, while the eastern one gradually narrows, eventually forming the Brenta Canal at the Trentino-Veneto border (Zampieri, 2003). Lake Caldonazzo (449 m a.s.l.) marks a hydrographic and geomorphological threshold between the wider north-western alluvial plain and the narrower central and eastern fluvial section (Fig. 1). Bounded by Monte Marzola (1738 m a.s.l.) to the west and the Pliocene/Pleistocene Tenna-Zava ridge (711 m a.s.l.) to the east, this 5.6 $km^2$ basin (max depth 49 m) formed through post-LGM (27.5–16.5 ka BP, Monegato et al., 2017) damming by alluvial fans from northern (Fersina, Susà-Costasavina) and southern (Centa) streams (Trener, 1952). Fed by three main tributaries (Rio Merdar, Rio Spino, Torrente Mandola) and smaller streams, it drains via the Brenta River. Until the 18th century CE, its waters extended to Pergine Valsugana (Barbieri et al., 1994). The lake deteriorated into severe eutrophication by the 1970s, but was later restored through management efforts (Marchesoni, 1952a, 1952b; Vittori, 1985; Vittori et al., 1990; Flaim et al., 2016).

### 2.2. Geology and geomorphology

The Valsugana features a complex geological stratigraphy and structural architecture, shaped by Permian (299–251 Ma BP) and Mesozoic (251–65 Ma BP) rifting faults associated with Tethyan continental rifting phases, later inverted during the Neogene Alpine orogeny (23.03–2.58 Ma BP; Cucato et al., 1988; De Zanche and Mietto, 1989; Barbieri et al., 2007; Avanzini et al., 2010). The South-East - North-West trending Calisio Line, the dominant structure and dextral ramp of the Valsugana thrust, intersects the basin of Lake Caldonazzo, separating phyllites and quartz-phyllites to the west and acid metavolcanic and metavolcaniclastic rocks to the east. Valsugana has a long history of mining. In this area, the geological units produced by late Hercynian volcanism are associated with polymetallic vein deposits (pyrite, chalcopyrite, galena, sphalerite, etc.), with quartz, fluorite, and barite. The deposits consist of quartz or fluorite gangue veins with mixed sulphides a few meters thick, cutting through the metamorphic basement of the Southern Alps or the Permian Atesino Volcanic Group. They are thought to have originated from the circulation of mineralising fluids within fractures in the surrounding rocks, originating from a series of cooling magmatic masses, the principal one being the Cima d'Asta granite pluton. Metalliferous mineralisations are located also in the basal sedimentary units, predominantly argentiferous galena, subordinate to blende, pyrite, chalcopyrite, barite, and fluorite. A second phase of mineralogenesis is attributable to Triassic magmatism, which reclaims and inherits the metal stock from previous mineralizations, concentrating it in pyritic-copper vein bodies (Janković and Petrascheck, 1987; Ferretti, 2020).

In the plain south of Pergine Valsugana Quaternary deposits include: post-LGM and Holocene sediments of glacial, fluvial-glacial and gravitational origin, and wetland aggradation deposits (Barbieri et al., 1994; Castellarin et al., 1998; Selli, 1998; Avanzini et al., 2010). Overlying the metamorphic basement of Lake Caldonazzo there are: sand and gravel from glacial contact and fluvial-glacial Garda Synthem, alluvial laminated sand and silt, lacustrine silt and clay of the Alpine Postglacial Synthem, encompassing postglacial alluvial fans and slope deposits (Avanzini et al., 2010; Fig. 2).

### 2.3. Modern climate

The Valsugana is an exalpine/macro temperate environment area with sub-oceanic climatic influences, characterized by more moderate summer temperatures and slightly colder winter conditions compared to the Adige Valley (Gafta and Pedrotti, 1996; Prosser et al., 2019). The precipitation regime follows a characteristic bimodal annual distribution, with peak rainfall occurring during spring and autumn seasons, while summer and winter typically experience drier conditions. Meteorological data from the T0010 monitoring station in the Levico Terme (502 m a.s.l.) reveals a mean annual temperature of 11.1°C, with average minimum temperatures of 5.9°C and average maximum temperatures reaching 18.3°C over the 1994–2023 period. The station recorded an average annual precipitation of 1172 mm.[1]

### 2.4. Modern vegetation

The landscape of the western sector of the Valsugana has undergone profound modifications through wetland reclamation and infrastructure development, significantly altering land use patterns and natural valley-bottom vegetation (Blasi, 2010; Bertolli, 2012; Prosser et al., 2019). Between 1777 and 1820 CE, extensive drainage works eliminated vast *Carex*-dominated marshes surrounding Lake Caldonazzo, which originally extended northward to Pergine Valsugana (Barbieri et al., 1994). Remnants of this lacustrine vegetation persist in two protected shoreline segments, now conserved within the Canneti di San Cristoforo biotope.[2] This area maintains characteristic reed beds of *Phragmites australis* (Cav.) Trin. ex Steud., with black alder (*Alnus glutinosa* L.) riparian woodlands in its eastern sector. Notably, white water lily (*Nymphaea alba* L.) has been successfully reintroduced (Barbieri et al., 1994). The south-eastern lakeshore harbours another significant reed bed community, accompanied by typical wetland species (i.e., *Lythrum salicaria* L., *Stachys palustris* L., *Lysimachia vulgaris* L.).[3] Nearby, the Pizè biotope, a relic wetland in the Brenta watershed near Lake Levico, preserves a mosaic of gray alder (*Alnus incana* L.), black alder, bay willow (*Salix pentandra* L.), and fern-rich reed beds species (i.e., *Matteuccia struthiopteris* L., *Impatiens noli-tangere* L., *Cardaminopsis halleri* L.).[4] The valley floor transitions to agricultural land dominated by orchards (Bertolli, 2012; Prosser et al., 2019). Surrounding slopes support mesic transitional forests of maple-linden (*Acer-Tilia*) and maple-ash (*Acer-Fraxinus*) communities, with thermophilous species like hop hornbeam (*Ostrya carpinifolia* Scop.) and manna ash (*Fraxinus ornus* L.), grading into beech (*Fagus sylvatica* L.) forests at higher elevations (Bertolli, 2012; Odasso et al., 2018; Pedrotti, 2018; Prosser et al., 2019; Fontana et al., 2023).

### 2.5. Pre-protohistoric archaeological context

#### 2.5.1. Settlement dynamics between the Upper Palaeolithic and the Early Iron Age

Human presence in south-eastern Trentino is well-documented during the Upper Palaeolithic (~43/38,000–9700 BCE; Douka and Higham, 2017; Peresani, 2023), with evidence from sites such as Andalo (Guerreschi, 1984), Palù Echen (Dalmeri et al., 2013), Riparo Dalmeri (Dalmeri et al., 2011, 2012), and Riparo Cornafessa (Angelucci et al.,

[1] http://storico.meteotrentino.it/web.htm
[2] http://www.areeprotette.provincia.tn.it/riserve_provinciali/biotopi_riserve/-riserve_provinciali/pagina21.html
[3] http://www.areeprotette.provincia.tn.it/riserve_provinciali/biotopi_riserve/-biotopi_da_istituire/pagina75.html
[4] http://www.areeprotette.provincia.tn.it/riserve_provinciali/biotopi_riserve/-riserve_provinciali/pagina20.html

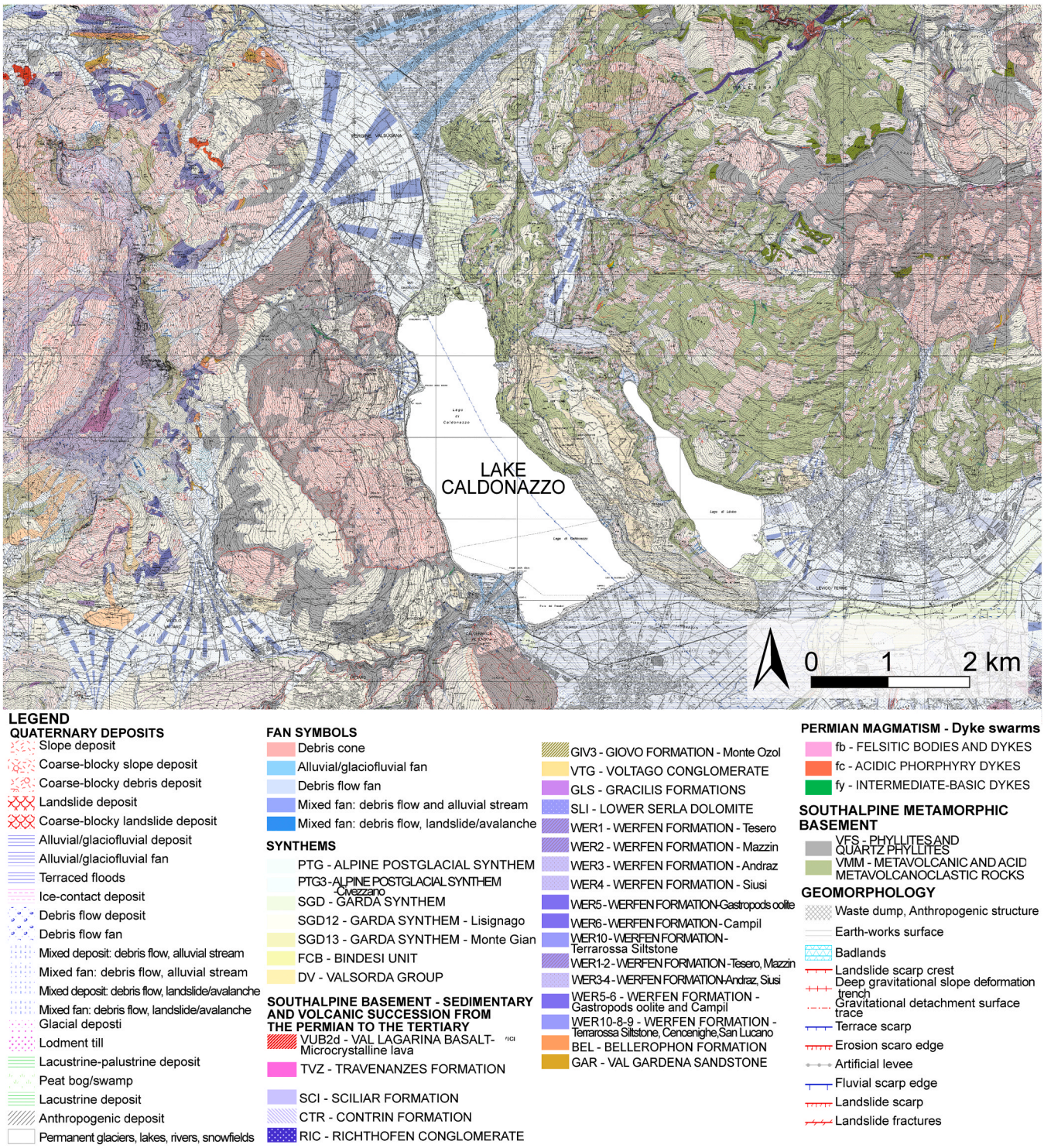


**Fig. 2.** Geological setting and corresponding legend of Lake Caldonazzo area (base map by Carta Geologica della Provincia Autonoma di Trento, Sezione N° 060110-Pergine Valsugana, 060120-Frassilongo, 060150-Vigolo Vattaro, 060160-Levico, 081030-Centa San Nicolò, 81040-Caldonazzo).

2023; Fig. 1). In contrast, for the Mesolithic (~9700–5500 BCE; Fontana et al., 2023), the Neolithic (~5500–3400 BCE; Tiné, 2015; Starnini et al., 2018), and most of the Copper Age (~3400–2200 BCE; de Marinis and Pedrotti, 1997; de Marinis, 2013), no evidence of settlements has yet been documented in the Valsugana area (Mottes and Nicolis, 2002; Angelucci et al., 2009; Mottes et al., 2014; Mottes, 2019, 2021). This pattern contrasts sharply with the well-attested and long-lived occupation in the Adige Valley, at sites such as Riparo Gaban (Bagolini and Pedrotti, 1996; Koszlowski and Dalmeri, 2002), Romagnano (Perini, 1971; Fontana et al., 2016), and La Vela (Bazzanella et al., 2001; Fig. 1).

Between the late Copper Age (~2500–2200 BCE), and the Early Bronze Age (~2200–1650/1625 BCE; Billamboz and Martinelli, 2015; de Marinis, 2022) settlement in the area appears to have become more stable (Pedrotti, 2001b; Marzatico and Tecchiati, 2002; Di Pillo, 2023), marked by the establishment of the settlement at Montesei di Serso (Broglio and Perini, 1964; Perini, 1969, 1973, 1978) and by further activity documented at Croz del Cius (Perini, 1989; Fig. 1). Smelting evidence from both sites indicates the onset of local copper ore

exploitation by the mid-to-late 3rd millennium BCE, chronologically consistent with the earliest isotopically-attested copper production in the south-eastern Alps (Angelini et al., 2013; Artioli et al., 2015, 2024).

During the Middle Bronze Age (~1650/1625–1350/1300 BCE; Cardarelli, 2010, Cupitò and Leonardi, 2015), occupation of the area remained rather sparse, at least in quantitative terms. Nevertheless, the settlement of Montesei di Serso clearly consolidated its role as a key hub within the territorial unit, while the site of Dossi di Vigolo Vattaro, on the Vigolana plateau, appears to signal the beginning of increased interest in the exploitation of higher zones (Marzatico, 1992; Marzatico e Tecchiati, 2002; Fig. 1).

