Towards understanding health, diet and mobility in early medieval valleys, South Tyrol (Alto Adige-Südtirol) Italy

Dissertation

der Mathematisch-Naturwissenschaftlichen Fakultät

der Eberhard Karls Universität Tübingen

zur Erlangung des Grades eines

Doktors der Naturwissenschaften

(Dr. rer. nat.)

vorgelegt von

Alice Paladin

aus Venedig, Italien

Tübingen

2020

Gedruckt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der Eberhard Karls Universität Tübingen.

Tag der mündlichen Qualifikation: 19/03/2021

Stellvertretender Dekan: Prof. Dr. József Fortágh

1. Berichterstatter: Prof. Dr. Katerina Harvati-Papatheodorou
2. Berichterstatter: Prof. Dr. Albert Zink

Table of Contents

Acknowledgements	5
Abbreviations	7
List of Figures	9
List of Tables	11
Zusammenfassung	13
Abstract	15
List of publications and declaration of personal contribution	17
1. Introduction	19
1.1 Geographical, historical and archaeological background	19
1.2 State-of-the-art of the bioarchaeological research in South Tyrol	26
2. Objectives and expected output of the doctoral research	30
3. Results and discussion	31
3.1 Health status: metabolic diseases and trauma in early medieval South Tyrol	31
3.1.1 Metabolic diseases (scurvy) (Article I)	31
3.1.2 Trauma analysis and interpersonal violence (Article II)	40
3.2 Dietary habits and subsistence strategies in South Tyrolean valleys (Article III)	48
3.2.1 Fauna	48
3.2.2 Human groups	51
3.3 Mobility within and among valleys in early medieval South Tyrol (Article III)	55

4. Concluding remarks and future work 59

Reference list 61

Appendix: tables 76

Appendix: Article I 120

Appendix: Article II 134

Appendix: Article III 145

Acknowledgments

Aspiring to list all the people who, in one way or another, have encouraged me to end this path is not an easy task and not entirely feasible, but I will try it.

My first sincere thanks go to ALL (I emphasize it with pride) my colleagues of the Institute for Mummy Studies of Eurac Research and to all the students who were part of this group, at some point. I am very grateful to the people I have the luck to work with. They were and are important for my personal growth, always ready to encourage me to trust in my abilities: Christina, Frank, Giovanna, Marco and Valentina! Certainly Niall and Paola cannot absolutely be forgotten. Is my supervisor, Prof. Dr. Albert Zink, who gave me the opportunity to start this path. Since his first “hallo”, he believed in me, encouraging and supporting me (often condemning himself to endure my enthusiasm).

Thank you, grazie a tutti voi, festeggeremo come si deve!

I am grateful to Prof. Dr. Katerina Harvati-Papatheodorou for accepting me as an external PhD student. I would also take the advantage of this opportunity to sincerely thank Prof. Dr. Joachim Wahl, not only for his important teachings and recommendations, but also for his authentic kindness and availability.

Thanks also are due to Dr. Catrin Marzoli, head of the Archeological Office of Bolzano, for placing her trust in me, allowing all the performed analyses and providing me with access to the unpublished data. Special thanks go to Roland, Umberto, Gianni and Valentina and to the team of archaeozoologists of the storehouse in Frangarto for their help and patience (and coffee too!).

I would naturally thank the (former) team of the Department of Physical Anthropology, Institute of Forensic Medicine of the University of Bern in Switzerland. Many thanks to Negi and Inga for their teachings and important support, and to Prof. Dr. Sandra Lösch for giving me this unique opportunity of collaboration. I had a great time with you all!

Thanks to Kathrin Renner for her invaluable help in making maps. Many thanks to Angela Graefen for the English editing, abstract’s translation and moral support, and to Enrico Cavada for sharing his broad historical and archaeological knowledge regarding the Alps.

Huge thanks go to my soul sisters “Lagunagirls”, Giulia and Cugi who have never made their distance felt, despite being kilometers far away. I sincerely thank my extended families, “No.Na” and my grandmother Laura.

Dulcis in fundo, the deepest thanks go to you Fulvio and to our baby girl Rita, who exemplifies our love.

Abbreviations

AD	*Anno Domini* (after birth of Christ)
BC	Before Christ
BP	Brefore present
cf.	compare
e.g.	*exempli gratia* (for example)
m. a.s.l.	Meter above sea level
MNI	Minimum number of individuals
SD	Standard deviation
SFT	Sharp force trauma
$\delta^{13}C$	Delta carbon (stable isotope ratio of carbon)
$\delta^{15}N$	Delta nitrogen (stable isotope ratio of nitrogen)
$\delta^{34}S$	Delta sulphur (stable isotope ratio of sulphur)

List of Figures

1.1 Geographical, historical and archaeological background

Figure. 1 Central European Alps. The red border highlights the Italian region of South Tyrol. Map made with the support of Dr. Kathrin Renner (tool: ESRI ArchGIS).

Figure. 2 Map from Heitmeier (2005, p. 52) recreating the political status quo of the Roman provinces of Raetia prima, Raetia secunda and Noricum until the 7th cent. AD. Legend: striped red area, late antique Frankish kingdom; green area, Bavarian Ducat/ territory; grey area, Alpine Slavs; orange area, Langobard kingdom; dark green lines, Bavarian permanent -dark green- and temporary -light green- pressure; dashed red line, former border of the Roman provinces; dashed orange line, after-effect border of the Ostrogoth at the edge of the Alps.

Figure. 3 Grave goods found in tomb 1, in Nalles. Picture from Marzoli *et al.* 2009, p. 156.

1.2 State-of-the-art of the bioarchaeological research in South Tyrol

Figure. 4 Map of South Tyrol showing the valleys and the archaeological sites investigated in this work. Adige valley: (1) Montagna, Pinzano (Montan, Pinzon), (2) Appiano, San Paolo Castelvecchio (Eppan, St. Paul Altenburg) ,(3) Terlano (Terlan), (4) Nalles (Nals); Conca di Merano (Merano basin): (5) Maia Bassa (Untermais) and (6) Castel Tirolo (Schloss Tirol); Isarco valley: (7) Sabiona (Säben) (8) Bressanone, Elvas necropoli 17 (Brixen, Elvas); Venosta valley: (9) Tanas (St. Peter's path), (10) Malles, Maso Pauli (Mals, Paulihof), (11) Malles, Burgusio Santo Stefano (Mals, Burgeis St. Stephan). Dark grey colour indicates the sites not tested for stable isotopes, as the samples were not available at the time of the analysis. Map made with the support of Dr. Kathrin Renner (tool: ESRI ArchGIS).

3.1.1 Metabolic diseases (scurvy) (Article I)

Figure. 5 Castel Tirolo (Merano basin), tomb 27, adult female TCT27. Maxilla (left) and mandible showing severe parodontitis and bone inflammation (black arrows highlight some examples), and severe dental calculus (red arrows). Pictures made by the author of the present dissertation and authorised by the Institute for Mummy Studies of Eurac research.

Figure. 6 Castel Tirolo (Merano basin), tomb 27, adult female TCT27. The calcified object (right) and its inner structure (CT-scan image, left). Pictures authorised by the Institute for Mummy Studies of Eurac research.

Figure. 7 Sabiona-Säben (Isarco valley), tomb 123 crypt D, subadult SK123. Endocranial vessels impressions and abnormal pores (above). Abnormal pores and new bone

formation at the mandible (below). Pictures authorised by the Institute for Mummy Studies of Eurac research.

3.1.2 Trauma analysis and interpersonal violence (Article II)

Figure. 8 Sabiona-Säben (Isarco valley), tomb 114, mature male individual SK114. Perimortem sharp force trauma (arrows) in the petrous bone and mastoid process of the left temporal bone. Picture by Tumler, Paladin, Zink, *paper submitted for publication* and authorised by the Institute for Mummy Studies of Eurac research.

Figure. 9 Total number of studied individuals and corresponding injured cases per valley-basin.

Figure. 10 Castel Tirolo (Merano basin), tomb 19, adult male TCT19. Sharp force trauma in the diaphysis of the left femur. Anterior (left picture) and posterior (right) detail of the injury. Pictures made by the author of the present dissertation and authorised by the Institute for Mummy Studies of Eurac research.

Figure. 11 Malles Burgusio Santo Stefano (Venosta valley), tomb 2, mature male BSS2/484-US119. Blunt force trauma on the frontal bone of the cranium. Picture made by the author of the present dissertation and authorised by the Institute for Mummy Studies of Eurac research.

Figure. 12 Naturno San Procolo (Venosta valley), individual from tomb 26. Cranium displaying both blunt (red arrow) and sharp force (black arrow) trauma. Picture from Reinhart 1991, Fig. 38-39, page 185.

Figure. 13 San Floriano Chapel, Rio di Pusteria (Pusteria valley), individual RPS3C93a. Sharp force trauma in the cranium. The healed lesion is 50 mm long and 21 mm wide. Picture from www.paleopatologia.com/it/paleopatologie-e-indicatori-di-stress/evidenze-scheletriche-da-trauma/37-trauma.html.

3.2.1 Fauna

Figure. 14 Archaeological drawing of tomb 11 of the cemetery of Terlano, which encompassed the burial of a subadult pig in an east-west orientation. Unpublished document provided by the Archaeological Office, Autonomous Province of Bolzano, Italy.

3.2.2 Human groups

Figure. 15 a) Number of human samples (total n=91) per valley and basin. **b)** Bone samples with good collagen for carbon and nitrogen (n=85) grouped per valley and basin. **c)** Bone samples with good collagen for sulphur (n=40) grouped per valley and basin.

3.3 Mobility within and among valleys (Article III)

Figure. 16 Reconstruction (based on Marzatico & Migliario 2011) of the Roman road system (used also in the Early Middle Ages) that connected Aquileia, Altinum (near Venice, Italy) and Ostiglia to the northern areas until reaching *Augusta Vindelicorum* (Augsburg, in Gemany). The black arrow highlights the only one *Via Claudia Augusta* (red line) Roman branch passing through the Venosta valley (denoted by X). White square: Adige valley, circle: Merano basin, diamond: Isarco valley; red squares: main mountain passes; purple lines: starting routes, pink lines: lateral routes; yellow line: connection among Venosta valley and Coira (Chur, Switzerland). Map made in by the author of the present dissertation (tool: Google My Maps).

List of Tables

3.1.1 Metabolic diseases (scurvy) (Article I)

Table. 1 List of scorbutic macroscopic features in adults by Brickley & Ives 2008 (Table 4.3 at page 61, modified). As stated by the authors, none of the following changes are pathognomic. Legend: D, diagnostic feature; G, general change.

Table. 2 Results of the paleopathological analysis of SK106 (6 months to 1 year old), SK107A (6 months to 1 year old) and SK123 (4 to 6 years old). The differential diagnosis was based on the extended scoring system of Snoddy *et al.* (2017). Legend: Ind., individual; p, porous lesions; nb, new bone formation; *, bilateral lesion; o, absent; -, not observable, thus the bone is absent or it is poorly preserved; RI, rickets; SC, scurvy.

<u>Appendix</u>

Table. 1A Provenience, archaeological data, radiocarbon dating for all (173 MNI) of the individuals studied. Legend: -, missing data; Ref., reference.

Table. 2A Bone representativity (R.) / preservation (P.), sex and age at death estimations for all (173 MNI) of the individuals studied. Legend: < 25, less than 25% of the skeleton is completed; 25–50, less than 50% of the skeleton is represented; 50–75, more than 50% of the skeleton is completed; > 75, nearly complete skeleton; 1, poorly preserved skeleton; 2, medium state of preservation; 3, in a good state of preservation; *, data included also in a bachelor and master theses (Unpublished data, Institute for Mummy Studies, Eurac research).

Table. 3A Sex and age at death distribution per valley and archaeological site. Legend: MNI, minimum number of individuals; Freq. frequency; *, data included also in a bachelor thesis (Unpublished data, Institute for Mummy Studies, Eurac research).

Table. 4A Paleopathological evidence (excluded the results of the trauma anaylsis that is presented in the following table, Tab.5A) and selected non-metric traits (in other remarks). Legend: CO, Cribra Orbitalia; Degen., degenerative; DJD, degenerative joint disease; sOA, spinal osteoarthritis; (), uncertain; - , not present; x, present; nd, not determinable; /, few indicative bone lesions not diagnostic for a specific metabolic disease; *, data included also in a bachelor thesis (Unpublished data, Institute for Mummy Studies, Eurac research); **, due to the bad state of preservation of the majority of the skeletal remains from the site of Elvas Bressanone, the paleopathological investigation was often limited. In general, when the majority of the cells are indicated as "nd", it means that the bones preservation was very poor limiting the paleopathological investigation.

Table. 5A List of the recorded traumata at the postcranium (descriptive protocol by Lovell 1997, modified). Legend: N, quantity of recorded traumata per individual (total N=39); R, right; L, left; * direct trauma; nd, not determinable.

Zusammenfassung

Im Frühmittelalter (500-1000 n. Chr.) spielte Südtirol in den italienischen Alpen eine wichtige militärische und geographische Rolle als Transitgebiet zwischen Süd- und Nordeuropa. Die wenigen historischen Quellen aus dem Frühmittelalter dokumentieren einen Wandel der alpinen Gesellschaften nach der Schwächung des Weströmischen Reiches, dem Rückzug der römischen Truppen aus den Alpen und dem Aufstieg der römisch-barbarischen Königreiche. Archäologische Quellen bezeugen den gegenseitigen kulturellen Austausch zwischen zuvor sesshaften (rätischen) und allochthonen Völkern (βάρβαροι oder "Barbaren") durch einen komplexen Prozess der kulturellen Hybridisierung im Laufe der Zeit. Sowohl historische als auch archäologische Quellen sind jedoch nicht immer schlüssig, was die Ansiedlung barbarischer Gruppen in diesem Gebiet betrifft. Zwar könnten anthropologische und paläopathologische Analysen dazu beitragen, die damalige Lebensweise direkt aus menschlichen Überresten zu rekonstruieren, doch wurden bisher nur wenige solcher Untersuchungen in diesem Gebiet durchgeführt, und es wurden bisher keine Daten zu stabilen Isotopen veröffentlicht. Daher fördert die vorliegende kumulative Dissertation eine multidisziplinäre Synergie zwischen den Forschungsgebieten der Anthropologie, Paläopathologie und Geochemie (Analyse stabiler Isotope).

Die Ziele sind: 1) Einblicke in den Gesundheitszustand der Bewohner des frühmittelalterlichen Südtirols mit Schwerpunkt auf Stoffwechselkrankheiten und Traumata zu geben, 2) Ernährungs- und 3) Mobilitätsmuster innerhalb und zwischen den Tälern zu erforschen.

Um das erste Ziel zu erreichen, befassen sich die beiden in Artikel I und Artikel II vorgestellten Studien mit der Paläopathologie und geben erste Hinweise zum Gesundheitszustand der Individuen, die zuvor noch nie anthropologisch untersucht worden waren. Insbesondere stellt der erste Artikel (Artikel I) Fälle von subadultem Skorbut (Vitamin-C-Mangel) auf dem frühmittelalterlichen Friedhof von Castel Tirol im Meraner Becken vor. Die Hinweise auf Unterernährung lieferten neue Erkenntnisse über mögliche klimatische Ereignisse sowie über den bisher wenig verstandenen soziokulturellen und lokalhistorischen Kontext, die ein anderes Szenario nahelegen, als bisher aufgrund der archäologischen Untersuchungen vermutet worden war. Die

Ergebnisse der zweiten paläopathologischen Studie (Artikel II) liefern Einzelheiten zur zwischenmenschlichen Gewalt im frühmittelalterlichen Säben-Sabiona (Eisacktal), bei dem ein junger erwachsener Mann (SK63) sowohl im Schädel als auch im Postkranium traumatische Läsionen aufwies, unter anderem perimortales Trauma durch scharfe Gewalt. Um das zweite und dritte Ziel der Dissertation zu behandeln, untersucht Artikel III mittels Analyse stabiler $\delta^{15}N$, $\delta^{13}C$ und $\delta^{34}S$ Isotopen die Ernährungs- und Mobilitätsmuster frühmittelalterlicher Menschen und Tiere aus verschiedenen Tälern, Höhenlagen und Standorten in Südtirol. Die Ergebnisse zeigen, dass die Unterschiede in den Subsistenzstrategien vom Umweltkontext, vor allem von den Höhenlagen, abhängig waren und auf einen höheren Mobilitätsgrad an niedrigeren Standorten (Etschtal) als in höheren Gebieten (Vinschgau) hinwiesen.

Insgesamt legt die vorgelegte Dissertation nahe, dass die neu gewonnenen paläopathologischen und isotopischen Ergebnisse besser im Kontext von ökologischen und geomorphologischen (durch das römische Straßennetz zugänglich gemacht) Faktoren interpretiert werden können, als im Hinblick auf damalige wirtschaftliche oder kulturelle Aspekte, z.B. Handel oder Austausch von Kultur oder Technologie. Es kann jedoch nicht ausgeschlossen werden, dass einige historische Ereignisse (z.B. Militarisierung des Territoriums, Durchzug und provisorische Ansiedlung von Truppen in bestimmten Gebieten, Begegnungen/Streitigkeiten zwischen Gruppen) auch den Gesundheitszustand der Personen beeinflusst haben könnten (z.B. sporadische Episoden von Vitamin-C-Mangel oder zwischenmenschliche Gewalt).

Der angewandte multidisziplinäre Dialog ist ein wirksamer Ansatz, um unser Verständnis der frühmittelalterlichen Bevölkerung in den nordöstlichen italienischen Alpen voranzubringen und produktive Forschungsbereiche für zukünftige Studien hervorzuheben.

Abstract

In the Early Middle Ages (500-1000 AD), South Tyrol, in the Italian Alps, played a key military and geographical role as a transit area between southern and northern Europe. The limited early medieval historical sources document a change in the Alpine societies, following the weakening of the Western Roman Empire, the withdrawal of Roman troops from the Alps and the rise of the Romano-Barbarian kingdoms. Archaeological sources attest mutual cultural exchanges among previously settled (Raetho-roman) and allochthonous (*βάρβαροι* or *barbari*) peoples through a complex process of cultural hybridization over time. However, both historical and archaeological sources are often inconclusive on the settling of barbaric groups in this territory. While anthropological and paleopathological analyses could help to reconstruct the lifestyle at that time directly from human remains, few such studies have been performed in this area, and no isotopic data have been published to date. Therefore, the present cumulative dissertation promotes a multidisciplinary synergy between the research fields of anthropology, paleopathology and geochemistry (analysis of stable isotopes).

The objectives are: 1) to provide insights into the health condition of the inhabitants of early medieval South Tyrol, focusing on metabolic diseases and trauma analyses, 2) to explore their dietary and (3) mobility patterns within and between valleys.

To address the first objective, the two studies presented in Article I and Article II deal with paleopathology, giving first information on the health status of the individuals, which had never anthropologically examined before. In particular, the first article (Article I) presents the subadult scurvy (vitamin C deficiency) cases in the early medieval cemetery of Castel Tirolo in Merano basin. Indication of malnutrition provided new insights into possible climatic events, as well as on the poorly understood sociocultural and local historical context, suggesting a different scenario to what had previously been supposed based on the archaeological investigations. Results of the second paleopathological study (Article II) provide details on interpersonal violence in early medieval Sabiona-Säben (Isarco valley), where a young adult male (SK63) exhibited traumatic lesions in both the cranium and postcranium, including perimortem sharp force trauma. To address the second and third objectives of the dissertation, Article III investigates, by means of stable $\delta^{15}N$, $\delta^{13}C$ and $\delta^{34}S$ isotopes analysis, the dietary and mobility patterns of early medieval

human communities and fauna from various valleys, altitudes and sites in South Tyrol. The results show that the differences in subsistence strategies were dependent on the environmental context, mainly altitudes, and they indicated a higher degree of mobility at lower sites (Adige valley) than at higher areas (Venosta valley).

Overall, the presented doctoral thesis suggests that the newly obtained paleopathological and isotopic results can be better interpreted in the light of environmental and geomorphological (exploited by the Roman road network) factors rather than economical or cultural aspects, e.g. trading, cultural or technologies exchanges, at that time. However, it cannot be ruled out that some historical events (e.g., militarization of the territory, passage and provisional settlement of troops in certain areas, encounters/disputes between groups) might also have influenced the individuals' health status (e.g., sporadic episodes of vitamin C deficiency or interpersonal violence).

The applied multidisciplinary dialogue was an effective approach towards progressing our understanding of early medieval populations in north-eastern Italian Alps, highlighting productive areas of research for future studies.

List of publications and declaration of the personal contribution

The three listed articles, as part of this cumulative dissertation, have been published in international scientific journals. According to *§ 5 Abs. 2 No. 8 of the PromO of the Faculty of Science*, the percentages represent my contribution to the articles with regard to scientific ideas, data generation, data analysis and interpretation, and writing.

Article I (published)

Personal contribution: 80%, 100%, 90%, 90%.

Paladin A, Wahl J, Zink A. **2018**. *Evidence of probable subadult scurvy in the Early Medieval cemetery of Castel Tirolo, South Tyrol, Italy.* International Journal of Osteoarchaelogy. 28: 714–726.

Article II (published)

Personal contribution: 60%, 40%, 50%, 50%.

Tumler D*, **Paladin A***, Zink A. **2019**. *Perimortem sharp force trauma in an individual from the early medieval cemetery of Säben-Sabiona in South Tyrol, Italy*. International Journal of Paleopathology. 27: 46-55.

