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A geoarchaeological review of Balzi Rossi, Italy: A crossroad of Palaeolithic populations in the northwest Mediterranean

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ABSTRACT

The Balzi Rossi archaeological complex (comprised of caves, rock shelters, and open-air sites) is a globally significant site for Palaeolithic culture and understanding the transition from Neanderthal to Anatomically Modern Human populations in Europe. It also retains some of the earliest evidence of human interactions with their coastal environment. Balzi Rossi has been subject to excavation for over 150 years – traditionally as individual site locations – with most deposits removed when the discipline of archaeology was nascent, and the science not yet developed. The consequence was the unfortunate loss of materials and critically important stratigraphic context. However, valuable information regarding the Palaeolithic population, their coastal environment, and earlier sea-level change, remains in the literature and in museum repositories. In this work we have compiled and reviewed the extensive resources, available largely in French and Italian, to provide a summary and catalogue for each individual site. These 'Site Summaries' are available as appendices to this review, which provides a comprehensive synopsis of the history of excavations conducted at Balzi Rossi, a reconstruction of stratigraphy where possible, the evidence of Palaeolithic occupations, the evidence of Pleistocene sea-level fluctuations, and an assessment of the chronological constraint available for both the Palaeolithic populations and sea level. Finally, this synopsis identifies gaps in knowledge and provides comments on pathways for future research, suggesting a consilient approach that can be applied in other archaeological contexts.

1. Introduction

The Balzi Rossi archaeological area (Ventimiglia, northwestern Italy) is described as one of the most important centres of Palaeolithic finds in Europe with evidence of discontinuous human occupation spanning at least 250 ka BP to ca. 11 ka BP (Barral and Simone, 1987; Yokoyama, 1989; Bisson et al., 1994; Tomasso, 2014). Multiple karstic caves (7), rock shelters (4), and open-air sites (2) have been subject to archaeological excavation for nearly two centuries providing a rich collection of artefacts and palaeoenvironmental proxies (e.g., macrofauna skeletons) representing multiple Middle and Upper Palaeolithic cultures (which roughly coincide with late Middle through Late Pleistocene; see below Section 1.1). Significant finds include bone remains of an early Neanderthal, some of the most globally important burials of anatomically modern humans, evidence of coastal settlement in both the Middle and Upper Palaeolithic, and uncommonly old forms of Upper Palaeolithic mobiliary art, including "Venus" figurines (comprehensive works include: Rivière, 1887; de VilleneuveBoule et al., 1906-1919; de Lumley-Woodyear, 1969; White and Bisson, 1998; Mussi et al., 2004; Formicola and Holt, 2015; Rossoni-Notter et al., 2017; and references

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within). Balzi Rossi also preserves rare evidence of Palaeolithic parietal engravings on the Italian Peninsula (Vicino, 1972; Vicino and Simone, 1972; Vicino and Mussi, 2011; Sigari, 2022). The massive quantity of excavated sediment has produced biostratigraphic evidence spanning the Late Pleistocene in the form of mammal and bird bones and marine mollusc shell. Also uncovered are multiple indicators of palaeo sea level, representing at least three highstands.

The record at Balzi Rossi has been used in the ongoing debate regarding the demise of Neanderthals (*Homo neanderthalensis*) and transition to anatomically modern humans (AMH; *Homo sapiens*), i.e., the Middle (Mousterian) and Upper (Protoaurignacian) Palaeolithic transition, and possible dispersal routes of AMH into Europe (Douka et al., 2012; Benazzi et al., 2015; Negrino and Riel-Salvatore, 2018). The significance of Balzi Rossi for these discussions is due to its natural setting on the southern margin of the Maritime Alps, where steep cliffs of Jurassic limestone meet the Ligurian Sea of the Mediterranean (Fig. 1). Balzi Rossi, meaning red cliffs in Italian, is a descriptive name referring to the reddish colour of the rocks affected by pedogenesis. The coastal strip here, in continuation with the Roja Valley, forms part of a natural southern corridor between the Po Plain and Thyrrenian Italy and the Rhône valley and Western Europe. During periods of high sea level, the cliffs are located at or near the coastline in a region of mild and dry (optimal) climate, where anticyclonic conditions on the sea and over the surrounding mountains shelter the coast from cold air masses (Jacq et al., 2005). During past glacial periods, the narrow continental shelf provided ecological refugia for human groups when the surrounding mountain ranges were glaciated to elevations below 1000 m (Federici et al., 2017). Mammal bones found at Balzi Rossi also suggest the region served as a climate refugium during harsh climatic conditions (Hewitt, 2000).

To better understand how humans have responded to past rapid climate and sea-level change and inform contemporary responses, the intersect between human and social evolution and environmental change has become a focus of interdisciplinary research (Benjamin et al., 2017; Dong, 2018; Davis, 2020). The Balzi Rossi record is of particular significance for its potential to inform how Palaeolithic coastal inhabitants interacted and responded to coastal change – specifically how Middle and Upper Palaeolithic populations interacted with and responded to Mediterranean coastline shifts driven by global climatic change. However, to date, most investigations at the Balzi Rossi complex have had a singular discipline approach (archaeology) with focus on one site (e.g., a single cave or rock shelter), hampering the ability to fully understand the human response to environmental change.

In this paper we provide a first comprehensive geoarchaeological review of the Balzi Rossi complex – encompassing not only the history of archaeological excavation and evidence of Palaeolithic occupation for all sites, but also the thoroughness and quality of age constraint and the record of palaeo sea level. This will not be an in-depth review of lithics or industry, as such approaches have been made (Bulgarelli, 1974; Negrino, 2002; Grimaldi and Santaniello, 2014; Rossoni-Notter et al., 2017) but rather a general comparison of similarities and differences between the many archaeological sites of Balzi Rossi with respect to human and environmental (sea-level) histories. The sedimentological evidence is inclusive of both continental and near-shore marine deposition, representing the entire coastal biome. The comprehensive stratigraphic record enables an informed assessment of possible correlation between Palaeolithic cultural change and changes in their natural environment due to sea-level fluctuations. As such, this review provides the most complete synthesis of human cultural and environmental change yet published for Balzi Rossi and highlights that understanding interactions with and responses by human populations to their environment requires a multidisciplinary assessment of the complete biome.

1.1. Comments on terminology and interdisciplinarity

This undertaking is significant because although there is abundant literature regarding Balzi Rossi, most was published in French around the turn of the 19th century in journals or books that are either difficult to find or that are no longer in publication. Furthermore, comprehension of the literature can be difficult due to the (now) archaic terminology or the use of discipline-specific terminology, e.g., vocabulary common to archaeologists has little or no meaning to earth scientists and vice versa. However, to understand how the human populations at Balzi Rossi interacted with their coastal environment and responded to environmental changes (e.g., sea-level fluctuations) it is necessary to correlate the archaeological record with a chronological framework that reflects the sea-level record. Thus, this work requires not only translation within a discipline to reach a broader international audience, but also between the different disciplines involved – an effort towards consilience (Izdebski et al., 2016).

Much of the original materials removed and excavated from the Balzi Rossi complex have been lost. In recognition of this loss and the inability to reanalyse materials with our modern understanding, methods, and terminology, we retain use in some instances of the archaic terminology to avoid imposing meaning that cannot be confirmed. This approach was taken also with materials that have been reported within repositories but have not yet been re-examined. However, to assist in understanding, we have produced a table, which illustrates the correlation of old and new terminology, thus reflecting the development of the disciplines since the early investigations (Fig. 2).

Although much of the stratigraphy at Balzi Rossi is lost, the European Alpine Glacial Divisions, proposed at the beginning of the 20th Century (Penck and Brückner, 1901-09) provided the first framework of chronological constraint that was used at Balzi Rossi well into the second half of that century (Site Summaries; Fig. 2). Not long after, Issel (1914) defined the Tyrrhenian Quaternary marine stage for sea level occurring immediately before the Holocene and after the Sicilian Stage with the presence of the Senegalese fauna as a defining characteristic. However, since the establishment of these Quaternary terrestrial and marine chronologies, the Swiss Alps are recognized to have experienced at least fifteen glaciations and the Tyrrhenian Stage, as originally defined by Issel, encompasses two interglacials and two glacial periods and the term has been abandoned (Fig. 2; Asioli et al., 2005; Cita, 2008). As pointed out by Ivy-Ochs et al. (2008), the question then is, regardless of either geological or archaeological discipline, how to discuss earlier age attributions within the framework of our modern understanding of chronology?

There is a tendency to correlate incomplete terrestrial sequences with global isotopic records (marine and/or ice) because the latter provide a quasi-continuous record of climatic change (Gibbard and Hughes, 2021) and, for archaeological studies, the broad framework allows for the elucidation of human evolution in response to environmental change (Penkman et al., 2022). However, stratigraphic and geochronological constraints (i.e., fixed points, marker units, or horizons with indisputable ages), are recommended because of the difference in scale between records (local vs regional vs global) and to allow for correlation with other sites that can provide additional links to records of climate and environmental change and/or expand the human record (Gibbard and Hughes, 2021; Penkman et al., 2022). Although global boundaries for marine isotope stages (MIS) have been established using stacked marine and ice-core records (e.g. Lisiecki and Raymo, 2005), regional variability exists and boundaries are transient both spatially and temporally (Fig. 3). Similarly terrestrial responses to climate change are often diachronous and/or asynchronous and therefore terrestrial and marine stage boundaries are not necessarily time parallel (Tzedakis et al., 1997; Shackleton et al., 2003; Past Interglacials Working Group of PAGES, 2016; Gibbard and Hughes, 2021).

Such regional transience holds true for human cultural trajectory as well with softer boundaries in archaeology more broadly accepted than the Earth sciences. For this reason, it would be best to compare the archaeological record to regional terrestrial and marine records. As record resolution increases, so too does its meaning for understanding the

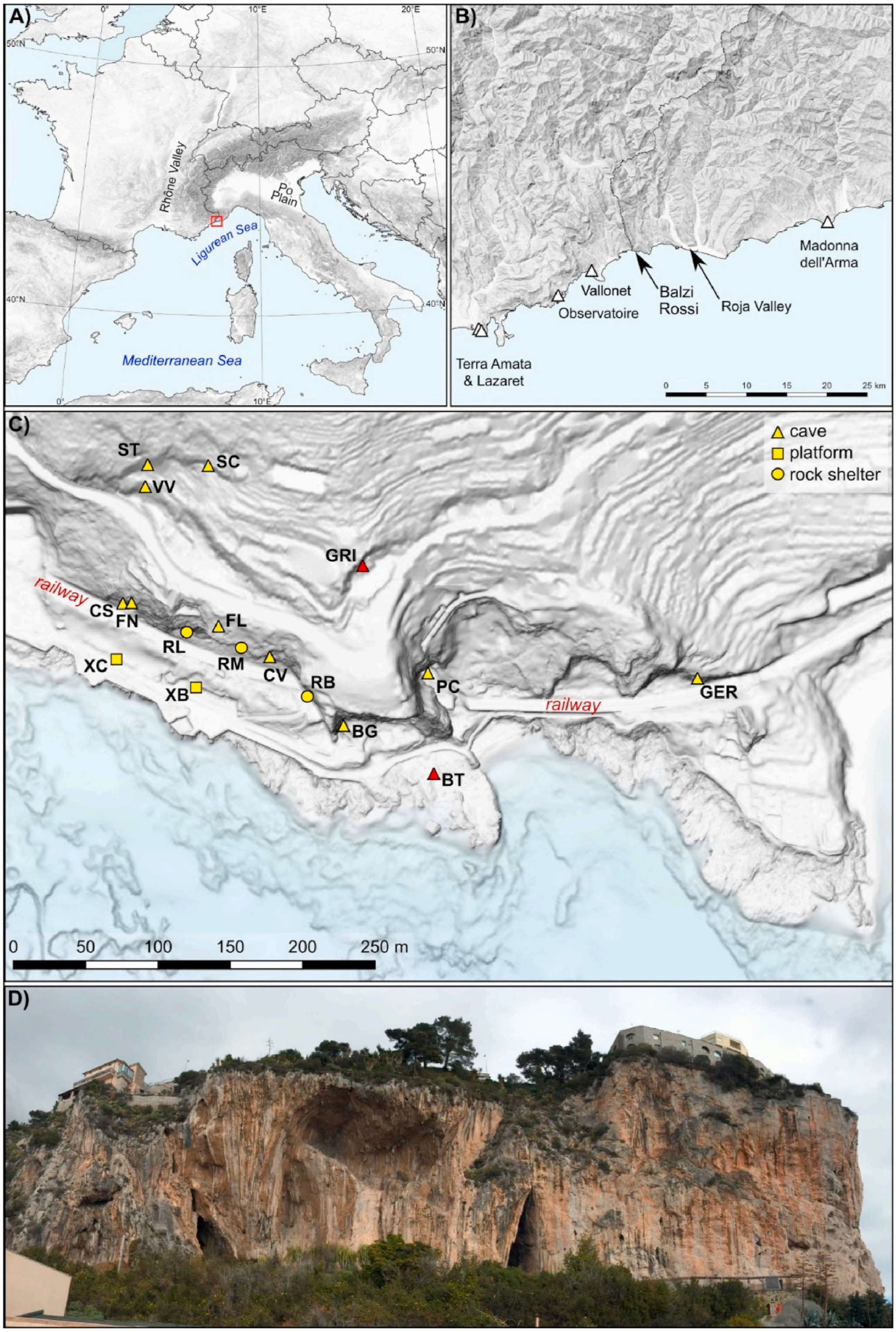

Fig. 1. A) The location of Balzi Rossi, on the southern margin of the Maritime Alps, positions it on a natural migration route between the Po Plain and Western Europe. B) Balzi Rossi is located <300 m to the east of the French-Italian border and is one of numerous sites along this stretch of the coast to show the use of caves by Palaeolithic human populations and/or to retain evidence of Pleistocene sea level at similar elevations to Balzi Rossi (white triangles). C) The archaeological complex includes twelve Palaeolithic sites at varying elevations. The open-air sites Ex-Casinò (**XC**) and Ex-Birreria (**XB**) are found upon a rocky shore platform. The rock shelters (Riparo Lorenzi – **RL**, Riparo Mochi – **RM**, and Riparo Bombrini – **RB**) and most of the caves (Grotta Costantini – **CS**, Grotta dei Fanciulli – **FN**, Grotta di Florestano – **FL**, Grotta del Caviglione – **CV**, Barma Grande – **BG**, Bausu da Ture – **BT**, and Grotta del Principe di Monaco – **PC**) are located near the foot or at middle elevations within the cliff. Barma dei Gerbai (**GER**) was found at a similar elevation but was walled shut before excavations could be completed due to instability. The caves Grotta Voronoff (**VF**), Statua (**ST**), Scimmia (**SC**), and Grotta di Grimaldi (**GRI**) are found at high elevations, ca. 105 m above sea level. These latter caves do not have any record of human occupation, but indicators of high sea level have been reported. Some caves have been partially (Barma Grande) or completely destroyed (red triangles). The individual site names are given in Italian; riparo meaning shelter and grotta meaning cave. D) The red cliffs of Balzi Rossi with the vaults of Grotta dei Fanciulli (left) and Grotta del Caviglione (right) visible. Photograph by A. Zerboni.