Between the Recent Bronze Age (~1350/1300–1150; Cardarelli, 2010, Cupitò and Leonardi, 2015;) and the Final Bronze Age (~1150–950/900 BCE; Bagolan and Leonardi, 2000; Bianchin Citton, 2015), the Trentino region underwent a cultural regionalisation marked by the emergence of the Luco/Laugen A facies towards the end of the 12th century BCE (Marzatico 2012a; 2019). This period was characterised by an increase in population and social complexity (Di Pillo, 2023), and by the onset of intensive copper ore mining and smelting activity in the south-eastern portion of the region (Silvestri et al., 2019; Bellintani and Silvestri, 2021; Marzatico, 2022). This unprecedented scale of primary production is directly evidenced by more than 200 smelting sites documented across the Valsugana area (Bellintani and Silvestri, 2021; Marzatico, 2022), including major production centres such as Acqua Fredda-Passo del Redebus (Perini, 1989; Cierny, 2008) and Luserna Platz von Motze (Cierny, 2008; Nicolis et al., 2021; Fig. 1). Beyond this extensive production network, strategic settlements like Montesei di Serso and Doss Predoccia (Perini, 1978; Silvestri et al., 2019) were complemented by sites controlling key communication routes (e.g., Civezzano, Fai della Paganella; Dalmeri, 1985; Bersani, 2008; Nicolis, 2010; Fig. 1). The existence of an elite, central to this emergent social complexity, is reflected in the deposition of prestigious bronze hoards, such as the Masetti greaves and the Passo Vezzena hoard (Mottes et al., 1999; Marzatico, 2004; Tecchiati, 2007; Marzatico, 2012b; Fig. 1). However, while settlement and mineral resource exploitation show an overall expansionist trend in the period spanning the Recent Bronze Age to the early phases of the Final Bronze Age (~1300–1000 BCE), both settlement pressure and metallurgical activities underwent a sharp decline during the advanced Final Bronze Age (~1000–950/900 BCE). The crisis was likely precipitated by a confluence of factors, including declining metallurgical output, economic pressures, competition from other copper-producing regions, and broader socio-political transformations (Marzatico, 1997, 2002, 2004, 2021; Leonardi, 2010; Steiner, 2021). However, this did not culminate in a systemic collapse. Instead, it prompted a generalised reorganisation of settlement systems, characterised by the selection and concentration of populations into a limited number of sites that held strategic importance for territorial control and trade (Marzatico, 1997, 2002; Marzatico et al., 2010, Di Pillo, 2023). This restructured model of territorial organisation and resource management persisted without significant change into the initial phase of the Early Iron Age (~950/900–800 BCE; Marzatico, 2002; Bietti Sestieri, 2018).

#### 2.5.2. *Mining and smelting from the earliest evidence to the beginning of the Iron Age*

The earliest copper artefacts in south-eastern Trentino are from phases 2 and 3 of the site of Isera, dating to the late 5th to mid-4th millennium BCE (Middle and Recent Neolithic; Pedrotti, 2001a; Pearce, 2007). Isotopic analyses indicate that these early objects originated from copper ore Balkan sources, reflecting early transalpine connections (Höppner et al., 2005; Artioli et al., 2020, 2024; Radivojević et al., 2021). In contrast to region such as Liguria (Campana, 1998; Maggi and Pearce, 2005) and Tuscany (Dolfini et al., 2020; Iaia and Dolfini, 2021), where the exploitation of local metal ore resources is documented by approximately the mid-4th millennium BCE, a primary mining and smelting activity was absent in the south-eastern Alps during Copper Age 1–2 (~3400–2500 BCE; Artioli et al., 2024). The subsequent northward circulation of central Italian metal is strikingly demonstrated by the axe of the Alpine 'iceman' Ötzi, discovered on the Similaun glacier and dated to ~3350–3120 BCE (Kaufmann, 2014; Artioli et al., 2017).

The earliest evidence for copper smelting in south-eastern Trentino (1st phase) dates to the late Copper Age 2/early Copper Age, as documented by the identification of Alpine ores in northern Italian metal artefacts (Artioli et al., 2016, 2024) and by furnaces and smelting slags from sites across the south-eastern Alps (Perini, 1989; Angelini et al., 2013; Mottes et al., 2014; Pearce et al., 2022). Its precise contemporaneity with the appearance of the Bell Beaker Culture in the region (Nicolis, 2001; Müller, 2013; Olalde et al., 2018), noted for integrating earlier metallurgical traditions into a new pan-European network (Labuane, 2013; Roberts and Frieman, 2013), suggests that this phenomenon played a decisive role. The exploitation of mineral resources continued at least into the early phases of the Early Bronze Age (~2200–2000 BCE; Angelini et al., 2013; Pearce et al., 2022), with the Polada Culture (Rapi, 2013). The early processing technology, identified at open-area sites and those situated near or under rock shelters on the floor of the Adige Valley (Perini, 1989; Angelini et al., 2013; Silvestri et al., 2019), was relatively basic. It was characterised by clay-lined pits and simple furnaces that were less efficient than the more advanced methods developed in the subsequent Bronze Age (Perini, 1992; Angelini et al., 2013; Artioli et al., 2015). Technological continuity from the late Copper Age into the Early Bronze Age indicates stable logistical organisation and modest production volumes. This is supported isotopically, as south-eastern Alpine copper circulated widely during the Bell Beaker and Polada phases within a multi-source procurement system (Artioli et al., 2013, 2015, 2024).

While Middle Bronze Age (~1650/1625–1350/1300 BCE) mining and smelting evidence remains elusive (Rageth, 1974; Perini, 1987; Marzatico, 2021, 2022), isotopic data show south-eastern Alpine copper artefacts already reaching Venetian and Friulian territories (Artioli et al., 2016; Ling et al., 2019), Germany, Scandinavia and western Baltic area (Melheim et al., 2018; Kristiansen, 2019; Ling et al., 2019; Kristiansen et al., 2020; Nørgaard et al., 2021), and the Balkans (Mehofer et al., 2021; Gavranović et al., 2022). This discrepancy between archaeological evidence and isotopic data remains contentious for reconstructing Trentino's metallurgical history (Pearce et al., 2019, 2021; Bellintani et al., 2021, Marzatico, 2021, 2022).

Between the Recent and Final Bronze Age (~1350/1300–950/900 BCE; specifically, between the advanced RBA and the initial FBA; Luco/Laugen A facies), The south-eastern Alpine region was rapidly transformed into a specialised mining district (2nd phase), with Trentino emerging as one of Europe's primary copper production centres (Stöllner, 2008). The scale of this phenomenon is macroscopically evident from the archaeological record alone: more than 200 smelting sites are known for this period, a density of approximately one per km$^2$, many of which are characterised by exceptionally large slag heaps (Marzatico, 2001, 2020, 2022; Bellintani and Silvestri, 2021; Di Pillo, 2023). Isotopic data provide further confirmation of the area's metallurgical dominance during this period. Analyses demonstrate that Alpine copper became the predominant source for the Po Plain (Angelini et al., 2015; Canovaro et al., 2019; Armigliato et al., 2025) and supplied secondary production centres across central-northern and eastern Europe (Ling et al., 2019; Mehofer et al., 2021; Gavranović et al., 2022). This clearly demonstrates that the territorial unit was now fully and organically integrated into the international exchange network that characterised the later Bronze Age (Kristiansen, 2018; Ling et al., 2019; Radivojević et al., 2019; Cardarelli et al., 2020), with all the consequent technological, socio-political, and cultural implications (Vandkilde, 2016; Iversen, 2017; Derluguian, 2022; Kristiansen, 2022; Ling et al., 2022).

The factors driving this pivotal shift can be summarised as follows:

- the adoption of more complex furnace designs and refinen smelting techniques that improved production efficiency and quality (Cierny, 2008; Staudt, 2021; Töchterle et al., 2021);
- the strategic relocation of smelting sites to inner valleys and high plateaus (~800–2000 m a.s.l.), optimising access to both wood and water sources (Silvestri et al., 2019);
- the emergence of integrated production networks linking smelting sites with mines, particularly evident in the Valsugana sites of Calceranica e Vetriolo, and in the Valle dei Mocheni (Preuschen, 1962; Artioli et al., 2013, 2015, 2016; Silvestri et al., 2014, 2022; Fig. 1).

The establishment of this new metallurgical cycle was synchronous with the Terramare apogee in the Po Plain (Bernabò Brea et al., 1997) and the rise of the exchange centre of Frattesina in the Polesine (Cupitò et al., 2020; Cardarelli, 2022) following their crisis (Cremaschi et al., 2006, 2016; Cardarelli, 2010), firmly linking its development to the copper demand from these successive systems. Afterwards, during the advanced Final Bronze Age, archaeological evidence for primary metallurgy contracted drastically across the region, effectively disappearing and remaining absent throughout the early Iron Age (Marzatico, 2020, 2021; Di Pillo, 2023). Given the current lack of isotopic analyses on 10th-9th century BCE bronze artefacts, a definitive interpretation on the interruption of metallurgical activity must be withheld pending further evidence.

## 3. Material and methods

### 3.1. Cores and construction of the master sequence

In 2003, in the framework of the OLOAMBIENT project led by the Museo Tridentino di Scienze Naturali (now MUSE - Museo delle Scienze, Trento), 14 gravity cores and 4 piston cores were retrieved from the lakebed of Lake Caldonazzo (Frisia, 2005; Frisia et al., 2005a, 2005b; Fig. 3). For the present study, piston cores CA03_P1 (872 cm long) and CA03_P4 (565.7 cm long) were selected to construct a master sequence based on their state of preservation and stratigraphic integrity (Fig. 4). Core CA03_P4 served as the primary reference due to its better macroscopic preservation, assessed two decades after the coring, in June 2023. It also contained a key $^{14}$C date relevant to our objectives: UtC 13672, 1742–1116 2σ cal. BCE (Table 2). To address a depositional hiatus in CA03_P4 (302.8–280.7 cm), a segment from CA03_P1 (328–271 cm) was spliced into the master sequence, corresponding to the interval 343–287 cm in the CA03_P4 stratigraphy. The correlation between the two cores was based on lithostratigraphic description, comparing sediment texture, colour, and composition (Schnurrenberger et al., 2003), which allowed the identification of four key tie-point markers (Fig. 4; Table 1). This correlation was partially supported by the chronology derived from the independent age-depth models of both cores, considering the associated uncertainties (Fig. 5). This paper focuses on the stratigraphic interval from 497 to 208 cm within the master sequence.

### 3.2. Chronology and age-depth models

21 $^{14}$C AMS ages were obtained on botanical macro-remains and bulk sediment samples from the Lake Caldonazzo CA03 cores (Table 2). Ages. Ages were calibrated using the IntCal20 calibration curve (Reimer et al., 2020) within the Oxcal 4.4.4 software (Bronk Ramsey, 2009), available at http://c14.arch.ox.ac.uk/oxcal. Two different age-depth models, one for each core, were built using Bayesian analysis based on the Markov chain Monte Carlo algorithm, standard codes and P_Sequence with $K_0$= 1 cm$^{-1}$, interpolation rate= 2 cm$^{-1}$ and variability in k allowed between a factor of $10^{-2}$ e $10^{2}$ (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). Both models were constrained using seven reliable $^{1}$ $^{4}$C AMS ages per core (Fig. 5).

**Fig. 3.** Location of the cores CA03_P1 and CA03_P4 in Lake Caldonazzo (base map by Ortofoto2015 © Provincia Autonoma di Trento - Servizio Geologico - Ufficio Sistemi Informativi).

### 3.3. Loss on ignition

Loss on ignition (LOI) was performed on 50 volumetric samples with an ELTRA TGA Thermostep-thermo-gravimetric analyser (software Tga1.4.3.2a3) at the Laboratory of Palynology and Dedndroarchaeology of the Institute of Prehistoric and Protohistoric Archaeology of Kiel University. Samples were weighed and progressively heated to 105°C, 550°C, and 950°C until the weight loss stabilised, or for a maximum of 12, 4, and 2 h respectively, to estimate water content, total organic matter and sulphides, and siliciclastic residuum and oxides (Heiri et al., 2001; Santisteban et al., 2004). The carbonate fraction, which includes also both sulphides and sulphates (Földvári, 2011), was determined stoichiometrically (Dean, 1974; Fig. 6a; Table S1).