* shared first co-authorship, as both authors contributed equally to this work.

Article III (published)

Personal contribution: 90%, 100%, 70%, 70%.

Paladin A, Moghaddam N, Stawinoga A E, Siebke I, Depellegrin V, Tecchiati U, Lösch S and Zink A. **2020** *Early medieval Italian Alps: reconstructing diet and mobility in the valleys.* Archaeological and Anthropological Sciences. 12, 82. Open access.

I certify that the above statement is correct.

____

Signature of the candidate

I certify that the above statement is correct.

____

Signature of one of the supervisors

1. Introduction

1.1 Geographical, historical and archaeological background

South Tyrol (Alto Adige, Südtirol) is an alpine region located in north-east Italy (Fig. 1). This territory had a strategic geographical role, due to its habitat characterized by traversable passageways (valley floors) located between alpine passes and the Po plain in Veneto, Italy (Marzatico & Migliario 2011). The geomorphology of this area includes highly diverse geographical zones (valleys, hills, mountains) having different altitudes (from 200 m. a.s.l. in the Adige valley to approximately 4000 m a.s.l. in the Venosta valley) and various levels of precipitation and temperatures (Winckler 2012).

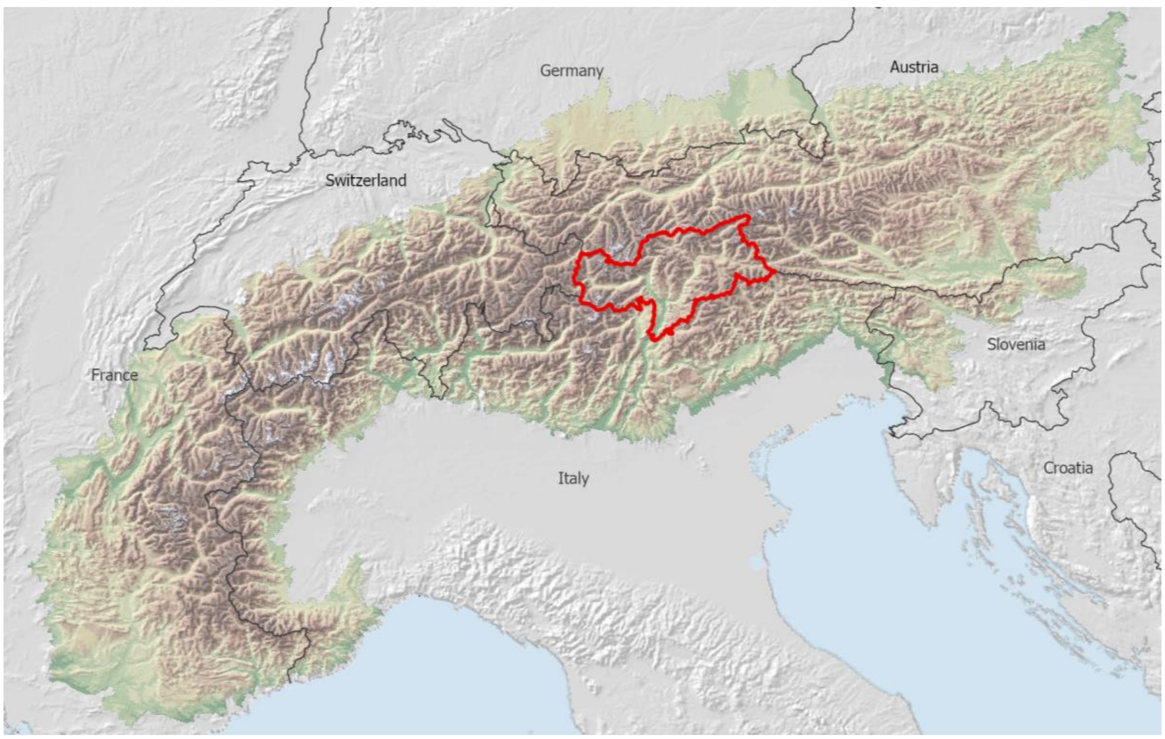


Figure. 1 Central European Alps. The red border highlights the Italian region of South Tyrol. Map made with the support of Dr. Kathrin Renner (tool: ESRI ArchGIS).

The Alps acquired a logistical centrality, particularly starting with the Alpine wars of the Emperor Augustus (25-14 BC) that initiated a free macro-regional transit between the south and the north of Europe lasting several centuries (Marzatico & Migliario 2011).

Thus, this region became part of three Roman provinces *Raetia prima*, *Raetia secunda*, *Noricum mediterraneum* (Fig. 2) led by different *procuratores* (leaders), and these territories were adjoined with the roman *Municipium* of *Tridentum* (*Regio X*) (Gleirscher 1989; Marzatico & Migliario 2011). At that time, autochthonous alpine groups (e.g., *Reti, Breuni, Venosti*), the *barbari* according to the Romans, underwent a gradual process of acculturation by the Romans (Romanization process) and this led, since that time, to a progressive exchange of culture, trading and technologies amongst peoples (Marzatico & Migliario 2011). This shows that the encounters/disputes between Romans and *barbari* began long before (1st century AD) the end of the Western Roman Empire (476 AD, conventionally considered the beginning of the Early Middle Ages), in contrast to what had been popularized in the 18th-20th centuries, with the now obsolete expression "barbaric invasions" by Germanic or Slavic populations, that aimed to picture the Romans and *barbari* as two opposite worlds (Albertoni 2005).

The historical sources on early medieval events in South Tyrol are, unfortunately, limited to the account *Historia Langobardorum* (8th century AD) by Paul the Deacon, who mainly took the historical records from the work *Succinta de Langobardorum gentis historiola* (7th century AD) by Secondio from Trento or Non (Trentino, Italy). Few other historical documents are stored in the Venetian and Lombardian Italian archives (Cavada 2004, 2016). Additionally, the historical records of that time are often biased towards the elite, being stereotypical and unrealistic (James 2009), which underlines the fact that there are significant gaps in our knowledge regarding the interactions of cultures and people in this area (Dal Ri & Rizzi 1995). Only later, from the 12th century AD, thanks to a Bishops' documentary initiative, the historical documents are more substantial (Albertoni & Varanini 2011).

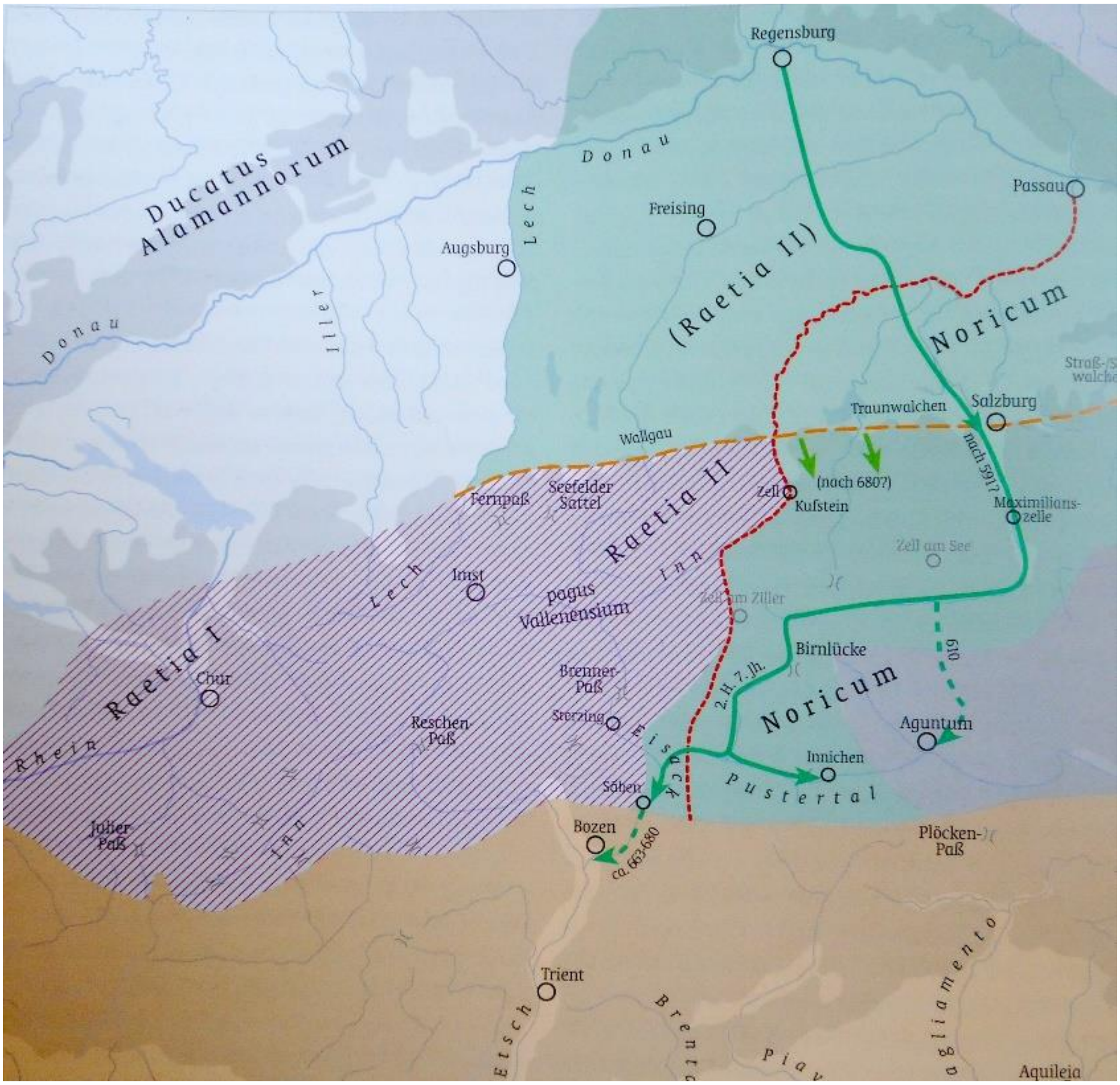


Figure. 2 Map from Heitmeier (2005, p. 52) recreating the political *status quo* of the Roman provinces of *Raetia prima*, *Raetia secunda* and *Noricum* until the 7th cent. AD.
Legend: striped red area, late antique Frankish kingdom; green area, Bavarian Ducat/territory; grey area, Alpine Slavs; orange area, Langobard kingdom; dark green lines, Bavarian permanent -dark green- and temporary -light green- pressure; dashed red line, former border of the Roman provinces; dashed orange line, after-effect border of the Ostrogoth at the edge of the Alps.

Despite the paucity of the written sources, the following historical *excursus* makes it tempting to highlight the complexity of the intertwining of political, economic, social and cultural changes that occurred during that time (5^{th} – 11^{th} centuries AD) in South Tyrol.

In the 5^{th} century AD, with the official withdrawal of the last Roman troops from the north of the Alps, the Danube–Rhine *limes* (boundary) lost its defensive function, and the political settings in the Alps changed significantly, enabling Romano-barbarian kingdoms to become established (Giostra & Lusuardi Siena 2004; Haas-Gebhard 2004). Odoacer of Shinto-Gothic lineage, named *rex gentium* (king of the barbarian groups), deposed the last emperor of the Western Roman Empire, *Romulus Augustulus* (Albertoni & Varanini 2011). After defeating Odoacer, Theodoric "the Great", king of the Ostrogoths, supported by the Eastern Roman Emperor Zenone, ruled over the Goths and Romans (489-526 AD) in the whole Italian peninsula, strategically preserving the Roman traditions (*romanitas*) (James 2009; Heather 2005). At that time, due to the general political instability, the people progressively abandoned the valley floor settlements, preferring the better-defended *castra* at higher altitudes (Marzoli *et al.* 2009). In the valleys, the customs also underwent clear changes in the early medieval societies, promoting the status of "warrior-man" instead of "Roman *togatus*" (man wearing a toga: a status symbol) (Marzatico & Migliario 2011). In the 6^{th} century AD, the Roman Emperor Justinian, together with the Franks (striving for military control of the Adige valley), declared war to the Ostrogoths, leading to the outbreak of the Punic-Greek war (535-552 AD) broke out. This led to Theodoric's death and caused ruinous effects for the whole Italian peninsula, which in the 6^{th} century AD (568 AD) had to deal with the arrival of 10,000-15,000 people led by Alboin (Albertoni & Varanini 2011), the so-called Langobards, from the Danubian region (today Austria and Hungary), as documented by the Langobardian historian Paul the Deacon. In Trentino-South Tyrol, there is a lack of historical sources regarding the Langobards before the 7^{th} century AD. Therefore, an early agreement with the local populations has been hypothesized by the hystoricians, and small settlements were probably founded in strategic locations for agriculture and especially road control under the Langobardian *Duchy of Tridentum* (former Roman *municipia*) (Albertoni & Varanini 2011). The Langobardian domain was precarious, as the Franks tried to conquer the Adige valley in the 575-76 AD and in 590 AD (Giostra & Lusuardi Siena 2004). In this context, the alliance of the Langobards with the Bavarians was fundamental in the fight against the Franks, sanctioned by the marriage between Theodelinda of Bavarian lineage and the king of the Langobards (first Autari then Agilulf). The Bavarians (a mix of Ostrogoth and Rhaetian groups), who do not appear in historical sources before the 6th century AD, controlled the *Duchy of Tridentum* (Trento, Trentino), including *Bauzanum* (Bolzano, South Tyrol) through marriage-based alliances with the Langobards (616-712 AD, Bavarian dynasty). From late 8th until the 9th centuries AD, the South Tyrolean valleys were military controlled by the Carolingian Empire and with the treaty of Verdun (843 AD), part of the region (Sabiona, Isarco valley) was ruled by the kingdom of the Eastern Franks (Germany or Teutonic Kingdom), while Trentino remained part of the Italian kingdom (Albertoni & Varanini 2011). Due to the limited historical sources on the territorial limits of these two reigns in South Tyrol, Bolzano's early medieval political position is still unclear (Albertoni & Varanini 2011). Marked political instability and conflicts for the conquest of the royal title characterized the 10th century AD. In the 11th century AD (conventionally considered the end of the Early Middle Ages), the political powers of the Bishops of the Bishoprics of Trent (under Aquileia) and of the Sabiona-Bressanone (including Isarco and Pusteria valleys, northern part of Brennero and the Inn valley) were established (Kustatscher & Romeo 2010).

Direct evidences of the early medieval cultural and social changes occurred in South Tyrol are particularly provided by the archaeological sources, that in this territory mainly come from three contexts, such as the churches, the settlements and the necropoles (funerary archaeology). The latter has returned a considerable amount of archaeological data (Archaeological Office of the Autonomous Province of Bolzano); however, only some of these data have been systematically investigated and outlined (e.g., Bierbrauer and Nothdurfter 2015; Marzoli et al. 2009; Reuß 2016). The necropolis do not follow a standard organization, as the dynamic cultural admixture arise novel ideals, uses and customs and new ways of conceiving death (Augenti 2020). Particularly, the grave goods (Fig. 3) found in the funerary contexts, although offering only select information on their cultural habits, are powerful findings as they constitute direct evidence of human customs of that time. They were common especially from the mid-6th century AD, rarely appearing in the middle of the 7th century AD and sporadic from the 8th century AD; however, many tombs did not include any goods (Augenti 2020).

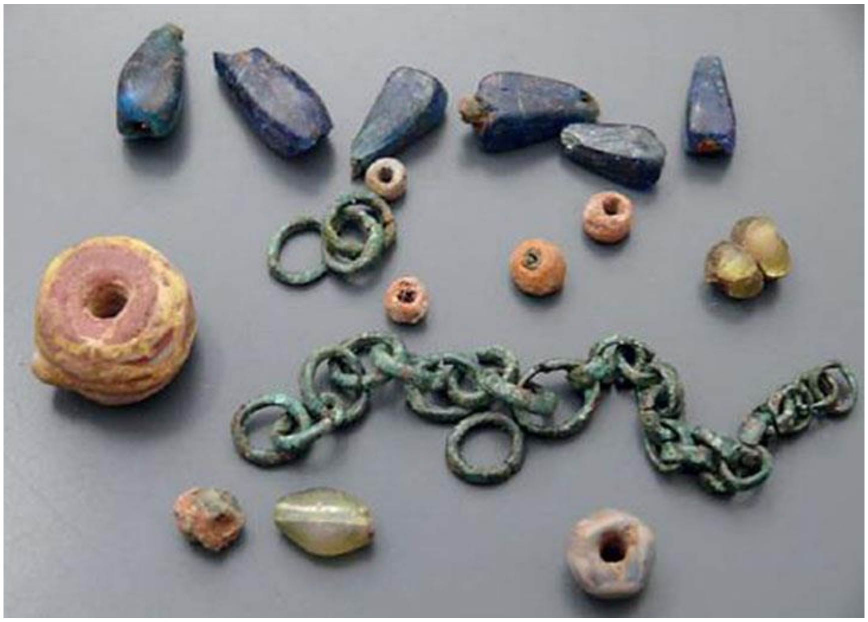


Figure. 3 Grave goods found in tomb 1, in Nalles. Picture from Marzoli *et al.* 2009, p. 156.

The goods can be clustered within cultural models, representing a population “identity” or its “sense of us”, thus they mainly represent family/community status symbols rather than ethnicity markers (Bierbrauer 2005; La Rocca 2004; Delogu 2007). The latter has been one of the most widely discussed topics in medieval studies (Pohl 1998), as, over time, grave goods have often undergone interpretive distortion (Härke 1997). This is because traditional archaeology traces the movement of people through the artefacts, thereby illusively generating a bridge between mobility and identity. However, in reality, this is not such a straightforward process, as culture is a dynamically changing phenomenon (cf. Härke 1997; Evans *et al.* 2006; Knipper *et al.* 2012; Hakenbeck 2013). The goods of that time are indeed the result of a slow and broad hybridization between different cultures (e.g., Roman, Langobardian and Bavarian) (Albertoni 2005; Dal Ri & Rizzi 1995; Gasparri & La Rocca 2013).The early medieval cemetery of Sabiona (Säben, Isarco valley), dated to the 5th-8th centuries AD, represents an example of cultural mixture in South Tyrol. Both autochthonous and possibile allochthonous tombs were located inside or outside the church and, based on the grave goods' types (e.g., pearl necklaces, golden threads, rings and multipart belt sets), the archaeologists attributed eight of the tombs to Bavarians, while the graves with combs, knives were ascribed to local groups (Bierbrauer & Nothdurfter 2015). However, many of the tombs lacked any grave goods, rendering any attempts of cultural attribution impossible (Kaufmann 2017).

From the above, it emerges that both historical and archaeological sources point toward cultural changes or mixture in this territory, but are not conclusive to the evidence of new groups settled in this territory (Cavada 2016).

1.2 State-of-the-art of the bioarchaeological research in South Tyrol

As mentioned above, the funerary archeology (based on necropoli) in this geographical area has returned a considerable amount of material, although these have not always been extensively scientifically investigated. These included not only the grave goods, but also the human skeletal remains. The latter are fundamental biological resources as direct evidence of human lifestyle and they can be an object of scientific investigations, such as anthropological, paleopathological and geochemical (stable isotopes) analyses.

However, in South Tyrol, until recently, anthropological studies were limited, focusing mainly on individual early medieval skeletons or a small number of specimens. Additionally, apart from the well-known Tyrolean Iceman (e.g., Gostner *et al.* 2011, Murphy *et al.* 2003; Seiler *et al.* 2013), to the author's knowledge, only few studies also include paleopathological examinations (cf. Giovannini 2002, 2003; Paladin & Zink 2015; Renhart 1991, 2006; Tecchiati *et al.* 2011). A notable exception is the project lead by J. Rizzi (*Società Ricerche Archeologiche di Rizzi Giovanni & Co.*) who aimed to create an open access database (for further details, please refer to http://www.paleopatologia.com/it/home.html) on pathological evidence observed in the skeletal remains from the 400 to the 1600 AD ossuaries of the St. Floriano Chapel in Rio di Pusteria in South Tyrol (Conzato 2002/2003; Conzato & Rizzi 2007; Conzato *et al.* 2010; Zanatta 2014). However, the database reports little information on the biological profiles or the exact chronology of the presented diseases, rendering it difficult to compare the data with other skeletal collections. Hence, there is still a scarcity of available paleopathological studies that are based on a systematic approach, preventing a broader understanding of the health status of the populations present at that time in the north-eastern alpine valleys (Paladin & Zink 2015).

The study of stable isotopes is significantly developed since its first application (e.g. Ambrose 1986; DeNiro 1985; Krueger & Sullivan 1984; Schoeniger, DeNiro 1984) and, more recently, the investigation of isotopes in early medieval skeletal remains is also gaining attention (e.g., Hakenbeck *et al.* 2010, 2017; Hemer *et al.* 2013; Knipper *et al.* 2012; McGlynn 2007). The analysis of stable isotopes within the context of a bioarchaeological study are of high value, as they may yield information on the circumstances of peoples' lives, exploring paleodietary, mobility and migration in ancient societies. Insights into the diets during the lifetimes of humans and animals are mainly provided by carbon ($\delta^{13}C$, $^{13}C/^{12}C$) to distinguish C_3 (e.g., wheat) from C_4 (e.g., millet, sorghum) plants dietary intake, and nitrogen ($\delta^{15}N$, $^{15}N/^{14}N$), which indicates whether animal protein consumption was derived from marine and/or terrestrial sources (cf. Craig *et al.* 2009; DeNiro & Epstein 1978, 1981; Halffman & Velemínský 2015; Richards*et al.* 1998; Schoeniger 2011). Sulphur ($\delta^{34}S$, $^{34}S/^{32}S$) isotope analysis can also offer information on palaeo-diet (e.g., freshwater sources), past environments, and particularly on migration and mobility patterns (cf. Bollongino *et al.* 2013; Lösch *et al.* 2014; Moghaddam *et al.* 2016; Nehlich 2015; Nehlich and Wahl 2011; Nehlich *et al.* 2012; Oelze *et al.* 2012; Privat *et al.* 2007; Richards *et al.* 2003; Vika 2009).