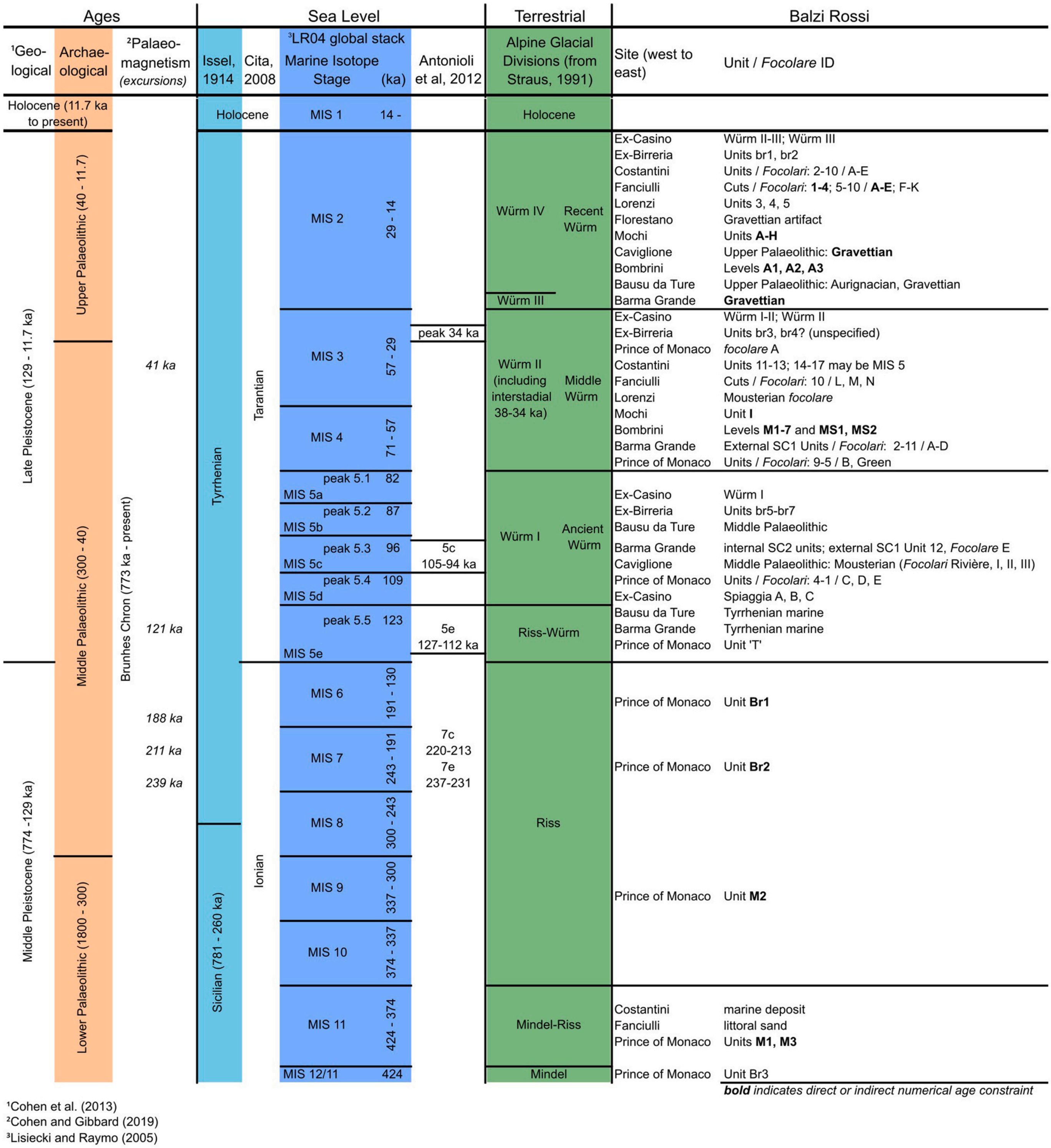

Fig. 2. Global and regional chronostratigraphies shown in comparison with the record of Balzi Rossi (Issel, 1914; Cita, 2008; Antonioli et al., 2021; Straus, 1991; Cohen et al., 2013; Cohen and Gibbard, 2022; Lisiecki and Raymo, 2005).

link between environmental change and human activity. For example, the most recent Mediterranean sea-level record was developed from cave speleothems around Mallorca and within the Tyrrhenian and Adriatic Seas (Antonioli et al., 2021, Table 1). This record provides a comparatively regional record for timing of sea-level highstands within MIS 7 and MIS 5 somewhat offset from the global record by Lisiecki and Raymo (2005), although estimates for the Mediterranean are not as complete. The implication for regional sea-level highstand estimates varies depending on location, but overall variability from the eustatic signal is estimated to be within 2.5 m based upon three different ice sheet models (Stocchi et al., 2018); however, deviations from the eustatic increase during interstadial and glacial periods. Regional variability in the glacial record exists as well, with far fewer Middle Pleistocene glacial/glaciofluvial units recognized for the Italian sectors of the Alps in comparison with the northern and eastern sectors (Monegato et al., 2023).

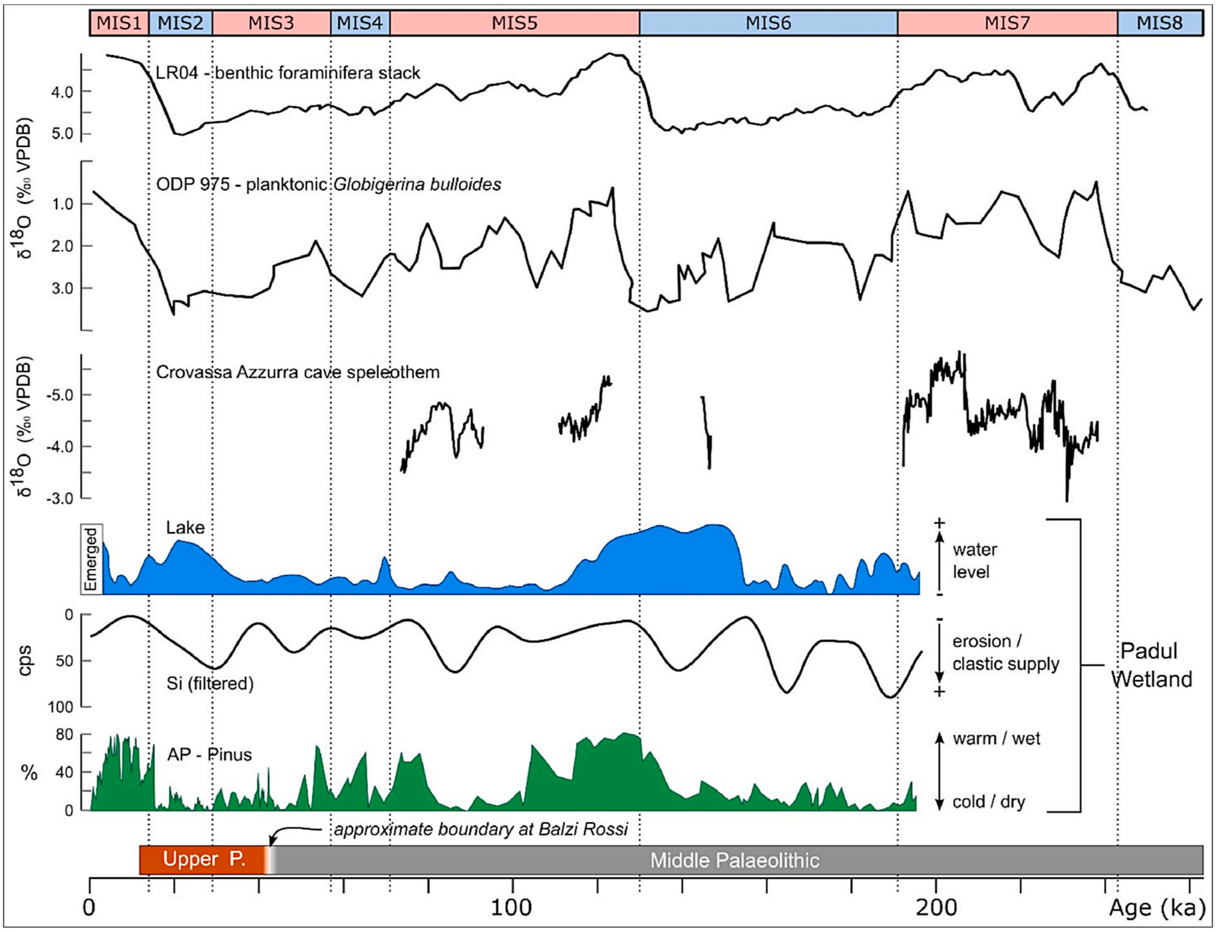

Fig. 3. Palaeoclimate proxies for the past 240 ka of the Western Mediterranean with the LR04 global sea-level curve (Lisiecki and Raymo, 2005) provided for comparison. The higher amplitude of $\delta^{18}O$ oscillation in ODP Site 975 (Menorca Rise) curve in comparison with the global LR04 stack reflects the more restricted environment of the Mediterranean Basin from Atlantic water advection at the Gibraltar strait, and sensitivity to evaporation/precipitation budgets (Pierre et al., 1999). The hiatuses during MIS 5 within the Crovassa Azzurra cave speleothem (Sardinia) coincide with periods of climate instability identified in other Mediterranean speleothem records (Columbu et al., 2019). The Padul-15-05 sediment record (Iberian Peninsula) provides regional palaeoenvironmental and palaeoclimate proxies for precipitation (lake level) and erosion and clastic input and/or biogenic dilution (filtered Si data provided as counts per second), and climate (warm/wet or cold/dry) as indicated by arboreal pollen (AP) percentages with *Pinus* excluded (Camuera et al., 2018). Also shown is the approximate boundary of the Middle to Upper Palaeolithic transition, when *H. sapiens* and Protoaurignacian/Aurignacian industries replace *H. neanderthalensis* and Mousterian industry at Balzi Rossi (see references in text). MIS boundaries are shown as determined from the LR04 curve.

An alternative, more absolute, stratigraphic framework is provided by the palaeomagnetic record (Fig. 2). Excursion events within the Brunhes Chron (Cohen and Gibbard, 2022), where identified, can provide a high-resolution age constraint to a marker unit within a stratigraphic sequence. Since magnetic excursions are globally synchronous, they serve as one of the most definitive markers for correlating worldwide events. However, magnetic excursions are, comparatively, extremely short events within the otherwise long Chron age intervals. In other words, they are rare and can be hard to find.

1.2. Intentions and resources

This review is intended as a summary and guide for the more substantial resources provided as supplementary materials. For each individual site at Balzi Rossi there is a "Site Summary", which are intended as resources for researchers and other interested parties to easily find information particular to a site, including a summary description of the site, a section reproduction where possible (Fig. 4), a synthesis of excavation campaigns, a synthesis of units in order of recognition during excavations, evidence of human occupation, chronological constraint, sample repository locations, and any other information deemed of interest. The synthesis of units of each site is generally listed in a top-down order, contrary to the typical geological approach of oldest to youngest. This approach was chosen because of the overall lack of lithological descriptions and age constraint necessary to define a stratigraphic unit. As elaborated below, many of the deposits were removed in the late 19th – early 20th century before the development of stratigraphic classification methods, or even the recognition of the concept. Our 'top-down' approach reflects the progression of excavation at a site, and in some cases, reflects the development of scientific investigation methods through time.

2. History of excavations

Clarifying the history of excavations and the stratigraphic record preserved within the literature is of utmost importance because most of the original deposits from the caves have been removed and the option of ground-truthing the Palaeolithic sequences and most of the sea-level deposits no longer remains. Moreover, before the introduction of modern laws protecting the archaeological record and heritage in Italy, most of the skeletal remains from the burials and artefacts (e.g., mobiliary art) resulting from the early excavations ended up in private collections that were sometimes sold and transferred abroad (de Villeneuve et al., 1906–1919; Bisson and Bolduc, 1994; Mussi et al., 2008), contributing

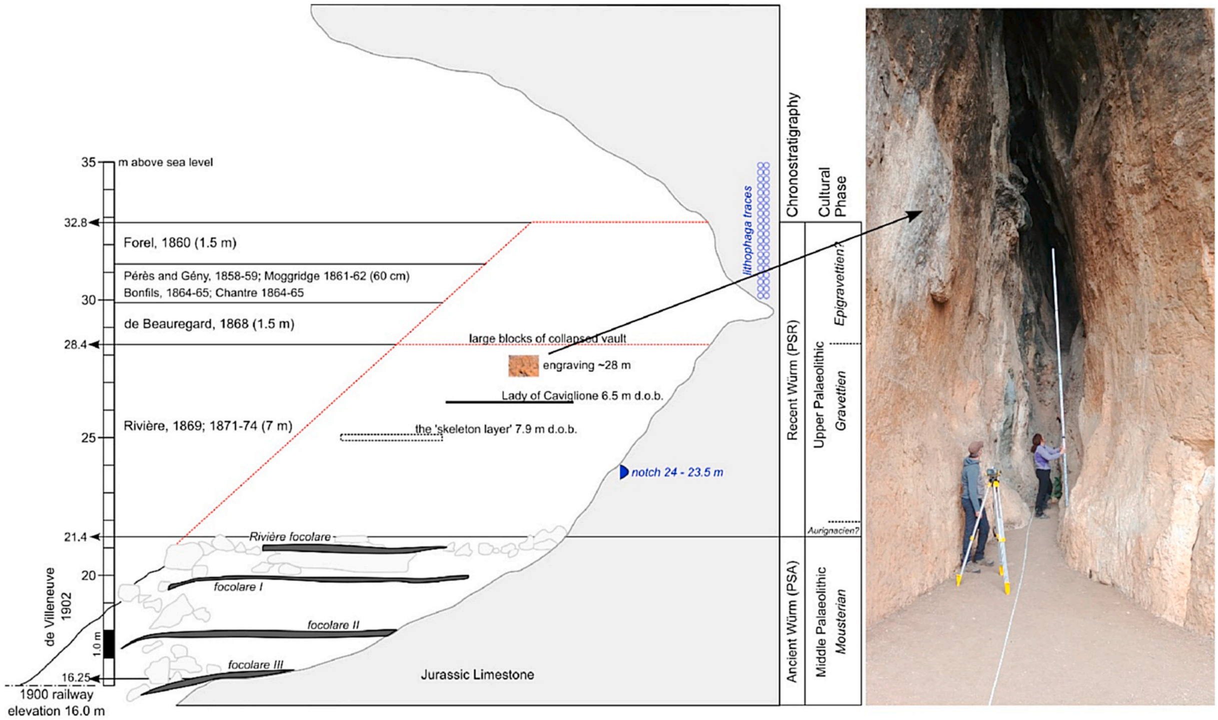

Fig. 4. The Caviglione cave section is provided as an example of a reproduction of cave stratigraphy assembled from descriptions published in earlier literature. This section used as source material, Rivière (1887), Boule (1906), and de Villeneuve (1906–1919) (see Site Summary for figure at full scale and for additional details). For comparison and to illustrate the amount of material that has been removed from the caves, a photo of the cave interior in 2022 with arrow pointing to the approximate location of the top of the engraving indicated at left. The cave floor below the engraving is at approximately 22.5 m above sea level. Photograph by D. D.R.

to the current worldwide dispersion of material culture and incompleteness of the Balzi Rossi legacy.