### 3.4. Palaeoecology

52 samples of sediments (0.5 cm$^3$) for pollen analysis were processed at the Palynology Laboratory of the Department of Geosciences at the University of Padova following standard methods, including addition of *Lycopodium* tablets (13911 spores) for concentration estimations (Stockmarr, 1971), KOH, HCl, HF, and acetolysis. A minimum sum of 600 pollen grains of upland plants was counted, comprising a minimum of 500 pollen grains from arboreal taxa. Identification was carried out at × 400, × 630 and × 1000 magnifications under a Nikon Eclipse Ci light microscope. Pollen identification followed Moore et al. (1991), Reille (1992), (1995), (1998), Beug (2004), and Pini et al. (2016). Size classes of Poaceae pollen were distinguished by measuring grain diameter (D) and annulus diameter (d). Grains with D > 47 μm and d > 11 μm have been referred to cereals (cultivated *Avena* and *Triticum* species, i.e., Cerealia type *sensu* Joly et al., 2007). These size limits (Joly et al., 2007), more restrictive than those currently used in the Alpine region

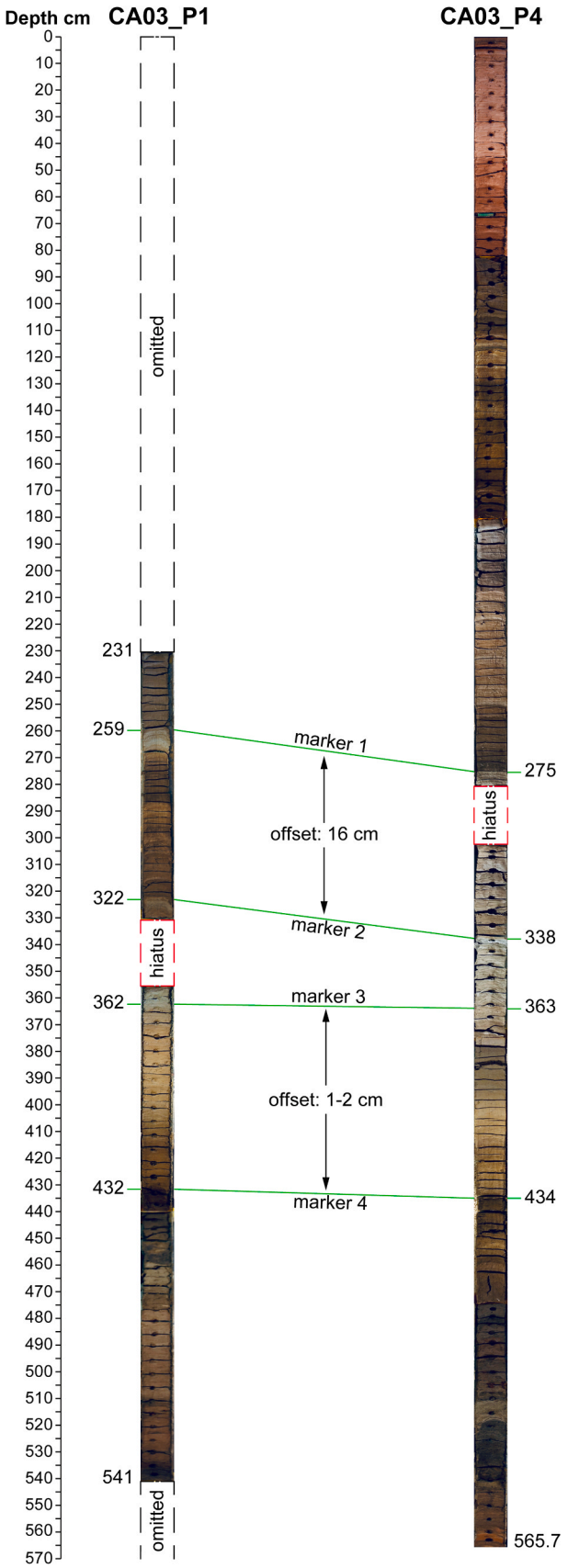


**Fig. 4.** Lithostratigraphic correlation between sediment cores cores CA03_P1 (section 541–231 cm) and CA03_P4 (565.7–0 cm). Relative depth scale. Key stratigraphic markers are indicated in green. Note the extensive network of desiccation cracks, which developed during two decades of storage.

**Table 1**
Lithostratigraphic markers between cores CA03_P1 and CA03_P4. Descriptions denote the sediment transition at the specified depth marker.

| Marker | CA03_P1 Depth cm | CA03_P4 Depth cm | Lithostratigraphic transition |
|---|---|---|---|
| 1 | 259 | 275 | P1: 2.5Y 5/4 light olive brown, clayey silt, not laminated → 2.5Y 6/1 gray, clayey silt, rare iron mottles. P4: 2.5Y 5/4 light olive brown, clayey silt, not laminated → 2.5Y 6/2 light brownish gray, clayey silt, laminated. |
| 2 | 322 | 338 | P1: 2.5Y 4/3 olive brown, clayey silt, laminated, organic lenses → 5Y 5/2 olive gray, clayey silt, laminated, whitish mottles. P4: 2.5Y 5/3 light olive brown, clayey silt, shell fragments → 5Y 6/1 gray, clayey silt. |
| 3 | 362 | 363 | P1: 2.5Y 6/1 gray, clayey silt, laminated, whitish mottles → 2.5Y 6/2 light brownish gray, clayey silt, blackish organic fragments. P4: 2.5Y 5/2 grayish brown, clayey silt, laminated, gray/white laminae → 2.5Y 7/3 pale brown, clayey silt, laminated. |
| 4 | 432 | 434 | P1: 2.5Y 4/3 olive brown, clayey silt, blackish organic fragments → 2.5Y 3/3 dark olive brown, clayey silt, blackish organic fragments. P4: 2.5Y 5/3 light olive brown, clayey silt, laminated, blackish organic fragments → 2.5Y 3/3 dark olive brown, clayey silt, blackish organic fragments. |

(Andersen, 1979), allow to separate intermediate types having 37 μm < D < 47 μm and D > 47 with d < 11 μm, which includes both wild and cereal species (e.g., *Hordeum vulgare*, *Panicum miliaceum*; Andersen, 1979; Beug, 2004; Joly et al., 2007; Zohary et al., 2012). Non-pollen palynomorphs (NPPs) were named after van Geel et al. (1980), van Geel and Aptroot (2006), and Miola (2012). Online atlases were also consulted for their identification.[5] Pollen of aquatic and wetland plants, and NPPs were excluded from the pollen sum. Black, completely opaque, angular fragments were identified as micro-charcoal (Clark, 1988), categorised into two size classes: 10–50 μm and > 50 μm. Quantification was performed using CountPol v.4.2 software by I. Feeser (Kiel University), while pollen diagrams were drawn using Tilia v.2.6.1 (Grimm, 2015) and Adobe Illustrator v.27.0 (Figs. 7, 8). Pollen zonation was obtained by constrained incremental sum-of-squares cluster analysis (CONISS; Grimm, 2015). The analysis runs on taxa displaying statistical significance in proportion values, i.e., those having > 2 %.

Selected pollen taxa and NPPs were categorised into six ecological groups (Fig. 10): (1) pristine forest (*Abies alba, Fagus sylvatica, Picea*), (2) secondary forest (*Betula*, *Juniperus, Pinus sylvestris/mugo*) (3) thermophilous mixed forest (*Acer campestre* type*, Carpinus betulus*, deciduous *Quercus* group, *Fraxinus excelsior, Fraxinus ornus, Ostrya carpinifolia, Tilia, Ulmus, Corylus*) (4) pasture indicators (*Artemisia*, Amaranthaceae, *Centaurea nigra* type, *Centaurea scabiosa* type, *Orlaya grandiflora*, *Plantago lanceolata, Plantago major/media* type, and *Rumex acetosa* type) (5) open landscape indicators (Apiaceae, Caryophyllaceae, Cichorieae, and Ranunculaceae), and (6) animal husbandry indicatorsin (*Sordaria* type (HdV 55), *Sporormiella* type (HdV 113), *Trichuris* (HdV 531). The methodological framework of Behre (1981), Oeggl (1994), Gilck and Poschlod (2019), (2021), and Pini et al. (2021) was followed for the pasture indicators and open landscape indicators groups.

A Principal Component Analysis (PCA, Leardi, 2018) was performed on pollen taxa quantification data using CAT software (Leardi et al.,

[5] https://www.wikis.uni-kiel.de/non_pollen_palynomorphs/doku.php/home; https://non-pollen-palynomorphs.uni-goettingen.de

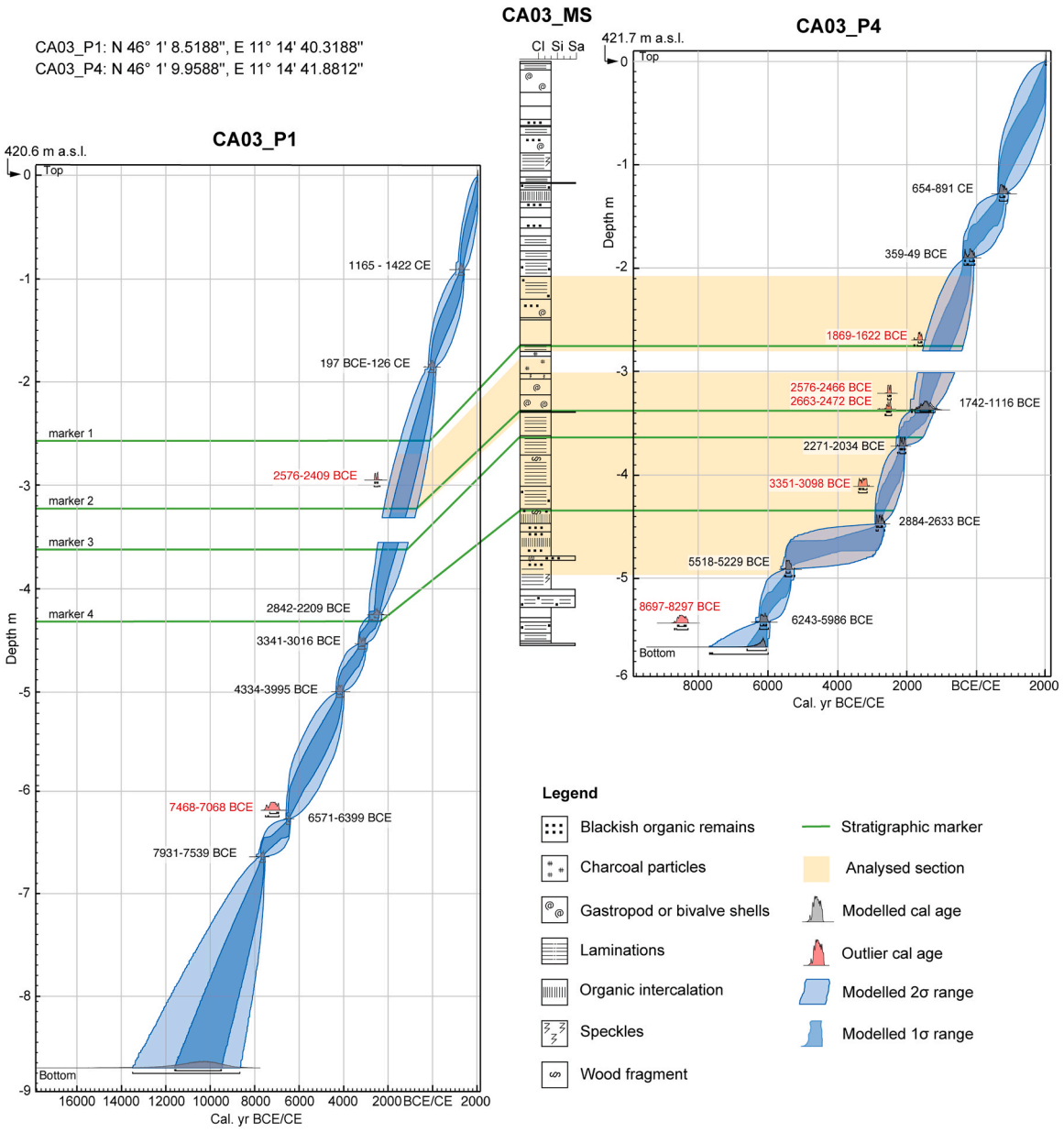


**Fig. 5.** Age-depth models for the sequences CA03_P1 and CA03_P4, derived using OxCal v4.4.4 (Bronk Ramsey, 2021) with the IntCal20 calibration curve (Reimer et al., 2020). The central panel shows the composite sedimentary log of the master sequence CA03_MS. Cores coordinates, elevation (m a.s.l.), key stratigraphic markers, and radiocarbon ages (including outliers) are presented.

2026; Supplementary Material 4).

### 3.5. Faecal biomarkers

Investigation of faecal steroids was conducted through Gas Chromatography-Mass Spectrometry analysis (GC-MS) on 29 samples (Table 4; Fig. 9a). The analytical procedure followed the methodologies proposed by Battistel et al. (2015) with some modifications detailed in Bortolini et al. (2024); Supplementary Material 2). The concentrations of all steroids are reported in ng $g^{-1}$ (Table S3). Faecal input was confirmed by R1 ratio (coprostanol + epi-coprostanol / coprostanol + epi-coprostanol + 5α-cholestanol) suggested by Grimalt et al. (1990). According to this ratio, values below 0.3 allow for the exclusion of faecal input, whereas values exceeding 0.7 indicate faecal contamination. The potential origin of contamination was assessed using the R4 ratio (coprostanol + epicoprostanol / coprostanol + epicoprostanol + 5β-stigmastanol + epi-5β-stigmastanol) introduced by Bortolini et al. (2024). For this ratio, values below 0.29 are attributed to herbivorous animals, values above 0.65 are associated with human fecal input, while values between 0.29 and 0.65 indicate an ambiguous or mixed signal.