Before the publication of Article III (Appendix), in South Tyrol, the only local available study on stable isotopes addressed the carbon, strontium and oxygen values of the Tyrolean Iceman mummy (Macko *et al.* 1999; Kutschera & Müller 2003). Thus, due to the lack of isotopic studies in South Tyrol, other geographical areas in northern and central Italy had to be considered as comparative data, even with some limitations as only few studies are available on the early medieval diet in this area (north-east Italy: Iacumin *et al.* 2014; Laffranchi *et al.* 2020; Marinato 2016, 2017, 2019; Maxwell 2019; north-west Italy: Reitsema & Vercellotti 2012; central Italy: Baldoni *et al.* 2016; Pescucci *et al.* 2013; Salamon *et al.* 2008 and only two analysed samples by Ricci *et al.* 2012 and Scorrano et al. 2014). C_4 plants, such as millet (*Panicum miliaceum* and *Setaria Italica*) and sorghum (*Sorghum bicolor*), were important dietary sources, especially in the north-eastern Italian areas (Laffranchi *et al.* 2020; Marinato 2017, 2019; Maxwell 2019), while different proportions of C_4 plants have been reported in populations associated with six early medieval necropoli in Friuli Venezia Giulia (north-eastern Italy, Iacumin *et al.* 2014) and Trino Vercellese (north-western Italy, Reitsema & Vercellotti 2012). A good and variable contribution of terrestrial animal proteins in the diet has been also presented from the above-mentioned areas. The results from central Italy have documented that the early medieval human diet in these regions was based on a wide choice of food resources (from agricultural to terrestrial animal products), mainly based on C_3 plants with a low-scale contribution of C_4 crops (millet), in contrast to the northern regions. Additionally, nitrogen data have displayed some indication of social difference in protein intake among people (Baldoni *et al.* 2016). It has been suggested that such dietary heterogeneity in Italy reflects an agriculture strictly dependent on geographical and climatic, but also historical events (Iacumin *et al.* 2014; Baldoni *et al.* 2016).

Although not exactingly within the Italian geographical context, the isotopic study on the early medieval population of Volders in the Austrian Tyrol region (McGlynn 2007) was also considered in the present thesis for comparison, as North Tyrol shares a border with South Tyrol, as well as being part of the same provinces in Roman times. According to McGlynn (2007) the diet of the Volders population was based solely on C_3 plants, and considerable differences in animal proteins consumption were also reported due to the great variabilities in nitrogen values.

In general, none of the aforementioned studies investigated sulphur stable isotopes analysis to reconstruct mobility patterns[1], despite sulphur ratios in organisms having a strong relationship with the local geology (Richards *et al.* 2003).

Overall, the above-described current status quo of bioarchaeological (paleopathology and stable isotopes) research suggests that South Tyrol is still not a fully explored territory, making it a suitable area to build new interpretations, through a systematic and multidisciplinary approach, on the peopling of the alpine valleys during one of the most debated historical periods, the Early Middle Ages.

In view of this, the area of study of the present doctoral thesis focuses on the three valleys Adige valley (Etschtal), Isarco valley (Eisacktal) and Venosta valley (Vinschgau), and one basin, Conca di Merano (Meraner Becken) (Fig. 4). The latter is located in a unique area that links three different valleys, such as Venosta from West, Passiria (Passeiertal) from north-east and Adige from the southern part of the territory. For this project, skeletal human remains from 11 burial sites (Fig. 4) dated to the Early Middle Ages were selected

[1] Even though not through the study of sulphur stable isotopes, some results on mobility and migration have been presented and discussed in the doctoral theses of: i) Marinato (2016), strontium traced three possible allochthonous in 4th-6th centuries AD necropolis of Spilamberto (Emilia Romagna, Italy); ii) McGlynn (2007), oxygen helped to identify the individuals engaged in transhumance or residing at higher altitudes of the Tyrolean Alps; iii) Maxwell (2009), oxygen helped to identify two potential Langobards in the studied cemeteries (Vicenza) and to document regional migration as common in both northern and southern areas, with individuals coming inland from coastal areas, as well as non-regional migrants from north Africa or Greece, possibly in the context of trade with the Byzantine coast.

for anthropological, paleopathological and stable isotopes analyses. More geographical and archaeological information, including radiocarbon dates, are presented in Table 1A in Appendix[2].

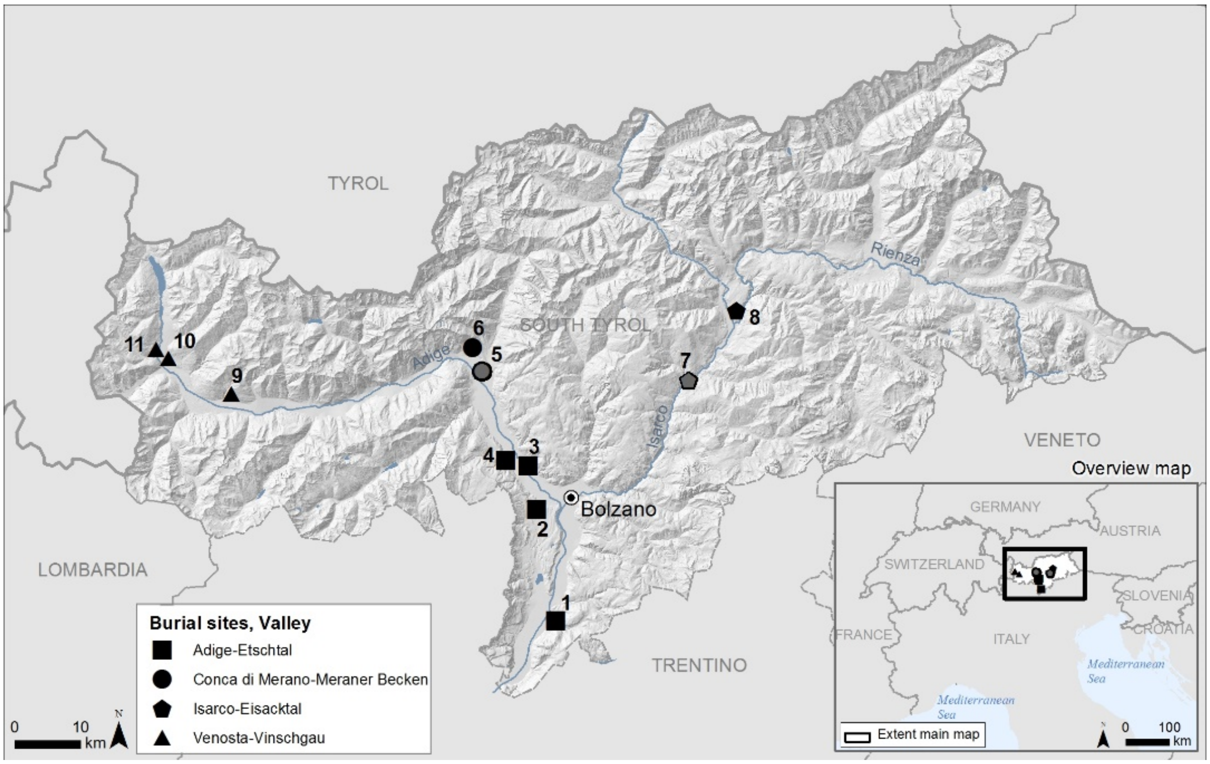


Figure. 4 Map of South Tyrol showing the valleys and the archaeological sites investigated in this work. Adige valley: (1) Montagna, Pinzano (Montan, Pinzon), (2) Appiano, San Paolo Castelvecchio (Eppan, St. Paul Altenburg) ,(3) Terlano (Terlan), (4) Nalles (Nals); Conca di Merano (Merano basin): (5) Maia Bassa (Untermais) and (6) Castel Tirolo (Schloss Tirol); Isarco valley: (7) Sabiona (Säben) (8) Bressanone, Elvas necropoli 17 (Brixen, Elvas); Venosta valley: (9) Tanas (St. Peter's path), (10) Malles, Maso Pauli (Mals, Paulihof), (11) Malles, Burgusio Santo Stefano (Mals, Burgeis St. Stephan). Dark grey colour indicates the sites not tested for stable isotopes, as the samples were not available at the time of the analysis[3]. Map made with the support of Dr. Kathrin Renner (tool: ESRI ArchGIS).

[2] Excepting the site of Sabiona-Säben, as it will be part of another Eurac Research project (unpublished data Institute for Mummy Studies).

[3] The isotopic analysis of Maia Bassa and Sabiona-Säben were performed at a later stage and reported in a master's thesis (L. Mundle, unpublished data Institute for Mummy Studies). The student was co-supervised by the author of the present doctoral thesis.

2. Objectives and expected output of the doctoral research

This cumulative doctoral thesis is the result of a bioarchaeological project performed on early medieval human skeletal remains from South Tyrol, Italy (Fig. 4).

This dissertation aimed to obtain new insights into the communities that lived in the eastern Italian alpine valleys, with a focus on health, diet, and mobility patterns.

The objectives of this study were:

1) to reconstruct the biological profile and health conditions of the studied individuals, with a focus on metabolic diseases and trauma, using a systematic approach (Articles I and II, Appendix);

2) to characterize the local dietary habits and subsistence strategies through carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) stable isotope analysis of human and animal bone collagen (Article III, Appendix);

3) to evaluate the mobility patterns in the South Tyrolean valleys through the analysis of sulphur ($^{34}S/^{32}S$) stable isotope (Article III, Appendix).

The expected outputs of this doctoral study have the potential to make an important contribution towards a better understanding of the history and the population dynamics of early medieval South Tyrol. This research has produced new data in the field of bioarcheology that support current archaeological and historical research. Additionally, this work has collected anthropological, paleopathological and isotopic data, which may prove useful also for future comparative analyses not only in the considered territory, but also to a broader level (e.g., Italian, European).

The published results of the paleopathological (Article I and Article II) and stable isotope (Article III) studies are presented in Appendix.

3. Results and Discussion

In this chapter, the key results from the three published papers forming this cumulative dissertation are presented, discussing the above-mentioned objectives and elaborating the main contributions to the paleopathological study of metabolic diseases and trauma, as well as stable isotopes analysis in the north-eastern Italian Alps.

The supplementary materials on the anthropological and paleopathological results are reported in Tables 2A, 3A and 4A (Appendix) in order to compile the numerous data obtained in the course of this doctoral project, which are partially inedited or distributed amongst the three published articles.

3.1 Health status: metabolic diseases and trauma in early medieval South Tyrol

The evaluation of health status is a significant indicator for biocultural diversity and demographic changes in (pre-) historic communities (Lewis 2007). In the following sections, two pathological case studies are presented which focus on metabolic disease in infants, suggesting variations in living conditions in Castel Tirolo (Merano basin) (Article I), and on sharp force trauma proposing episodes of interpersonal violence in Sabiona-Säben (Article II). In the next sections, in addition to that presented in the two articles, further paleopathological data obtained from other South Tyrolean sites in the context of this doctoral project, are also reported in order to provide a broader basis for discussion into metabolic diseases and trauma in this geographical area.

3.1.1 Metabolic diseases (scurvy) (Article I)

Studies on metabolic diseases, focusing on scurvy (vitamin C deficiency), are of growing interest in paleopathology (e.g., Bourbou 2014; Brickley & Ives 2008; Buckley *et al.* 2014; Schattmann *et al.* 2016; Snoddy *et al.* 2017) as they can provide important insights into different factors of past human life, such as subsistence strategies, nutrition and environmental events (Brickley & Ives 2008). Despite the increase of comparative studies and endeavours to apply microscopic (histology and chromatography) and diagnostic (radiology and computed tomography) methods, the diagnosis of infantile scurvy or

Möller-Barlow's disease (Barlow, 1883, 1894) caused by the deficiency of vitamin C, remains challenging. This is because the main macroscopic indicators for scurvy, like abnormal pores and new bone formation, are non-specific skeletal changes suggestive of a systemic pathological condition and that can occur in different pathologies, such as anaemia, rickets, and/or infectious diseases (Brickley & Ives 2008; Snoddy *et al.* 2017). However, in metabolic disorders other than scurvy, the abnormal pores and bone formations can be also accompanied by other skeletal manifestations (e.g., vitamin D deficiency or rickets causes the widening and diaphyseal cupping of the long bones). Therefore, an accurate differential diagnosis can be of great value in attempting to detect scurvy (Brickley & Ives 2006; Klaus 2017).

In Italy, very little case examples of subadult scurvy are available, one case including the possible scorbutic case from the Roman imperial necropolis of Collatina in Rome (Minozzi *et al.* 2012); other examples are underreported. This might be due to the common assumption that Italy had favourable environmental conditions and easy access to fresh vegetables and fruits, which might erroneously encourage researchers to rule out the occurrence of this pathology (Paladin *et al.* 2018b). However, scurvy can also occur in environments where fresh vegetables and fruits are usually available such as, for example, the Pacific islands (Buckley *et al.* 2014). In Article I, new insights into infant health status in early medieval Italian Alps were presented for the first time. In this study, the skeletal human remains from Castel Tirolo (Merano basin, Fig. 4) were anthropologically and paleopathologically examined. In total, a minimum number of 41 individuals (MNI) was calculated, including eleven adult males, two females, one adult individual with unclear sex and 27 indeterminate subadults. The latter were grouped in five perinates (36 to 40 weeks' gestational age), 13 infants from birth to 6 years old, eight from 7 to 14 years old, and one late juvenile (18-19 years). The higher frequency of subadults (61%, 27/41) as compared to adults is unique in the territory (Tab. 3A, Appendix), even compared to the site of Sabiona-Säben that yields the highest number of individuals (~230 MNI. 29% of the individuals are at an age < 18 years old). Moreover, the site of Castel Tirolo is the only site in South Tyrol with bisome graves in which adults were buried together with newborn individuals (Paladin *et al.* 2018). Different hypotheses can be formulated regarding the general under-representation of the subadults in South

Tyrol and the uniqueness of Castel Tirolo: i) taphonomic damage. The immature bones are generally poorly preserved due to their fragile bone structure, making them difficult to find. Moreover, concerning the South Tyrolean necropolis, often no experienced physical anthropologists were involved in the excavations, and thus the infantile bones might have not been recognized as human, especially if they were fragmented and partially destroyed (Milner et al 2008); ii) burial practices. In Castel Tirolo, children might have played a particular role in the social structure and were buried alongside adults for that reason. It is possible that, at the other sites, not all the infants were interred in the cemetery, e.g., due to religious reasons. Indeed, in medieval Europe, the baptismal status was essential to allow early infancy deaths being part of the Christian cemetery (Gilchrist & Sloan 2005; Hausmair 2017); iii) paleodemography. The subadult age distribution of the site of Castel Tirolo could be considered as more likely representative of a medieval population with high infant mortality as compared to the other sites. However, the skeletons from archaeological contexts are selected “mortality samples”, and thus rarely representative of an entire population (Milner *et al.* 2008).

The macroscopic examination of the pathological lesions observed on the immature bones from Castel Tirolo, followed by an attempt at differential diagnosis, suggest that 58% (n=14/24) of the subadults displayed pathological bone lesions consistent with metabolic disorders. In particular, two subadults found in tomb 13 (TCT13, 11–12 years old) and tomb 14 (TCT14, 12–14 years old) exhibited multiple diagnostic lesions consistent with scurvy. Another three infants (TCT9, TCT17, and TCT24) showed abnormal changes that could not be linked to a specific pathological condition, and another nine (TCT6A, TCT6B, TCT8A, TCT10, TCT11A, TCT11B, TCT20, TCT21-22A, and TCT186) had few lesions that were not diagnostic for a specific metabolic disease. A detailed overview of all the observed lesions in the studied anatomical regions is presented in Table 2 of Article I.

There are different reasons why scurvy could have affected these children. In Early Middle Ages, climatic changes such as harsh winters could have brought about episodes of famine or isolation of communities, so that people only had access to fresh fruit and vegetables during a restricted time of the year (Salis *et al.* 2005). Another reason could be found in historical events. The archaeological excavations partially conducted in the cemetery of Castel Tirolo and never in the original settlement (Marzoli *et al.* 2009), did not report any signs of building destruction. Based on that observation, the archaeologists supposed that this territory and its inhabitants were not negatively affected by the barbaric military incursions (personal communication, responsible of the excavation Gino Bombonato). However, the paleopathological investigation could suggest a different scenario. War and siege can also cause isolation, famine, malnourishment and pestilence (Prinzing & Westergaard, 1916), and according to the few historical records, the area of Merano basin, where Castel Tirolo is located (Fig. 4), was a border territory military contended by both Langobard and Bavarian groups (Marzoli *et al.* 2009). Therefore, it might be that, for example, the passage and provisional settlement of troops caused food resources restrictions to low-status people, suggesting that the population dynamics in Castel Tirolo are still not fully understood, as based on archaeology research alone.

Considering the hypotheses presented above (climate, historical aspects), we would also expect adult individuals of Castel Tirolo to display at least some of the pathological lesions that were observed in the subadults. The diagnosis of adult scurvy is even more challenging than in subadults, as this pathology, even if present in an adult individual, does not necessarily manifest in macroscopic pathognomic features at a skeletal level (Tab. 1, Brickley & Ives 2008).

Table. 1 List of scorbutic macroscopic features in adults by Brickley & Ives 2008 (Table 4.3 at page 61, modified). As stated by the authors, none of the following changes are pathognomic. Legend: D, diagnostic feature; G, general change.

Bones affected	Features	Code	Differential diagnosis
Cranium	New bone formation-orbits	D	Trauma
Dentition	Antemortem tooth loss single-rooted teeth particularly susceptible	G	Periodontal disease
	Inflammation in alveolar bone		
Vertebrae	Osteopenia and possible bi-concave compression.	G	Osteoporosis Trauma
Ribs	Transverse fractures at osteocartilaginous junction of ribs	D	Trauma
Pelvis	-	-	-
Long bones	New bone formation – particularly common towards ends	D	Trauma Infection

The paleopathological investigations conducted for the present doctoral work (thus in addition to the published subadult cases) revealed that in Castel Tirolo, the young adult male (20-25 years old) TCT26 from tomb 26, displayed a possibly healing lytic lesion on the anterior distal metaphysis of the left femur, similar in shape and location to the one observed in the scurvy subadult case TCT13 (please, see Figure 6 in Article I). Moreover, a 20-30-year-old female (TCT27 from tomb 27) presented dental and bone pathological defects that, following Brickley & Ives (2008), could be associated to scurvy. These included vascular impressions on the endocranial bone surfaces, antemortem tooth loss (AMTL) and severe inflammation and retraction of the alveolar bone (periodontal disease) in the maxilla and mandible (Fig. 5).

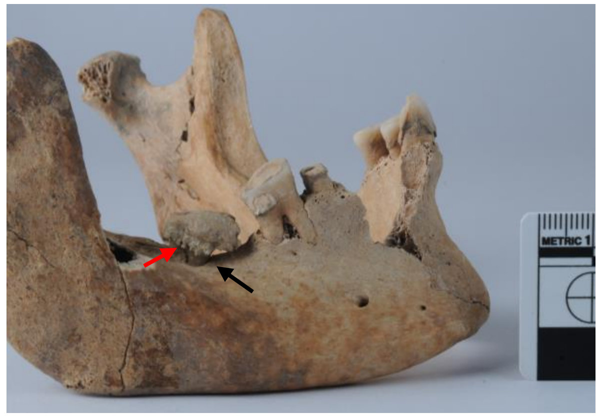


Figure. 5 Castel Tirolo (Merano basin), tomb 27, adult female TCT27. Maxilla (left) and mandible showing severe parodontitis and bone inflammation (black arrows highlight some examples), and severe dental calculus (red arrows). Pictures made by the author of the present dissertation and authorised by the Institute for Mummy Studies of Eurac research.

In the postcranium, the vertebrae showed osteopenia, whereas both femurs and tibiae presented new bone formation, as well as a trauma in the proximal section of the diaphysis of the right tibia. It is here considered appropriated, even if not necessarily connected to scurvy, to report the remarkable finding of an unknown calcified object (Fig. 6) found amongst the skeletal remains of TCT27 (unfortunately the location of the calcification was not reported during the excavation). The object is ovoid in shape (40 mm x 34 mm), compact in consistency with a pseudocalcified structure. The mass was CT-scanned (Fig. 6), the results of which confirm its calcified structure and reveal the inner part as being of a homogeneous trabecular composition[4]. A paleopathological investigation, including a differential diagnosis, to identify a conclusive diagnosis of this calcified object is ongoing.

[4] Molecular and histological analyses were also conducted in the laboratory for aDNA of the Institute for Mummy Studies (Eurac Research). The results are summarized in a bachelor thesis (Azzolini D. Unpublished data, Institute for Mummy Studies. The student was co-supervised, for the macroscopic and CT-scan data analyses, by the author of the present doctoral dissertation).