The earliest documentation of excavation at the Balzi Rossi archaeological complex dates to the middle 19th century and while works at some sites continued into the recent past or are ongoing (Table 1), most excavation at Balzi Rossi took place during the late 19th and early 20th century (Fig. 5; e.g., Forel, 1864; Rivière, 1887; de Villeneuve et al., 1906–1919; Verneau, 1908; see also Pappalardo et al., 2023). However, historical anecdotes of disturbance and excavation before the mid-19th century exist. In his comprehensive discussion of Balzi Rossi, de Villeneuve et al. (1906–1919) chronicles some of these activities: the building of the Roman Road Julia-Augusta (later Via Aurelia) through the site; amateur excavations in the mid-18th Century; multiple undocumented excavations in the 19th Century (Rivière, 1887); and, beginning in the late 18th Century, the partial excavation of some caves for use as limekilns (Fanciulli and Caviglione) and partial or complete destruction of others (Barma Grande, Bausu da Ture, and Grimaldi) through quarrying and as a source of soil. As early as 1858, the Florestano Cave is reported as fully excavated (Forel, 1864; de Villeneuve et al., 1906–1919) and although it is known that the excavation of this cave was directed by Prince Florestan I of Monaco in 1846-47 little other information regarding the work remains. Additionally, de Villeneuve et al. (1906–1919) notes that the presence of "debris" was well known to the regional inhabitants and that such works as mentioned above would not have failed to produce tool artefacts as well as faunal and human remains. Last but not least, is the construction of the railway connecting Ventimiglia (Italy) to Nice (France) in 1870 that literally cut through the Balzi Rossi archaeological area (Figs. 1 and 6), damaging some sites (e.g. the Bombrini rock shelter), while also providing the opportunity for the excavations by Rivière (1887). Therefore, while documentation of excavation begins in 1846, these activities would not have been upon 'pristine' previously unexplored deposits.

The early documented excavations (19th century) were themselves intensive, led by numerous investigators, both amateur and professional, with varying approaches and often completed before the development of modern archaeological methods and cataloguing. Common to the period, cubic meters of material would be removed without stratigraphic context and although finds would be reported, they were not necessarily attributed to a specific cave or location but instead attributed generically to the Balzi Rossi caves, thus hampering provenance of important materials (de Villeneuve et al., 1906–1919, p. 19–22). Limestone quarrying led to the entire destruction the Bausu da Ture cave and removal of the front third of the Barma Grande cave by the beginning of the 20th century. The quarrying works at Barma Grande only halted with the discovery of human burials (Verneau, 1908). These early events have unfortunately resulted in a scattered and incomplete record of stratigraphy and chronology, impeding correlation across the sites (Figure: 5). More detailed documentation began with excavations led by Emilie Rivière between 1870 and 1875, however, these works also lacked adequate stratigraphic context. It was under the direction of Prince Albert I of Monaco that Léonce de Villeneuve completed the earliest careful and well-documented excavations at Balzi Rossi, namely of the caves Fanciulli, Caviglione, Prince of Monaco, and the rock shelter Riparo Lorenzi (Boule, 1906; de Villeneuve et al., 1906–1919; Rossoni-Notter et al., 2021, Rossoni-Notter and Notter, 2022; Moussous et al., 2022). The excavations of both Émile Rivière and Léonce de Villeneuve have a lasting legacy at Balzi Rossi (Rossoni-Notter et al., 2016, 2017) followed by the significant work of Alberto Carlo Blanc and Luigi Cardini on behalf of the Istituto Italiano di Paleontologia Umana (Italian Institute of Human Palaeontology, formerly IIPU, now IsIPU) at the beginning of the 20th century. These early works can be considered a first phase of excavation during which much of the Balzi Rossi materials were removed and stratigraphic sequences destroyed (Table 1). This phase was followed by a second, which broadly spans the 1940s through 1970s, during which time excavations methods were improved but conducted principally by a single party. The third phase, beginning the

Table 1
Excavation history documented at Balzi Rossi.

	Ex-Casinó	Ex-Birreria	Costantini	Fanciulli	Lorenzi	Florestano	Mochi	Caviglione	Bombrini	Barma Grande	Bausu da Ture	Principe di Monaco	Grimaldi/ Gerbai
E. Rivière Classification:				1	2	3		4		5	6	7	9 (Gerbai)
1846						Prince Florestan I							
1847													
1858				F. Forel; S. Bonfils		F. Forel visits		F. Forel; A. Pérès & P. Gény		F. Forel; A. Pérès	F. Forel; A. Pérès		
1859				S. Bonfils									
1860													
1861								J.T. Moggridge					
1862					J.T. Moggride								
1863													
1864								S. Bonfils; E. Chantre					
1865													
1866													
1867													
1868								C. de Beauregard & M. Niepce		C. de Beauregard			
1869								E. Rivière exploration					
1870										E. Rivière			
1871					J.T. Moggride	E. Rivière		E. Rivière					
1872					E. Rivière								E. Rivière
1873											E. Rivière		
1874				E. Rivière									
1875										E. Rivière			
1882										Prince Albert I & Saige			
1883										Prince Albert I & Saige; L. Orsini			
1884										L. Jullien			
1887				G.B. Rossi	G.B. Rossi				E. Rivière report	F. Abbo			
1888													
1889													
1890													
1891													
1892													
1893													
1894													
1895					L. de Villeneuve & F. Lorenzi							L. de Villeneuve & F. Lorenzi	
1900				L. de Villeneuve & F. Lorenzi									
1901											L. de Villeneuve & F. Lorenzi; cave destruction		
1902					L. de Villeneuve & F. Lorenzi			L. de Villeneuve & F. Lorenzi					
1905												L. de Villeneuve & F. Lorenzi	
1912			L. de Villeneuve & F. Lorenzi										

(*continued on next page*)

Table 1 (*continued*)

	Ex-Casinó	Ex-Birreria	Costantini	Fanciulli	Lorenzi	Florestano	Mochi	Caviglione	Bombrini	Barma Grande	Bausu da Ture	Principe di Monaco	Grimaldi/ Gerbai
1928			[IISL] N. Puccioni et al.	[IISL] A. Mochi et al.						[IISL] A. Mochi & A.C. Blanc			
1929													
1930													
1938							[IISL] A.C. Blanc et al.		[IISL] L. Cardini	[IISL] L. Cardini			
1941							[IISL] L. Cardini						
1942										[IISL] L. Cardini			
1949							[IISL] L. Cardini						
1958								[IISL] Cardini					
1959							[IISL] L. Cardini et al.						
1965												[MAP] L. Barral & S. Simone	
1968	[IsIPU] G. Vicino												
1969													
1970													
1976									[IsIPU] G. Vicino				
1980s													[MAP] S. Simone
1990		Università degli Studi di Milano (M. Cremaschi)											
1995							Università di Roma (A. Bietti)						
1996													
1997					Università di Roma (A. Bietti)								
1998													
1999													
2000									Università di Roma (A. Bietti)				
2001													
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2006													
2007							Università di Trento (S. Grimaldi)						
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2013													
2014													
2015									Università degli Studi di Genoa (F. Negrino) & Université de Montréal (J. Riel-Salvatore)				
2016													
2017													
2018													
2019													
2020													
2021													
2022													
present													

IsIPU - Istituto Italiano di Paleontologia Umana (Italian Institute of Human Palaeontology (formerly IIPU).
IISL - Istituto Internazionale di Studi Liguri (International Institute of Ligurian Studies).
MAP – Musée d'Anthropologie préhistorique de Monaco (Monaco Museum of Prehistoric Anthropology).

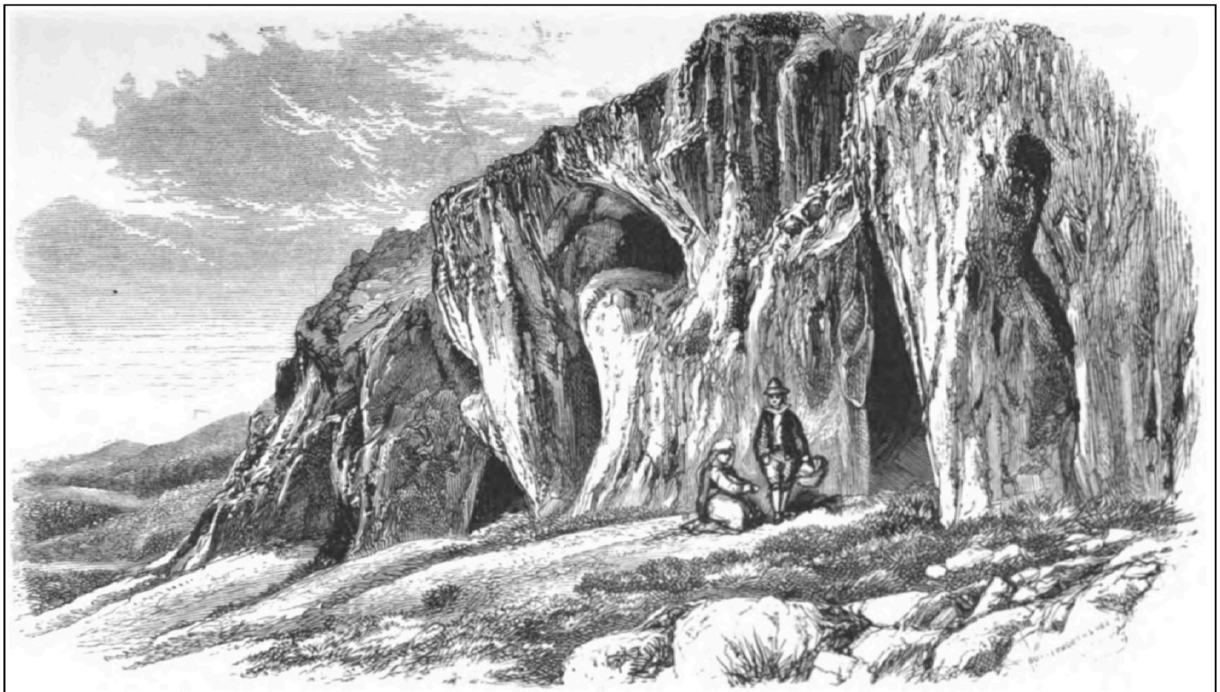


Fig. 5. An early print of the Balzi Rossi caves [the Bone Caves] included in an 1870 (Bennet) publication. The author describes the caves, "… which contain in great abundance organic remains – the bones of large and small mammifers [sic] – imbedded in hard sand and calcareous matter […] mixed with the flint weapons and utensiis [sic] and knives, which have excited so much attention during the last few years …" (page 50).

1990s and continuing today, includes excavations and research conducted by multiple specialists and the application of modern analytical and geochronological techniques.

The extensiveness, and thus significance, of the excavations led by Rivière and de Villeneuve, and conducted by Blanc and Cardini (IIPU/IsIPU), for Balzi Rossi requires, at the very least, the brief review provided here.

2.1. *Émile-Valère Rivière de Précourt (Paris, France, April 22, 1835–January 25, 1922)*

Émile Rivière was a French doctor with an amateur interest in prehistory. He was the co-founder of the Société Préhistorique de France in 1904 that would later become the Société Préhistorique Française in 1911 (Bossavy, 1922). Rivière conducted excavations at numerous Balzi Rossi sites in the 1870s: the caves Fanciulli, Florestano, Caviglione, Barma Grande, Bausu da Ture, and Barma dei Gerbai, as well as the rock shelter Lorenzi (Fig. 1, Table 1). He is also the first to report on the Bombrini rock shelter in 1887 (Rivière). The impetus for his excavations was the exposure, during the building of the railway line in 1870, of abundant evidence of human occupation in the cliff talus intermingled with an ancient marine unit:

> [translated from original French] 'The resulting cross-section showed us not only the considerable depth of the *focolari*[1] of the first four caves, but also how much they extended forward, almost to the edge of the sea, that is to say on the shellfish deposit. Indeed it is immediately above this deposit, whose very surface shows the traces of fire lit by men, that our primitive tribes settled upon their arrival in the country. We found there, so to speak welded in the same sediment and associated with the whitish quaternary marine shells, cut stones, burnt animal bones, as well as ashes and carbonaceous materials, real kitchen debris … ' (Rivière, 1887, p. 101).

Rivière intended to excavate the caves in their entirety, resulting in tens of meters of sediment (in both thickness and depth of the caves) to be removed in an extraordinarily short period of time in comparison with modern archaeological methods. Although the excavations proceeded in cuts of generally 25–30 cm thickness, they apparently did not follow (or record) any stratigraphy (Rivière, 1887; de Villeneuve et al., 1906–1919). Rivière assigned to each excavation site a number (from west to east), which continued to be referred to by later authors (Table 1; de Villeneuve et al., 1906–1919; de Lumley-Woodyear, 1969; de Lumley, 2016 p. 21). Following his death, his personal collection, including artefacts from Balzi Rossi, was auctioned at "Hôtel Drouot" in Paris and since then, much of his collection has been considered missing (Villotte and Henry-Gambier, 2010). It is likely that his excavation records have been destroyed as well.

2.2. *Léonce de Villeneuve (Locmalo, France, April 12, 1858–March 24, 1946)*

At the end of the 19th century, Prince Albert I of Monaco commissioned Léonce de Villeneuve (archaeologist, palaeontologist, clergyman), to excavate four sites: the caves Prince of Monaco, Caviglione, and Fanciulli, and the rock shelter Lorenzi (de Villeneuve et al., 1906–1919; Rossoni-Notter et al., 2016, 2017; de Brunhoff et al., 2019; Notter and Rossoni-Notter, 2022). de Villeneuve also explored the entrance of the Costantini Cave (Notter et al., 2023). Prince Albert I wanted to develop methods of excavation that preserved all potential scientific knowledge (de Villeneuve et al., p. 30–31) and the work by de Villeneuve pioneered many techniques that are now standard in archaeological excavation. Excavations officially began in 1895 and unearthed an extensive and previously undisturbed record of Middle Palaeolithic Mousterian culture. Detailed documentation of the

[1] Rivière, like de Villeneuve after him, was writing in French and therefore in the original text the term '*foyer*' is found. The use of the Italian '*focolare*' was chosen to keep consistency with the use of Italian nomenclature at Balzi Rossi.