### 3.6. Trace elements analysis

Trace element analysis was conducted on 29 samples by means of Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES; Table 4; Fig. 9b). Preparation of samples followed the methodology described in Argiriadis et al. (2021), as explained in Supplementary Material 3. The elements arsenic ($^{75}$As), copper ($^{63}$Cu), lead ($^{206}$Pb), antimony ($^{121}$Sb), tin ($^{118}$Sn), and zinc ($^{66}$Zn) are commonly associated with anthropogenic activities (Hong et al., 1996; Mighall et al., 2002; Kabata-Pendias, 2010; Shotyk et al., 2017; Knierzinger et al., 2021) and they were here investigated through ICP-MS. The results were expressed as Enrichment Factor (EF) in comparison with their concentration in the

**Table 2**
$^{14}$C AMS ages for the cores CA03_P1 and CA03_P4 by the Van de Graaff Laboratory (Utrecht University, UtC) and the Aarhus AMS Centre (Aarhus University, AARAMS). Asterisk marks outlier ages.

| Core | ID - year | Depth cm | Material dated | $\delta^{13}$C ‰ Yield% | $^{14}$C age uncal. yr BP | 1σ range cal. yr BCE/CE | 2σ range cal. yr BCE/CE |
|---|---|---|---|---|---|---|---|
| CA03 P1 | UtC13664–2005 | 91 | leaf | -34 | 700 ± 90 | 1229–1394 CE | 1165–1422 CE |
| | UtC13665–2005 | 186 | leaf | -22 ± 7 | 2030 ± 60 | 104 BCE-66 CE | 197 BCE-126 CE |
| | *AAR40106–2024 | 293.5 | bulk sediment | 0.3 % | *3977 ± 27 | 2564–2466 BCE | 2576–2409 BCE |
| | UtC13666–2005 | 428.5 | twig | -26 ± 4 | 3970 ± 70 | 2576–2347 BCE | 2842–2209 BCE |
| | AAR37101–2023 | 456 | charcoal | -25 ± 1 | 4462 ± 35 | 3327–3031 BCE | 3341–3016 BCE |
| | UtC13667–2005 | 503.5 | bud | -21 ± 1 | 5340 ± 70 | 4316–4055 BCE | 4334–3995 BCE |
| | *UtC13668–2005 | 619 | wood | -26 ± 6 | *8230 ± 70 | 7344–7082 BCE | 7468–7068 BCE |
| | - 2006 | 627.5 | leaf | - | 7616 ± 44 | 6496–6399 BCE | 6571–6399 BCE |
| | UtC13669–2005 | 664 | wood | -26 ± 4 | 8630 ± 60 | 7715–7587 BCE | 7931–7539 BCE |
| CA03 P4 | UtC13670–2005 | 128 | leaf | -29 ± 6 | 1260 ± 60 | 672–826 CE | 654–891 CE |
| | UtC13671–2005 | 190 | leaf | -29 ± 7 | 2149 ± 44 | 349–60 BCE | 359–49 BCE |
| | *AAR40105–2024 | 270.5 | bulk sediment | 0.2 % | *3413 ± 28 | 1745–1638 BCE | 1869–1622 BCE |
| | *AAR40107–2024 | 319.5 | bulk sediment | 1.8 % | *4001 ± 28 | 2567–2473 BCE | 2576–2466 BCE |
| | *AAR40108–2024 | 335.5 | bulk sediment | 0.5 % | *4044 ± 26 | 2621–2492 BCE | 2663–2472 BCE |
| | UtC13672–2005 | 337.3 | wood | -26 ± 6 | 3170 ± 120 | 1602–1271 BCE | 1742–1116 BCE |
| | AAR40109–2024 | 372.5 | bulk sediment | 0.1 % | 3733 ± 29 | 2199–2046 BCE | 2271–2034 BCE |
| | *AAR40110–2024 | 410.5 | bulk sediment | 0.4 % | *4503 ± 28 | 3339–3104 BCE | 3351–3098 BCE |
| | AAR37102–2023 | 447 | wood | -29 ± 2 | 4172 ± 28 | 2876–2697 BCE | 2884–2633 BCE |
| | - 2006 | 490.9 | wood | - | 6440 ± 60 | 5475–5366 BCE | 5518–5229 BCE |
| | - 2006 | 542.4 | leaf | - | 7250 ± 70 | 6221–6031 BCE | 6243–5986 BCE |
| | *UtC13673–2005 | 543 | bulk sediment | -26 ± 5 | *9260 ± 70 | 8607–8350 BCE | 8697–8297 BCE |

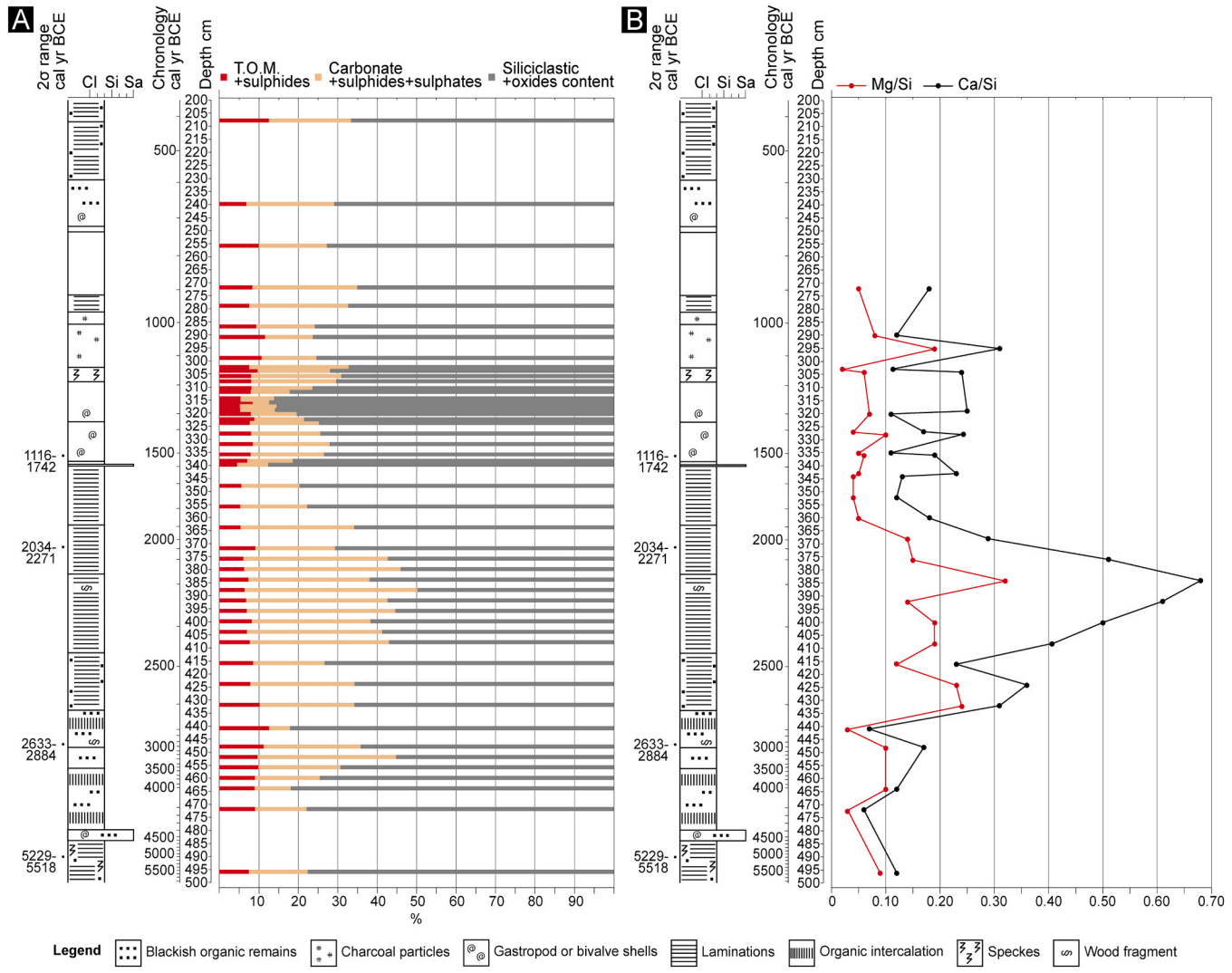


**Fig. 6.** Geochemical record of CA03_MS with sedimentary log and calibrated ages BCE (2σ range). (a) LOI data: percentage of total organic matter+sulphides, carbonate+sulphides+sulphates, siliciclastic+oxides content. (b) Molar ratio profiles of Mg/Si (red) and Ca/Si (black).

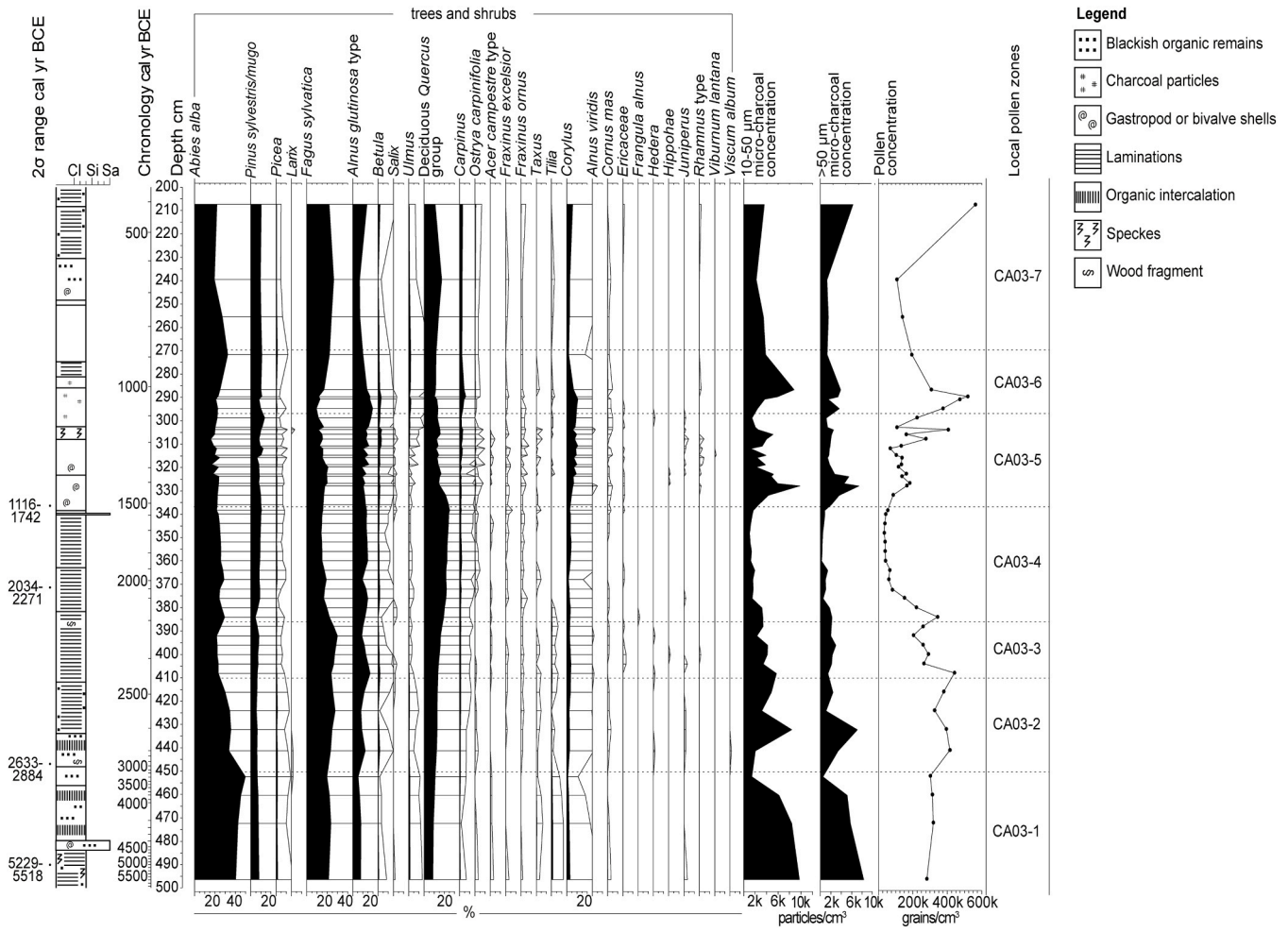


**Fig. 7.** Pollen record of CA03_MS with sedimentary log: percentages of selected trees and shrubs (magnification curves x10); micro-charcoal concentrations; pollen concentration; pollen zonation.

Earth's crust (Rudnick and Gao, 2014). The equation proposed by Reimann and de Caritat (2000) was used replacing Aluminium with Titanium as normalising element of the data.

$EF_i = ([i]_{sample} / [Ti]_{sample}) / ([i]_{ref} / [Ti]_{ref})$

$[i]_{sample}$ = concentration of the investigated element in the sample.

$[i]_{ref}$ = concentration of the investigated element in the Earth's crust (Rudnick and Gao, 2014).

$[Ti]_{sample}$ = concentration of Titanium in the sample.

$[Ti]_{ref}$ = concentration of Titanium in the Earth's crust (Rudnick and Gao, 2014).

The major elements Si, Ca and Mg were investigated through ICP-OES analysis. The comparison of Ca and Mg values with the results of the LOI analyses help in the interpretation of the carbonate values, defining their origin (biological from algal photosynthesis or minerogenic from input from outside the basin) and their implication with the lake's water regime (Verrecchia, 2007). Their concentration in g/Kg was converted into molar concentration (mol/Kg) and then expressed in relation to that of Si. The original concentration of the elements is expressed in mg/Kg (Table S4).

## 4. Results

### 4.1. Chronology and lithology of the CA03_MS sequence

Based on the mean calibrated BCE age (2σ range) from the age-depth model (Fig. 5), the CA03_MS record spans from 6832 BCE to 1950 CE (8782 years) with an average sedimentation rate of 0.065 cm/yr and temporal resolution of ~16 yr/cm. Three distinct depositional phases are evident: a slow phase (565.7–490.9 cm; 6832–5372 BCE; 0.05 cm/yr; 20 yr/cm), a significantly slower phase (490.9–447 cm; 5372–2762 BCE; 0.017 cm/yr; 59 yr/cm), and an accelerated phase (447–0 cm; 2762 BCE-1950 CE; 0.1 cm/yr; 11 yr/cm).