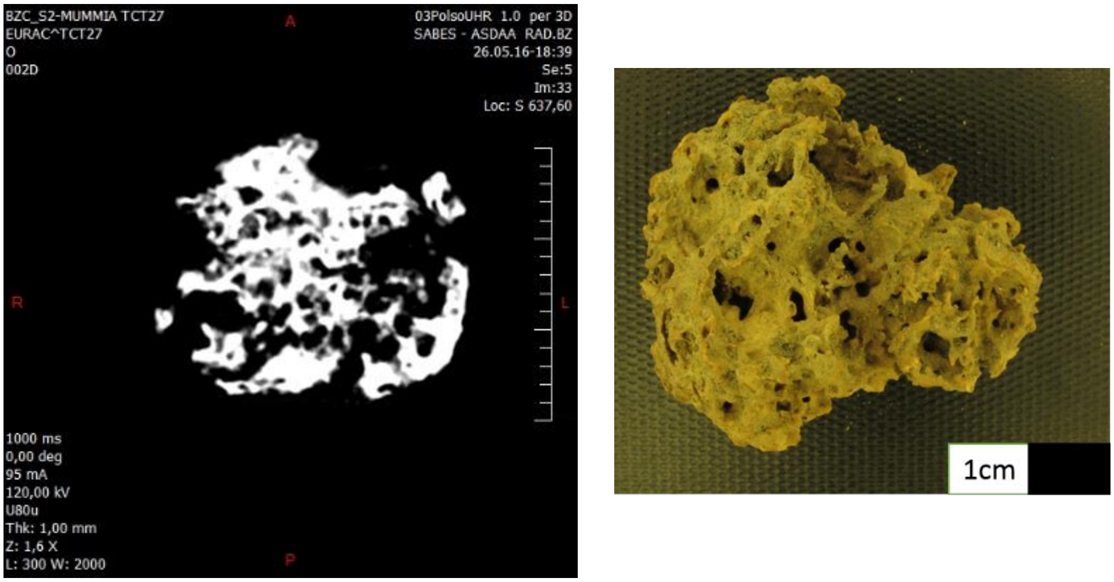


Figure. 6 Castel Tirolo (Merano basin), tomb 27, adult female TCT27. The calcified object (right) and its inner structure (CT-scan image, left). Pictures authorised by the Institute for Mummy Studies of Eurac research.

Additional vitamin deficiencies (scurvy and rickets) cases were also reported in early medieval infants from Sabiona-Säben in Isarco valley (Paladin *et al.* 2018a, poster presentation). In total, three (MNI) subadults, aged from 6 months to 1 year old (SK106 and SK107A) and 4 to 6 years old (SK123), were paleopathological examined. The cranial and postcranial bones of the subadults displayed pathological changes, such as abnormal porosity and periosteal new bone formation (Tab. 2, Fig. 7), comparable to the one of TCT13 and TCT14 (Article I). Differently from the Castel Tirolo cases, the individual SK106 (Sabiona-Säben) showed the widening and cupping of the left tibia and left femur metaphyses that is usually observed in vitamin D deficiency cases. Therefore, SK107A and SK123 were the only subadults displaying pathologic features possibly consistent with vitamin C deficiency, while SK106 was more likely a case of rickets (vitamin D deficiency). However, comorbidity of both scurvy and rickets cannot be excluded.

In conclusion, in South Tyrol, different factors could have caused metabolic diseases in children, such as inaccessibility of fresh food, for example, as a result of isolation of communities due to conflict and/or climate events (e.g., harsh winters). The preliminary study on Sabiona-Säben supports and increases the previous published work (Article I in

Appendix), also suggesting the general underestimation of metabolic diseases in the Italian paleopathological studies.

Table. 2 Results of the paleopathological analysis of SK106 (6 months to 1 year old), SK107A (6 months to 1 year old) and SK123 (4 to 6 years old). The differential diagnosis was based on the extended scoring system of Snoddy *et al.* (2017). Legend: Ind., individual; p, porous lesions; nb, new bone formation; *, bilateral lesion; o, absent; -, not observable, thus the bone is absent or it is poorly preserved; RI, rickets; SC, scurvy.

Ind.	**ectocranium**	**endocranium**	**orbital roof**	**greater wing**	**facies orbitalis**	**maxilla**	**palatumdurum**	**mandible**	**supraspinousfossa**	**costochondral junction**	**ilium**	**humerus**	**femur**	**tibia**	**Diagnosis**
SK 106	-	-	-	-	-	o	p	-	p	-	o	nb* p*	nb*	nb*	RI
SK 107A	p	p	p nb	-	-	-	p, nb	p*	-	p*	o	p*	nb* p*	nb*	SC
SK 123	p*	p	p*	p	p	p*	o	p* nb*	p	o	p	p	-	-	SC

Figure. 7 Sabiona-Säben (Isarco valley), tomb 123 crypt D, subadult SK123. Endocranial vessels impressions and abnormal pores (above). Abnormal pores and new bone formation at the mandible (below). Pictures authorised by the Institute for Mummy Studies of Eurac research.

3.1.2 Trauma analysis and interpersonal violence (Article II)

Trauma analysis contributes to the understanding of socio-cultural practices, human interaction, daily activities and lifestyle in past societies, also providing insights into episodes of interpersonal violence and conflicts within and amongst past communities (e.g., Mariotti & Belcastro 2017; Vazzana *et al.* 2018).

In Article II (Appendix), the results of the systematic macroscopic and microscopic examinations of antemortem injuries and multiple perimortem sharp force traumata observed in individual SK63 from the early medieval site of Sabiona-Säben (Isarco valley) were presented. Individual SK63 was found in a single stone-lined earth grave (tomb 63) dated to the 7th-8th centuries AD and located in the western part of the southern side of the early medieval church (Bierbrauer & Nothdurfter 2015). The skeletal remains belonged to a 19-25-year-old male, who was found in primary deposition, west-east oriented (head-feet), and in supine position with the lower arms flexed above the pelvis. After a detailed and systematic paleopathological investigation, multiple (n=29) antemortem (10.3%, 3/29) and mainly perimortem (89.7%, 26/29) traumatic injuries to the cranium (17.2%, 5/29) and (82.8%, 24/29) postcranium were recorded and examined. All of the perimortem lesions were identified as sharp force trauma (for a detailed trauma location please refer to Fig. 3 in Article II, Appendix). Sharp force trauma (SFT) in bones are injuries caused by dynamic compression or shearing forces over a narrow area and, if enough force is applied, causing a wound in the bone. The appearance of the lesion depends on the angle of contact, on the force applied and on the type of weapon employed (e.g., knife, sword, lance or axe). The SFT observed in the cranium and postcranium of SK63 suggests that this individual was probably struck by bladed weapons, most likely sword and knife, indicating interpersonal violence rather than large-scale conflict. Additionally, the face-to-face fight probably happened in a direct hand-to-hand frontal attack, between right-handed opponents (Boucherie *et al.* 2017; Fiorato *et al.* 2007), as the left side of the skeleton presented a clear predominance of cut marks.

Additional antemortem and perimortem traumata to those described in Article II have also been recorded (Tumler, Paladin, Zink, Trauma patterns and injury prevalence in early medieval Sabiona-Säben, Italy, *paper submitted for publication*) in the skeletal human remains found in the same necropolis (Sabiona-Säben). In particular, out of 37 (16.4%, 37/226) individuals who displayed trauma, seven (46%, 7/37) had multiple injuries, including SFT in the crania, that can be suggestive of deliberate aggression events (Fig. 8).

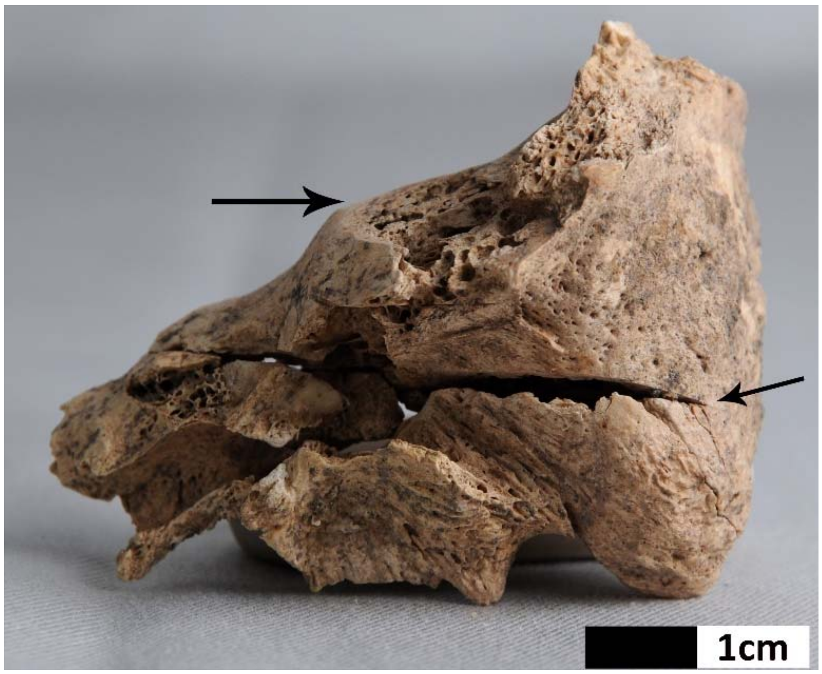


Figure. 8 Sabiona-Säben (Isarco valley), tomb 114, mature male individual SK114. Perimortem sharp force trauma (arrows) in the petrous bone and mastoid process of the left temporal bone. Picture by Tumler, Paladin, Zink, *paper submitted for publication* and authorised by the Institute for Mummy Studies of Eurac research.

Moreover, in the context of the present doctoral work, of the studied 173 MNI from different valleys in South Tyrol (Fig. 4; Tab.2A and 3A in Appendix), 17.3% (30/173) of the individuals displayed traumata (results currently unpublished; Fig. 9), including twenty males (66.6%, 20/30), six females (20%, 6/30) and one indeterminate adult, of which only two (6.6%, 2/30) exhibited SFT (Fig. 10). These frequencies are comparable to the one collected from the above-mentioned necropolis of Sabiona-Säben, where 18% (40/226 MNI) of the individuals featured traumatic injuries with adult males (72.5%, 29/40 MNI) showing more trauma than females and subadults (Tumler, Paladin, Zink, Trauma patterns and injury prevalence in early medieval Sabiona-Säben, Italy, *paper submitted for publication*).

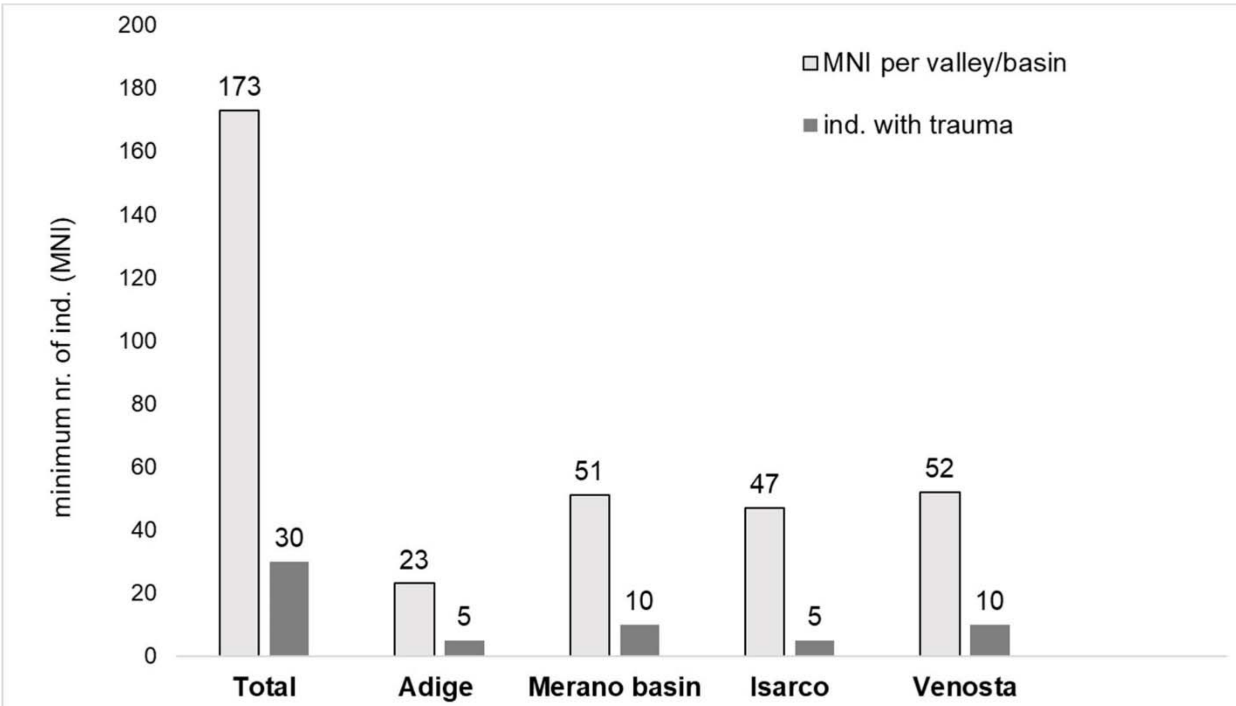


Figure. 9 Total number of studied individuals and corresponding injured cases per valley-basin.

Concerning the age at death distribution of the injured individuals (30 MNI), 18 adults (four females, 13 males and one indeterminate), nine mature (one female and eight males) and three senile (two females and one male) were recorded. None of the examined subadults presented trauma.

Figure. 10 Castel Tirolo (Merano basin), tomb 19, adult male TCT19. Sharp force trauma in the diaphysis of the left femur. Anterior (left picture) and posterior (right) detail of the injury. Pictures made by the author of the present dissertation and authorised by the Institute for Mummy Studies of Eurac research.

In total, 42 fractures were recorded, of which 7.1% (3/42) were in the region of the cranium (BSS2/484-US119, probably BSS-163A and BEN14) and 92.9% (39/42) in the postcranium, with a minimum of one and a maximum of three traumata per individual (Tab. 5A, Appendix). One example of cranial injury was the antemortem healed blunt force trauma of elliptical shape observed on the frontal bone of the mature male BSS2/484-US119 (tomb 2, Malles Burgusio Santo Stefano, Venosta valley) (Fig. 11).

Figure.11 Malles Burgusio Santo Stefano (Venosta valley), tomb 2, mature male BSS2/484-US119. Blunt force trauma on the frontal bone of the cranium. Pictures made by the author of the present dissertation and authorised by the Institute for Mummy Studies of Eurac research.

Concerning the postcranium, when possible, a classification of the type of trauma was attempted according to the descriptive protocols for fractures by Lovell (1997). Thereby, the injuries were classified as extra or intra-articular, direct or indirect trauma, and fracture occurring secondary to physical stress or other diseases. Direct trauma includes transverse, penetrating, and comminuted trauma, whereas indirect trauma encompasses spiral, oblique, and impacted, caused e.g. by blunt tools (Lovell 1997). Additionally, the laterality (left or right side of the body) of healed and unhealed trauma was taken into consideration, as this information can provide indications of the nature of the incident, for example in case study SK63 (Article II). As presented in Table 5A (Appendix), the traumata were distributed throughout different postcranial bones, including 7.7% (3/39) in the vertebrae, 12.8% (5/39) in the upper limbs (hands included), 28.2% (11/39) in the ribs and 51.3% (20/39) in the lower limbs (feet included). Four (10.3%, 4/39) possible direct trauma and 19 (48.7%, 19/39) indirect trauma were observed, including greenstick, oblique and spiral indirect traumata, which are usually the result of accidents (Gilmour *et al.* 2015). The majority of the greenstick fractures were to the ribs, as is common in adult individuals (Lovell 1997). With regard to lesion laterality, no clear differences were observed concerning the frequency of injuries to the left (n=16) and right (n=18) body sides, respectively. Moreover, the majority of the antemortem traumata presented a callus formation (43.5%, 17/39) or showed consolidation/partial consolidation (38.5%, 15/39), suggesting the survival of the individuals after the traumatic event. Five traumata could be evaluated as being, in all likelihood, secondary to a pathology, i.e. osteoarthritis or resulting from stress caused by intense physical activities (Tab. 5A in Appendix).

In South Tyrol, other examples of trauma caused by physical labour have been documented by Giovannini (2003) in an anthropological study on 10 individuals found in the necropolis of Castelfeder in the Adige valley, dated to the 9th – 10th centuries AD. A female individual of approximately 70 years old (SE 44, tomb 6) displayed one healed trauma in the frontal bone of the cranium and one possible direct trauma (no other detailed information on the type of trauma is available) in the left femur, possibly caused by physical activities (Govannini 2003, p. 106). Other traumata included SFT in local communities, as documented by Reinhart (1991, p. 181) in the early medieval (6th – 8th centuries AD) cemetery of Naturno San Procolo in the Venosta valley. Two injuries, one blunt force and one SFT in the cranium (Fig. 12) in a mature male individual in tomb 26, were attributed to violent events, while one trauma in the distal third of the diaphyses of the left ulna and radius of a female individual (tomb 28) was associated to an act of self-defence. Moreover, a trauma in the left clavicle of a senile female (tomb 128), one in the left tibia of the individual of tomb 148 and one in the right femur neck of a senile individual from tomb 21, possibly secondary to physical stress or a pathology, were also reported (Reinhart 1991).

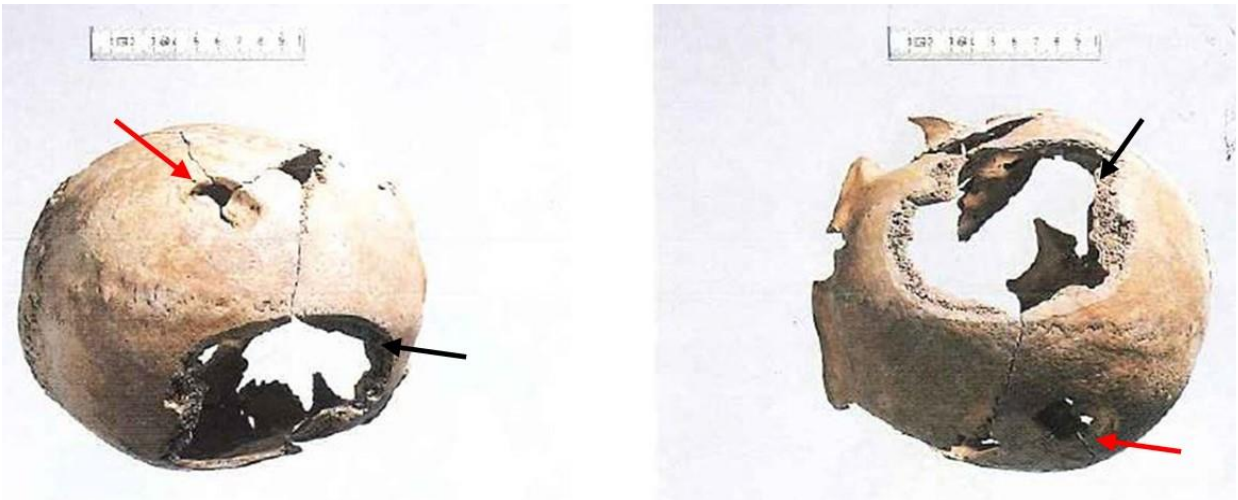


Figure. 12 Naturno San Procolo (Venosta valley), individual from tomb 26. Cranium displaying both blunt (red arrow) and sharp force (black arrow) trauma. From Reinhart 1991, Fig. 38 – 39, page 185.

Other examples of SFT in South Tyrol, albeit dated to later periods (medieval – 17th century AD) than the one considered in this thesis, are shown as images in the above-mentioned open-source database (www.paleopathology.it, Fig. 13) (Conzato & Rizzi 2007). Although other examples of trauma are included in the database, systematic information on the number of affected individuals, on the quantity and type of lesions with the reference to their bone location and laterality are missing, rendering the data unsuitable as reference material.

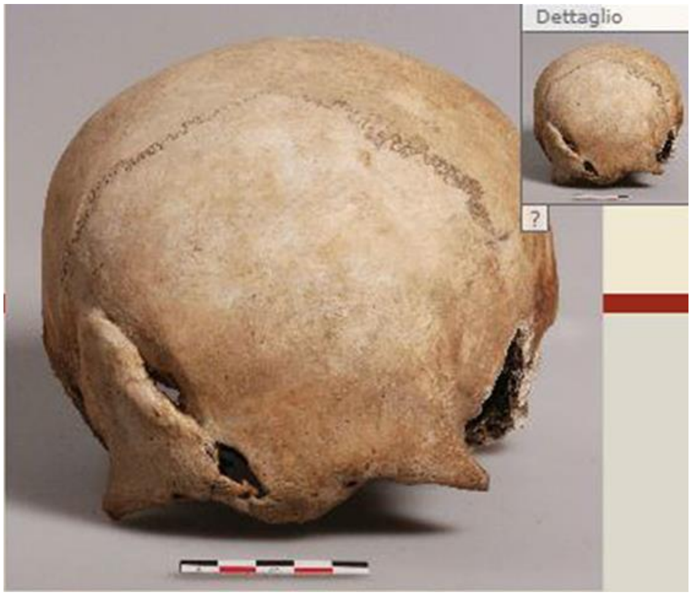


Figure. 13 San Floriano Chapel, Rio di Pusteria (Pusteria valley), individual RPS3C93a. Sharp force trauma in the cranium. The healed lesion is 50 mm long and 21 mm wide. Figure from www.paleopatologia.com/it/paleopatologie-e-indicatori-di-stress/evidenze-scheletriche-da-trauma/37-trauma.html

In conclusion, the presented trauma investigation (Article II and unpublished data) provide preliminary indications of the health status and lifestyle of the individuals living in early medieval South Tyrol. In contrast to the site of Sabiona-Säben (46%, 7/37), where multiple SFT cases were recorded including the exceptional case SK63 (Article II in Appendix), the human skeletal remains from the other investigated early medieval sites (Fig. 4) did not show clear evidence for interpersonal violence (with individual TCT19 constituting a possible exception). Indeed, the types of the observed trauma were more indicative of intense physical activities (e.g., trauma in the area of the vertebrae and/or lower limbs), especially if observed in combination with other pathologies such as spondylosis or degenerative joint disease (DJD), and/or labour-related accidents, such as farming or hunting in the alpine habitat.