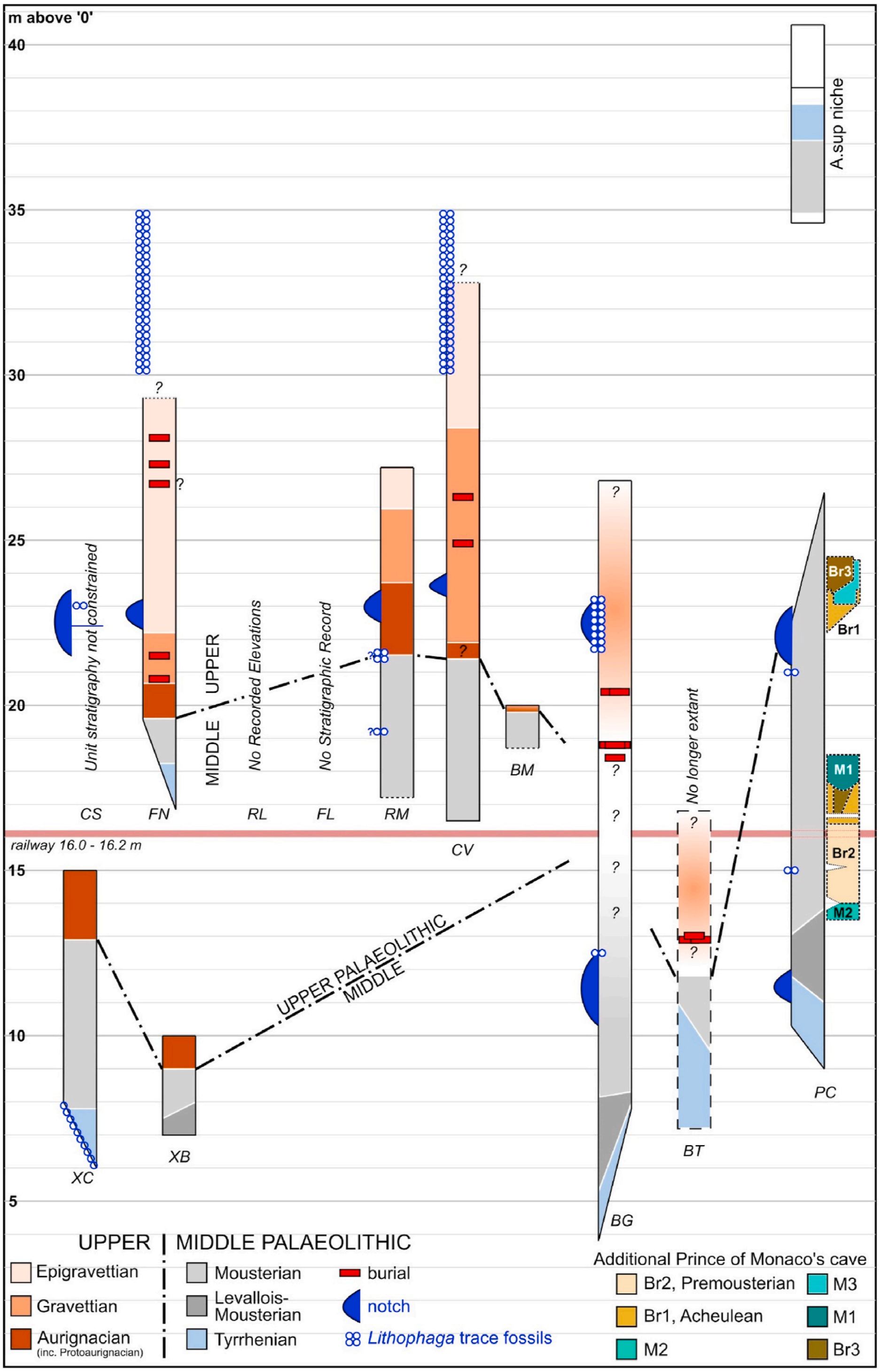


Fig. 6. Correlation of the recorded cultural phases and units across Balzi Rossi, excluding the high elevation caves at the top of the cliff (>100 m) and Barma dei Gerbai. Sections were drawn from elevations provided within the literature (Site Summaries). '?' denote uncertainties or unknowns. Where multiple elevations for cave floor (bedrock) were available, the elevation nearest shoreline (cave mouth) is to right, with elevation further into the cave to the left. The rocky shore platform at the Ex-Casinò site undulates and the bedrock is not representative of the platform slope but rather its variability in elevation. The ca. 1900 railway elevation is shown (reported between 16.02 and 16.20 m asl) when most excavations occurred. From left to right: Ex-Casinò open-air site (XC), Costantini cave (CS), Fanciulli cave (FN), Ex-Birreria open-air site (XB), Lorenzi rock shelter (RL), Florestano cave (FL), Mochi rock shelter (RM), Caviglione cave (CV), Bombrini rock shelter (BM), Barma Grande Cave (BG), Bausu da Ture cave (BT), Prince of Monaco cave (PR).

excavations and stratigraphic drawings (the first from Balzi Rossi) were published in 1902 (Gaudry) and 1906–1919 (de Villeneuve et al.) and remain primary resources for these sites. Boule (1904) and de Villeneuve et al. (1906–1919, p. 119–127) also provides the first detailed description, synthesis, and discussion of marine units and sea-level change at Balzi Rossi. The samples and original documentation from these works are preserved at the Musée d'Anthropologie préhistorique de Monaco [Monaco Museum of Prehistoric Anthropology].

The definition of *focolare* (singular; plural *focolari*), crucial cultural layers throughout Balzi Rossi, is from de Villeneuve et al. (1906–1919) who describes *focolari* as areas, ' … of darker earth, containing ashes and pieces of coal, levels that are particularly rich from a palaeontological point of view and correspond to periods of human occupation' [translated from French, p. 84]. *Focolare* translates directly from Italian into hearth. However, these layers were a more significant feature, alike to an occupation surface but with considerable thickness, and given their magnitude for understanding the Palaeolithic occupation of Balzi Rossi, we chose to recognize their greater meaning by use of the term *focolare*. The sediments between *focolari* were generally considered sterile and very little detail remains of these units. At many of the sites, details of the *focolari* (and the associated burials) are the only stratigraphic information remaining. The cultural changes evidenced by finds associated with *focolari* are also, in most cases, the only chronological constraint.

2.3. *Alberto Carlo Blanc (Chambéry, France, July 30, 1906 – Roma, Italy, July 3, 1960) and Luigi Cardini (13th September 1898–1971); Istituto Italiano di Paleontologia Umana*

In 1928, the newly created Istituto Italiano di Paleontologia Umana (IIPU/IsIPU) was informed of the existence of still unexplored deposits within the Balzi Rossi archaeological area. Financial support from Count D. Costantini made possible excavations, led by Aldobrandino Mochi between 1928 and 1930, of the previously untouched basal Mousterian layers of Barma Grande and Fanciulli caves as well as the entire sequence of the Costantini Cave (see site summaries and references therein). Between 1938 and 1942, the deposits seaward of Barma Grande, near to the original cave mouth, were explored in excavations led by Luigi Cardini, Gian Alberto Blanc, and Alberto Carlo Blanc. During this time the Palaeolithic sequences at the rock shelters Bombrini and Mochi were discovered (Blanc, 1938). Multiple field campaigns until 1959 at the Mochi rock shelter revealed evidence of the transition between Middle and Upper Palaeolithic cultures (Douka et al., 2012).

The IIPU members used the most advanced excavations methods at the time. Investigations began with explorative trenches and more extensive excavations proceeded in select areas using 5 or 10 cm horizontal cuts; artefacts and organic remains were recovered using advanced techniques (Douka et al., 2012). Surviving field notes are available at the IIPU/IsIPU repository in Anagni (Rome). Some materials unearthed during this phase of excavation are exhibited in the National Prehistoric Museum of Balzi Rossi [Museo preistorico Nazionale dei Balzi Rossi], while the remainder is in storage at the IIPU/IsIPU in Anagni.

3. Evidence of Palaeolithic occupation

The Lower-, Middle- and Upper Palaeolithic stages and cultures are differentiated by changes in tool-making techniques and materials. A simple synthesis of industry progression through time in Europe would be: Lower Palaeolithic lithic industry with pebble tools and flakes, then Acheulean hand-axes > Middle Palaeolithic Late Acheulean, Levallois and Mousterian flake technologies > Upper Palaeolithic blade technology and tool industries of greater complexity and sophistication and regional differences. Lower Palaeolithic industry is generally associated with species predating the Neanderthals (e.g., *Homo heidelbergensis*, *Homo erectus*), the Middle Palaeolithic witnesses the expansion of the Neanderthals (*Homo neanderthalensis*) and the widespread use of fire, whereas the Upper Palaeolithic marks the arrival and dispersal of anatomically modern humans (AMH, *Homo sapiens*) through Europe. Although strict boundaries are not placed on the transitions between Palaeolithic stages and cultures because the emergence of new technologies can vary with space and time and the function of the site, and because there can be overlap of industry use, the stages within Europe are broadly associated as such: Lower Palaeolithic (ca. 1600-300 ka), Middle Palaeolithic (ca. 300-40 ka) and Upper Palaeolithic (ca. 40–11.7 ka; Richter, 2011; Jöris, 2013).

Industries of both Middle and Upper Palaeolithic cultures have been identified at every Balzi Rossi site except for the higher elevations caves (Voronoff, Scimmia, Statua and Grimaldi) and the Gerbai Cave. The industries thus far identified at Balzi Rossi are, in increasing age, Upper Palaeolithic Epigravettian, Gravettian, Aurignacian, Protoaurignacian, and Middle Palaeolithic Mousterian (Table 2; Fig. 6). Our text includes

Table 2
Middle and Upper Palaeolithic cultures by site and unit/layer identification.

Cultureal Evidence	Palaeolithic					
	Middle (ca. 300 to 40 ka)			Upper (ca. 40 to 11.7 ka)		
Industry:	Premousterian/final Acheulean	Early (Levallois-) Mousterian	Mousterian	Aurignacian	Gravettian	Epigravettian
Ex-Casinó			Würm II; Würm I-II; Würm I, Beach C	**Würm II-III	Würm III	
ˆ Ex-Birreria		Breccia 5–7; Unit AR	Breccia 3, 4	Breccia 2		
Costantini		Units 11, 12	Units 13, 15, 17		Units 2-10	
Fanciulli			*Focolari* L, M, N	Focolare K	*Focolari* G, H, I; single male burial; the Negroids double burial	*Focolari* A, B, C, (juvenile mandibles, single female burial, the Children's burial); *Focolari* D, E, F
Lorenzi			*focolare*			US3/US4/US5
Florestano					steatite artifact	
Mochi			Unit I	**Unit F, G	Units C, D	Unit A
Caviglione			Rivière *focolare*; *Focolari* I, II, III	lost artefacts	lost artefacts; cave engraving; Dama del Caviglione burial; the 'skeleton layer'	lost artefacts
Bombrini			MS1/MS 2, M1 through M7	**A1/A2/A3		
Barma Grande		Units 7 through 13	Units 2 through 6	undescribed artefacts	Burials: BG1, BG5, BG6, and the Triple burial (BG2, 3, 4); multiple Venus figures	undescribed artefacts
Bausu da Ture			lost artefacts	lost artefacts	All burials	
Principe di Monaco	Units Br1, Br2	Units A, B, C, D, E				

**signifies the presence of Protoaurginacian in at least one of the units.
ˆUnits T1-T14 are not included in the table because due to the nature of the deposits (talus), it is unlikely that they are in their original place of deposition.