The 497–208 cm interval of CA03_MS record spans from the mid-6th to mid-1st millennium BCE (Fig. 5).

The CA03_MS sediments (565.7–0 cm) consist predominantly of laminated brownish-grey carbonate silts. Lithological variations include laminated intervals (248–208 cm, 434–342 cm, 497–484 cm), massive sediments (342–248 cm, 484–434 cm), organic-rich lenses (484–434 cm), and two sandy layers (340–339 cm, 484–480 cm). Geochemical analysis reveals distinct compositional peaks: organic content ranges from 12.7 % (441–442 cm) to 4.5 % (340–341 cm), carbonate values exhibit a maximum of 43.7 % (388–389 cm) compared to a 20.5 % mean, and siliciclastic sediment forms the predominant fraction, averaging 71.4 % with a peak of 87.5 % (316–317 cm). The sediment record reflects changing lacustrine conditions driven by an inverse relationship between biogenic carbonates and terrigenous siliciclastic input (Fig. 6a). The provenance of the sedimentary components is determined by the local geology. Since the inlets drain non-calcareous bedrock (Avanzini et al., 2010), the carbonate fraction must originate from within the lake, primarily through algal and microbial biological activity, with molluscs being a secondary contributor (Reeves Jr., 1968; Verrecchia, 2007; Nichols, 2009). In contrast, the siliciclastic content is sourced externally from terrigenous input via runoff and inlets, which erode the metamorphic rocks of the basin and thus reflect its specific

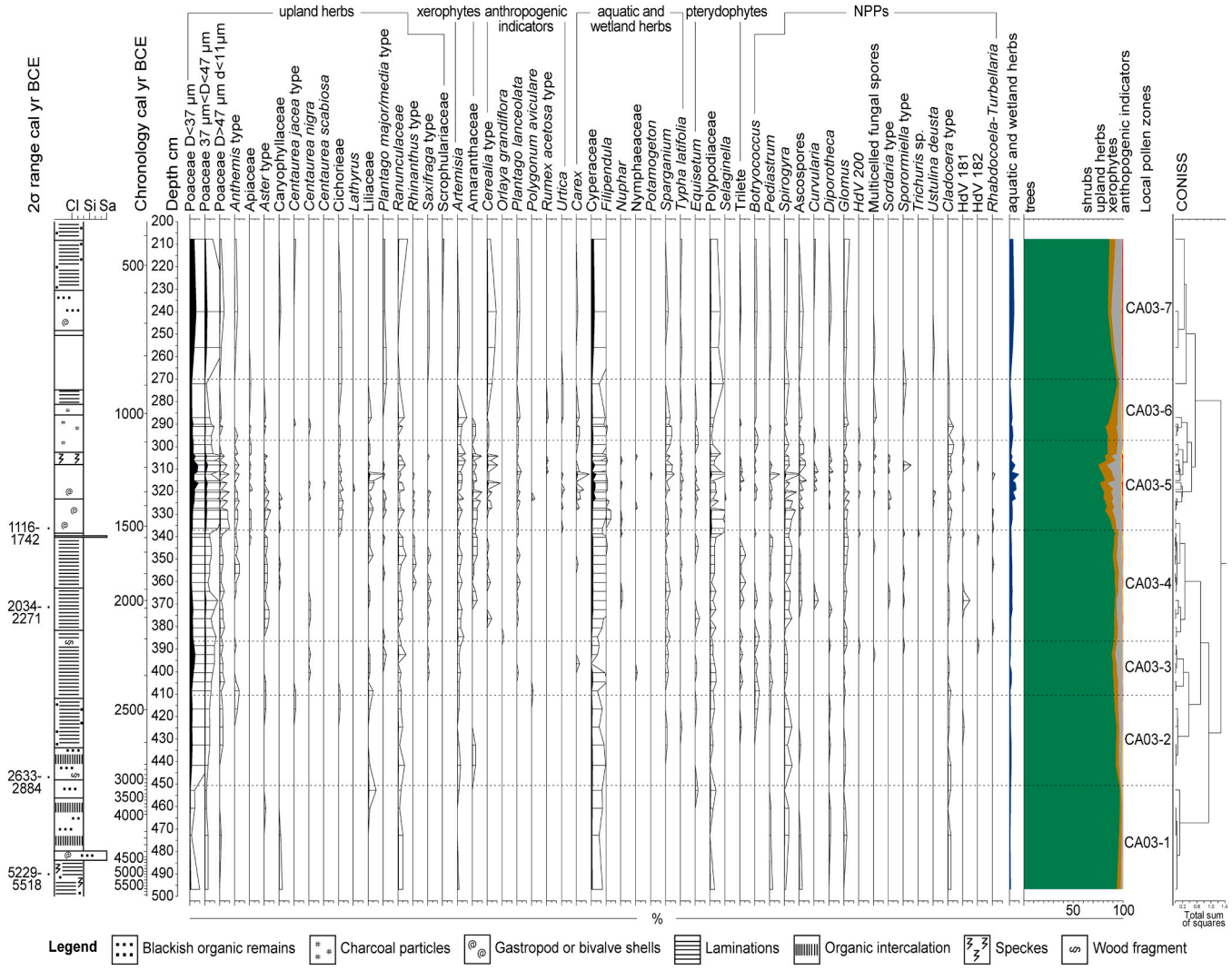


**Fig. 8.** Pollen record of CA03_MS with sedimentary log: percentages of selected upland herbs, xerophytes, anthropogenic indicators, aquatic and wetland herbs, and NPPs (magnification curves x10); sums of the groups; pollen zonation; constrained clustering.

lithology (Verrecchia, 2007; Nichols, 2009).

### 4.2. Pollen analysis

60 pollen types were identified, including 28 arboreal, 24 herbaceous, and 8 aquatic and wetland types. Furthermore, 4 pteridophytes taxa, 3 algae, 10 fungal spores, and 4 other non-pollen palynomorphs (NPPs) types were counted (Figs. 7, 8). The mean pollen concentration (aquatic and wetland types excluded) reaches 211,965 grains/cm$^3$ , with maximum values recorded at 208–209 cm (564,069 grains/cm$^3$) and minimum values at 348–349 cm (34,153 grains/cm$^3$; Fig. 7). 10–50 µm micro-charcoal fragments display an average concentration of 3618 particles/cm$^3$ , peaking at 328–329 cm (9804 particles/cm$^3$) and reaching their lowest concentration at 348–349 cm (1055 particles/cm$^3$). For > 50 µm micro-charcoal fragments, the average concentration stands at 2426 particles/cm$^3$ , with maximum values observed at 496–497 cm (8347 particles/cm$^3$) and minimum values at 360–361 cm (203 particles/cm$^3$; Fig. 7). Based on the CONISS cluster analysis, the diagram was clustered into seven local pollen zones (CA03–1–CA03–8; Figs. 7, 8), summarised in Table 3.

PCA analysis revealed three significant components explaining 40.3 % of total variance (PC1 =21.4 %, PC2 =10.1 %, PC3 =8.8 %). The PC1-PC3 score plot displayed a V-shaped temporal trend, allowing sample classification into four chronological groups: ~5500–3500 BCE, ~3500–2000 BCE, ~2000–1250 BCE, and ~1250–400 BCE. The analysis tracks a mid-Holocene vegetation shift from pristine conifer-beech forests to Bronze Age mixed landscapes with thermophilous species and open areas. This transition highlights increasing anthropogenic impact, particularly during the second half of the 2nd millennium BCE (Supplementary Material 4).

### 4.3. Faecal biomarkers

The presence of faecal contamination is confirmed by the R1 ratio values (Grimalt et al., 1990), which range from 0.92 to 1 (Table S3). Fig. 9a presents the curve of the R4 fecal biomarker ratio, which is used to assess the origin of fecal contamination (Bortolini et al., 2024). The samples exhibit variable trends with depth, with values ranging from 0.51 to 0.83 (Table 4). Within the interval of 497–441 cm, a mixed faecal input is evident, with a predominant contribution from herbivores, as indicated by the abundant presence of 5β-phytostanols (5β-stigmastanol and epi-5β-stigmastanol). At dephts between 433-416 cm, 401–384 cm, and 361–272 cm, a rapid increase in faecal traces from omnivores, which may include both wild animals and humans, is recorded. This is suggested by the rise in R4 values, caused by the dominant contribution of coprostanol and epicoprostanol to the ratio, i.e., the stanols most abundant in human and pig faeces (Bull et al., 2002).

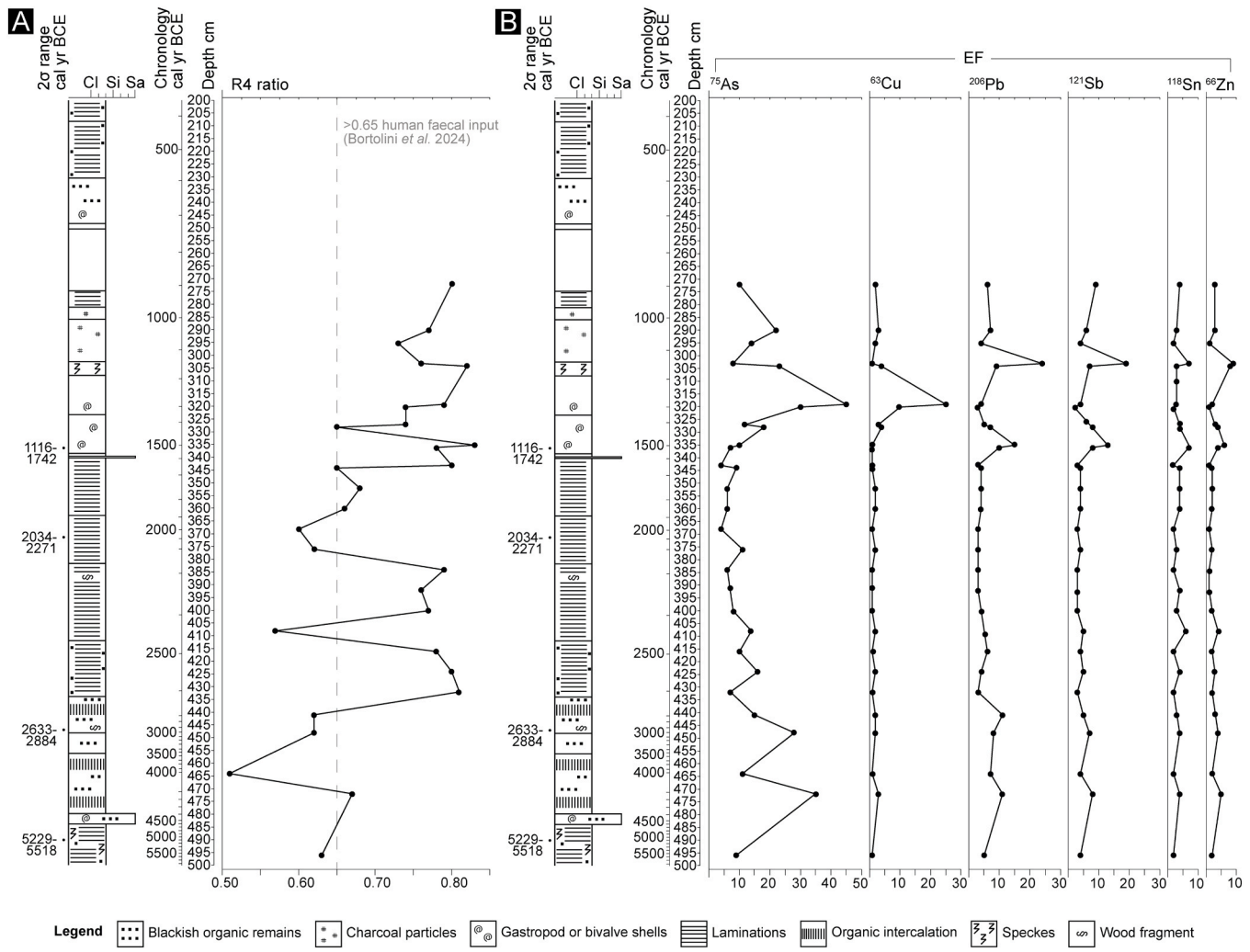


**Fig. 9.** Bio-geochemical record of CA03_MS with sedimentary log and calibrated ages BCE (2σ range). (a) R4 ratio curve of faecal biomarkers (Bortolini et al., 2024). (b) Enrichment factor profiles for elements: $^{75}$As, $^{63}$Cu, $^{206}$Pb, $^{121}$Sb, $^{118}$Sn, $^{66}$Zn.

### *4.4. Trace elements analysis*

The molar ratios of Ca/Si and Mg/Si show a parallel trend (Fig. 6b). Major Ca/Si peaks are recorded within the intervals 465–448 cm (0.12; 0.17), 433–424 cm (0.31; 0.36), and 409–376 cm (0.41; 0.50; 0.61; 0.68; 0.51). The upper section (above ~340 cm) is more variable, with elevated values at 340–339 cm (0.23), 328–329 cm (0.24), 319–320 cm (0.25), 304–305 cm (0.24), and 295–296 cm (0.31). The Mg/Si ratio follows a similar pattern, with corresponding peaks at 433–424 cm (0.24–0.23), 385–384 cm (0.32), and in the upper section at 295–296 cm (0.19; Table 4).