3.2 Dietary habits and subsistence strategies in South Tyrolean valleys (Article III)

In the third published article (Article III in Appendix), the isotopic variabilities of early medieval communities in South Tyrol were examined. The first aim was to gain insights into subsistence strategies and environmental human adaptations according to geographical (valley, altitudes) and chronological parameters. Therefore, the bone collagen of 32 faunal and 91 human bone samples, from nine sites located in three valleys (Adige, Isarco and Venosta) and Merano basin and at different altitudes (from 395 to 1427 m a.s.l.; Fig. 4; Tab. 1A in Appendix), was extracted for the analysis of stable carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and sulphur ($\delta^{34}S$) isotopes.

3.2.1 Fauna

The stable isotopes analysis of faunal remains is fundamental to reconstruct the animal-human trophic relationship, which is a measure of diet structure displaying animal and human positions in the food web (Bonafini *et al.* 2013; Bonhommeau *et al*. 2013; Katzenberg 2008).

Faunal bones, contemporary to the humans, were sampled from both domesticated and wild animals (n=32) found in the above-mentioned valleys and sites (more data are presented in Table S2 in the supplementary materials of Article III in Appendix). Collagen of good quality was obtained from 94% (30/32) of the animals in question and was therefore used for stable isotope analyses.

Both carbon and nitrogen values reflected a terrestrial-based diet. In terms of $\delta^{13}C$ values (data ranges: -21.52‰ to -18.01‰, mean and SD -20.29 ±0.81‰), forest-dwelling animals (bear and deer) showed the lowest values, with the deer having the most negative $\delta^{13}C$ mean value (-21.08 ± 0.39‰, Fig. 3a-b in Article III, Appendix). The observed ^{13}C-depletion signal was consistent with expectations, as it suggests that these animals foraged in forest enviroments. In ecology, ^{13}C-depletion is also referred to as the "canopy effect", which causes a growth of ^{13}C-depleted plants "(..) *that corresponds to a vertical gradient in the $\delta^{13}C$ values of forest trees, with high $\delta^{13}C$ values at the top of the canopy and low values at the bottom* (..)*"* (Drucker *et al.* 2008). The "canopy effect" signal was also observed in horses (-21.08 ± 0.39‰, Fig. 3a-b in Article III, Appendix), suggesting that these domesticated animals were mainly fed in forested enviroments or with plants growing under closed canopy. This result could reflect the forest management system typical of Late Antiquity and early medieval period, characterised by faunal remains including both wild animals and domesticates, as have been historically reported in the Trentino area (Forlin 2015). High carbon values, on the other hand, were observed in dogs, with one individual (AP-AL CF) in the Adige valley displaying a clear C_4 plant signal (-16.36‰). This value could suggest that AP-AL CF was a hunting dog, because, at that time, these animals were often fed with a substantial proportion of millet (unpublished data, Castel Tirolo museum). As a more general observation, this signal suggests that the dogs, as expected, had an omnivorous diet, reflecting their owner's dietary habits (Guiry 2012). Some intake of C_3 plants (e.g. acorns) were recorded in pigs, fed in open lands, as commonly practiced according to medieval farming procedures (Montanari & Barruzzi 1981).

In terms of $\delta^{15}N$ values, all faunal remains showed a high variation (from + 2.60‰ to + 10.65‰, mean value of +5.61‰, with a SD of ±2.16‰), with the bear displaying the lowest nitrogen value (+2.73‰) after a deer (+2.60‰). This could indicate that the bear was predominantly dependent on a plant-based diet, as already documented in medieval Germany (Lösch 2009), but also it could be the consequence of the metabolic process during hybernation (Nelson *et al.* 1998) or of nutritional stress due to harsh climatic conditons (Bocherens *et al.* 2006). In contrast, the dogs showed higher nitrogen mean values (+8.38‰, Fig. 3a-b in Article III, Appendix) displaying, as suggested by the carbon values, strong similarities in dietary behaviour to the human individuals found in the same territory. An omnivorous diet, as expected, was also observed in pigs, which displayed high nitrogen values (+8.01‰) with partial plants consumption. One finding of special interest was a pig (TE SSD) buried in a single stoned-lined pit grave (tomb 11) in Terlano, Adige valley (Fig. 14). The trophic level of TE SSD was similar to the local humans, and the single burial might have had a ritualistic purpose, as documented in *De agri cultura* (160 BC):

“Lucum conlucare Romano more sic oportet: porco piaculo facito [...]” (Marcus Porcius Cato, *De agri cultura* 139,1)
(English translation: “According to the Roman habit, a sacred wood must be deforested in this way. You will offer a pig in atoning sacrifice [...]”)

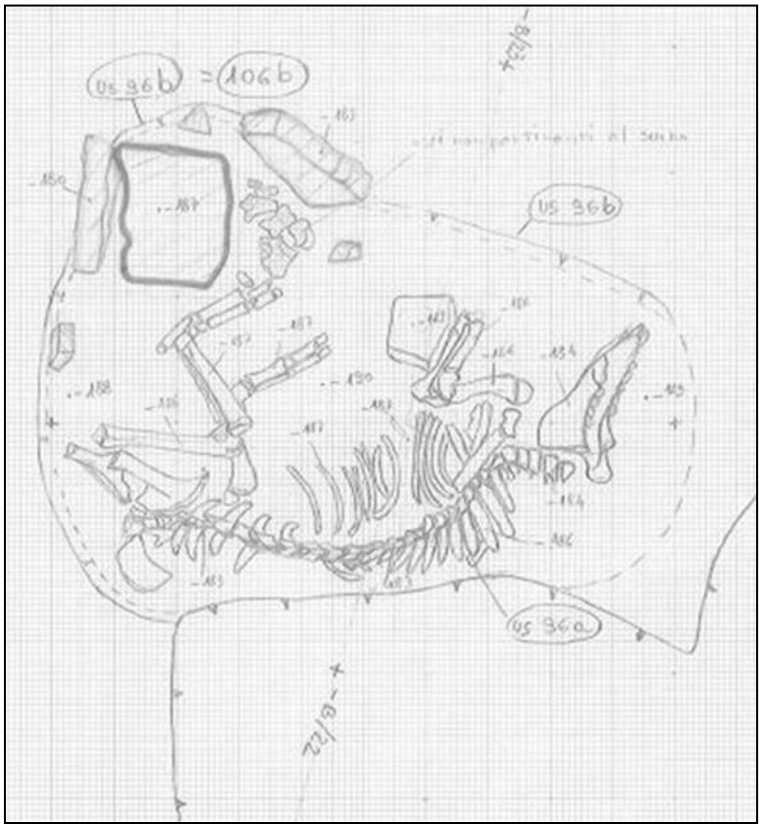


Figure. 14 Archaeological drawing of tomb 11 of the cemetery of Terlano, which encompassed the burial of a subadult pig in an east-west orientation. Unpublished document provided by the Archaeological Office, Autonomous Province of Bolzano, Italy.

The highest isotopic variation in animals of all species was observed in the $\delta^{34}S$ values. The data ranged from +2.17‰ to +11.67‰ (mean and SD +7.14 ±2.20‰). In Article III, swine were taken into consideration for the reconstruction of the human-faunal baseline of sulphur values to answer questions on human mobility, as, in the literature, they are generally characterised as non-migratory animals (Scheeres *et al.* 2013) and as they have a digestive physiology similar to that of humans (Iacumin *et al.* 2014). However, in this work, the low sample size of non-migratory animals must be taken into consideration, and further baseline samples are required to verify the hypothesis made regarding mobility patterns (cf. section 3.3).

3.2.2 Human groups

Of 91 human bones samples (Fig. 15a), collagen of good quality was obtained from 85 samples (93%, 85/91) for $\delta^{13}C$ and $\delta^{15}N$ (Fig. 15b), and 40 (44%, 40/91) yielded collagen of good quality for $\delta^{34}S$ stable isotope analysis (Fig. 15c).

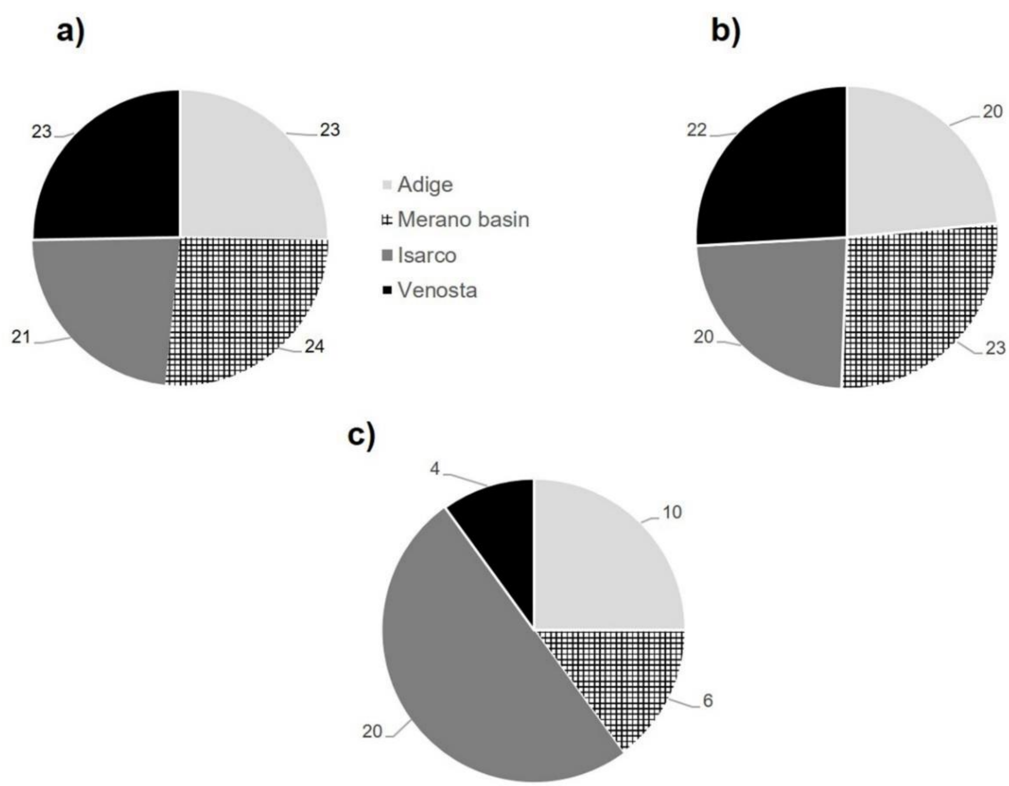


Figure.15 a) Number of human samples (total n=91) grouped per valley and basin. **b)** Bone samples with good collagen for carbon and nitrogen (n=85) grouped per valley and basin. **c)** Bone samples with good collagen for sulphur (n=40) grouped per valley and basin.

The results of the stable isotope analyses suggest that the human communities of the different locations (valleys and basin) had a mixed terrestrial diet (C_3/C_4 plants). Statistically significant differences were observed within and between valleys (Tables 1 and 2 in Article III, Appendix). The variation of $\delta^{13}C$ data was mostly associated with the different altitudes. The individuals found at higher areas (Venosta valley) displayed a diet mainly based on C_3 plants (e.g., wheat, barley). This corresponds with the reported carbon results from the neighbouring region of Tyrol (McGlynn 2007), and with the Italian site of Spilamberto in Emilia Romagna (Marinato 2016, 2019). In contrast, the individuals living at lower altitudes (Adige valley) showed more positive carbon values, and thus a more significant intake of C_4 plants (e.g., millet, sorghum). With regard to the data per valley and archaeological sites, the adult male TCT15A from Castel Tirolo (Merano basin, tomb 15) displayed the highest signal (- 15.84‰) of carbon, indicative of C_4 plants (e.g., millet and sorghum) consumption[5]. The observed C_4 plant intake corresponds with other carbon values obtained in other sites in early medieval South Tyrol (unpublished data, Institute for Mummy Studies)[6] as well as with the available data from northern Italy (north-eastern Italy: Iacumin *et al.* 2014; Laffranchi *et al.* 2020; Marinato 2019, Maxwell 2019 and north-western Italy: Reitsema & Vercellotti 2012). The isotopic data of early medieval Veneto (north-eastern Italy) reported C_4 plants (possibly millet) as being important dietary sources (e.g, Laffranchi *et al.* 2020, Marinato 2017, 2019) supporting the hypothesis of a farming tradition in the Po plain specifically based on C_4 crops, that was already established in the course of the last millennium BC (e.g., Laffranchi *et al.* 2016; Varalli *et al.* 2016). Examples of mixed diets featuring a variable proportion of millet and/or sorghum in human populations, similar to that observed in South Tyrol, have been already reported

[5]Not only the diet was different for TCT15A, but also the funerary deposition was unique. Indeed, differently from the other inhumates, TCT15A was buried in a double-grave together with a perinate individual (TCT15B) located on TCT15A's left arm. The anthropologically estimated sex of TCT15A has been genetically confirmed (unpublished data. BioArchEM project).

[6] Bone collagen was extracted from 79 samples (n=56 humans and n= 23 fauna). These were selected from different South Tyrolean territories, including three additional sites compared to Article III, like Maia Bassa (Merano basin), Sabiona-Säben (Isarco valley) and San Lorenzo (Pusteria valley) (L. Mundle, master thesis). A revaluation of the bone collagen quality and data analysis of 72 humans and faunal samples, as well as the statistical analyses, are undergoing by the author of the present doctoral thesis, in the frame of BioArchEM project (Institute for Mummy Studies, Eurac research).

for early medieval Friuli Venezia Giulia (Iacumin *et al.* 2014) and Trino Vercellese (Reitsema & Vercellotti 2012), where a high intake of millet in the diet of low status males was attested, as reported in the local historical sources (Reitsema & Vercellotti 2012). In South Tyrol, millet, rye and barley were important sources of nourishment for both farmers and nobles, and in particular, millet was eaten in form of porridge (*mosa*) that, still today, is a typical dish of local tradition (unpublished archaeobotanical data, Castel Tirolo museum). In Isarco valley, carbonized cereals including millet, fruit seeds and grapevine (*Vitis vinifera*), were found in early medieval graves (Kaufmann & Demetz 2004; Öggl 1993). At the site of Mezzocorona (Adige valley, Trentino), botanical specimens of different cereals including millet, legumes and fruits were also discovered (Cavada 2016). In the doctoral thesis of Maxwell 2019, the major incorporation of C_4 plants resources in early medieval Veneto was hypothesized as being "*indicative of an economically stressed population, struggling with the impact of war, the plague, and the Langobard occupation, or it could signify a social change*" (Maxwell 2019, p: 291). In contrast, in South Tyrol, it is more likely that the environmental and climatic conditions affected the subsistence strategies more than socio-cultural events. The climate is indeed an important element to be considered when investigating human subsistence strategies. In Early Middle Ages, the climatic *pessimum* (6^{th}–8^{th} cent. AD) with cold, humid weather and increased precipitation, and climatic *optimum* phase (950–1250 AD), characterised by warmer climatic conditions (Hughes & Diaz 1994; Ortolani & Pagliuca 2007), influenced changes in farming practices and, consequently, human diet at that time. In particular, the four chronological phases considered in Article III (for more details, please refer to "statistical tests" in Materials and Methods, Article III in Appendix), displayed differences (p value = 0.011) in the carbon values only when testing phase 2 (7^{th}–8^{th} cent. AD) against phase 3 (8^{th}–10^{th} cent. AD). The latter phase showed enriched carbon values (mean and SD -18.14 ±1.24‰), indicating a possible climatic *optimum* phase, as the C_4 photosynthetic rate normally increase in environments with warmer temperatures (Ehleringer *et al.* 1991, 2002).

In terms of $\delta^{15}N$ values, the terrestrial-based diet in the valleys suggests greater consumption of animal proteins at higher altitudes (Venosta valley), probably due to a diet richer in meat and, in particular, dairy products. Since the Iron Age, both sheep/goat and cow milk were used for cheese production in this area (Carrer *et al.* 2016). Additionally, sex-related differences in animal proteins consumption were statistically significant (p value = 0.030) among the adults (20-40 years old), with males having increased $\delta^{15}N$ values. In the site of Elvas Bressanone necropolis 17 in the Isarco valley, the nitrogen signature showed higher protein intake in males buried with weapons (e.g., knifes, dagger) than the one without goods. This would suggest status-specific dietary differences between males and females, as have already been reported in the literature (e.g., Le Huray & Schutkowski 2005, Moghaddam *et al.* 2018), with the "weaponry group" consuming more animal protein – possibly as a status symbol since at the time, meat production was costly.

In Article III (Appendix), stable sulphur ($\delta^{34}S$) isotope analysis was mainly considered for its application regarding inference of mobility, but also to identify possible freshwater fish consumption in the human diet. This is because the considered valleys are traversed by the Adige and Isarco rivers, and because the archaeological record includes hooks, suggesting fishing in this area (Dal Ri 2009; Tecchiati 2009). The higher means for $\delta^{34}S$ values were indeed observed in humans from the Adige (+7.94‰ ±2.28‰) and Isarco valleys (+7.10‰ ±1.06‰), suggesting a possible proportion of freshwater fish in their diet. However, it must be pointed out that at the Austrian (Tyrolean) site of Volders, the carbon and nitrogen values did not suggest any consumption of freshwater fish, although Volders is located in an area rich in rivers, lakes and streams (McGlynn 2007). To draw that conclusion, McGlynn 2007 referred to the work of Asam and colleagues (2004), who examined nitrogen and carbon ratios in European freshwater fishes from Neolithic Bavaria (Germany), demonstrating that the ratios of different freshwater fish species ranged from 8-10.5‰ for nitrogen and -23 to -27‰ for carbon values. However, in these studies, sulphur was not taken into consideration, and thus the working hypothesis on Adige and Isarco valleys in the present doctoral thesis requires further investigations. In fact, at present, no isotopic data is available from freshwater fish from South Tyrol, generally limiting the conclusions that can be drawn regarding fish consumption in early medieval diet in this area.

3.3 Mobility within and among valleys (Article III)

In the third published article, inter- and intra-isotopic variabilities among communities were investigated – not only to reconstruct dietary habits (objective 2), but also to obtain first insights into early medieval mobility (objective 3) in the South Tyrolean valleys, through the analysis of sulphur stable isotopes, and particularly to start constructing an isotopic dataset for broader future comparisons. As mentioned above (cf. section 1.1), the population dynamics of this historical period are still insufficiently understood, and the archaeological materials are often poor indicators of movement of peoples.

The obtained results reveal significant statistical differences in $\delta^{34}S$ data between valleys and sites (Tab. 2 in Article III, Appendix). Higher variability in sulphur values was observed at lower altitudes (Fig. 3c-d in Article III, Appendix). Specifically, in the Adige valley, the $\delta^{34}S$ values ranged from +5.04 to +10.66‰ (mean +7.94), with a higher standard deviation (± 2.28‰) than that observed in the other valleys (Tab. 1 in Article III, Appendix). This signal may indicate greater mobility in the Adige valley than in the other territories. Particularly, two adult males (TE7 from tomb 7 and TE-sett. A1 from sector A) found in Terlano showed lower values (5.04‰ and 5.24‰, respectively) than the faunal baseline (pigs from Adige, mean and SD 8.34 ± 2.59‰). Therefore, a different origin for these individuals and/or a change in dietary habits to their belonging community was proposed. Interestingly, the adult male individual TE7 was the sole early medieval individual found with a grave good (i.e. sharp object). This finding could also support the hypothesis of a different origin, based on sulphur stable isotope analysis. As mentioned above (cf. section 1.2), no comparative data for sulphur from Italy is available, thus impeding any comparison of the presented results with other early medieval sites. However, the signal indicative of higher mobility in Adige is consistent with the genetic results already published by Coia *et al.* 2012 on modern populations from Adige valley, in the Trentino area (bordering territory with South Tyrol). Additionally, the historical and archaeological records state that, as early as the 2nd century BC, the Adige valley was connected by different Roman routes from the Padana plain (Veneto) to the transalpine provinces (Banzi 2005; Marzatico and Migliario 2011). In contrast, the Venosta valley showed a lower mobility signal that, once again, is in line with the Roman road network, as only one single branch of the main Roman road (*Via Claudia Augusta*) traversed this area (Galliazzo 2010; Marzatico & Varanini 2011), while the other valleys were crossed by more complex and interconnected road system (*Via Claudia Augusta* and other lateral roads) (Fig. 16). The possible mobility of single individuals, within the valleys (from lower to higher areas), was however proposed for two individuals (BSS2-133 and TA4) from Venosta valley. They displayed stronger C_4 plant intake in their diet than that of the other individuals of the same valley, despite the fact that a decrease of this signal was detected at higher altitudes. Unfortunately, these data cannot be cross-checked with the sulphur values, as the latter were discarded for these samples for reasons of insufficient quality.