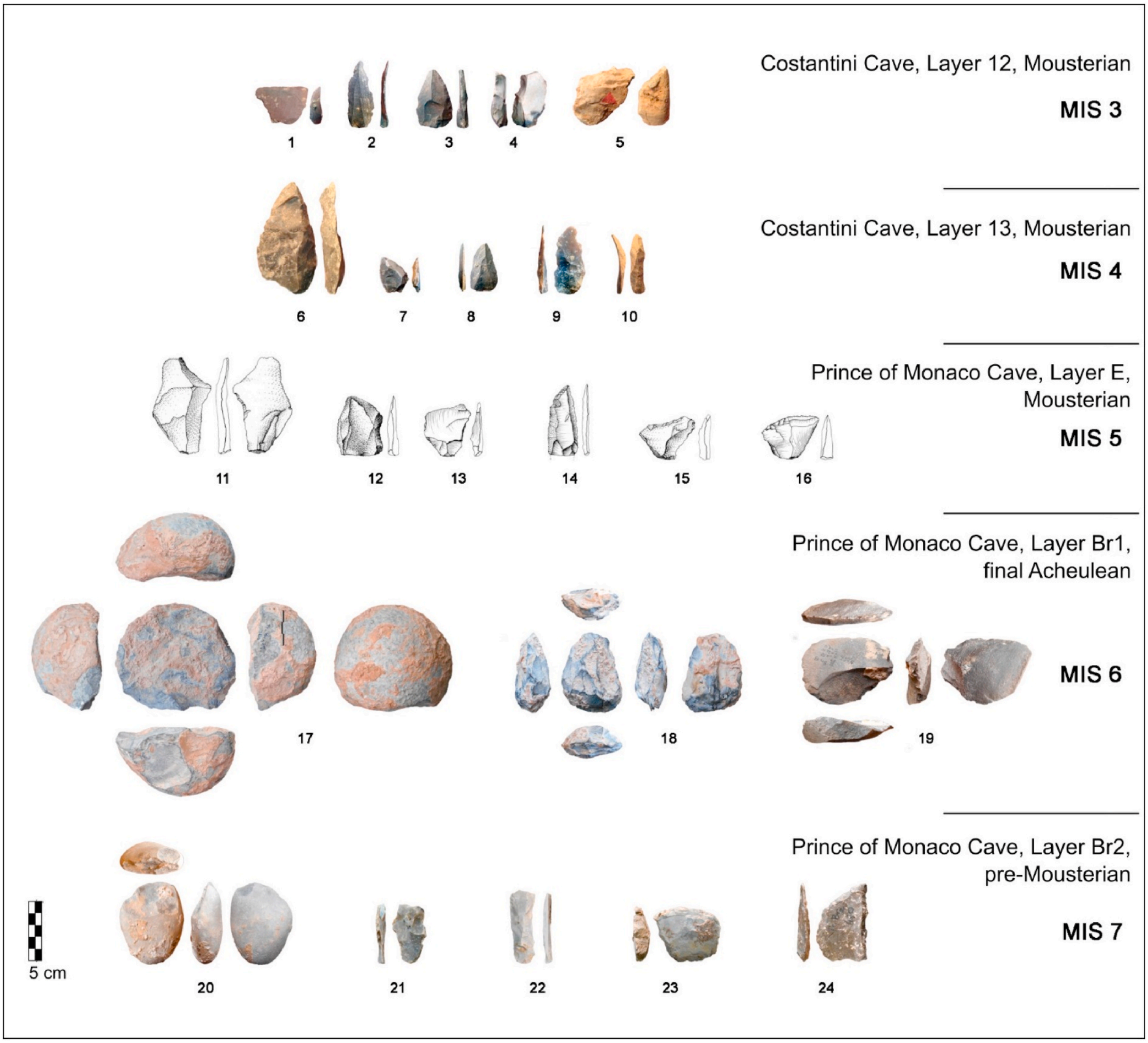
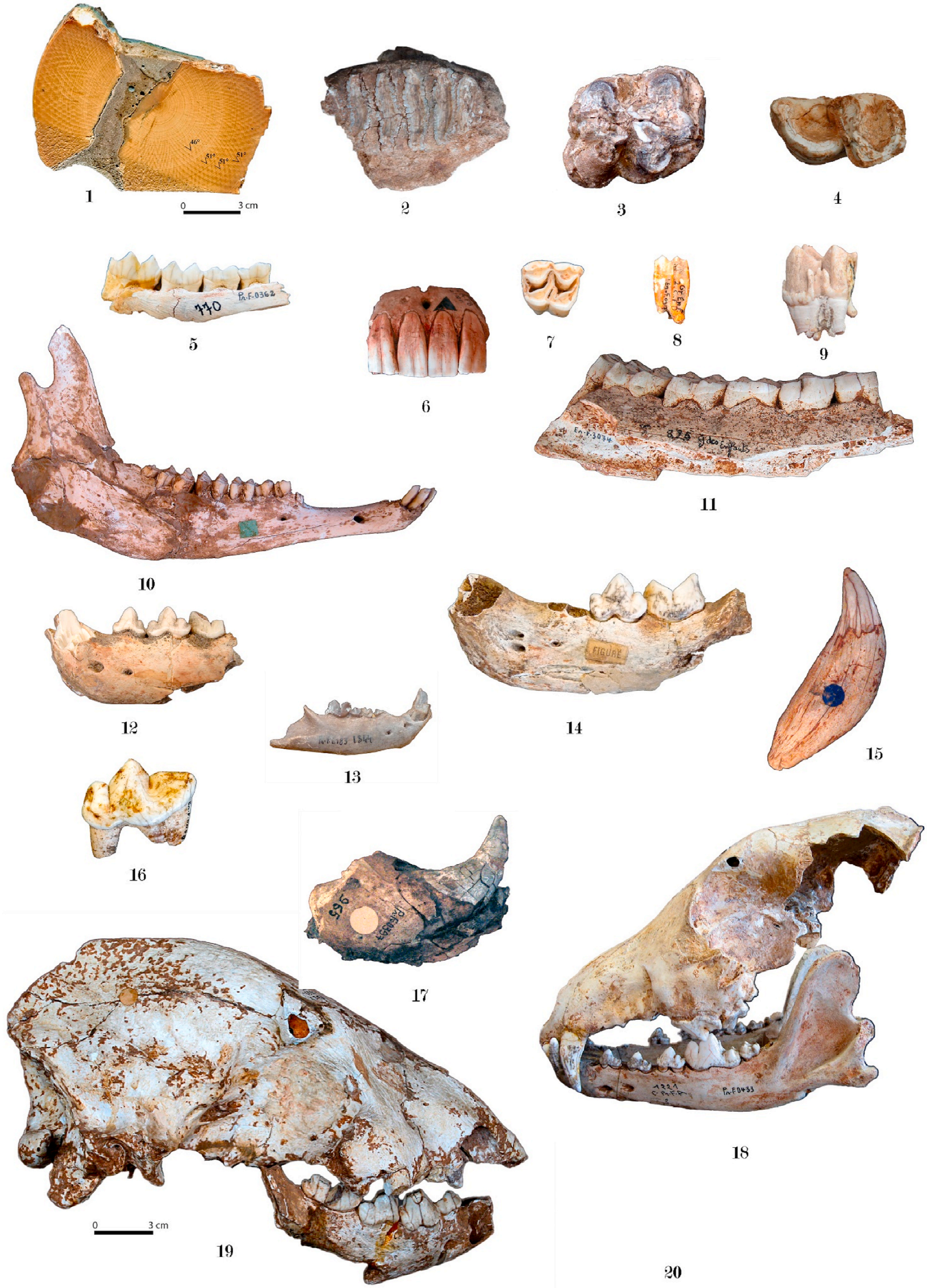


Fig. 7. Examples of the Middle Palaeolithic lithic industry identified at Balzi Rossi. Costantini Cave: **1**. Scraper, limestone; **2**. Levallois point, limestone; **3**. Point on Levallois flake, limestone; **4**. Denticulate, allochthonous flint; **5**. Chopper, I Ciotti flint; **6**. Point, I Ciotti flint; **7**. Transverse scraper, I Ciotti flint; **8**. Levallois point, Perinaldo flint; **9**. Levallois blade, I Ciotti flint; **10**. Blade, Perinaldo flint. Prince of Monaco Cave: **11**. Levallois flake, microquartzite; **12**. Levallois flake, volcanic rock; **13**. Core edged Levallois flake, black flint; **14**. Levallois blade, Ciotti flint; **15**. Transversal scraper, thin Ligurian quartzite; **16**. Transversal scraper on Levallois flake, flint; **17**. Epannelé, marly limestone; **18**. handaxe, glauconitic limestone; **19**. Transversal scraper, black limestone; **20**. Chopping-tool on pebble, marly limestone; **21**. Levallois blade, I Ciotti flint; **22**. Side scraper on blade, I Ciotti flint; **23**. Transversal scraper, limestone; **24**. Point, microquartzite.. (Photographs O. Notter & drawing R. Guillard.)

use of the outdated term Levallois-Mousterian to describe some lithic assemblages where previously designated as such in the old literature but, which have not been re-examined. Lithics attributed to Acheulean have also been identified within the Prince of Monaco Cave (Barral and Simone, 1971; Simone, 1970, 2008; Rossoni-Notter et al., 2016). Here, we present a very brief summary of the evidence for the industries identified at Balzi Rossi. For greater detail and a comprehensive list of resources, please see the Site Summaries (Supplemental Materials).

3.1. Middle Palaeolithic (late Acheulean and Mousterian)

The earliest industry yet identified at Balzi Rossi comes from the Prince of Monaco Cave (Fig. 7). Remnants of breccia deposits (labelled in decreasing age as Br3, Br2, Br1) have been attributed to a period preceding the last interglacial (Kharbouch, 1990; Shen, 1985, Table 3; Figure 5). The supposed oldest, Br3, is 'sterile', or without archaeological evidence. According to the published evidence, Br2 yielded some Levallois flakes associated with ibex, red deer, bear, wolf, and hippo bones (Simone, 1970; Barral and Simone, 1976). An early human iliac bone was found in association with Br2 and dated to 220 ± 120/50 ka by U/Th analysis resulting in association with marine isotope stage (MIS) 8 (Barral and Simone, 1987), a cool period between 300-243 ka (Lisiecki and Raymo, 2005). Br1, higher stratigraphically, was attributed to MIS 6. Additional analyses of the lithics and faunal assemblages assigned the industry to Acheulean and adjusted the age of the units slightly, Br2 to MIS 7 (243 -191 ka) and Br1 to MIS 6 (191-130 ka; Simone, 2008; Rossoni-Notter et al., 2016; Notter et al., 2023). Pollen from Br2 indicates a temperate climate with the micromammal fossils indicative of both open environments and forests (Mussi, 2001). The macrofauna of Br1 indicates a colder climatic phase. The scarce lithic industry of Br1 includes Levallois and discoid methods, scrapers and other archaic types such as choppers, chopping tools and a few hand axes. Although the Acheulean technocomplex can extend into the Lower Palaeolithic, artefacts of the Acheulean can be present within a Mousterian context (Jöris, 2013), and the Prince of Monaco cave deposits are assigned to the beginning of the Middle Palaeolithic.



(caption on next page)

Fig. 8. Examples of big mammal fossil fauna found in association with Upper Pleistocene (predominantly Upper Palaeolithic) units and *focolare* at Balzi Rossi. **1**: Cavillon Cave, *focolare* III n°197: *Mammuthus primigenius*, sectioned tusk fragment showing Schreger lines and angles significantly less than 90°; **2**: Prince of Monaco Cave, layer D n°112: *Palaeoloxodon antiquus*, right maxilla with D3 and alveolus of D4, occlusal view; **3**: Prince of Monaco Cave, layer D n°2102: *Hippopotamus amphibius*, upper molar, occlusal view; **4**: Prince of Monaco Cave, layer D n°2109: *Stephanorhinus kirchbergensis,* Lower right second molar, occlusal view; **5**: Prince of Monaco Cave, layer D n°362: *Dama dama,* Left Mandible, lingual view; **6**: Cavillon Cave, layer II n°211: *Equus caballus germanicus,* premaxilla, labial view; **7**: Prince of Monaco Cave, layer B or C n°4522: *Rangifer tarandus,* Right superior second molar, occlusal view; **8**: Children's Cave, indeterminate layer n°917: *Rupicapra rupicapra,* Right superior third molar, vestibular view; **9**: Children's Cave, layer 5 n°2709: *Cervus elaphus*, Right superior third molar, lingual view; **10**: Prince of Monaco Cave, layer B n° 686: *Capra ibex*, right mandible, side view; **11**: Children's Cave, layer 7 n°3074: *Alces alces*, left mandible, Wearing the dental series P3-M3, side view; **12**: Cavillon Cave, layer, layers superior n°10892: *Lynx lynx,* left mandible with canine, P3, P4 and M1 of an elderly individual, side view;**13**: Prince of Monaco Cave, layer E n°6183: *Felis silvestris*, right mandible, side view; **14**: Prince of Monaco Cave, layer B n°69: *Panthera pardus,* left mandible, side view; **15**: Prince of Monaco Cave, layer C n°775: *Ursus spelaeus*, right lower canine, vestibular view; **16**: Children's Cave, layer 4 n° 48: *Panthera (Leo) spelaea*, left superior fourth premolar, side view; **17**: Prince of Monaco Cave, layer E n°397: *Ursus arctos*, right mandible, side view; **18**: Prince of Monaco Cave, layer A n°433: *Canis lupus*, skull and mandible, side view; **19**: Prince of Monaco Cave, layer D n°457: *Crocuta crocuta spelaea*, skull and mandible, side view. (Photographs by A. Moussous. See Summaries for stratigraphic context and additional details.)The early Upper Palaeolithic Protoaurignacian and Aurignacian lithic artefacts found at Balzi Rossi testify to the presence of the earliest groups of AMH settling the area. Lost or undescribed artefacts attributed to the Aurignacian were reported at the Caviglione, Barma Grande, and Bausu da Ture caves (Site Summaries). Aurignacian, and in some locations, the earlier Protoaurignacian, have been identified in the slope deposits at the Ex-Casinò and Ex-Birreria open-air sites, Mochi and Bombrini rock shelters, and the Fanciulli cave. The sequence continues into the Gravettian, which has been identified at most Balzi Rossi sites.

Mousterian lithics have been confidently identified at every site in Balzi Rossi (Table 2; Fig. 6). Significantly, Mousterian lithics are found intermingled with Tyrrhenian (Section 5) marine sediments at the Ex-Casinò and Ex-Birreria open-air sites and Barma Grande and Prince of Monaco caves (Site Summaries). Excavations at Ex-Casinò and Ex-Birreria relate the fossil beach preserved at the base of the continental sequence to the 'Tyrrhenian' highstand (MIS 5e) and show it to be settled by a group of Neanderthals soon after sea level began to fall while the shoreline was still very close (Vicino, 1974, 1976; Cremaschi et al., 1991; Mussi, 2001, p. 128). The lithic industry exploits marine *Callista chione* shell and beach pebbles from the local siliceous formation "I Ciotti", but analyses remain largely unpublished (Vicino, 1974; Negrino, 2002; Douka and Spinapolice, 2012). Within the terrestrial unit directly overlaying the beach unit at Ex-Casinò some charcoals were documented and fauna remains composed mainly of red deer with minor quantities of aurochs, rhinoceros, wild boar, bear and rabbit (Vicino, 1976). Charcoals and burnt bones were found at the adjacent Ex-Birreria within a coeval *terra rossa* soil-type developed upon the rocky shore platform (Cremaschi et al., 1991).

A *focolare* I, likely of similar age to the charcoals at Ex-Casinò, was documented upon the Tyrrhenian beach at the entrance of Barma Grande cave (Cardini, 1938). A few unretouched chert artefacts and some fauna, including auroch, were collected from this context. A large quantity of ashes, spread over tens of square meters, on the Tyrrhenian beach inside and outside of the Prince of Monaco cave were also mentioned by de Villeneuve et al. (1906–1919). This evidence of extensive fire is tentatively used as an indication of a wooded landscape (Mussi, 2001, p. 129).

A recent (Rossoni-Notter et al., 2017) re-examination of the lithic collections preserved in France and the Monaco Principate found the Mousterian industries from the Caviglione and Prince of Monaco caves to have in common the use of hard hammers and Levallois method to produce points and blades and volumetric reduction. However, the earliest assemblages from the Prince of Monaco cave (the units associated with *focolari* D and E) are distinguished by the presence of large flakes, pebble tools, and 'limaces', frequently showing scaled retouch. These units share some commonalities with the early Mousterian units at Ex-Birreria and Ex-Casinò. Other units from the various Balzi Rossi sites yielded more idiomatic assemblages. Still within the Caviglione cave, the youngest Mousterian unit (the Rivière *focolare*) is distinguished by massive, elongated blades produced by Levallois method and blade reduction. The Mousterian assemblage from the Lorenzi rock shelter is characterized by an over-representation of prepared-core techniques (SSDA, blade reduction, Levallois methods; Rossoni-Notter et al., 2017). Arguably the longest and most well constrained (both stratigraphically and geochronologically) Mousterian record is that from the Mochi rock shelter with investigations still ongoing. As this work progresses, correlations with other sites at Balzi Rossi may be found and, potentially, contact with the MIS 5e marine deposits.

3.2. *Upper Palaeolithic (Protoaurignacian, Aurignacian, Gravettian, Epigravettian)*

The Upper Palaeolithic record across Balzi Rossi is less precise (Table 2; Fig. 6; Site Summaries). Many of these units correspond to those excavated in the late 19th and early 20th centuries and would have been the source of much of the material that has been lost with time; although the Musée d'Anthropologie préhistorique de Monaco [Monaco Museum of Prehistoric Anthropology] retains numerous big mammal fauna remains, which serve as palaeoenvironmental proxies (Fig. 8; Moussous et al., 2014; Notter and Rossoni-Notter, 2022).

The Gravettian culture is marked by ornamental funerary behaviour, burials containing multiple individuals (also described as multiple burials), and artistic production not only at Balzi Rossi but across Europe, indicating a cultural homogeneity and an expanded network of direct or indirect contacts between distant populations (Formicola and Holt, 2015). Over a dozen burials have been uncovered at Balzi Rossi, to-date only within cave environments; specifically, Fanciulli, Caviglione, Bausu da Ture, and Barma Grande (Figure: 5). Documentation of burial finds during the late 18th century (predominantly by Rivière) is poor and some skeletons have been partially or completely lost. However, decoration of the skeletons, often with marine shell and ochre, and inclusion of other grave goods is a common theme (Rivière, 1887, de Villeneuve et al., 1906–1919, Verneau, 1908; Site Summaries). Burials containing multiple individuals were found in the Fanciulli cave (the 'Fanciulli' [Children's] burial, the double sepulchre, and a burial containing the mandibles of two children) and in Barma Grande cave (the 'Triple' burial).