The Enrichment Factor (EF) profiles for $^{75}$As, $^{63}$Cu, $^{206}$Pb, $^{121}$Sb, $^{118}$Sn and $^{66}$Zn are presented in Fig. 9b. Below 340 cm, EF values are low and stable for most elements, with isolated peaks for $^{75}$As at 472–473 cm (35) and 448–449 cm (28). A distinct zone of elevated values occurs between approximately 337–304 cm. Within this zone, $^{206}$Pb, $^{121}$Sb, $^{118}$Sn and $^{66}$Zn show a concurrent peak between 337 and 335 cm and at 303–304 cm. In contrast, the EF $^{75}$As rise between 337 and 304 cm, while the values of $^{63}$Cu rise sharply between 321–304 cm, both culminating in a maximum at 319–320 cm (EF $^{75}$As = 45, EF $^{63}$Cu = 25; Table 4).

## 5. Discussion

### *5.1. Two decades in the archive: assessing taphonomic bias and chronological uncertainty in a stored palaeorecord*

This study provides a long-awaited update to the Holocene palaeoenvironmental dataset for south-eastern Trentino (Cattani, 1977; Kofler, 1994; Calderoni et al., 1996; Arpenti and Filippi, 2007; Filippi et al., 2007; Joannin et al., 2013, 2014). However, the two-decade interval between coring and analysis introduced significant analytical challenges. To address the common issue of depositional hiatuses, arising from both natural processes and coring operations, we developed a master sequence by integrating two available cores. Despite being kept in a cooling chamber, lithological correlation between them was complicated by the absence of continuous XRF scanning and post-storage dehydration features (Fig. 4), requiring reliance on only four markers and on chronology. The chronological framework itself presents challenges. We supplemented thirteen existing radiocarbon dates with eight new one (Table 2). Of these, six were obtained from bulk sediment due to a scarcity of terrestrial macrofossils; five yielded anomalously old ages and were excluded from final age-depth model of CA03_P4 as probable artefacts of reservoir effects or storage-related organic matter degradation (Fig. 5). Although the inclusion of new dates aimed to refine the chronology, the bulk sediment anomalies weakened the model reliability, which exhibits considerable

**Table 3**
Summary of CA03_MS local pollen zones, from the older to the most recent, and inferred terrestrial, lakeside and aquatic vegetation (AP=arboreal pollen; NAP=non arboreal pollen; MCC=micro-charcoal concentration).

| Acronym Depth cm Chronology | Local pollen zone definition | Terrestrial vegetation in the pollen source area | Aquatic and lakeside vegetation |
|---|---|---|---|
| CA03–1 497–450 cm 5548–3264 BCE | AP 96 % (max), *Abies* (44.5 %) and *Fagus* (21.8 %) dominant. Low NAP (4 %). MCC decrease. | Fir-beech forest. Limited deciduous mixed oak wood (oak, elm, linden). | Lakeside marshy thicket (alder, willow). Cyperaceae. |
| CA03–2 450–410 cm 3264–2450 BCE | AP 92.8 %, conifers decrease, *Fagus* dominant (25.4 %), deciduous *Quercus* group (12.8 %), *Corylus* (2.8 %) increase, spreading of *Betula, Juniperus,* Poaceae, and Xerophytes. Sporadic MCC peak. | Beech-dominated forest. Developing deciduous mixed oak wood (oak hornabeam, ash). Pioneer open areas species (birch). | Lakeside alder forest.Cyperaceae stable. *Sparganium* and *Thypa* appearing. |
| CA03–3 410–386 cm 2450–2305 BCE | AP 90 %, *Fagus* peak (30.2 %), deciduous *Quercus* group (15.5 %), *Corylus* (3.5 %), *Carpinus* (1.1 %) expansion. Ulmus decline. Upland herbs expansion (Poaceae). First anthropogenic indicators (*Plantago lanceolata* and *Polygonum aviculare*). MCC low. | Beech-dominated forest. Deciduous mixed oak wood. Elm decline favouring hazel understory. Limited dry pastures. | Lakeside alder forest.Cyperaceae, *Sparganium,* Nymphaceae. |
| CA03–4 386–337 cm 2305–1535 BCE | AP 91.4 %, deciduous *Quercus* group max (22.4 %), *Fagus* reduction. Herbs diversity increase. *Orlaya grandiflora* and Cerealia type presence. MCC very low. | Oak-hornbeam forest. Declining fir-beech forest. Fields, dry pastures and dry fallow. | Lakeside alder forest. Cyperaceae, *Sparganium, Filipendula, Typha.* |
| CA03–5 337–297 cm 1535–1085 BCE | AP min (81.9 %), deciduous *Quercus* group decrease (15.4 %). Consistent *Corylus*. Anthropogenic and upland herbs expansion. MCC frequent peaks. | Forest openings. Expansion of overall anthropogenic environments (fields, dry pastures). | Lakeside marshy thicket (alder, willow). Cyperaceae, *Sparganium* increase. |
| CA03–6 297–270 cm 1085–887 BCE | AP recovery (86.9 %), deciduous *Quercus* group decrease (12 %), *Carpinus* and *Ulmus* increase. Consistent *Corylus.* Cerealia type and *Plantago lanceolata* presence. MCC peak. | Fir-beech forest. Fluctuations of anthropogenic environments. | Decrease of lakeside alder forest and aquatics. |
| CA03–7 270–208 cm 887–415 BCE | AP stable (86.7 %), *Fagus* recovery (24.2 %). Shrubs decline, upland herbs (Poaceae) and anthropogenic indicators increase. MCC decrease. | Fir-beech forest. Grasslands, dry pastures, fields. | Decrease of lakeside alder forest. Cyperaceae. |

uncertainty, most notably between ~350–250 cm in depth. In this interval, the chronology hinges on a single date (UtC-13672: 3170 ± 120 BP; Table 2) with a large error margin. The propagation of this uncertainty complicates the palaeoenvironmental interpretation. For instance, the pronounced peak in the copper enrichment factor at 319–320 cm has a 2σ range of 1746–826 cal BCE, spanning from the Early Bronze Age to the Iron Age (Fig. 9b). Furthermore, the comparison of the individual core chronologies reveals additional complications. The CA03_P4 model indicates a marked reduction in sediment accumulation/hiatus, between 490.9 and 447 cm (5372–2762 cal BCE), a feature absent in CA03_P1 (Fig. 5). This discrepancy may reflect genuine spatial variability in sedimentation, consistent with the cores' location (55 m away; Fig. 3) and elevation difference (1.1 m; Fig. 5). A possible alternative is that the date in CA03_P4 at 490.9 cm (Table 2; Fig. 5) is an outlier, rendering its age-depth model analogous to that of CA03_P1. We adopt the former, more conservative interpretation here, establishing the beginning of the studied sequence portion in the mid-sixth millennium BCE. The latter scenario would shorten the chronology substantially, placing the beginning in the mid-fifth millennium BCE. Therefore, signals from such archives must be interpreted with caution, acknowledging their inherent dating uncertainties and dependence on a statistical model. This underscores the critical importance of analysing multiple, independent archives within a region to corroborate and contextualise palaeoenvironmental data.

### 5.2. Palaeohydrological and sedimentary dynamics

The bottom portion of the sequence of Lake Caldonazzo is punctuated by a high-energy depositional event at ~4550–4400 cal. BCE, marked by a distinct sandy-silty layer interrupting otherwise clay-dominated sediments. Post-event reworking resulted in homogenised, non-laminated deposits. A carbonate enrichment phase (~4000–3000 cal. BCE), marked by elevated LOI-derived carbonate content (though less evident in Ca/Si and Mg/Si ratios), potentially reflects biogenic production during a prolonged lake high stand (Verrecchia, 2007; Nichols, 2009; Figs. 6, 10). This interval shows broad alignment, within chronological uncertainties, with Lake Ledro's high stand phase (3850–3250 cal. BCE), which has been attributed to increased Alpine precipitation during the Atlantic-Subboreal transition (Magny, 2004; Magny et al., 2009, 2012). Reduced basin erosion during this interval is corroborated by low values of *Glomus* (HdV 207) spores (Marinova and Atassanova, 2006; Figs. 8, 10). Following this period, an erosive episode is recorded. Declining carbonate content and rising siliciclastic influx (peaking at ~2700 cal. BCE) signal enhanced terrigenous input, mirrored by Mg/Si and Ca/Si trends. The resurgence of *Glomus* (HdV 207) spores and reduced carbonate preservation further support intensified erosion (Figs. 8, 10). At 434 cm depth (~2614 cal. BCE), a stratigraphic shift is recorded, as laminated structures replace massive clayey silt with organic lenses. Oscillating but overall high carbonate values between ~2600–1900 cal. BCE, coupled with concurrent peaks in Ca/Si and Mg/Si ratios, nevertheless indicate a trend of rising lake level. This pattern is consistent with regional palaeohydrological trends, as evidenced by lake-level reconstructions from Lake Ledro (Magny et al., 2009, 2012; Vannière et al., 2012). These high stands likely represent a regional response to Late Holocene Alpine moisture maxima (Wanner et al., 2008; Peyron et al., 2013), also related to the effects of the 4.2 ka BP event on the southern Alps (i.e., precipitation increase; Furlanetto et al., 2018; Helama, 2024). A three-century low stand evidenced by carbonate minima follows (~1800–1550 cal. BCE). At 340–339 cm depth, a sandy lens precedes a return to massive clayey silts and a subdued high-water stand (~1550–1300 cal. BCE), temporally overlapping Lake Ledro's high stand (Magny et al., 2009, 2012). Divergent Ca/Si-Mg/Si and carbonate trends suggest decoupled sediment sourcing and carbonate precipitation mechanisms. The top of the sequence records the transition to massive carbonate silts, with laminated structures re-emerging between 381 and 375 cm depth (early 1st millennium BCE). Following roughly a century characterised by higher siliciclastic influx, the carbonate component displays an increasing trend from the ~12th century BCE onward, despite inherent variability. This pattern partially departs from the known chronology of

**Table 4**
Results of bio-geochemical analyses of CA03_MS sequence. R4 ratio faecal steroids (Bortolini et al., 2024); molar ratios between Ca/Si and Mg/Si; Enrichment Factor (EF) of $^{75}$As, $^{63}$Cu, $^{206}$Pb, $^{121}$Sb, $^{118}$Sn and $^{66}$Zn.

| Depth cm | R4 ratio | Ca/Si | Mg/Si | EF$^{75}$As | EF$^{63}$Cu | EF$^{206}$Pb | EF$^{121}$Sb | EF$^{118}$Sn | EF$^{66}$Zn |
|---|---|---|---|---|---|---|---|---|---|
| 272–273 | 0,80 | 0,18 | 0,05 | 10 | 2 | 6 | 9 | 4 | 3 |
| 290–291 | 0,77 | 0,12 | 0,08 | 22 | 3 | 7 | 6 | 3 | 3 |
| 295–296 | 0,73 | 0,31 | 0,19 | 14 | 2 | 4 | 4 | 2 | 1 |
| 303–304 | 0,76 | 0,11 | 0,02 | 8 | 1 | 24 | 19 | 7 | 9 |
| 304–305 | 0,82 | 0,24 | 0,06 | 23 | 4 | 9 | 7 | 3 | 8 |
| 319–320 | 0,79 | 0,25 | 0,07 | 45 | 25 | 4 | 4 | 3 | 2 |
| 320–321 | 0,74 | 0,11 | 0,07 | 30 | 10 | 3 | 2 | 2 | 1 |
| 327–328 | 0,74 | 0,17 | 0,04 | 12 | 3 | 5 | 7 | 4 | 3 |
| 328–329 | 0,65 | 0,24 | 0,10 | 18 | 4 | 7 | 8 | 4 | 4 |
| 335–336 | 0,83 | 0,11 | 0,05 | 10 | 1 | 15 | 13 | 7 | 6 |
| 336–337 | 0,78 | 0,19 | 0,06 | 7 | 1 | 10 | 8 | 7 | 4 |
| 343–344 | 0,80 | 0,23 | 0,05 | 4 | 1 | 3 | 3 | 2 | 1 |
| 344–345 | 0,65 | 0,13 | 0,04 | 9 | 1 | 4 | 4 | 4 | 2 |
| 352–353 | 0,68 | 0,12 | 0,04 | 6 | 2 | 4 | 4 | 4 | 2 |
| 360–361 | 0,66 | 0,18 | 0,05 | 6 | 2 | 4 | 4 | 4 | 2 |
| 368–369 | 0,60 | 0,29 | 0,14 | 4 | 1 | 3 | 3 | 2 | 1 |
| 376–377 | 0,62 | 0,51 | 0,15 | 11 | 2 | 3 | 4 | 3 | 2 |
| 384–385 | 0,79 | 0,68 | 0,32 | 6 | 1 | 3 | 3 | 2 | 1 |
| 392–393 | 0,76 | 0,61 | 0,14 | 7 | 1 | 3 | 3 | 4 | 1 |
| 400–401 | 0,77 | 0,50 | 0,19 | 8 | 1 | 4 | 3 | 3 | 2 |
| 408–409 | 0,57 | 0,41 | 0,19 | 14 | 2 | 5 | 5 | 6 | 4 |
| 416–417 | 0,78 | 0,23 | 0,12 | 10 | 1 | 6 | 4 | 2 | 2 |
| 424–425 | 0,80 | 0,36 | 0,23 | 16 | 2 | 4 | 5 | 4 | 3 |
| 432–433 | 0,81 | 0,31 | 0,24 | 7 | 1 | 3 | 3 | 2 | 2 |
| 441–442 | 0,62 | 0,07 | 0,03 | 15 | 2 | 11 | 5 | 3 | 3 |
| 448–449 | 0,62 | 0,17 | 0,10 | 28 | 2 | 8 | 7 | 4 | 4 |
| 464–465 | 0,51 | 0,12 | 0,10 | 11 | 1 | 7 | 4 | 2 | 2 |
| 472–473 | 0,67 | 0,06 | 0,03 | 35 | 3 | 11 | 8 | 4 | 5 |
| 496–497 | 0,63 | 0,12 | 0,09 | 9 | 1 | 5 | 4 | 2 | 2 |

Lake Ledro's high stands (Magny et al., 2009, 2012), suggesting a potentially distinct local palaeohydrological signal (Figs. 6a, 10).