Apart from mobility, two other factors could have led to higher sulphur values in Adige, such as: i) variation in dietary habits such as consumption of freshwater fish (cf. section 3.2), and/or ii) other different geological factors, such as the drinking of water rich in sulphur, possibly as a consequence of the presence of sulphurous water springs near areas of Roman worship in Adige valley (Tecchiati & Zanforlin 2010). Nevertheless, as stated above, these overall hypotheses require further data for comparison purposes.

In terms of chronological phases, no statistical differences were observed between the tested chronological intervals (for more details, please refer to “statistical tests” in Materials and Methods, Article III in Appendix). However, the highest SD (±2.65‰) of $\delta^{34}S$ values was recorded for phase 2, suggesting greater mobility in the 7th–8th centuries AD (Fig. 7b in Article III, Appendix). This corresponds generally with the archaeological records which document a greater cultural admixture between autochthonous and allochthonous groups, during that phase (Bierbrauer 2005).

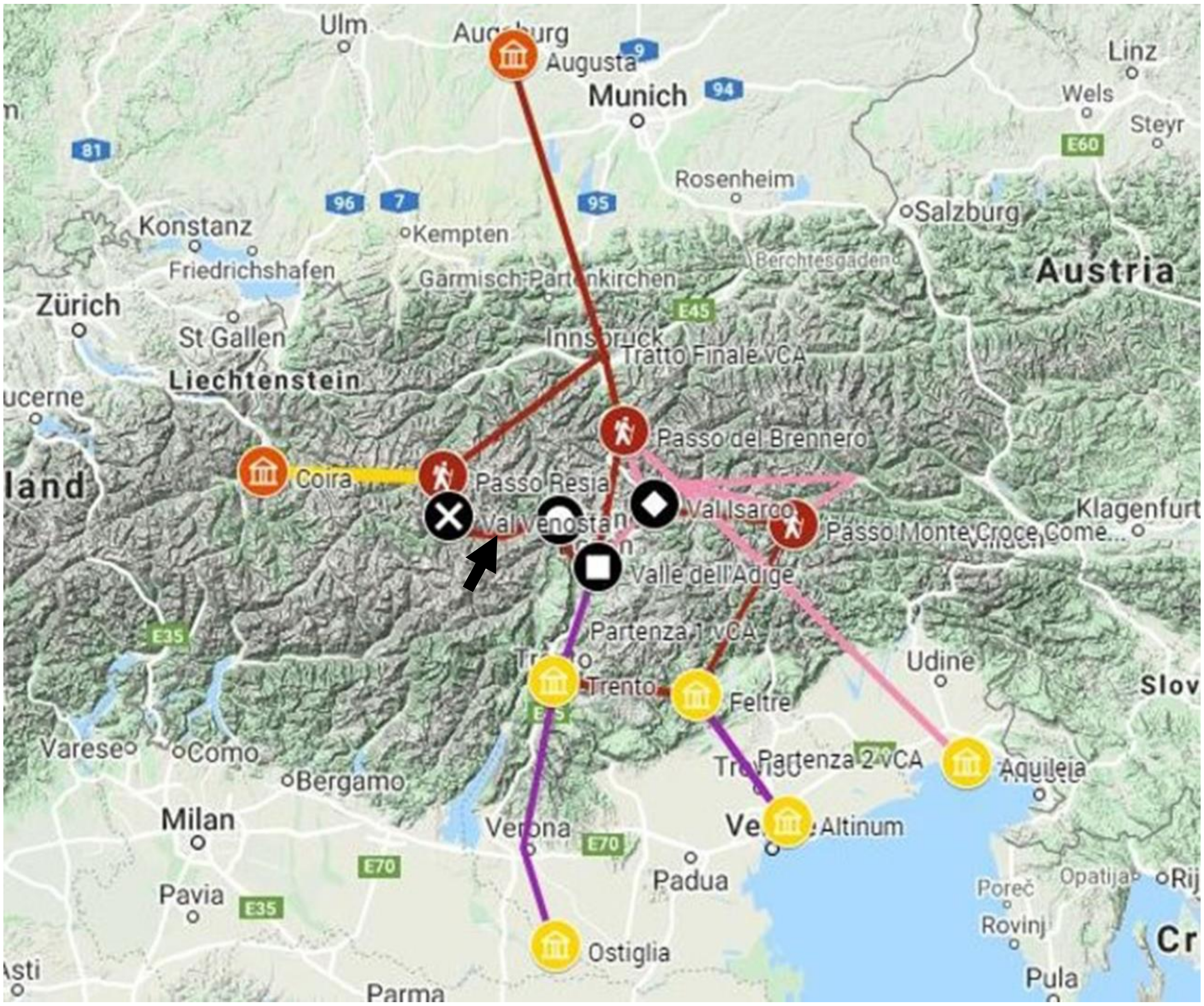


Figure. 16 Reconstruction (based on Marzatico & Migliario 2011) of the Roman road system, used also in the Early Middle Ages, that connected Aquileia, Altinum (near Venice, Italy) and Ostiglia to the northern areas until reaching *Augusta Vindelicorum* (Augsburg, in Gemany). The black arrow highlights the only one *Via Claudia Augusta* (red line) Roman branch passing through the Venosta valley (denoted by X). White square: Adige valley, circle: Merano basin, diamond: Isarco valley; red squares: main mountain passes; purple lines: starting routes, pink lines: lateral routes; yellow line: connection among Venosta valley and Coira (Chur, Switzerland). Map made in by the author of the present dissertation (tool: Google My Maps).

4. Concluding remarks and future work

This cumulative doctoral thesis provides new insights into early medieval health conditions, sociocultural habits and population dynamics in the Italian alpine context, through a multidisciplinary approach. The two paleopathological studies, on subadult scurvy (Möller-Barlow's diseases) and multiple sharp force trauma, provide unique evidence of nutritional and physical stress, as well as of episodes of occasional interpersonal violence in this area. Additionally, this dissertation shows that metabolic diseases, in particular scurvy, are under-represented in paleopathological studies in Italy. Therefore, more attention should be drawn to the study of such diseases in future work on sites in the Italian peninsula.

Carbon, nitrogen and sulphur stable isotopes were analysed to obtain original evidence on dietary habits and mobility in early medieval South Tyrol. These indicated different subsistence strategies and adaptations to the alpine environment between individuals living at higher (greater animal protein or dairy products consumption) and lower altitudes (increased C_4 plants intake), as well as apparently greater mobility at lower areas (Adige valley). The results presented suggest that the dietary habits, subsistence strategies and, possibly, nutritional stresses depended on geological and environmental factors. However, it cannot be ruled out that different historical events (e.g., militarization of the territory, passage and provisional settlement of troops in certain areas), could have caused episodes of community isolation and interpersonal violence.

Importantly, this doctoral work initiated a bioarchaeological data collection, unique in its kind in South Tyrol, for comparative analyses, as the provided raw data permit repeatability. This systematic bioarchaeological study resulted in a research (data-) base for current ongoing projects on the genetic history and oral microbiota of the skeletal material (Institute for Mummy Studies, Eurac Research).

Future work on stable isotopes will contribute to the dataset by including data from other sites, valleys and chronological periods, and also aim to strengthen the collaborations network with the already involved institutions (e.g. cultural heritage offices, universities) and/or to encourage new collaborative opportunities. Moreover, future projects will address the analyses of oxygen ($\delta^{18}O$) and strontium ($^{87}Sr/^{86}Sr$) stable isotopes for selected communities in order to identify other possible early medieval allochthonous individuals in the north-eastern Italian Alps.

Reference list

1. Albertoni G (2005). Romani e Germani come questione storiografica. In W Landi (Editor). Romani e Germani nel cuore delle Alpi tra V e VIII secolo. Athesia, Bolzano, pp 17–27.
2. Albertoni G, Varanini GM (2011). Il territorio trentino nella storia europea vol.2. L'età medievale. Fondazione Bruno Kessler (FBK) press, Trento.
3. Ambrose SH (1986). Stable carbon and nitrogen isotope analysis of human and animal diet in Africa. J. Hum. Evol. 15(8): 707–731.
4. Asam T, Bösl C, Grupe G, Lösch S, Manhart H, Mekota AM and Peters J (2004). Palaeoecosystem reconstruction and the Neolithic Transition in temperate climates. In G Grupe and J Peters (Editors). Documenta Archaeobiologiae: Conservation policy and current research. Vol.2, pp. 97–137.
5. Baldoni M, Nardi A, Müldner G, Lelli R, Gnes M, Ferraresi F, Meloni V, Cerino P, Greco S, Manenti G, Angle M, Rickards O, Martínez-Labarga C (2016). Archaeobiological reconstruction of the Italian medieval population of Colonna (8th–10th centuries CE). J. Archaeol. Sci. Rep. 10: 483–494.
6. Banzi E (2005). Sistema daziario sulla rete viaria romana nel territorio altoatesino: vecchi e nuovi dati epigrafici. In G Ciurletti, N Pisu (Editors). I territori della Via Claudia Augusta. Incontri di archeologia. Trento, pp 173–189.
7. Barlow T (1883). On cases described as “acute rickets” which are probably a combination of scurvy and rickets, the scurvy being an essential, and the rickets a variable, element. Med. Chir. Trans. 66: 159–220.
8. Barlow T (1894). Infantile scurvy and its relation to rickets. BMJ 2: 1029–1034.
9. Bierbrauer V (1994). Archeologia degli Ostrogoti in Italia. In EA Arslan, O von Hessen, V Bierbauer, MT Fiorio (Editors). I Goti. Exhibition catalog, Milano, pp. 51-171.
10. Bierbrauer V (2003). Romanen. In J Hoops, H Beck (Editors). Reallexikon der Germanischen Altertumskunde, Berlin, vol. 25, pp. 210–224.
11. Bierbrauer V (2005). Romani e Germani fra V e VIII secolo dal punto di vista della ricerca archeologica. In W Landi (Editor). Romani e Germani nel cuore delle Alpi tra V e VIII secolo. Athesia, Bolzano, pp. 215–240.

12. Bierbrauer V, Nothdurfter H (2015). Säben I – Die Ausgrabungen im Spätantik-Frühmittelalterlichen Bischofssitz Sabiona-Säben in Südtirol I. Verlag C.H. Beck München, München.

13. Bocherens H, Drucker DG, Billiou D, Geneste JM, van der Plicht J (2006). Bears and humans in Chauvet cave (Vallon-Pont-d'Arc, Ardèche, France): insights from stable isotopes and radiocarbon dating of bone collagen. J. Hum. Evol. 50 (3): 370-376. https://doi.org/10.1016/j.jhevol.2005.12.002

14. Bollongino R, Nehlich O, Richards MP, Orschiedt J, Thomas MG, Sell C, Fajkosova Z, Powell A, Burge RJ (2013). 2000 years of parallel societies in Stone Age Central Europe. Science. 342 (6157):479–481. https://doi.org/10.1126/science.1245049.

15. Bonafini M, Pellegrini M, Ditchfield P, Pollard AM (2013). Investigation of the "canopy effect" in the isotope ecology of temperate woodlands. J. Archaeol. Sci. 40 (11): 3926-3935.

16. Bonhommeau, S, Dubroca L, Le Pape O, Barde J, Kaplan DM, Chassot E & Nieblas AE (2013). Eating up the world's food web and the human trophic level. PNAS 110(51): 20617-20620.

17. Boucherie, A, Jørkov S ML, Smith M (2017). Wounded to the bone: digital microscopic analysis of traumas in a medieval mass grave assemblage (Sandbjerget, Denmark, AD 1300–1350). Int. J. Paleopathol. 19: 66–79. https://doi.org/10.1016/j.ijpp.2017.10.005

18. Bourbou C (2014). Evidence of childhood scurvy in a Middle Byzantine Greek population from Crete, Greece (11th–12th centuries A.D.). Int. J. Paleopathol. 5: 86-94. https://doi.org/10.1016/j.ijpp.2013.12.002

19. Brickley MB & Ives R (2006). Skeletal manifestations of infantile scurvy. Am. J. Phys. Anthropol. 129: 163–172. https://doi. org/10.1002/ajpa.20265

20. Brickley MB & Ives R (2008). The bioarchaeology of metabolic bone disease. Oxford: Academic Press.

21. Buckley HR, Kinaston R, Halcrow SE, Foster A, Spriggs M and Bedford S (2014). Scurvy in a tropical paradise? Evaluating the possibility of infant and adult vitamin C deficiency in the Lapita skeletal sample of Teouma, Vanuatu, Pacific islands. Int. J. Paleopathol. 5: 72–85. https://doi.org/10.1016/j.ijpp.2014.03.001

22. Carrer F, Colonese AC, Lucquin A, Petersen Guedes E, Thompson A, Walsh K, Reitmaier T, Craig OE (2016). Chemical analysis of pottery demonstrates prehistoric origin for high-altitude Alpine dairying. PLoS One 11: ARTN e0151442. https://doi.org/10.1371/journal.pone.0151442

23. Cavada E (2004). Città territorio nell'alto medioevo alla luce delle fonti archeologiche. In A Castagnetti and GM Varanin (Editors). Storia del Trentino III, L'età medievale. Il Mulino, Bologna, pp. 195–223.

24. Cavada E (2016). Tarda antichità e Alto Medioevo tra Alpi retiche e Prealpi tridentine: vecchi e nuovi protagonisti. In V Mariotti (Editor). Dinamiche insediative nelle Alpi centrali tra antichità e medioevo. Mantova, Società archeologica padana, pp. 73–93.

25. Coia V, Boschi I, Trombetta F, Cavulli F, Montinaro F, Destro-Bisol G, Grimaldi S, Pedrotti A (2012). Evidence of high genetic variation among linguistically diverse populations on a micro-geographic scale: a case study of the Italian Alps. J. Hum. Genet. 57(4): 254–260. https://doi.org/10.1038/jhg.2012.14

26. Conzato A (2002/2003). Paleodemografia degli inumati della cappella di San Floriano, Rio di Pusteria (V-XVII sec.): aspetti antropologici dell'osso coxale. Dissertation. University of Padova.

27. Conzato A, Rizzi J (2007). Rio di Pusteria e il suo vaso di Pandora. L'ossario della cappella San Floriano: banca dati paleopatologica on-line. Antrocom 4 (1): 99-103.

28. Conzato A, Rizzi J, Drusini A (2010). Analisi statistica della distribuzione dei markers da parto in un numeroso campione di coxali: utilità dell'identificazione sessuale in antropologia forense. Atti Acc Rov Agiati. 260, VIII, volume X, B: 237–254.

29. Craig OE, Biazzo M, O'Connell TC, Garnsey P, Martinez-Labarga C, Lelli R, Salvadei L, Tartaglia G, Nava A, Renó L, Fiammenghi A, Rickards O, Bondioli L (2009). Stable isotopic evidence for diet at the Imperial Roman coastal site of Velia (1st and 2nd centuries AD) in southern Italy. Am. J. Phys Anthropol. 139: 572–583. https://doi.org/10.1002/ajpa.21021

30. Dal Ri L (2009). L'insediamento fortificato di Lamprecht nel comune di Appiano (Bolzano). Atti Acc Rov Agiati. 259, VIII, volume IX, A, II, 1: 97–129.

31. Dal Ri L, Rizzi G (1995). Il territorio atesino alla fine del VI e nel VII secolo d.C. In G.P. Brogiolo (Editor). Città, castelli, campagne nei territori di frontiera (secoli VI-VII). 5° seminario sul tardoantico e l'alto medioevo in Italia centro-settentrionale. Monte Barro, 9-10 giugno 1994 (Documenti di archeologia, 6), Mantova, pp. 87-114.

32. DeNiro MJ (1985). Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. Nature 317(6040):806809.

33. DeNiro MJ & Epstein S (1978). Influence of diet on the distribution of carbon isotopes in animals. GCA 42: 495-506.

34. DeNiro MJ & Epstein S (1981). Influence of diet on the distribution of nitrogen isotopes in animals. GCA. 45: 341–351.

35. Delogu P (2007). Conclusioni. In GP Brogiolo, A Chavarria Arnau (Editors). Archeologia e societá tra Tardo Antico e Alto Medioevo. Mantova, pp. 401–404.

36. Drucker DG, Bridault A, Hobson KA, Szuma E, Bocherens H (2008). Can carbon-13 in large herbivores reflect the canopy effect in temperate and boreal ecosystems? Evidence from modern and ancient ungulates. Palaeogeogr. Palaeoclimatol. Palaeoecol. 266: 69–82.

37. Ehleringer JR, Sage RF, Flanagan LB, Pearcy RW (1991). Climate change and the evolution of C_4 photosynthesis. Trends Ecol. Evol. 6: 95–99. https://doi.org/10.1016/0169-5347(91)90183-X

38. Ehleringer JR, Bowling DR, Flanagan LB, Fessenden J, Helliker B, Martinelli A, Ometto P (2002). Stable isotopes and carbon cycle processes in forests and grasslands. Plant. Biol. 4:181–189.

39. Evans JA, Stoodley N, Chenery C (2006). A strontium and oxygen isotope assessment of a possible fourth century immigrant population in a Hampshire cemetery, southern England. J. Archaeol. Sci. 33(2): 265-272.

40. Fiorato V, Boylston A, Knüsel C (2007). Blood Red Roses the Archaeology of a Mass Grave from the Battle of Towton AD 1461, 2nd ed. Oxbow Books, Oxford.

41. Forlin P (2015). The Periphery during the Seventh Century: The Rise of a New Landscape within the Core of the Alps. Climate Change, Land Use and the Arrival of the Lombards in the Eastern Trentino, Northern Italy (Sixth-Seventh Centuries

AD). In A Gnasso, E Intagliata and BN Morris (Editors). The Long Seventh Century: Continuity and Discontinuity in an Age of Transition, Peter Lang, Bern, pp.87-106.

42. Galliazzo V (2010). Via Claudia Augusta. Un'arteria alle origini dell'Europa: ipotesi, problemi, prospettive, Aurelia, Feltre.

43. Gasparri S, La Rocca C (2013). Tempi barbarici. L'Europa occidentale tra antichità e medioevo 300-900. Carrocci Editore, Roma.

44. Gilmour RJ, Gowland R, Roberts C, Bernert Z, Kiss KK, Lassányi G (2015). Gendered Differences in Accidental Trauma to Upper and Lower Limb Bones at Aquincum, Roman Hungary. Int. J. of Paleopat. 11: 75–91. https://doi.org/10.1016/j.ijpp.2015.08.004

45. Giostra C, Lusuardi Siena S (2004). Le popolazioni germaniche in Italia: le testimonianze di epoca altomedievale a sud dello spartiacque alpino. In P Gleirscher and F Marzatico (Editors). Guerrieri Principi ed Eroi fra il Danubio e il Po dalla preistoria all'alto Medioevo. Museo Castello Buonconsiglio, Trento, pp. 513–527.

46. Giovannini F (2002). Studi di resti scheletrici umani d'età tardoantica rinvenuti in Alto Adige: malattie, alimentazione, aspetti demografici ed etnici. In L Dal Ri and S di Stefano (Editors). Archeologia Romana in Alto Adige: Studi e contributi (Beni culturali in Alto Adige – Studi e ricerche I), Bolzano–Vienna, pp. 1091–1105.

47. Giovannini F (2003). Skelettfunde auf Castelfeder (9.–10. Jahrhundert nach Christus). In Montan, Band 1, Schützenkompanie Montan, Montan, pp. 95–111.

48. Gleirscher P (1989). Vallis Norica. In Mitteilungen des Instituts für Österreichische Geschichtsforschung, 97, pp. 1–12.

49. Goodman AH, Rose JC (1990). Assessment of systemic physiological perturbations from dental enamel hypoplasias and associated histological structures. Yearb. Phys. Anthropol. 33 (suppl. 11): 59–110.

50. Gostner P, Pernter P, Bonatti G, Graefen A, Zink AR (2011) New radiological insights into the life and death of the Tyrolean Iceman. J Archaeol Sci. 38(12): 3425–31.

51. Guiry EJ (2012). Dogs as analogs in stable isotope-based human palaeodietary reconstruction. J Archaeol Method Theory. 19(3): 351–376. https://doi.org/10.1007/s10816-011-9118-z

52. Haas-Gebhard B (2004). A Nord delle Alpi: Franchi, Alamanni e Baiuvari. In P Gleirscher, F Marzatico (Editors) Guerrieri Principi ed Eroi fra il Danubio e il Po dalla preistoria all'alto Medioevo. Museo Castello Buonconsiglio, Trento, pp. 529–540:

53. Hakenbeck S (2013). Potential and limitations of isotope analysis in Early Medieval archaeology. PCA. 3: 2039-7895.

54. Hakenbeck S, Evans J, Chapman H, Fóthi E (2017). Practicing pastoralism in an agricultural environment: an isotopic analysis of the impact of the Hunnic incursions on Pannonian populations. PLoS One. 12(3): e0173079. https://doi.org/10.1371/journal.pone.0173079

55. Hakenbeck S, McManus E, Geisler H, Grupe G, O'Connell T (2010). Diet and mobility in early medieval Bavaria: a study of carbon and nitrogen stable isotopes. Am J Phys Anthropol. 143(2): 235–249. https://doi.org/10.1002/ajpa.21309

56. Halffman CM, Velemínský P (2015) Stable isotope evidence for diet in early medieval great Moravia (Czech Republic). J Archaeol Sci. 2: 1–8. https://doi.org/10.1016/j.jasrep.2014.12.006

57. Härke H (1997). The nature of burial data. In CK Jensen, N Høilund (Editors), Burial and Society, Aarhus University press, Aarhus, pp.19–27.