Instances of Gravettian art have been found throughout Balzi Rossi. Parietal [cave] art has been documented at Fanciulli, Florestano, Caviglione and Barma Grande caves, as well as at the Mochi rock shelter (Vicino and Simone, 1972, 1976; Sigari, 2022). The most well -known instance, is the engraving within Caviglione cave that has been interpreted as a horse (Vicino and Simone, 1976) or reindeer (Sigari, 2022). This engraving was found in 1971 on the western wall of the cave ~4.4 m below the original surface of the deposit at a level equivalent to Gravettian deposits and on the opposite wall from where the "Lady of Caviglione" burial was located, although the burial was at a depth ~2 m lower (see Site Summary). The engraving has been attributed to the Gravettian due to this stratigraphic association, although an Epigravettian age is also possible (Douka and Spinapolice, 2012). Other notable examples of Gravettian art cultural material are the Venus figurines from the Barma Grande and Prince of Monaco caves discovered by Louis Jullien, a French antiquities dealer, in the late 19th century.

These figurines, significant for their implications for AMH societal beliefs and broad European networks, were subject to much controversy regarding provenance and authenticity (Bisson and Bolduc, 1994; Mussi et al., 2000, 2008; Formicola and Holt, 2015). Parts of the collection, thought permanently lost, were only relocated in 1990 and are now considered most likely authentic (Bisson et al., 1994).

At present, the Mochi sequence is the most complete Palaeolithic record at Balzi Rossi, conserving layers of the Epigravettian, Gravettian, Aurignacian, Protoaurignacian and late Mousterian. According to recent analysis (Frouin et al., 2022) the oldest Mousterian levels date to MIS 4 with the deposit continuing below the current bottom level of the excavation. Excavations at Mochi rock shelter began only in 1938, led by the Italian A.C. Blanc, with more modern methods, and continued through the 1950s led by L. Cardini, but the materials remained largely unpublished for a long time (Laplace, 1977, Table 3). Excavations resumed in the 1990s and are ongoing. The completeness of the Mochi record recommends its use as the reference stratigraphy for establishing the main period of human presence at Balzi Rossi and helps to correlate the evidence gathered during past excavations at other Balzi Rossi sites. It also provides a record of palaeoenvironmental change from MIS 5 through MIS 3, providing insight into potential climatic drivers of Neanderthal population demise (Perez et al., 2022).

3.3. Synopsis

Except for the high elevation caves at the top of the cliff, all the caves and shelters at Balzi Rossi were undoubtedly settled during the Middle and Upper Palaeolithic. Unfortunately, because excavations have been conducted at different locations within the archaeological complex, by different research groups with separate analysis (Section 2), a perception has been created that each site is a unique location. Actually, Balzi Rossi represents a large composite settlement system with the various locations within the cliffs most probably visited and/or occupied contemporaneously by the same human groups for their subsistence activities.

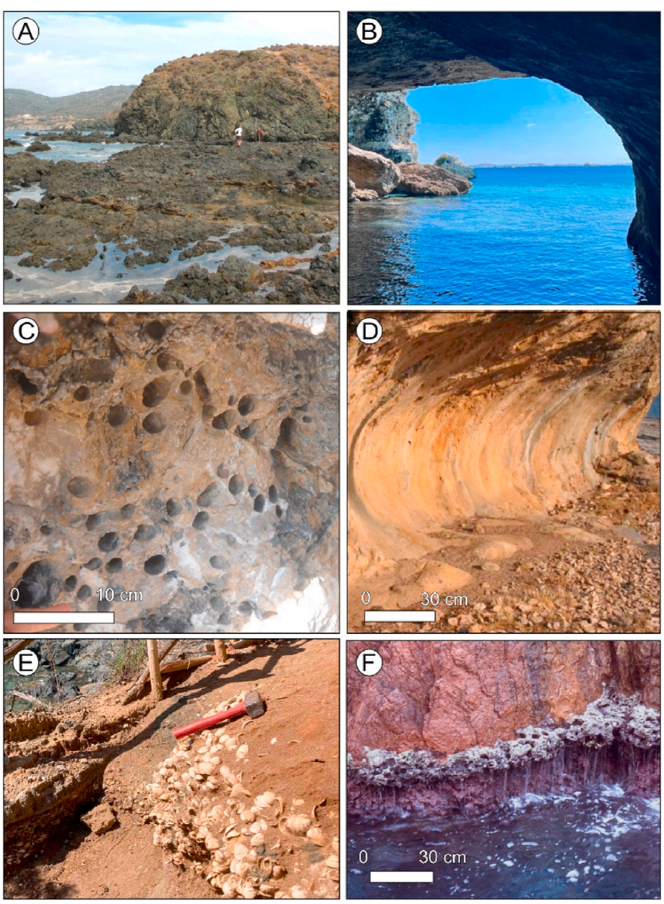


Fig. 9. Examples of landforms, trace fossils, and deposits commonly used as sea-level indicators within the Mediterranean. A) Relict shore platform in Lesvos Island (Greece). B) Modern coastal cave in Corsica Island (France). C) Relict boreholes (*Lithophaga lithophaga*) in Lesvos Island (Greece). D) Relict abrasion notch in northern Morocco. E) Relict beach deposit in central Tuscany (Italy). F). *Lithophyllum byssoides* rims in Corsica Island (France).

The likelihood of contemporaneous occupation is supported by the records from the Mochi and Bombrini rock shelters. Excavations at these two locations are consequential as they have been conducted using modern archaeological methods upon largely intact Palaeolithic deposits. Separated by a distance less than 50 m, the rock shelters provide well constrained evidence of a swift transition between Middle and Upper Palaeolithic industries and cultures with multiple layers correlated across the two sites (Holt et al., 2019; Frouin et al., 2022; Perez et al., 2022). The transition from Mousterian types to Protoaurignacian/Aurignacian is significant due to its implications for the debate surrounding the arrival of *H. sapiens* into western Europe and the demise of *H. neanderthalensis*, both events which occurred within MIS 3 around 42 ka (Fig. 3; Douka et al., 2012; Grimaldi et al., 2014; Benazzi et al., 2015; Falcucci et al., 2017; Perez et al., 2022). MIS 3 (57-29 ka; Fig. 2) was a period characterized by rapid climate oscillations and instability (Weber et al., 2018; Badino et al., 2020, 2023). During this period of intermediate sea level at roughly 40 m below present (Gowan et al., 2021), the coastline would have been ~1.5 km to the south of the Balzi Rossi complex and reaching ~2 km to south at the close of MIS 3, producing a relatively broad coastal landscape at the front of Balzi Rossi.

The discovery of Mousterian industry intermingled with Tyrrhenian marine deposits make Balzi Rossi one of the few locations in the world showing Neanderthal interaction with and exploitation of the coastal environment at such an early date in Europe (Douka and Spinapolice, 2012). The documentation from the no longer extant Bausu da Ture Cave does not indicate whether the Mousterian industry was found intermingled with the marine sediments, however, given its similar elevation to the other sites, it would seem likely. Continued excavation at the Mochi rock shelter will enable the exploration of Mousterian and potentially other Middle Palaeolithic cultures using modern archaeological methods, with the potential at depth, to find further evidence of Neanderthal interaction with their coastal environment. This opportunity is also available at the Bombrini and Lorenzi rock shelters; however, to-date these excavations are closed.

4. Relative (palaeo) sea-level indicators

Palaeo sea-level indicators are used in the reconstruction of past global mean sea level and sea-level change (Fig. 9: Shennan, 1986; Rovere et al., 2023a; b). Ancient interglacials (periods of high sea level and optimal climatic conditions) are useful as process analogues and for investigating climate feedbacks and the interplay between ice melt at high latitudes and ocean circulation (Hansen et al., 2016). Marine isotope stage (MIS) 5e and MIS 11 are interglacials of particular interest to the global community for having characteristics predicted in models of future climatic change. The MIS 5e (the Last Interglacial, ca. 125 ka) is notable for its warmer global temperatures, smaller ice sheets, and higher global mean sea level, whereas MIS 11 (ca. 400 ka) was a particularly long interglacial with similar orbital characteristics to Earth today that also likely had a higher global mean sea level (Siddall et al., 2007; Raymo and Mitrovica, 2012; Past Interglacials Working Group of PAGES, 2016). Palaeo sea-level indicators are also used for constraining palaeo-ice sheet limits, to improve models of dynamic topography and glacio- and hydro-isostatic adjustment (GIA), and for future predictions of ice-sheet and sea-level responses to regional warming (Capron et al., 2019; Golledge, 2020).

Estimates of palaeo sea level from the geological record are

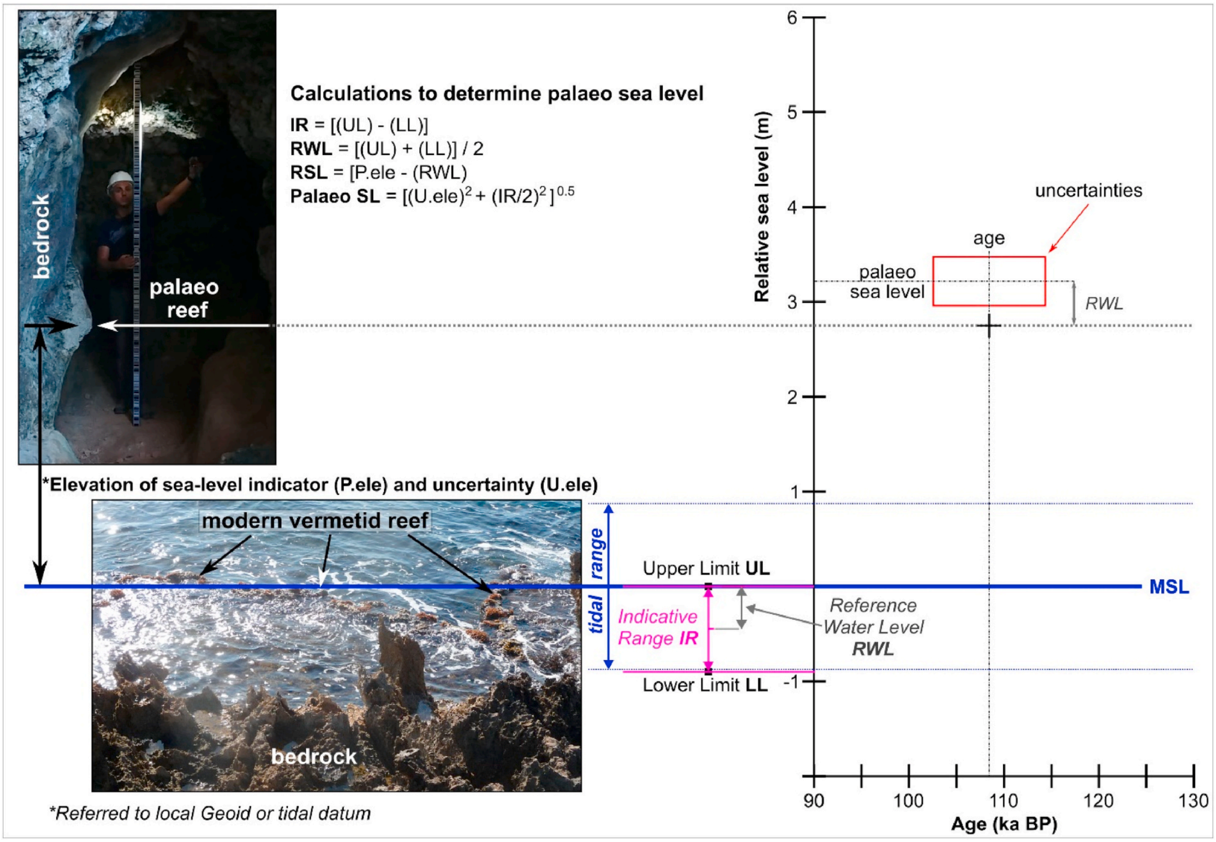


Fig. 10. An illustrative example of how palaeo sea level is determined from a sea-level indicator and modern analogue. This example is of a biological vermetid reef. The indicative range is determined by the location where the modern analogue is found in relation to the tidal range; modern vermetid reefs grow within the lower mesolittoral (upper limit) and upper infralittoral (lower limit) zones (Chemello and Silenzi, 2011). Palaeo sea-level estimates incorporate uncertainties in both elevation measurements and numerical age determination.

Table 3
Sea-level indicators at Balzi Rossi. (Elevations are provided above a generic '0 m' sea level as tidal datum is not defined in literature.)

SEA-LEVEL INDICATORS	Bedrock Elevation	Older Pre-Tyrrhenian			Mindel-Riss			Tyrrhenian (Riss-Wurm/MIS 5)		
		unit(s)	notch (es)	*Lithophaga*	unit(s)	notch (es)	*Lithophaga*	unit(s)	notch (es)	*Lithophaga*
Ex-Casinó	6–8 m							Beach A, B, C; Senegalese fauna; shore platform		6–8 m
Ex-Birreria	7 m							shore platform		
Costantini	n/a				beach and coastal sands	23.5–21.5 m	23.8 m			
Fanciulli	16.82			35 - 30 m	littoral dunes	23.2–22.3 m				
Lorenzi	n/a	none								
Florestano	n/a	none								
Mochi	n/a					23-5 - 22.5 m	21.7–21.3 m			
Caviglione	16.25 m			35 - 30 m		24.0–23.5 m				
Bombrini	n/a	none								
Barma Grande	7.8 m					23.3–21.7 m		Unit 13 with Senegalese fauna	12.5–10.3 m	
Bausu da Ture	7.2 m							Tyrrhenian with Senegalese fauna		
Principe di Monaco	9–10.3				M1/M3 (Midel-Riss), M2 (Inter-Riss)	23–22.2 m	22 m (Mindel-Riss)/15 m (Inter-Riss)	Unit T with Senegalese fauna; A-sup Level 2	12 - 11 m	
Grimaldi Caves	n/a	sediments & oysters (Grimaldi 105 m); Statua; Voronov		108 m (Voronov)						

determined from the measurement, analysis, and interpretation of the relationship of the palaeo feature with contemporary mean sea level (Fig. 10). Geological indicators of relative sea-level are landforms, sedimentary or biological deposits whose formation/deposition can be correlated with a tidal datum (van de Plassche, 1986; Shennan, 1986; Shennan and Horton, 2002). 'Relative' is used in the discussion of palaeo sea-level indicators within the geological record to encompass any post-depositional processes that may explain the elevation difference between the palaeo marker and the elevation of modern analogues (Khan et al., 2015; Rovere et al., 2016). Regional palaeo sea-level records typically vary from estimates of contemporaneous global mean sea-level due to the localized effects of proximity to ice sheets and vertical land movements (e.g., tectonics, dynamic topography). Additionally, constraints on sea-level elevation estimates differ by indicator type due to variability in the indicative range, i.e., how well constrained an indicator is to a tidal range (Rovere et al., 2016; see below).