### 5.3. Climate-environment-human interactions

#### 5.3.1. Middle Holocene pristine forest and incipient Neolithic disturbance

During the Middle Holocene (Atlantic chronozone; Orombelli and Ravazzi, 1996; Ravazzi, 2003), the Valsugana landscape was characterised by a stable and predominantly pristine vegetation, defined by a clear altitudinal gradient. Dense silver fir (*Abies alba*) forests dominated the slopes and summits, while extensive beech (*Fagus sylvatica*) stands prevailed at mid-elevations. The valley floors supported diverse mixed deciduous woodlands and the riparian corridors along lake margins were occupied by black alder (*Alnus glutinosa*) stands (Figs. 7, 10). This ecosystem finds strong parallels in other Holocene lacustrine sequences from South Trentino, such as Lake Lavarone (Filippi et al., 2007) and Lake Ledro (Joannin et al., 2013), confirming a regional pattern of well-established forest communities.

During this period, climate appears to have been the primary driver of vegetation dynamics. This is evidenced by the pollen data, which lack strong anthropogenic indicators such as cereal pollen, a marked contrast to the record from Lake Ledro (Joannin et al., 2013), highlighting a local disparity. This climate-driven interpretation is further supported by micro-charcoal peaks that align with regional aridity phases and low stands of Lake Ledro (~5200–4350 BCE and ~4200–3850 BCE; Magny et al., 2009, 2012; Fig. 10), suggesting a climate-controlled fire regime. However, the presence of open-land indicators between ~5500–4150 BCE (Figs. 8, 10), followed by the decline of certain deciduous taxa (e.g., beech, alder, linden, hazel) between ~4100–3400 BCE (Fig. 7), suggests that low-intensity human activity may have influenced the local landscape since the Neolithic period. Despite the absence of known Neolithic settlements within the Valsugana itself (Pedrotti, 2001a; Rottoli, 2013; Mottes, 2021), the resource-rich environments of Lakes Caldonazzo and Levico would have been prime attractions for seasonal exploitation at least. The valley likely functioned as an intermittent subsistence zone for hunting, gathering, and fishing, a pattern consistent with archaeological evidence from the nearby Adige Valley (Dalmeri et al., 2008; Gibaja et al., 2025; Perini, 1971). This interpretation is reinforced by sites like Riparo Gaban, which demonstrate a persistent reliance on wild resources during the Early Neolithic (Pedrotti, 2010; Zanetti et al., 2020). Recent archaeobotanical studies confirm that this pattern extended also into later Neolithic phases, as evidenced by data from Riva del Garda (Rottoli and Cottini, 2021) and Molino Casarotto (Breglia et al., 2025; Nicosia et al., 2025b).

From the mid-4th millennium BCE, a slight but synchronous increase is observed in the enrichment factors of copper, lead, tin, antimony, and zinc, alongside a more pronounced rise in arsenic (Fig. 9b). These metal enrichments are positively correlated with a phase of siliciclastic input (Figs. 5a, 10) and are therefore attributed to sedimentological dynamics and natural weathering processes, rather than to anthropogenic metallurgy (Thevenon et al., 2011; Bertrand et al., 2024).

#### 5.3.2. Synergistic drivers of changes in the forest cover composition during the Copper Age

From the second half of the 4th millennium BCE, the record of Lake Caldonazzo reveals a gradual yet persistent decline in forest cover (Figs. 7, 10), a trend attributable to a combination of climatic and anthropogenic factors. This period coincides with the Atlantic-to-Subboreal chronozone transition (~3500 cal. BCE), the subsequent waning of the Holocene Thermal Maximum (~3000 cal. BCE), and Northern Italy's Neolithic-Copper Age cultural shift, as documented in regional palaeoclimate (Orombelli and Ravazzi, 1996; Ravazzi, 2003; Kaufman, 2004; Wanner et al., 2011; Renssen et al., 2012; d'Oliveira et al., 2025) and archaeological records (Barfield, 2002; Mottes and Nicolis, 2002; Pearce, 2019). The climatic shift was primarily driven by changes in orbital forcing (Renssen et al., 2006; Wanner et al., 2011; Solomina et al., 2015), which led to increased climatic variability and a general cooling trend in the Alps (Baroni and Orombelli, 1996; Magny and Haas, 2004; Mayewski et al., 2004; Holzhauser et al., 2005; Magny et al., 2006; Nussbaumer et al., 2011), ultimately altering forest composition and tree line elevation through time (Nicolussi et al., 2005; Tinner and Vescovi, 2007; Badino et al., 2018; Furlanetto et al., 2018).

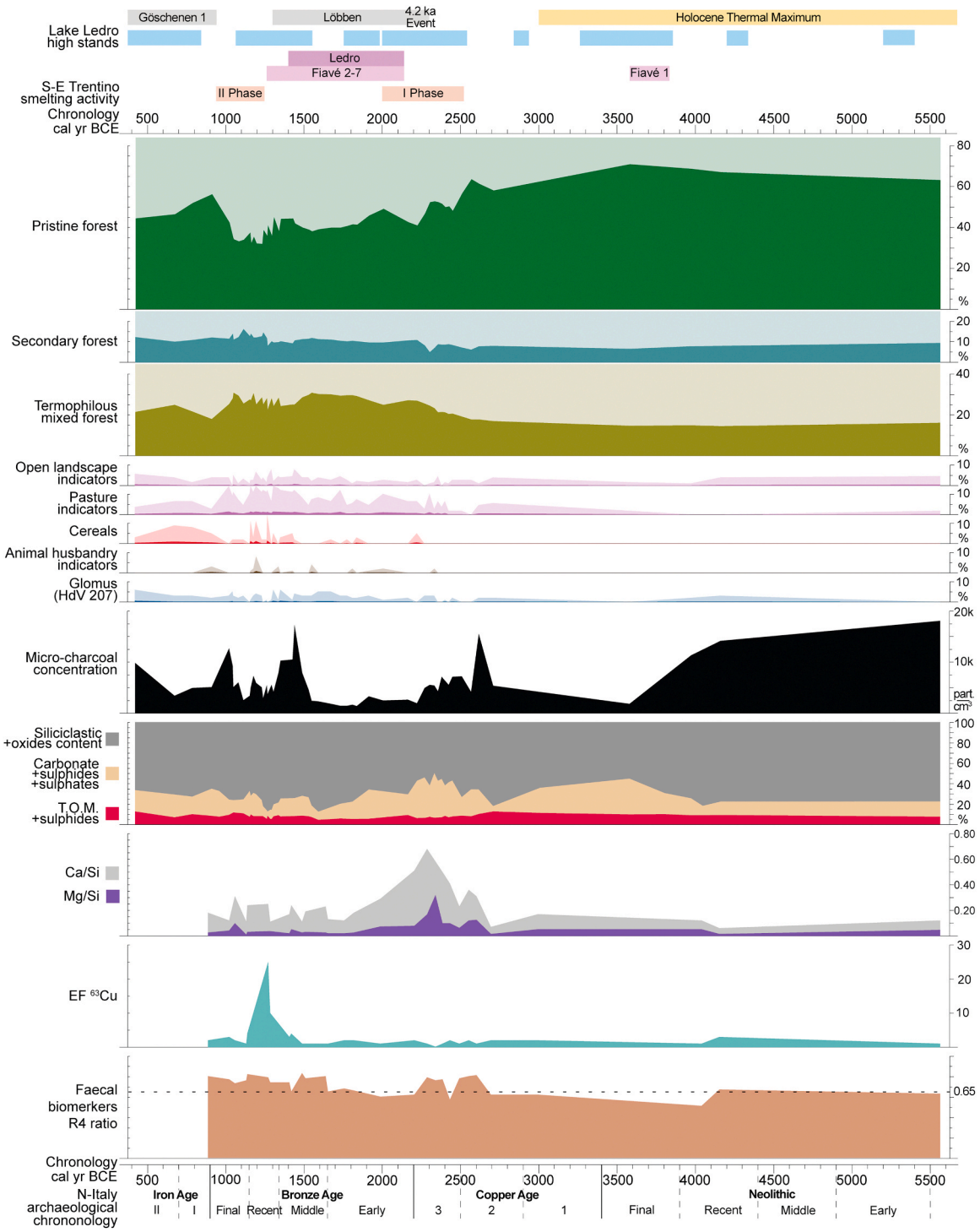


**Fig. 10.** Ecological-climatic-cultural proxies from southern Alps and multi-proxy from the CA03_MS sequence. From top to bottom: major climatic oscillations in the Alps (Zoller and Schindler, 1966; Deline and Orombelli, 2005; Wanner et al., 2011; Renssen et al., 2012; Le Roy et al., 2015; Badino et al., 2018)(); high stands of Lake Ledro (Magny et al., 2009, 2012); chronological sequences of the ettlements of Fiavé (Perini, 1984, 1987, 1994) and Molina di Ledro (Battaglia, 1943; Cortesi and Leonardi, 2002; Bellintani, 2017); south-eastern Trentino metallurgy phases (Silvestri et al., 2019; Bellintani and Silvestri, 2021; Marzatico, 2022; Pearce et al., 2022; Artioli et al., 2024); ecological groups percentages: pristine forest, secondary forest, thermophilous mixed forest, pasture indicators, open landscape, and animal husbandry indicators (magnification curve x10); *Glomus* (HdV 207) percentage (magnification curve x10); micro-charcoal concentration; selected geochemical record: LOI percentages, molar ratio Mg/Si and Ca/Si, EF $^{63}$Cu; faecal biomarkers record (R4 ratio; Bortolini et al., 2024).

Notably, the expansion of black alder riparian woodland near the shores of the lake (Fig. 7) may be linked to a wetter phase. Such environmental changes likely destabilised the existing socio-economic systems of local human communities (Magny, 2004; Ravazzi and Pini, 2013; Pini et al., 2017). Copper Age archaeological evidence indicates the emergence of pastoral economies linked to nomadic/semi-nomadic practices (Barker, 1999; de Marinis and Pedrotti, 1997; Fedele, 2013). Through heightened mobility, human groups expanded their exploitation (i.e, forest clearance, shifting cultivation; Cremaschi et al., 2008; Marzatico, 2009; Rottoli, 2013; Tecchiati et al., 2013) into higher-altitude zones (Carrer,

2013; Festi et al., 2014; Putzer et al., 2016; Reitmaier et al., 2021), encroaching upon montane conifer forests (Fedele and Wick, 1996; Ravazzi and Pini, 2013; Pini et al., 2017). The opposite trends in pollen values of fir (decline) and beech (rise) recorded in the sequence may thus reflect these synergistic drivers (Fig. 7), consistent with the established palaeoecological framework of Alpine vegetation history (Pini, 2002; Tinner et al., 2005; Wick and Möhl, 2006; Badino et al., 2018; Furlanetto et al., 2018). The resistance of beech to fires, its excellent response to pruning and early leafing, combined with the technical qualities of its wood favoured its growth in forest competition and in human selection (Küster, 1997; Karg, 1998; Magny, 2004; Valsecchi et al., 2008). The latter became particularly pronounced during the second half of 3rd millennium, when a new reduction in pristine forest pollen values is visible in the record (Fig. 10). This trend that is synchronous with increases in both open-land/pastoral indicators and with faecal biomarker values exceeding the human input threshold (R4 = 0.65; Bortolini et al., 2024; Figs. 9a, 10), all pointing to a stronger anthropogenic signal reflecting pressure from heightened human presence in the region (Pedrotti, 2001b; Mottes et al., 2014; Pearce et al., 2022). The major micro-charcoal peak (~2600 cal. BCE) immediately preceding this phase suggests fire was an initial disturbance agent. Following this prominent peak, a phase of elevated micro-charcoal, persisting until the onset of the Bronze Age, indicates recurrent fire activity (Fig. 10). Future analysis of macro-charcoal particles could refine the interpretation of these fire regimes and their potential causes (Finsinger et al., 2014; Vannière et al., 2016; Saeidi Ghavi Andam et al., 2024). Although the onset of the 1st phase of south-eastern Trentino metallurgy is contemporaneous with these landscape changes (Fig. 10), its specific impact cannot be isolated within the composite palaeoecological signal of human activity. Furthermore, the interpretation of the geochemical data also presents an ambiguity. The modest values recorded for this period (Fig. 9b) could, on the one hand, corroborate archaeological evidence for metallurgical exploitation of limited scale (Angelini et al., 2013; Pearce et al., 2022). On the other hand, they could be explained by a reduced siliciclastic input and thus be attributed to natural sedimentary dynamics (Fig. 6a).