58. Heather P (2005). I Goti. Dal Baltico al Mediterraneo la storia dei barbari che sconfissero Roma. ECIG Edizioni Culturali Internazionali, Genova.

59. Heather P (2010). Empires and Barbarians: The Fall of Rome and the Birth of Europe. Oxford University Press, Oxford.

60. Heitmeier I (2005). I Baiuvari nelle valli dell'Inn, dell'Isarco e val Pusteria. Lotte di egemonia ne primo medioevo e lo sviluppo degli insediamenti nella regione tirolese. In W Landi (Editor). Romani e Germani nel cuore delle Alpi tra V e VIII secolo. Athesia, Bolzano, pp. 17–27.

61. Hemer KA, Evans JA, Chenery CA, Lamb AL (2013). Evidence of early medieval trade and migration between Wales and the Mediterranean Sea region. J Archaeol Sci. 40: 2352-2359.

62. Hughes MK, Diaz HF (1994). The medieval warm period. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-1186-7

63. Iacumin P, Galli E, Cavalli F, Cecere L (2014). C_4-consumers in southern Europe: the case of Friuli V.G. (NE-Italy) during early and central Middle Ages. Am J Phys Anthropol. 154:561–574. https://doi.org/10.1002/ajpa.22553

64. James E (2009). I Barbari. Il Mulino, Bologna.

65. Katzenberg MA (2008). Stable isotope analysis: a tool for studying past diet, demography, and life history. In MA Katzenberg, SR Saunders (Editors). Biological anthropology of the human skeleton. Wiley-Liss academic journals, Hoboken, pp 413–441.

66. Kaufmann G (2017). Ein Meilenstein. Der Schlern 91: 73–87.

67. Kaufmann G, Demetz S (2004). Dal riparo alla città. Cenni sulla preistoria e sulla prima storia di Bressanone. In B Fuchs, M Heiss, C Milesi, G Pfeifer (Editors) Bressanone. Volume I. La storia. Athesia, Lana, pp. 29–88.

68. Klaus HD (2017). Paleopathological rigor and differential diagnosis: Case studies involving terminology, description, and diagnostic frameworks for scurvy in skeletal remains. Int J Paleopath. 19: 96-110. https://doi.org/10.1016/j.ijpp.2015.10.002.

69. Knipper C, Peters D, Meyer C, Maurer AF, Muhl A, Schöne BR, Alt KW (2012). Dietary reconstruction in migration period Central Germany: a carbon and nitrogen isotope study. Archaeol Anthropol Sci. 5(1):17–35. https://doi.org/10.1007/s12520-012-0106-3

70. Krueger HW, Sullivan CH (1984). Models for carbon isotope fractionation between diet and bone. In JR Turnlund, PE Johnson (Editors). Stable Isotopes in Nutrition. ACS. 258: pp. 205–222.

71. Kustatscher E, Romeo C (2010). Passaggi e prospettive, lineamenti di storia locale 1. In L Durnwalder, S Kasslatter Mur, F Mussner, C Tommasini (Editors). L'area tirolese dalla preistoria al tardo Medioevo. Athesia, Bolzano.

72. Kutschera W, Müller W (2003). “Isotope language” of the Alpine Iceman investigated with AMS and MS. Nucl Instrum Meth B. 204: 705-719. https://doi.org/10.1016/S0168-583X(03)00491-9

73. La Rocca C (2004). L’archeologia e i Longobardi in Italia. Orientamenti, metodi, linee di ricerca. In S Gasparri (Editor). Il regno dei Longobardi in Italia. Archeologia, societá e istituzioni. Spoleto, pp. 173–233.

74. La Rocca C (2009). Tombe con corredi, etnicità e prestigio sociale l'Italia longobarda del VII secolo attraverso l'interpretazione archeologica. In Archeologia e storia dei Longobardi in Trentino (secoli VI-VIII). Atti del convegno nazionale di studio. Mezzolombardo 25 ottobre 2008. Comune di Mezzolombardo, Mezzolombardo, pp. 55–75.

75. Laffranchi Z, Delgado-Huertas A, Jiménez-Brobeil SA, Granado-Torres A, Riquelme-Cantal JA (2016). Stable C & N isotopes in 2100 year- B.P. human bone collagen indicate rare dietary dominance of C4 plants in NE-Italy. Sci Rep. 6:38817. https://doi.org/10.1038/srep38817.

76. Laffranchi Z, Mazzucchi A, Thompson S, Delgado-Huertasd A, Granadosd A, Milella M (2020). Funerary reuse of a Roman amphitheatre: paleodietary and osteological study of Early Middle Ages burials (8th -9th century AD) discovered in the Arena of Verona (Northeastern Italy). Int J Osteoarchaeol. 1–14. https://doi.org/10.1002/oa.2872

77. Le Huray JD, Schutkowski H (2005). Diet and social status during the La Tène period in Bohemia: carbon and nitrogen stable isotope analysis of bone collagen from Kutná Hora-Karlov and Radovesice. J Anthropol Archaeol. 24:135–147. https://doi.org/10.1016/j.jaa.2004.09.002

78. Lösch S (2009). Paläopathologisch-anthropologische und molekulare Untersuchungen an mittelalterlichen und frühneuzeitlichen Bevölkerungsgruppen Ernährung und Gesundheitszustand Süd und nordbayerischer Bevölkerungsstichproben. Dissertation, Universität München, Germany. Available at https://edoc.ub.unimuenchen. de/9899

79. Lösch S, Moghaddam N, Grossschmidt K, Risser DU, Kanz F (2014). Stable isotope and Trace element studies on gladiators and contemporary romans from Ephesus (Turkey, 2nd and 3rd Ct. AD) – implications for differences in diet. PLoS One. 9 (10). https://doi.org/10.1371/journal.pone.0110489

80. Lovell NC (1997). Trauma Analysis in Paleopathology. Yearb Phys Anthropol. 40:139–170.

81. Macko SA, Lubec G, Teschler-Nicola M, Andrusevich V, Engel MH (1999). The Ice Man's diet as reflected by the stable nitrogen and carbon isotopic composition of his hair. FASEB J. 13: 559-562.

82. Marinato M (2016). Isotopic analyses and bioarcheology as sources for the study of the population between Late Antiquity and Early Middle Ages in Northern Italy. Data from Bergamo, Modena and Verona provinces. PhD Thesis. University of Padua: Padua. Available at http://paduaresearch.cab.unipd.it/9445/

83. Marinato M (2017). Analisi degli isotopi stabili sulle sepolture altomedievali. In A Chavarria (Editor). Ricerche sul centro episcopale di Padova. Scavi 2011-2012, SAP Società Archeologica S.r.l. Mantova, pp.151–154.

84. Marinato M (2019). Alimentazione, salute e mobilità della popolazione in Italia settentrionale tra IV e VIII secolo. Approcci bioarcheologici. SAP Società Archeologica S.r.l. Mantova.

85. Mariotti M, Belcastro G (2017). I resti umani delle discariche e della vasca di epoca romana dello scavo Park Novi Sad (Modena). In D Labate, L Malnati (Editors). Parco Novi Sad Di Modena: Dallo Scavo Al Parco Archeologico. Archeologia, Antropologia, Storia e Ambiente di un insediamento periurbano di Età Romana e Medievale. All'insegna del Giglio, Firenze, pp. 69–86.

86. Marzatico F, Migliario E (2011). L'età antica, Il territorio trentino nella storia europea, I, Fondazione Bruno Kessler, Trento.

87. Marzoli C (2002). Die kirchengrabung von Tirol. In L Dal Ri & S Di Stefano (Editors), Archeologia Romana in Alto Adige, beni culturali in Alto Adige, studi e ricerche 1. Folio Editore Bolzano/Vienna, pp. 1053–1069.

88. Marzoli C, Bombonato G, Rizzi G (2009). Nuovi dati archeologici sull'insediamento tardo antico-altomedievale della Valle dell'Adige tra la conca di Merano e Salorno. Atti Acc Rov Agiati. 259, VIII, volume IX, A, II, 1: 145–183.

89. Maxwell AB (2019). Exploring variations in diet and migration from Late Antiquity to the Early Medieval period in the Veneto, Italy: A biochemical analysis. Doctoral thesis. University of South Florida, Tampa. Available at https://search.proquest.com/openview/8430d08659cee61dd8e0f4c11e9c1be1/1?pqorigsite=gscholar&cbl=18750&diss=y

90. McGlynn G (2007). Using 13C-, 15N- and 18O stable isotope analysis of human bone tissue to identify transhumance, high altitude habitation and reconstruct palaeodiet for the early medieval Alpine population at Volders, Austria. Doctoral thesis. Universität München, Germany. Available at http://edoc.ub.uni-muenchen.de/7327/1/McGlynn_George.pdf.pdf

91. Minozzi S, Catalano P, Caldarini C and Fornaciari G (2012). Palaeopathology of human remains from the Roman imperial age. Pathobiology. 79: 268–283. https://doi.org/10.1159/000338097.

92. Moghaddam N, Müller F, Hafner A, Lösch S (2016). Social stratigraphy in late Iron Age Switzerland: stable carbon, nitrogen and sulphur isotope analysis of human remains from Münsingen. Archaeol Anthropol Sci. 8:149–160. https://doi.org/10.1007/s12520-014-0221-4

93. Moghaddam N, Müller F, Lösch S (2018). A bioarchaeological approach to the Iron Age in Switzerland: stable isotope analyses (δ13C, δ15N, δ34S) of human remains. Archaeol Anthropol Sci. 10(5):1067–1085. https://doi.org/10.1007/s12520-016-0441-x

94. Montanari M, Baruzzi M (1981). Porci e porcari nel Medioevo: paesaggio, economia, alimentazione. CLUEB, Bologna.

95. Murphy WA Jr, Nedden Dz D, Gostner P, Knapp R, Recheis W, Seidler H (2003). The iceman: discovery and imaging. Radiology. 226 (3): 614–29.

96. Nehlich O, Fuller BT, Márquez-Grant N, Richards MP (2012). Investigation of diachronic dietary patterns on the islands of Ibiza and Formentera, Spain: evidence from sulfur stable isotope ratio analysis. Am J Phys Anthropol. 149:115–124.https://doi.org/10. 1002/ajpa.22104

97. Nehlich O, Wahl J (2011). Binnengewässer – eine unterschätzte Nahrungsressource –Stabile Kohlenstoff-, Stickstoff- und Schwefelisotope aus dem Kollagen menschlicher und tierischer Knochenreste aus der urnenfelderzeitlichen Nekropole von Neckarsulm. Fundberichte aus BadenWürttemberg 31:97–113.

98. Nelson DE, Angerbjörn A, Lidén K, Turk I (1998). Stable isotopes and the metabolism of the European cave bear. Oecologia. 116:177–181. https://doi.org/10.1007/s004420050577

99. Oelze V, Koch JK, Kupke K, Nehlich O, Zäuner S, Wahl J, Weise SM, Rieckhoff S, Richards MP (2012). Multi-isotopic analysis reveals individual mobility and diet at the early Iron Age monumental tumulus of Magdalenenberg, Germany. Am J Phys Anthropol. 148:406–42. https://doi.org/10.1002/ajpa.22063

100. Öggl KD (1993). Die Planzenreste aus der Ausgrabung bei der Kirche Sankt Laurentius, in Der Vinschgau und seine Nachbarräume. Vorträge des landeskundlichen Symposiums veranstaltet vom Südtiroler Kulturinstitut in Verbindung mit dem Bildunghaus Schloss Goldrain, Bolzen, pp. 65–69.

101. Ortolani F, Pagliuca S (2007). Evidenze geologiche di variazioni climatico-ambientalistoriche nell'Area Mediterranea. In F Wezel (Editor). Variabilità naturale del clima nell'Olocene ed in tempi storici: un approccio geologico. Società Geologica Italiana, Roma, pp. 13–17.

102. Paladin A, Moghaddam N, Stawinoga A E, Siebke I, Depellegrin V, Tecchiati U, Lösch S & Zink A (2020). Early medieval Italian Alps: reconstructing diet and mobility in the valleys. Archaeol Anthropol Sci. 12: 82. https://doi.org/10.1007/s12520-019-00982-6

103. Paladin A, Tumler D, Zink A (2018a). Vitamin deficiency in Early Medieval sub-adults: indications for metabolic disorders in the Eastern Italian Alps. Poster presentation. 22nd European Meeting of the Paleopathology Association (PPA), 28th August-1st September 2018, Zagreb, Croatia.

104. Paladin A, Wahl J, Zink A (2018b). Evidence of probable subadult scurvy in the Early Medieval cemetery of Castel Tirolo, South Tyrol, Italy. Int J Osteoarchaeol. 28:714-726. https://doi.org/10.1002/oa.2694

105. Paladin A, Zink A (2015). Studio antropologico e paleopatologico dei resti scheletrici umani altomedievali del sito di Appiano-Eppan località Langhütten-Gand (Bolzano). In G Kaufmann (Editor). Archäologie des Überetsch, Archeologia dell'Oltradige. Universitätsverlag Wagner, Innsbruck, pp. 391-403.

106. Pescucci L, Battistini A, De Angelis F, Catalano P (2013). Vivere al centro di Roma nell'VIII secolo d.C. indicazioni antropologiche. Bollettino di Archeologia On Line, Direzione Generale per le Antichità IV: 2–4. ISSN 2039 – 0076.

107. Pohl W (1998). Conceptions of Ethnicity in Early Medieval Studies. In LK Little and BH Rosenwein (Editors). Debating the middle Ages: Issues and Readings. Blackwell Publishers, Oxford, pp. 13–24.

108. Prinzing F and Westergaard H (1916). Epidemics resulting from wars. Clarendon Press, Oxford.

109. Privat K, O'Connell TC, Hedges REM (2007). The distinction between freshwater and terrestrial-based diets: methodological concerns and archaeological applications of sulphur stable isotope analysis. J Archaeol Sci. 34:1197–1204. https://doi.org/10.1016/j.jas.2006.10.008

110. Reid D. J. & Dean, M. C., 2000. Brief communication: the timing of linear hypoplasias on human anterior teeth. Am J Phys Anthropol. 113 (1): 135-139.

111. Reitsema, LJ, Vercellotti G (2012). Stable isotope evidence for sex- and status-based variations in diet and life history at medieval TrinoVercellese, Italy. Am J Phys Anthropol. 148: 589–600.

112. Renhart S (1991). Anthropologie: den Menschen von St. Prokulus auf der Spur. In H Nothdurfter (Editor). Sonderaustellung in Schloß Tirol-St. Prokulus in Naturns-Ergrabene Geschichte von den Menschen des Frühmittelalters und der Pestzeit. Südtiroler Landesmuseum für Archäologie, Schloß Tirol, pp. 153–190.

113. Renhart S (2006). Anthropologische untersuchungen von 11 Frühmittelalterlichen Baumsargbestattungen aus Elzenbaum (Gem. Freienfeld, Südtirol), Grabungsjahr 1996. Atti. Acc. Rov. Agiati, a. 256, ser. VIII, vol. VI, B: 363-387.

114. Reuß OM (2016). St. Stephan ob Burgeis im Kontext des mittelalterlichen Kirchenbaus im Alpenraum. Auswertung der Grabungen und historische Kontextualisierung. Athesia, Bolzano, Italy.

115. Ricci P, Mongelli V, Vitiello A, Campana S, Sirignano C, Rubino M, Fornaciari G, Lubritto C (2012). The privileged burial of the Pava Pieve (Siena, 8th Century AD). Rapid Commun Mass Sp. 26(20): 2393-2398. https://doi.org/10.1002/rcm.6302

116. Richards MP, Hedges REM, Molleson TI, Vogel JC (1998). Stable isotope analysis reveals variations in human diet at the Poundbury camp cemetery site. J Archaeol Sci. 25:1247–1252. https://doi.org/10.1006/jasc.1998.0307

117. Richards MP, Pearson JA, Molleson TI, Russell N, Martin L (2003). Stable isotope evidence of diet at Neolithic Çatalhöyük, Turkey. J Archaeol Sci. 30(1):67–76. https://doi.org/10.1006/jasc.2001.0825

118. Salamon M, Coppa A, McCormick M, Rubini M, Vargiu R, Tuross N (2008). The consilience of historical and isotopic approaches in reconstructing the medieval Mediterranean diet. J Archaeol Sci. 35 (2008) 1667e1672. https://doi.org/10.1016/j.jas.2007.11.015

119. Salis N, Massa Detton E, Fulcheri E & Rabino ME (2005). Pathological lesions attributable to vitamin deficiency in skeletal remains from Puy St. Pierre (Briançon, France). Int J Anthropol. 20: 325–330.

120. Schattmann A, Bertrand B, Vatteoni, S and Brickley M (2016). Approaches to co-occurrence: Scurvy and rickets in infants and young children of 16–18th century Douai, France. Int J Paleopath. 12: 63–75. https://doi.org/10.1016/j.ijpp.2015.12.002

121. Scheeres M, Knipper C, Hauschild M, Schönfelder M, Siebel W, Vitali D *et al.* (2013). Evidence for “Celtic migrations”? Strontium isotope analysis at the early La Tène (LT B) cemeteries of Nebringen (Germany) and Monte Bibele (Italy). J Archaeol Sci. 40(10): 3614–3625. https://doi.org/10.1016/j.jas.2013.05.003

122. Schoeniger MJ, DeNiro MJ (1984). Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. GCA. 48(4): 625-639.

123. Schoeniger MJ (2011). Diet reconstruction and ecology using stable isotope ratios. In CS Larsen (Editor): A companion to biological anthropology. Wiley-Blackwell, Chichester, pp. 445–464.

124. Scorrano G, Brilli M, Martínez-Labarga C, Giustini F, Pacciani E, Chilleri F, Scaldaferri F, Gasbarrini A, Gasbarrini G, Rickards O (2014). Palaeodiet reconstruction in a woman with probable celiac disease: A stable isotope analysis of bone remains from the archaeological site of Cosa (Italy). Am J Phys Anthropol. 154(3): 349-356. https://doi.org/10.1002/ajpa.22517

125. Seiler R, Spielman AI, Zink A, Rühli F (2013). Oral pathologies of the Neolithic Iceman, c.3.300 BC. Eur J Oral Sci. 121: 137–141.

126. Snoddy AME, Halcrow SE, Buckley HR, Standen VG & Arriaza BT (2017). Scurvy at the agricultural transition in the Atacama Desert (ca 3600–3200 BP): Nutritional stress at the maternal-foetal interface? Int J Paleopath. 18: 108–120. https://doi.org/10.1016/j.ijpp.2017.05.011

127. Stein F (1999). Da erhoben sich die Langobarden aus ihren Sitzen und wohnten etliche Jahre in Rugiland. Zu den Grenzen von Siedlungsräumen nach schriftlichen und archäologischen Quellen. In W Haubrichs, KU Jäschke, M Oberweis (Editors). Grenzen erkennen- Begrenzungen überwinden. Festschrift für R. Schneider, Sigmaringen, pp. 35-101.

128. Tecchiati U (2009). I resti faunistici dell'abitato tardoantico e del primo Medioevo di Lamprecht pressoAppiano. Atti Acc Rov Agiati. 259, ser. VIII, vol IX, A, fasc. II, 1: 131–143.

129. Tecchiati U, Biollo N, Gambaro L, Perini A, Pezzo MI, Rizzi G and Rizzi Zorzi J (2011). Risultati degli scavi archeologici e delle indagini antropologiche e dendrocronologiche condotte a Vipiteno, commenda dell'ordine teutonico-Sterzing, Deutschordenshaus (Bz) scavi 2006. Atti Acc Rov Agiati. 261, IX, volume I, B: 119-144.

130. Tecchiati U, Zanforlin L (2010). Topografia archeologica della Bassa Atesina (Prov. di Bolzano). In L Dal Ri, P Gamper, H Steiner (Editors). Höhensiedlungen der Bronze- und Eisenzeit. Kontrolle der Verbindungswege über die Alpen – Abitati d'altura dell'età del Bronzo e del Ferro. Controllo delle vie di comunicazione attraverso le Alpi. Forschungen zur Denkmalpflege in Südtirol, VI, Beni culturali in Alto Adige. Studi e ricerche, pp. 597–646.

131. Varalli A, Moggi-Cecchi J, Dori I, Boccone S, Bortoluzzi S, Salzani P, Tafuri MA (2016). Dietary continuity vs. discontinuity in Bronze Age Italy. The isotopic evidence from Arano di Cellore (Illasi, Verona, Italy). J. Archaeol. Sci. Reports. 7: 104-113. https://doi.org/10.1016/j.jasrep.2016.03.047

132. Vazzana A, Scalise LM, Traversari M, Figus C, Apicella SA, Buti L, Oxilia G, Sorrentino R, Pellegrini S, Matteucci C, Calcagnile L, Savigni R, Feeney RNM, Gruppioni G, Benazzi S (2018). A multianalytic investigation of weaponrelated injuries in a Late Antiquity necropolis, Mutina, Italy. J. Archaeol. Sci. Reports. 17, 550–559. https://doi.org/10.1016/j.jasrep.2017.12.009

133. Vika E (2009). Strangers in the grave? Investigating local provenance in a Greek Bronze Age mass burial using delta S-34 analysis. J Archaeol Sci. 36(9): 2024-2028. https://doi.org/10.1016/j.jas.2009.05.022

134. Winckler C (2012). Die Alpen im Frühmittelalter, Die Geschichte eines Raumes in den Jahren 500 bis 800. Böhlau, Wien.