With the awareness for the variability of regional sea-level records and the need for well-constrained relative sea-level indicators, there has been a push to standardize how geological sea-level information is both collected and stored (Rovere et al., 2016, 2023a). Most of the excavations at Balzi Rossi occurred before the recognition of sea-level change as an important record of global climate variability and when the study of global sea level as a science was still in the early stages of development. Rovereto (1939), in an early discussion of Quaternary marine evidence at Balzi Rossi, recalls that De Saussure (1780, pg. 186) mentioned that some features along the cliff, including the caves themselves, had been sculptured by the sea. Rovereto also provides a synoptic cross-section of the cliff along-profile (Fig. 193, pg. 697) with the elevations of marine features and assigns tentative ages, which challenge a sea-level history proposed by Boule (1906). However, although the early investigators of Balzi Rossi may have made note of a marine unit and/or provided a species list of marine fossils recovered from each site, stratigraphic and lithological descriptions are largely absent (site summaries and references therein). The fossil assemblages were not collected with the intention of palaeoecological insight and as a result, the taxa list can only provide a qualitative palaeoecological interpretation. Additionally, most of the described features are missing an important property for a high-quality sea-level indicator, that is an elevation referred to a defined height datum. Although altitudes are available in the literature, a sea-level datum has not been defined and it is not certain, in many instances, that the measurement is in reference to mean sea level, or, if to sea level, what national reference was used. It is for this reason that the elevation measurements provided here (Fig. 6 and Site Summaries) are referred to an elevation above *assumed* sea level (asl).

Like the continental deposits, the marine depositional units have in almost every case been completely removed or had their original context destroyed and ground-truthing the literature is not possible. Other sea-level indicators common at Balzi Rossi are *Lithophaga* trace fossils and marine notches. These features are rarely reported in the early literature (Boule, 1906) and the first comprehensive record of them is found in de Lumley-Woodyear (1969), but it is unclear from the text who first made these records.

4.1. Erosional morphologies: coastal caves, notches, and abrasion surfaces

The caves at Balzi Rossi are karstic features, formed along fault lines within the Jurassic limestone bedrock by chemical dissolution (driven by the location of groundwater as dictated by sea level), and altered by bioerosion and mechanical abrasion processes, including wave action (Carobene, 2015; Van Hengstum et al., 2015). In support of the apparent marine contribution to cave formation, sea-level indicators have been found in all the caves except for Florestano (Table 3; Fig. 6). The level of the bedrock floor near the cave entrance can provide a minimum marker for sea level corresponding to the minimum level of constant wave action (Rovere et al., 2016). Bedrock elevations have been recorded at the mouths of five caves. At the higher elevation Caviglione and Fanciulli caves the bedrock is recorded at ~16.5 m asl (de Villeneuve et al., 1906–1919; Graziosi, 1939), whereas the elevation at the lower Barma Grande and Bausu da Ture caves is ~7.5 m asl (de Villeneuve et al., 1906–1919; Cardini, 1938). The bedrock near the mouth of the Prince of Monaco Cave is found at ~9.0 m asl (de Villeneuve et al., 1906–1919). This cave differs from all other sites at Balzi Rossi in that the rock forming the base of the cave is Cenomanian marl.

The same processes forming the coastal caves, are responsible for the development of the marine notches identified within many of the caves and the rocky shore platforms underlying the sedimentary sequences at the Ex-Casinò and Ex-Birreria sites (Griggs and Trenhaile, 1994; Stephenson, 2000; Carobene, 2015; Kennedy, 2015; Trenhaile, 2015). However, where they form in association with sea level differs.

Notches have been reported in the literature within the Costantini, Fanciulli, Caviglione, Barma Grande, and Prince of Monaco caves, as well as on the cliff surface exposed by the Mochi shelter excavations. Most of these features are first reported in de Lumley-Woodyear (1969). Notches formed within coastal caves are argued to form under slightly different processes (bioerosive) than those externally (abrasion or tidal) resulting in a different relationship to sea level, typically forming slightly below mean sea level (Carobene, 2015). The external notch identified at the Mochi shelter could be either an abrasion notch formed by the movement of sand, gravel, or pebbles against the rocky surface by wave action, or a tidal notch formed from bioerosion, wave action, and tidal wetting and drying cycles. Abrasion notches typically from between storm swash height and the breaking depth of waves, whereas tidal notches form within the tidal zone and therefore are a more precise indicator of former relative sea level (Rovere et al., 2016). The notches at Balzi Rossi are broadly divisible into two elevation ranges asl: 23.5 m–21.5 m and 12 to 10 m (Table 3; Fig. 6; Boule, 1906; de Lumley-Woodyear, 1969); although notches at intervening elevations have been reported in the Prince of Monaco Cave (Barral and Simone, 1976).

The preferred sea-level indicator of rocky shore platform features, such as those underlying the sediments at Ex-Casinò and Ex-Birreria, is the landward margin, where the sub-horizontal surface meets the vertical rocky cliff (Kelsey, 2015; Rovere et al., 2016). Where that contact point is not visible, such as is the case at Balzi Rossi, abrasion surfaces are usually considered as indicators for minimum heights of sea level because although it is certain that they formed at breaking wave depth or above, there is no way to constrain the peak height of the sea-level transgression from which they formed. The abrasion surfaces at Ex-Casinò and Ex-Birreria measure between 6 and 8 m asl.

One other marine abrasion surface has been identified at Balzi Rossi and that is the sill-pothole structure at the bottom of the Barma Grande cave. Potholes are sub-cylindrical rockpools formed by the exploitation of a pre-existing depression (generally a fracture or joint pattern) by high-energy waves (Shaocheng et al., 2018; Green et al., 2023). The sill is the bedrock high seaward of the pothole. The wave energy creates turbulence, or even a vortex, within which sediments impact upon or are dragged along the bedrock surface. The main factors therefore that determine the formation and shape of a pothole are the bedrock type, the presence of sediment, and the occurrence of mechanical erosion, namely abrasion. Potholes form within the intertidal zone, typically at its seaward margin (Miller and Mason, 1994; Green et al., 2023).

4.2. Biological indicators: lithophaga trace fossils and bioencrustations

Lithophaga lithophaga are rock-boring date mussels common to the Mediterranean coastline. These bivalve molluscs inhabit rocky coastlines by boring into the rock, usually limestone. The boreholes created by the molluscs are usually all that remains in the geological record, hence their reference as a trace fossil. The common habitat zone of *Lithophaga*, from mean lower low water (MLLW) to ca. 5 m water depth

Table 4
Published numerical ages.

Culture	Fanciulli		Mochi		Caviglione		Bombrini		Barma Grande		Prince of Monaco
UPPER PALAEOTHIC											
Epigravettian											
	radiocarbon (1 - *Phorcus turbinatus* shell)	Thommeret and Thommeret, 1973									
	radiocarbon (GE1 skeleton)	Formicola, 2005									
	radiocarbon (animal bone)	Tomasso (2014)									
									radiocarbon (BG2 burial)	unclear	
									radiocarbon (unk bone fragment)	Bisson et al. (1996)	
									radiocarbon (rodent bone)	Bisson et al. (1996)	
									radiocarbon (deer antler)	Bisson et al. (1996)	
									radiocarbon (BG6 metatarsal)	Formicola et al. (2004)	
Gravettian											
			radiocarbon (2 - *Tritia neritea* shell)	Douka et al. (2012)	radiocarbon (3 - *Tritia neritea* shell)	Valladas et al. (2016)					
Aurignacian											
			radiocarbon (charcoal ABA)	Bietti et al. (2004)			radiocarbon (3 -charcoal)	Holt et al. (2019)			
			radiocarbon (4 - marine shells)	Douka et al. (2012)							
Proto-aurignacian											
			radiocarbon (5 - charcoal ABA)	Hedges et al. (1994)			radiocarbon (4 - marine shells)	Higham et al. (2014)			
			radiocarbon (charcoal ABA)	Bietti et al. (2004)			radiocarbon (12 -bone)	Benazzi et al. (2015)			

(*continued on next page*)

Table 4 (*continued*)

Culture	Fanciulli	Mochi		Caviglione	Bombrini		Barma Grande	Prince of Monaco	
		radiocarbon (6 - marine shells)	Douka et al. (2012)		radiocarbon (3 - charcoal)	Benazzi et al. (2015)			
		radiocarbon (charcoal ABAx-SC)	Douka et al. (2012)						
		radiocarbon (charcoal)	Frouin et al. (2022)						
		luminescence (4 -quartz)	Frouin et al. (2022)						
		luminescence (4 -feldspar)	Frouin et al. (2022)						
MIDDLE PALAEOLITHIC									
Mousterian									
		radiocarbon (3 - marine shells)	Douka et al. (2012)		radiocarbon (4 - marine shells)	Higham et al. (2014)			
		radiocarbon (3 - charcoal)	Douka et al. (2012)		radiocarbon (2 - charcoal)	Holt et al. (2019)			
		luminescence (7 -quartz)	Frouin et al. (2022)						
		luminescence (7 -feldspar)	Frouin et al. (2022)					ESR; U–Th (stalagmitic floors)	Shen (1985, 1986); Falguères (1986)
Premousterian								U–Th (bone)	Barral and Simone (1987)

(Laborel and Laborel-Deguen, 1996), is used as an indicative range for palaeo sea level. However, it is important in the field to assess their accuracy. When the boreholes form a dense and definite band, the upper limit can be considered to correspond with the lower intertidal boundary or to a shallow subtidal depth (Laborel and Laborel-Deguen, 1996). Boreholes which do not form a dense band must be considered with caution because their depth within the water column cannot be constrained. Other sources of uncertainty are provenance and age-determination. Boreholes rarely contain shell material with which to confirm generation by *Lithophaga* and other mussel genera with different ecological niches produce boreholes. Finally, dating *Lithophaga* traces is impossible unless they occur in connection with datable deposits or landforms, and even then, it is difficult to confirm correlation (Rovere et al., 2016). Successive sea-level stillstands at similar elevations and ecological conditions could result in multiple borehole populations occupying the same elevation.

Lithophaga trace fossils have been reported, with different levels of accuracy, at the high elevation Voronoff Cave (108 m), at the same elevation within the Caviglione and Fanciulli caves (35-30 m), and slightly lower elevations at Costantini Cave (23.8 m), Prince of Monaco Cave (22 and 15 m), at the Mochi rock shelter (21.7–21.3 m), and on the rocky shore platform at Ex-Casinò (6–8 m; Fig. 6; Table 3). These elevations are consistent with the above evidence of two different sea levels at Balzi Rossi with the addition of highstands at ~35 m and ~108 m. The literature however, provides very little detail regarding the character of these boreholes, i.e., do they form the dense band that can be confidently considered a sea-level indicator?

A remnant of a vermetid reef was found at the back of the Prince of Monaco Cave at ~12 m asl in association with a notch above the remnants of the Tyrrhenian marine deposit, which had filled the floor of the cave (Blanc, 1955; Federici and Pappalardo, 2006). Vermetid reefs are a biological encrustation, endemic in the Mediterranean, composed of the gastropods *Vermetus triquetrus* and *Dendropoma cristatum* (formerly *Dendropoma petraeum*) in association with coralline algae such as *Lythophyllum byssoides* (Chemello and Silenzi, 2011). Vermetid reefs are considered very accurate sea-level indicators as the living portion of the reef is constrained within the intertidal zone (Laborel and Laborel-Deguen, 1996; Vacchi et al., 2016; Rovere et al., 2023b). Generally, relict vermetid reefs are reported at lower latitudes within the Mediterranean basin and because of their fragility, are mainly associated to Holocene sea-level. Few Pleistocene vermetid reefs have been reported within the Mediterranean basin with the nearest to Balzi Rossi being reported in southwest Sardinia (Carboni et al., 2014), nearly 450 km to the south.

4.3. Beach deposits

Above the modern shoreline, at open air sites and within the caves, coastal sediments have been reported (Rivière, 1887; de Villeneuve et al., 1906–1919; Boule, 1906; Cardini, 1938; Barral and Simone, 1965, 1971; de Lumley-Woodyear, 1969; Vicino, 1974, 1976; Cremaschi et al., 1991); however, it is often difficult to accurately attribute depositional environment from the unit description. Generally, they are described as variably cemented shelly marine conglomerates, in some cases with overlying dune sand or lying upon a shore platform. Given the morphology of the region (steep coastal cliff) the conglomerates are most likely beach deposits, although we cannot necessarily be certain of sub-aqueous, intertidal, or sub-aerial (storm waves) deposition as the contextual information that would help with that determination is often not provided. Without contextual constraint, beach deposits have a relatively large indicative range, with the lowest potential limit being wave base (often between −10 and −30 m water depth) and the highest limit the toe of a beach dune, potentially several meters above sea level (Otvos, 2000; Rovere et al., 2016).

The highest elevation marine units reported come from the caves above the Balzi Rossi archaeological site (Fig. 1). A marine conglomerate found in the Statua Cave at an unreported elevation and a marine sand with the oyster *Saccostrea kegaki* (formerly *Ostrea cucullata*) was found at ca. 105 m in the no longer extant Grimaldi Cave (Del Lucchese, 1984). These deposits were attributed to the ancient Calabrian sea level (1.8–0.77 Ma) but there is no additional information for these deposits.

A beach deposit of pebbles and marine shells within a coarse, poorly-sorted sand is described at 22.4 m above “absolute altitude” within the Costantini cave (Fig. 6; Table 3; de Lumley-Woodyear, 1969, p. 97). It is unclear if this elevation refers to the bottom or top of the deposit, which is covered by an undescribed dune sand. A sand attributed to the Mindel-Riss interglacial was found at the base of the Fanciulli cave sequence, between *Focolare* M and bedrock at ca. 17.8 m asl (Bachechi and Revedin, 1996).

The Prince of Monaco Cave still contains remnants of four marine units: M3 (23.8-22.7- m), M1 (18.5–17.5 m), M2 (14–13.5 m), and ‘T’ (12.0–9.0 m) (Figure: 5). M3 is a strongly cemented biocalcarenite composed of microfauna and a fine detrital matrix. Both M1 and M2 are cemented marine assemblages consisting of bryozoans, marine bivalves and gastropods, echinoids, sponge spicules, and foraminifera within a coralligenous biogenic matrix (Barral and Simone, 1967, 1971). The M units when first described were considered littoral detritus deposited at a water depth of ca. 40 m and attributed to the Mindel-Riss sea-level highstand or interstadials of the Riss (Barral and Simone, 1971), periods which are now recognized as encompassing the MIS 11, 9, and 7 sea-level highstands.