#### 5.3.3. Climate oscillation and pastoralism in the Early Bronze Age

The alpine climate of the late 3rd millennium BCE was marked by interconnected climatic oscillations. The 4.2 ka BP event (Zanchetta et al., 2016; Bini et al., 2019; Helama, 2024;), whose regional effects are already detectable in the Alps between ~2400–2300 BCE through increased precipitation and rising lake levels (Magny et al., 2009, 2012; Furlanetto et al., 2018), was followed by the Löbben Oscillation (~2000–1200 BCE), a cold phase that triggered renewed glacial advances (Deline and Orombelli, 2005; Luetscher et al., 2011; Le Roy et al., 2015; Badino et al., 2018). In Valsugana, the wetter conditions appear to have facilitated beech forest expansion between ~2450–2250 BCE, while the subsequent colder phase favoured silver fir stands at the expense of beech. While this dynamic could partly reflect human activities, other deciduous species, such as oak (deciduous *Quercus* group), show no comparable decline (Fig. 7). Concurrently, the pollen record documents a significant rise in pastoral indicators, including the appearance of anthropogenic markers such as cereals and white lace flower (*Orlaya grandiflora*; Figs. 8, 10). The latter species is typically associated with dry grasslands and shrubby pastures or the margins of cereal fields, and its systematic spread in northern Italy is attributed to the Bronze Age grazing pressure (Perego et al., 2011), as attested by several pollen records from the southern alpine forelands (Dal Corso, 2018; Zanon et al., 2019; Furlanetto et al., 2022; Dal Corso et al., 2025; Nicosia et al., 2025a; Perego et al., 2025). The signal from animal husbandry indicator spores further supports the inference of increased pastoral activity (Fig. 10). In the southern Alps, the Early Bronze Age marks the definitive establishment of alpine pastoralism (Marzatico, 2007; Carrer, 2013; Joannin et al., 2014; Dietre et al., 2020; Caf et al., 2023), though high-altitude sites exhibit a delayed adoption of pastoral regime (Speranza et al., 1996; Heiss et al., 2005; Filippi et al., 2007; Festi et al., 2014). From approximately the 18th century BCE, faecal biomarker analyses indicate an increasing contribution of human faecal matter in the sediments of Lake Caldonazzo (Figs. 9a, 10), reinforcing evidence for sustained occupation and agropastoral activity. The combined proxies suggest a gradual intensification of human presence within the Valsugana, entirely consistent with the broader regional context of the Early Bronze Age. During this period, an extensive process of landscape colonisation, including upland areas, was initiated, accompanied by the emergence of long-term settlement dynamics (Marzatico and Tecchiati, 2022; Di Pillo, 2023).

#### 5.3.4. Intensive land use in the Middle Bronze Age and the question of the 2nd phase of metallurgy

The paleoecological record indicates that the anthropogenic pressure initiated in the Early Bronze Age continued and, at times, intensified throughout the Middle Bronze Age. This trajectory aligns with the archaeological record of the Trentino area, which documents continuity in settlement and site occupation across this transitional period (Marzatico and Tecchiati, 2022; Di Pillo, 2023). Strong signals of this human-driven landscape modification include: (I) a pronounced transformation of the regional vegetation cover, marked by an abrupt decline in arboreal pollen, most notably of deciduous oaks, with an expansion of shrubs and upland herbs (Figs. 7, 8); (II) the presence of anthropogenic indicators, such as sporadic cereal pollen (Figs. 8, 10); (III) an increase in grazing indicators (Amaranthaceae, Plantago lanceolata) and open-environment taxa (Cichorieae and Ranunculaceae; Figs. 8, 10); and (IV) elevated values of faecal biomarkers, confirming substantial human and/or livestock activity (Bortolini et al., 2024; Figs. 9A, 10). This period is further defined by a convergence of fire and geochemical signals: high values of micro-charcoal (~1500–1350 BCE; Figs. 7, 10) coincides with a first sequential rise of metal enrichment factor, beginning with $^{206}$Pb, $^{121}$Sb, $^{118}$Sn and $^{66}$Zn (~1600–1450 BCE), followed by $^{75}$As (~1550–1350 BCE), and then by $^{63}$Cu (~1450–1350 BCE; Fig. 9b). These signals could point to the beginning local metallurgy, potentially resulting in increased charcoal dispersion and metal contamination linked to smelting activity. If substantiated, this interpretation would place the onset of the 2nd phase of south-eastern Trentino metallurgy in the Middle Bronze Age. This proposed chronology stands in apparent contradiction to the regional archaeological record, which currently contains no definitively attributable smelting sites from this phase (Marzatico, 2022). Nonetheless, potential corroboration may be found in the contemporary and wide-ranging circulation of artifacts manufactured from Alpine copper (Artioli et al., 2016; Melheim et al., 2018; Ling et al., 2019; Mehofer et al., 2021). The enduring discrepancy between archaeological and archaeometric datasets continues to be debated (Pearce et al., 2019; Bellintani and Silvestri, 2021; Marzatico, 2021, 2022). However, due to the substantial chronological uncertainty inherent in the age-depth model for the CA03_MS sequence, the evidence presented in this study cannot be considered definitive for resolving this question.

#### 5.3.5. Environment upheaval during the Recent-Final Bronze Age

Human impact on vegetation is evident through altered afforestation rates affecting both high-elevation conifer woodland and lowland deciduous forests. Shrubs such as hazel (*Corylus*) and cornel (*Cornus mas*) became notably more abundant in valley woodlands (Fig. 7), suggesting possible anthropogenic selection for the use of cornelian cherries and hazelnut. This aligns with frequent occurrences of cornel fruits in Bronze Age archaeobotanical records from northern Italy (Jones and Rowley-Conwy, 1984; Nisbet, 1984; Castelletti et al., 1992; Rottoli, 1997, 2001; Perego, 2017). Concurrently, open landscapes expanded, supporting greater diversity of herbaceous taxa including Apiaceae, Caryophyllaceae, *Centaurea nigra*, Cichorieae, Ranunculaceae, *Artemisia*, and Amaranthaceae (Fig. 8). Cereal pollen further confirms the presence of cultivated fields (Figs. 8, 10). The rise in *Glomus* spores (HdV 207;

Figs. 8, 10) suggests a link between landscape opening, accelerated soil erosion, and increased flood frequency. This association aligns with evidence from other Bronze Age mountain contexts (Vannière et al., 2012; Joannin et al., 2014; Rapuc et al., 2024). However, this erosional signal lacks a clear counterpart in the local siliciclastic input record (Fig. 6a), which limits its interpretative scope. Despite this constraint, deforestation would have altered soil stability, potentially promoting surface runoff and providing further evidence of anthropogenic environmental impact.

Elevated faecal biomarker values further confirm substantial increase in human activity within Valsugana during the Recent-Final Bronze Age (Bortolini et al., 2024; Figs. 9a, 10), reinforcing the link between demographic pressure and landscape transformation.

Following the peak during the Middle bronze Age, which can be also linked to intensified fire use for land clearance and domestic activities, the micro-charcoal record shows a clear divergence from the mid-14th century BCE. The smaller fraction (10–50 μm) displays frequent, sharp peaks, consistent with a regional signal linked to the lake's wide catchment area, potentially recording activities such as smelting in the distant highlands and peripheral valleys. In contrast, the larger fraction (>50 μm) stabilises at lower but more consistent levels, indicating steady local burning nearer to the basin (Fig. 7). The pattern of fire regime aligns with geochemical evidence for intensive metallurgy, marked by rising EF-$^{75}$As and EF-$^{63}$Cu curves that culminate in a significant peak at the beginning of the 13th century BCE (~1280 BCE). These signals confirm south-eastern Trentino's role as a mining district of continental importance during the Recent and Final Bronze Age, as archaeological attested by over 200 identified smelting sites in the Valsugana area (Bellintani and Silvestri, 2021; Marzatico, 2022). Signs of intense anthropogenic impact in the Valsugana persist until approximately the end of the 2nd millennium BCE, albeit with distinct patterns across different proxy records. Pastoral indicators and the micro-charcoal curve, for instance, show values that decline in the 12th century only to rise again in the 11th (Fig. 10). In contrast, the EF-$^{63}$Cu values exhibit a more definitive trajectory, decreasing sharply by the mid-12th century BCE and showing only a minor increase towards the end of the 11th century. This trajectory suggests a significant decline in the scale of smelting operations was already underway by the start of the Final Bronze Age, with activity continuing only at a much-reduced level through the period's later phase. The decline likely resulted from a combination of resource depletion, socio-demographic and political realignments (Marzatico, 1997, 2002, 2021; Leonardi, 2010; Capuzzo et al., 2018), and potentially the ecological disruption, such as soil degradation from deforestation, triggered by the overall human impact itself.

#### 5.3.6. *Post-mining vegetation recovery and Early Iron Age land use change*

While the impacts of mining activities in Valsugana on vegetation were unprecedented in the palaeorecord of Lake Caldonazzo, they ultimately proved reversible. Starting from the mid-11th century BCE a rapid recovery of forest cover occurred, particularly of fir and beech woodland (Figs. 7, 10). These species thrived under reduced anthropogenic pressure, successfully recolonising the now less-frequented high-altitude areas. This is followed by a new decline in afforestation rates, primarily affecting fir stands. We emphasise that the beginning of the 1st millennium BCE coincides with the onset of the Göschenen 1 cold phase (~1000–350 cal. BCE; Zoller and Schindler, 1966; Badino et al., 2018; Boxleitner et al., 2019), which may have influenced regional vegetation distribution. However, it remains unclear to what extent these climatic effects were masked by human impact. Sustained pollen of cereal, pasture indicators, and open landscape indicators (Fig. 10) in the sequence of Lake Caldonazzo attest to enduring agropastoralism, albeit with a marked transition toward crop-centered production, superseding the earlier Bronze Age emphasis on pastoral exploitation. The Early Iron Age human communities modified their land use practices, decreasing pastoral pressure while maintaining agricultural cultivation, as also evinced in the record of Lake Ledro (Joannin et al., 2014). This transition aligns with post-mining landscape reorganisation in south-eastern Trentino, where archaeological data reveal the emergence of fewer settlements controlling the territory in the alpine valleys (Marzatico, 1997, 2002; Marzatico et al., 2010, Di Pillo, 2023).

## 6. Conclusions

This multi-proxy study of the palaeorecord of Lake Caldonazzo provides a detailed narrative of human-environment interactions in south-eastern Trentino from the 6th to the 1st millennium BCE. While a quantitative assessment of relative roles of climate and human impact is beyond our scope, our high-resolution dataset delineates the sequence of events and identifies the primary drivers of ecological change. The key finding is a clear transition from climate-dominated vegetation dynamics to increasingly dominant human influence on the environment, marked by several pivotal phases: the Neolithic onset of pastoralism, Copper Age forest clearance synergising with climatic instability, and Bronze Age intensification of agropastoral land use. Furthermore, mining and smelting left an unambiguous, multi-faceted signature. The Recent–Final Bronze Age metallurgical activity is defined by a strong increase in copper enrichment, synchronous with proxies for deforestation and soil erosion. This palaeoecological evidence corroborates the archaeological model of south-eastern Trentino as a continental-scale production hub prior to its abrupt collapse. For the Middle Bronze Age, however, the narrative is less clear. While intensive agropastoral exploitation is well-documented, geochemical and charcoal proxies suggest possible incipient metallurgy. The timing of these early signals remains contentious, as it conflicts with an archaeological record lacking definitively dated smelting sites for this period. This discrepancy, possibly compounded by chronological uncertainties, highlights the need for further research. Following the cessation of metal production, the landscape demonstrated a remarkable capacity for recovery, with forests rapidly regenerating.

Our multi-proxy record allows us to evaluate the efficacy of different indicators in detecting specific anthropogenic impacts. Regarding metallurgical activity, trace elements provide direct evidence of metal contamination in sediments. However, interpreting these as anthropogenic in origin requires caution and must be verified against the sedimentary and geochemical context to rule out natural sources such as bedrock weathering. Agropastoralism is most clearly tracked through the combined use of pollen, coprophilous faecal spores, and faecal biomarkers. Meanwhile, fire regimes are best understood through micro-charcoal, although its anthropogenic drivers can only be confidently distinguished when correlated with other proxies to rule out climatic causes. To further refine these reconstructions, future work should prioritise high-resolution analysis of the remaining sequence, macro-charcoal quantification, and the identification of complementary sedimentary archives.

This study establishes pre-protohistoric resource exploitation as a transformative force in the Alpine landscape. By correlating specific archaeological activities with their distinct palaeoecological signatures, our framework provides a template for understanding past human-environment dynamics, offering also a deep-time perspective on contemporary challenges in mountain ecosystems.

## CRediT authorship contribution statement

**Riccardo Leardi:** Writing – review & editing, Software, Formal analysis. **Jesper Olsen:** Investigation. **Federico Polisca:** Writing – review & editing, Formal analysis. **Michele Cupitò:** Conceptualization, Writing – review & editing. **Marco Avanzini:** Writing – review & editing, Supervision, Resources. **Giorgio Piazzalunga:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Cristiano Nicosia:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Marta Dal Corso:** Writing – review & editing,

Supervision, Methodology, Data curation. **Maela Baldan:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Mara Bortolini:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Ingo Feeser:** Writing – review & editing, Software, Investigation. **Emanuele Farinini:** Writing – review & editing, Formal analysis. **Dario Battistel:** Writing – review & editing, Methodology, Data curation.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepSeek-V3.2 to assist in the drafting of the English text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this papaer.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ancene.2026.100530.

## Data availability

Data are available in the supplementary material and micro botanical data are available on Neotoma.

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