The ‘T’ unit consisted of pebbles and cobbles with marine shell in a coarse and poorly sorted sand matrix, which covered most, if not the entire cave floor, up to a thickness of 2 m, but has been largely removed. The shelly conglomerate was described by Boule (1906) as covering a ‘fairly large’ area of the coast outside the cave. Directly outside the cave he measured the base of the conglomerate, resting upon bedrock, at an elevation of 6.32 m asl. The conglomerate was correlated through the marine faunal assemblage, which included *Thetystrombus latus* [formerly *Strombus bubonius*]. *T. latus* is a large marine gastropod, a key species of the Senegalese fauna assemblage, which is regarded as an indicator of Tyrrhenian sea level within the Mediterranean (Asioli et al., 2005; De Torres et al., 2009; Repetto et al., 2020). The Tyrrhenian highstand (further described in Section 5) is correlated with MIS 5e. In addition to the Prince of Monaco cave, Senegalese fauna and *T. latus* were identified in the marine sediments at Bausu da Ture (Boule, 1906), Barma Grande (Cardini, 1938), and Ex-Casinò (Vicino, 1974, 1976) and subsequently these deposits have been attributed to the Tyrrhenian highstand. The correlation of these units is further supported by their consistent elevations (Figure: 5).

One other potential marine deposit of interest is found at the Prince of Monaco cave. Within the cliff face, adjacent to the roof of the cave, is a niche between 40.6 and 34.6 m asl containing seven units (Figure: 5). Units 2 and 3, but particularly 2, contains marine shell typical of *Posidonia* (sea grass) environment, which have been attributed to storm wave deposition during the Tyrrhenian (Simone et al., 2010).

4.4. Synopsis

The sea-level indicators identified at Balzi Rossi are divisible into three types: morphologies formed on bedrock (cave floors, notches, abrasion surfaces), biological (*Lithophaga* trace fossils and vermetid reefs), and sedimentological (beach deposits). Unfortunately, the fossil assemblages associated with the beach deposits were not sampled with the aim of palaeoecological insight, limiting any interpretation of palaeo water temperatures and preferred habitats (reflecting water depth and tidal zone) to generalities.

The sea-level indicators occur over a broad range of elevations, but there is some consistency. The deposits attributed to the Tyrrhenian in general occur between 7 and 12 m asl (Fig. 6; Table 3). Other consistent elevations for sea-level indicators are the notches and *Lithophaga* traces between 21 and 24 m asl and Costantini marine deposit within that range, the *Lithophaga* traces between 30 and 35 m asl, and the reported marine deposits from the high elevation caves at ca. 105–108 m asl, which have been attributed to a Calabrian Sea, ~1.8–0.774 Ma (Del Lucchese, 1984). Additionally, there are the M1 (18.5–17.5 m), M2 (14–13.5 m), and M3 (22.7–23.8 m) marine deposits within the Prince of Monaco Cave; the latter consistent with other sea-level indicators at Balzi Rossi. The collection of sea-level indicators implies at least four distinct sea-level highstands, between MIS 5e (~125 ka) and the Calabrian are recorded at Balzi Rossi.

5. Chronological constraint

Chronological constraint at Balzi Rossi is complicated by two things: the age of much of the work and the limited numerical dating applied. Most of the excavations occurred before the methods and techniques applied in the geosciences for the analysis of stratigraphy were applied to archaeological contexts (i.e. geoarchaeology) and before geochronological methods were developed. Critically, from the excavations of the 19th century very little documentation or material remains. What does remain, although incomplete and dispersed globally, are human burials, fossil assemblages and some samples of *focolari* and other sediments, fortunately preserved within museum collections (Site Summaries). These records were effectively ignored (or forgotten) for many years due to a lack of alternative methods of study other than typology (Formicola and Holt, 2015) and nascent terrestrial and marine chronologies. However, in recent years assemblages remaining is museums and other repositories have been revisited to reassess chrono-cultural attributions and environmental context (e.g., Onoratini et al., 2012; Tomasso, 2014; Moussous et al., 2014; Rossoni-Notter et al., 2016; 2017). Results from such work are compared with more complete sites at Balzi Rossi (e.g. Mochi and Bombrini shelters) and/or sites of comparable age within the region (e.g. Observatoire Cave, Monaco; Terra Amata, Nice; Fig. 1) to build a regional framework of industry (technology) and cultural change, or fossil fauna as influenced (or not) by environmental change. For example, Tomasso (2014) found that the major environmental changes that occurred during the first half of the Late Glacial, did not have an impact on the size of material supply territories for Late Epigravettian populations of the region. Onoratini et al. (2012) and Moussous et al. (2014) were able to establish biostratigraphic correlation between individual sites at Balzi Rossi using the fossil fauna remains (specifically Proboscidean taxa) preserved at the Musée d'Anthropologie Préhistorique in Monaco, comparing those records to other caves within the region.

Another biostratigraphic marker common to Balzi Rossi is the "Senegalese fauna" used to identify the Tyrrhenian marine sediments. This faunal assemblage is named for a shallow marine assemblage recovered by Professor Lovisato from outcrops in the Gulf of Cagliari, Italy (Asioli et al., 2005). It is characterised by tropical, warm water taxa including the well-recognized *Thetystrombus latus* [formerly *Strombus bubonius*]. Senegalese faunal assemblages are mainly attributed to the Last Interglacial (MIS 5e) highstand within the western Mediterranean; although, some deposits associated with the MIS 7 highstand have been identified in Spain (Zazo et al., 2013; Benjamin et al., 2017; Cerrone et al., 2021). Interestingly, one taxon typical of the Senegalese group, *Patella ferruginea*, has been identified within the M1 fossil assemblage from the Prince of Monaco's cave and could indicate a highstand of elevated water temperatures within the Mediterranean predating the Last Interglacial.

Numerical ages are available from the Fanciulli, Caviglione, Barma Grande, and Prince of Monaco caves, and from the Mochi and Bombrini rock shelters (Table 4). Most ages have been determined using radiocarbon (^{14}C), with additional ages from luminescence (quartz and/or feldspar), electron spin resonance (ESR), and uranium-thorium (U–Th) methods. The latter two methods were applied to the stalagmitic floors within the Prince of Monaco cave, with U–Th analysis also used to analyse the early Neanderthal iliac bone discovered there with a resulting age of $220^{+120}/_{-50}$ ka (Shen, 1985, 1986; Falguères, 1986; Barral and Simone, 1987; Site Summary). These works were done in the mid-1980s and methodological uncertainties surrounding these early ages are considered high. Substantial advancements and changes to applications for the methods have occurred since, which have led to higher resolution capabilities of U–Th (i.e., minimizing detrital contaminations and a reduction of needed sample material) and the abandonment of ESR in the study of cave-entrance carbonates. (Duval et al., 2020; Wendt et al., 2021).

The radiocarbon method was used as early as the 1970s at Balzi Rossi. However, more recent ages (since 2012) have been reported at Fanciulli and Caviglione caves and Bombrini rock shelter with extensive radiocarbon analyses reported from Mochi shelter in 2012 (Table 4 and references therein). Notice in our Site Summary compilations that only those results which were accepted in the original publications were included. The Mochi radiocarbon ages have been complimented recently with luminescence analysis of both quartz and feldspar grains to develop an age-depth model from Bayesian methods for the site and provide a chronostratigraphic succession between the Middle to Upper Palaeolithic (Frouin et al., 2022). Their results place the transition from Neanderthal groups to AMH between 44.3 and 41.1 ka, in agreement with developing chronologies from other sites in the north and south of Italy. Similarly, a Bayesian age-depth model was developed for the Bombrini succession using radiocarbon ages (Benazzi et al., 2015). Frouin et al. (2022), in comparing the two models, found the transition from the Middle Palaeolithic (Mousterian) to the Upper (Protoaurignacian) to be a few millennia later at Bombrini and recommends additional analyses. An attempt to constrain the transition was also attempted using cryptotephra from the Bombrini succession; however, despite encouraging results, more data from Balzi Rossi and other nearby archaeological sequences are needed to refine the isochron and allow lateral correlations (Hirniak et al., 2020).

To date, no numerical ages to have been published for the marine associated deposits at Balzi Rossi. Age constraint has only been derived by the biostratigraphic marker provided by the Senegalese fauna at multiple locations and from position relative to U–Th ages of the stalagmitic floors within the Prince of Monaco cave (e.g., minimum and/or maximum ages).

6. Final comments: knowledge gaps and pathways forward

The loss of Palaeolithic and Late Pleistocene stratigraphy at Balzi Rossi cannot be understated for its consequences to chronostratigraphy and correlation between individual sites. Records of stratigraphic changes, which can serve as a proxy of environmental change (Davis, 2020) and be correlated, at least broadly, with terrestrial or marine chronological stages are largely absent. However, while the complex excavation history, scattered sample collections, and disparate age of journal publications has precluded a comprehensive consideration of all the information provided by the Balzi Rossi complex, this compilation illustrates that a significant body of information remains that can be utilized as a valuable resource for future investigations.

Mochi rock shelter, where excavations are ongoing, and any future works at either Bombrini or Lorenzi rock shelter, are the best sources for terrestrial chronostratigraphy of the Balzi Rossi archaeological complex. This is because these sites still retain their stratigraphic integrity having not been (or only to a limited extent) disturbed during the earlier excavation periods. To date, no burials have been discovered at either rock shelter and have only been reported from caves. It appears AMH preferred cave locations for interment; although, we must also consider that the cave environment may provide some sort of preservation bias hampering the effects of post-depositional disturbance and pedogenesis on the conservation of bone. A 'new' burial discovery would be of interest not only for the opportunity to examine this ancient cultural tradition at Balzi Rossi using modern archaeological methods, but also, due to apparent presence of later Gravettian burials into earlier

Mousterian units (e.g., Barma Grande), for understanding how AMH populations interacted with or utilized the Neanderthal levels. More generally, the application of advanced geoscience techniques (Morley et al., 2023) to the remaining stratigraphic archive of the Balzi Rossi area is becoming mandatory to improve the understanding of the local archaeological and anthropological record and the multifaceted aspects of a complex and diachronic exploitation of natural resources under different climatic conditions.

Balzi Rossi likely retained a sedimentary sea-level record spanning the early, middle, and late Pleistocene. Although many of the marine deposits have been removed or rehandled, the remaining intact sea-level indicators have not been subject to rigorous scientific documentation or analyses. Regardless of any apparent consistency in the reported elevations of sea-level indicators at Balzi Rossi, without robust reference (high-resolution elevation measurement) to a defined tidal datum, and persuasive age constraint, these sea-level indicators lack any significant meaning for sea-level science. A recent review of sea-level indicators in the western Mediterranean (Cerrone et al., 2021) that included the marine sediments from Ex-Casinò, Barma Grande, Bausu da Ture, and the Prince of Monaco Cave, resulted in a broad palaeo relative sea-level estimate from Balzi Rossi of 6–14 m above present. However, the confirmation that Balzi Rossi retains a record of multiple sea-level highstands is significant. The position of Balzi Rossi in a region of relatively minimal vertical land movement on a microtidal rocky coastline within the western Mediterranean implies negligible impacts to the relative sea-level record from processes such as wave climate and sediment supply. Multiple highstand records in one location, with well-constrained age and elevation constraints, provide better estimates of long-term vertical land movements and dynamic topography, in turn allowing for more refined estimates of palaeo sea level.

Balzi Rossi thus has the potential to help quantify the amplitude of maximum sea-level elevation between multiple interglacials and contribute to estimates of global sea level and palaeo ice-sheet extent during multiple interglacials. Although, at this point, we cannot confidently estimate the age of the higher sea-level indicators at Balzi Rossi, those formerly attributed to the Tyrrhenian are most likely Last Interglacial in age. Sea-level estimates from this interglacial alone are significant for their use as benchmarks for ice models to project future sea-level changes (DeConto et al., 2021) and their potential to help improve the accuracy of future sea-level projection (Gilford et al., 2020). Not only will better constraint of all sea-level indicators contribute to the global record of palaeo sea level, but additional, well-described data points will improve models of palaeo ice-sheet extent, glacio-isostatic adjustment, and regional rates of long-term vertical land movements.

To better understand how the Palaeolithic populations at Balzi Rossi interacted with and responded to coastline shifts and environmental change, the occupation of Balzi Rossi should be imagined as a whole use of space and not restricted to individual sites. For example, the discrepancy between the Mochi and Bombrini rock shelters of a few thousand years for the timing of the transition from Mousterian and Protoaurignacian cultures does not reflect the proximity of the locations. Separated by a distance less than 50 m, it is unlikely that one shelter was ignored for thousands of years. The entire complex (caves, rock shelters, and open-air sites) would have served as a unique ecological niche for the Palaeolithic foragers, offering a variety of shelters and natural resources reflecting coastline proximity and local environmental conditions. For this reason, a comprehensive interpretation of the archaeological and anthropological significance of the archaeological vestiges at Balzi Rossi should consider the area as an ecosystem in which the human population interacted with the biological and physical components of their surroundings and from which they communicated with nearby regions in Europe.

Advancements in archaeology, Earth science, and geochronology allow for more nuanced analyses and the potential to explore the offshore environment for submerged traces of Palaeolithic cultures and sea-level change. The length of time between the Last Interglacial and our current one, with similarly positioned coastlines, is more than 100,000 years – representing a significant portion of Palaeolithic cultural response to environmental change during which time sea-levels were up to 120 m lower than present. The different sedimentary environments distributed vertically along the Balzi Rossi cliff must be considered as a continuum and not as single sedimentary entities. From this perspective, natural and anthropogenic deposits (and correlated landforms) formed under different environmental conditions represent the multiple and multifaceted archives of environmental evolution of Balzi Rossi in response to Middle to Upper Pleistocene global and local climatic change. Correlations with broader regional environmental and cultural changes should be possible in the vertical and lateral variability of the stratigraphy of both natural and archaeological deposits as they were formed of the same processes. It is also likely that some chronological correlations can be identified, although they require a robust program of radiometric dating. By building consilience between the archaeological and Earth sciences communities and changing perspective to consider Balzi Rossi as a whole landscape with vertical and lateral continuity instead of isolated sites, we can herald in a fourth phase of scientific research at Balzi Rossi. This approach is key to new geoarchaeological interpretation and fuel for the current debate surrounding the Pleistocene peopling of the Mediterranean Sea shorelines that should be applied to geoarchaeological sites globally.

As written by de Villeneuve et al. (1906–1919, p. 30), the impetus behind the excavations directed by Prince Albert I of Monaco was his desire to develop excavation methods which retained all useful scientific knowledge from Balzi Rossi, not just a collection of prehistoric artefacts. This compilation is a baseline effort towards that goal to be used for future investigations of this significant site with the collaboration between disciplines representing the continued development of both sciences.

Credit author statement

The substantial supplemental materials were first compiled in Italian by M.S. These were translated to English by D.D.R. with support from E. S. and M.P. The section reproductions in the supplemental materials were drawn by D.D.R. with support from M.P. The supplemental materials were reviewed by E.S., E.R–N., O.N., A.Z., F.N., S.G., F.S. and A. M. The manuscript was drafted by D.D.R., who also compiled the Tables and created Figs. 1, 4–6 and 10. A.P. and A.Z. contributed to Fig. 1. M.P. and D.D.R. created Fig. 3. E.S. and M.P. contributed to Fig. 6. O.N. created Fig. 7. A.M. created Fig. 8. M.V. created Fig. 9. M.V., A.R. and M.P. contributed to Fig. 10. All authors provided expertise to the manuscript.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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