135. Zanatta A (2014). Paleopatologia e marker occupazionali dei reperti scheletrici rinvenuti nella Cappella di San Floriano, Rio di Pusteria (V-XVII sec.) Aspetti antropologici del femore. Antrocom. 10, 2: 225–247.

Appendix

Table. 1A Provenience, archaeological data, radiocarbon dating for all (173 MNI) of the individuals studied.
Legend: -, missing data; Ref., reference.

Valley	Site	Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
Adige/Etschtal	**Appiano Castelvecchio / Eppan Altenburg**	Hill, open-air	395	T.1	4,4C,3A	AP-AL1	-	-
				T.2	S3b,3d	AP-AL2	1290±35 BP/650-780 AD (93.8%)	Marzoli et al. (2009)
				T.3	20/Central	AP-AL-INF	-	-
				T.4	S32-2012,32b-2012/West	AP-AL4	-	-
				T.5	33b-12/West	AP-AL5	-	-
	Montagna Pinzano/ Montan Pinzon	Terrace, open-air	416	T.1	1/E	MO-P1	-	-
				T.2	2/E	MO-P2	1295±40 BP/656-782 AD (95.9%)	Marzoli et al. (2009)
				T.4	6/E	MO-P4	-	-
				T.5	8/E	MO-P5	1350±40 BP/637-725 AD (82.8%)	Marzoli et al. (2009)
				T.6	10/E	MO-P6	-	-
				T.7	12	MO-P7	-	-
	Nalles vicolo Gebreid/ Nals	Near an apse of a roman building with *hypokaustum*, open-air	329	T.1	153	NA1	1259±26 BP/671-858 AD (95.4%)	Paladin et al. (2020)
	Terlano/ Terlan	Near a paleochristian baptistery, open-air	253	T.1	76a-c/A	TE1	-	-
				T.2	80a-c/A	TE2	-	-
				T.3	81a-c/A	TE3	-	-
				T.4	82a-c/A	TE4	-	-
				T.7	88a-c/B (casette)	TE7	1157±40 BP/770-990 AD (95.4%)	Archaeol. Office
				T.10	95a-b/A	TE10	-	-
				T.12	103a-b/A	TE12	-	-

Valley and Site		Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
				T.13	106a-c/A, Under T.11	TE13	-	-
				-	45/B	TE-US45	-	-
				-	Sector A	TE-Sett.A1	-	-
				-	Sector A	TE-Sett.A2	-	-
Merano basin/Meraner Becker	**Castel Tirolo/ Schloss Tirol**	Hill, outside of an early medieval three-apses church	641	T.5	-	TCT5a	-	-
				T.5	-	TCT5b	-	-
				T.6	-	TCT6a	-	-
				T.6	-	TCT6b	-	-
				T.7	192/South	TCT7a	-	-
				T.7	192/South	TCT7b	-	-
				T.8	193/South	TCT8a	-	-
				T.8	193/South	TCT8b	-	-
				T.9	194/South	TCT9	-	-
				T.10	195/East	TCT10	-	-
				T.11	196/South-West corner	TCT11a	-	-
				T.11	196/South-West corner	TCT11b	-	-
				T.12	197/East	TCT12	-	-
				T.13	198/East	TCT13	-	-
				T.14	199/East	TCT14	-	-
				T.15	200/East	TCT15a	-	-
				T.15	200/East	TCT15b	-	-
				T.15	200/East	TCT15c	-	-
				T.16	201/East	TCT16a	-	-
				T.16	201/East	TCT16b	-	-
				T.16	201/East	TCT16c	-	-
				T.17	202/West	TCT17	1040±55 BP/888-1062 AD (85.7%)	Marzoli (2002)
				T.18	West	TCT18a	1438±45 BP/540-670 AD (95.4%)	Archaeol. Office
				T.18	West	TCT18b	-	-
				T.19	203/West	TCT19	-	-
				T.19	203/West	TCT19b	-	-

Valley and Site		Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
	Castel Tirolo/ Schloss Tirol			T.20	204/nartece II T.5	TCT20	-	
				T.21-22	205-206/South-East	TCT21-22a	-	-
				T.21-22	205-206/South-East	TCT21-22b	-	-
				T.24	219/South-West	TCT24	-	-
				T.25	222/East	TCT25a	-	-
				T.25	222/East	TCT25b	-	-
				T.26	223/South, partially under 3rd pillar	TCT26	-	-
				T.27	224/North of T.26 and under T.25	TCT27	-	-
				T.28	225/under T.25	TCT28	-	-
				T.30	235/East (enclosed area)	TCT30	-	-
				T.31	-	TCT31	-	-
				-	92c/West	TCT-US92c.1	-	-
				-	92c/West	TCT-US92c.2	-	-
				-	92c/West	TCT-US92c.3	-	-
				-	186	TCT186	-	-
	Maia Bassa/ Untermais	Open-air	374	T.1	84	MVH1	-	-
				T.2	98	MVH2	-	-
				T.3	100	MVH3	-	-
				T.5	140	MVH5	-	-
				T.6	148	MVH6	-	-
				T.7	156	MVH7	1526±30 BP/430-605 (95.4%)	Archaeol. Office
				T.8	159	MVH8	-	-
				T.9	162	MVH9	-	-
				T.10	165	MVH10	-	-
				T.11	168	MVH11	-	-

Valley and Site		Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
Isarco/Eisacktal	**Bressanone Elvas necropoli 17/ Brixen Elvas**	Hill, open-air	817	T.1	-	BEN1	-	-
				T.2	Sector E-M area: 20-21 Z1-Q2/B2	BEN2a	-	-
				T.2	Sector E-M area: 20-21 Z1-Q2/B2	BEN2b	-	-
				T.3	Sector E area: KJ-2-9:20	BEN3	-	-
				T.4	Sector M area: KJ2/21:22 and "mosso 2" M/J2/22	BEN4	-	-
				T.5	Sector E area: FG/2-19	BEN5	-	-
				T.6 (=T.7)	Sector E area: X1-Y1;19	BEN6	-	-
				T.7 (=T.6)	Sector E area: X1-Y1;20	BEN7	-	-
				T.8	Sector M area: DEF/21-23 and "mosso 1" M/d2-24	BEN8	-	-
				T.9	-	BEN9a	-	-
					-	BEN9b	-	-
				T.10	-	BEN10	-	-
				T.11	-	BEN11	-	-
				T.12	-	BEN12	-	-
				T.13	-	BEN13	-	-
				T.14	-	BEN14	-	-
				T.15	-	BEN15	-	-
				T.16	-	BEN16	-	-
				T.17	-	BEN17	-	-
				T.18	-	BEN18	-	-
				T.20	-	BEN20	-	-
				T.21	-	BEN21	-	-
				T.22	-	BEN22	-	-

Valley and Site		Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
	Bressanone Elvas necropoli 17/ Brixen Elvas			T.23	-	BEN23	1303±26 BP/660-770 AD (95.4%)	Univ. of Innsbruck
				T.24	-	BEN24	-	-
				T.26	-	BEN26	-	-
				T.27	-	BEN27	1360±22 BP/640-690 AD (95.4%)	Univ. of Innsbruck
				T.28	-	BEN28	-	-
				T.28	-	BEN28a	-	-
				T.29	-	BEN29	-	-
				T.31	-	BEN31	-	-
				T.32	-	BEN32	-	-
				T.34	-	BEN34	-	-
				T.35	-	BEN35	-	-
				T.36	-	BEN36	-	-
				T.37	-	BEN37	-	-
				T.38	-	BEN38	-	-
				T.39	-	BEN39	-	-
				T.40	-	BEN40	-	-
				T.41	-	BEN41	-	-
				T.42	-	BEN42	-	-
				T.43	-	BEN43	-	-
				T.44	-	BEN44	-	-
				T.45	-	BEN45	-	-
				T.46	-	BEN46	-	-
				T.47	-	BEN47	-	-
				T.49	-	BEN49	-	-
Venosta/Vinschgau	**Malles Burgusio S.Stefano/ Mals Burgeis St.Stephan**		1364	T.2	117/South-East corner of the central nave	BSS2-US117	-	-
				T.2	118/South-East corner of the central nave	BSS2-US118	1414±84 BP/428-770 AD (95.4%)	Reuß (2016)

Valley and Site		Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
	Malles Burgusio S.Stefano/ Mals Burgeis St.Stephan	Hill, inside and outside a early medieval church		T.2	133/South-East corner of the central nave	BSS2-US133	-	-
				T.2	97,119,133	BSS2/239-US117	-	-
				T.2	19, 97,117,118,133	BSS2/453-US119	-	-
				T.2	19, 97,117,118,134	BSS2/482-US119	-	-
				T.2	19, 97,117,118,135	BSS2/483-US119	-	-
				T.2	19, 97,117,118,136	BSS2/484-US119	-	-
				T.2	97,119,133	BSS2A	-	-
				T.2	97,119,133	BSS2B	-	-
				T.2	97,119,133	BSS2C	-	-
				T.2	97,119,133	BSS2D	-	-
				T.2	97,119,133	BSS2E	-	-
				T.3	100/ F-G10	BSS3-US100	-	-
				T.5	137/F6-7	BSS5-US137	-	-
				T.6	126/F-G6-7	BSS6-US126	-	-
				T.6	127	BSS6-US127	-	-
				T.7	105	BSS7-US105a	-	-
				T.7	105	BSS7-US105b	-	-
				T.7	105	BSS7-US105c	-	-
				T.8	112/ H4-5	BSS8-US112	-	-
				T.8	113	BSS8-US113	-	-
				T.8	120/ F-G3	BSS8-US120	-	-
				T.8	121/ G2	BSS8-US121	-	-
				T.8	125/ H4-5	BSS8-US125	-	-
				-	123/G10 (T.3 area)	BSS-US123	-	-

Valley and Site		Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
				-	-	BSS-US128	-	-
				-	142 (from soil 141)/Outside of the church	BSS-US142	-	-
				-	144/Outside of the church	BSS-US144	-	-
				-	158/South-East (outside of the apse) and from soil 141	BSS-US158	-	-
				-	163/South-East (outside of the apse)	BSS-US163A	-	-
				-	163/South-East (outside of the apse)	BSS-US163B	-	-
				-	163/South-East (outside of the apse)	BSS-US163C	-	-
				-	163/South-East (outside of the apse)	BSS-US163D	-	-
				-	167/South (outside)	BSS-US167	-	-
	Malles Maso Pauli/ Mals Paulihof	Open-air	1047	T.1	910-912/North	MHP1	970±30 BP/1020-1160 AD (95%)	Archaeol. Office
				T.2	-	MHP2	1020±30 BP/980-1030 AD (95%)	Archaeol. Office
				T.3	119,212,120/Area 1	MHP3	1070±30 BP/900-920, 940-1020 AD (95%)	Archaeol. Office
				T.4	127-128/Area 1	MHP4	970±30 BP/1020-1160 AD (95%)	Archaeol. Office
				T.5	249,250,257/141 Area 6	MHP5	-	-
				T.6	15 (West), 206,251,265/ 141	MHP6	1380±30 BP/620-670 AD (95%)	Archaeol. Office
				T.7	archaeological doc. not available	MHP7	1000±30 BP/990-1040; 1100-1120; 1140-1150 AD (95%)	Archaeol. Office

Valley and Site		Burial's location	Altitude (m a.s.l.)	Tomb	US/Sector	Ind.	^{14}C (BP)/2 sigma cal. AD (probability %)	Ref.
				-	902	MHP-US902A	-	-
				-	902	MHP-US902B	-	-
				-	902	MHP-US902C	-	-
				-	902	MHP-US902D	-	-
	Tanas/ Tanas	Terrace, open-air	1427	T.1	-	TA1	-	-
				T.2	-	TA2	-	-
				T.3	-	TA3	-	-
				T.4	-	TA4	1112±45 BP/800-1020 AD (94.2%)	Archaeol. Office
				-	Ostprofil	TA5-OS	-	-
				-	Streufunde	TA6-ST	-	-

Table. 2A Bone representativity (R.) / preservation (P.), sex and age at death estimations for all (173 MNI) of the individuals studied. Legend: < 25, less than 25% of the skeleton is completed; 25–50, less than 50% of the skeleton is represented; 50–75, more than 50% of the skeleton is completed; > 75, nearly complete skeleton; 1, poorly preserved skeleton; 2, medium state of preservation; 3, in a good state of preservation; *, data included also in a bachelor and master theses (Unpublished data as they belong to this doctoral thesis. Institute for Mummy Studies).

Site	Ind.	R.	P.	Sex	Age at death	Age group
Appiano Castelvecchio/ Eppan Altenburg*	AP-AL1	> 75	3	F	30-35	Adult
	AP-AL2	> 75	3	F	35-40	Adult
	AP-AL-INF	50-75	2	ND	40 weeks-1 month	Newborn
	AP-AL4	> 75	3	F	25-30	Adult
	AP-AL5	> 75	2	M	30-35	Adult
Montagna Pinzano/ Montan Pinzon*	MO-P1	25-50	2	M	25-35	Adult
	MO-P2	< 25	1	M	20+	Adult nd
	MO-P4	50-75	3	M	45-55	Mature
	MO-P5	25-50	1	F?	15-18	Juvenile
	MO-P6	25-50	1	F	20-25	Adult
	MO-P7	25-50	1	F	25-30	Adult
Nalles vicolo Gebreid/Nals*	NA1	50-75	2	F	20-25	Adult
Terlano/ Terlan*	TE1	25-50	1	M	50+	Senile
	TE2	> 75	3	M	40-45	Mature
	TE3	> 75	3	F	30-40	Adult
	TE4	> 75	3	F	30-40	Adult
	TE7	25-50	1	M	35-45	Adult

Site	Ind.	R.	P.	Sex	Age at death	Age group
Terlano/ Terlan	TE10	50-75	2	M	45-50	Mature
	TE12	25-50	1	F	25-35	Adult
	TE13	< 25	1	ND	20+	Adult nd
	TE-US45	25-50	1	M	35-40	Adult
	TE-Sett.A1	< 25	1	M?	20+	Adult nd
	TE-Sett.A2	< 25	1	M	20+	Adult nd
Castel Tirolo/ Schloss Tirol	TCT5a	< 25	1	M	35-40	Adult
	TCT5b	< 25	1	ND	8-9	Infant II
	TCT6a	25-50	1	ND	8-9	Infant II
	TCT6b	< 25	1	ND	5-6	Infant I
	TCT7a	< 25	2	ND	18-19	Juvenile
	TCT7b	< 25	2	ND	4-5	Infant I
	TCT8a	50-75	2	ND	3-4	Infant I
	TCT8b	25-50	2	ND	0-2 months	Newborn
	TCT9	25-50	1	ND	5-6	Infant I
	TCT10	50-75	1	ND	3-4	Infant I
	TCT11a	> 75	3	ND	3-9 months	Infant I
	TCT11b	50-75	2	ND	38 weeks	Foetus-Perinatal
	TCT12	> 75	3	M	30-40	Adult
	TCT13	> 75	2	ND	11-12	Infant II
	TCT14	> 75	2	ND	12-14	Juvenile
	TCT15a	50-75	3	M	25-30	Adult

Site	Ind.	R.	P.	Sex	Age at death	Age group
Castel Tirolo/ Schloss Tirol	TCT15b	25-50	1	ND	38-40 weeks	Foetus-Perinatal
	TCT15c	> 75	2	ND	0-2 months	Newborn
	TCT16a	25-50	2	F?	40-45	Mature
	TCT16b	< 25	1	ND	20+	Adult nd
	TCT16c	< 25	1	ND	6-10	Infant II
	TCT17	> 75	2	ND	10-12	Infant II
	TCT18a	25-50	1-2	M	30-40	Adult
	TCT18b	< 25	2	ND	7-8	Infant II
	TCT19	> 75	2-3	M	50-60	Mature
	TCT19b	< 25	2	M	30+	Adult
	TCT20	25-50	2-3	ND	11-12	Infant II
	TCT21-22a	25-50	2-3	ND	5-6	Infant I
	TCT21-22b	25-50	1-2	M	20-30	Adult
	TCT24	50-75	1-2	ND	4-5	Infant I
	TCT25a	< 25	1	M	30-40	Adult
	TCT25b	25-50	2-3	ND	4-5	Infant I
	TCT26	< 25	1-2	M	20-25	Adult
	TCT27	> 75	2	F	20-30	Adult
	TCT28	25-50	1-2	M	35-40	Adult
	TCT30	< 25	1	M	40-45	Mature
	TCT31	> 75	2	ND	38-40 weeks	Foetus-Perinatal
	TCT-US92c.1	< 25	1	ND	2-3	Infant I

Site	Ind.	R.	P.	Sex	Age at death	Age group
	TCT-US92c.2	25-50	1	ND	36-38 weeks	Foetus-Perinatal
	TCT-US92c.3	25-50	2	ND	38-40 weeks	Foetus-Perinatal
	TCT186	< 25	2-3	ND	4-5	Infant I
Maia Bassa/ Untermais*	MVH1	25-50	1	M	40-50	Mature
	MVH2	75-1	3	F	45-55	Mature
	MVH3	< 25	1	F?	60+	Senile
	MVH5	50-75	2	M	40-60	Mature
	MVH6	50-76	2	M	45-55	Mature
	MVH7	< 25	1	ND	20+	Adult nd
	MVH8	< 25	2	ND	20+	Adult nd
	MVH9	> 75	2	M	50-55	Mature
	MVH10	25-50	1	F	45-55	Mature
	MVH11	< 25	1	ND	20-25	Adult
Bressanone Elvas necropoli 17/ Brixen Elvas	BEN1	< 25	0-1	ND	20+	Adult nd
	BEN2a	< 25	1	M	40+	Mature
	BEN2b	< 25	2	ND	9-11	Infant II
	BEN3*	25-50	1	M	40-50	Mature
	BEN4	> 75	2	M	30-35	Adult
	BEN5	25-50	1-2	M	35-40	Adult
	BEN6	< 25	1	M	20+	Adult nd
	BEN7	< 25	0-1	ND	20+	Adult nd
	BEN8	25-50	1	F	30-40	Adult

Site	Ind.	R.	P.	Sex	Age at death	Age group
Bressanone Elvas necropoli 17/ Brixen Elvas	BEN9a	< 25	1-2	ND	15-17	Juvenile
	BEN9b	< 25	1	ND	20+	Adult nd
	BEN10	25-50	1	M?	35-45	Adult
	BEN11	< 25	0-1	F	35-45	Adult
	BEN12	25-50	1	M	30-35	Adult
	BEN13	25-50	1-2	F	20-25	Adult
	BEN14	< 25	1-2	F	35-40	Adult
	BEN15	< 25	0-1	M	30-40	Adult
	BEN16	25-50	1	ND	20-25	Adult
	BEN17	< 25	0-1	ND	20+	Adult nd
	BEN18	< 25	0-1	ND	25-35	Adult
	BEN20	< 25	0-1	ND	18-25	Adult
	BEN21	< 25	0-1	ND	20+	Adult nd
	BEN22	25-50	1	M	30-40	Adult
	BEN23	< 25	0-1	M	30+	Adult
	BEN24	< 25	2	ND	4-5	Infant I
	BEN26	< 25	0-1	ND	30+	Adult
	BEN27	< 25	0-1	M?	35-45	Mature
	BEN28	25-50	1-2	F?	45-50	Mature
	BEN28a	< 25	1	ND	30+	Adult
	BEN29	< 25	1	F	40-50	Mature
	BEN31*	25-50	1	M	25-30	Adult

Site	Ind.	R.	P.	Sex	Age at death	Age group
Bressanone Elvas necropoli 17/ Brixen Elvas	BEN32*	< 25	1	F?	20-30	Adult
	BEN34*	< 25	1	ND	20+	Adult nd
	BEN35	< 25	1	M	50-60	Mature
	BEN36	< 25	1	ND	18-25	Adult
	BEN37*	> 75	1-2	M	55+	Senile
	BEN38*	< 25	2	ND	6-7	Infant II
	BEN39*	< 25	0-1	ND	30-40	Adult
	BEN40*	< 25	0-1	M	30-40	Adult
	BEN41*	25-50	2	M	45-55	Mature
	BEN42	< 25	1-2	M?	20+	Adult nd
	BEN43*	< 25	1	ND	40-50	Adult
	BEN44*	< 25	1	ND	3-4	Infant I
	BEN45	< 25	1	ND	2-2.5	Infant I
	BEN46	25-50	1-2	ND	10-12	Infant II
	BEN47*	< 25	1	ND	20+	Adult nd
	BEN49*	25-50	1-2	F	40-45	Mature
Malles Burgusio S.Stefano/ Mals Burgeis St.Stephan	BSS2-US117	> 75	2	F	30-35	Adult
	BSS2-US118	> 75	2	M	35-40	Adult
	BSS2-US133	25-50	3	M	20-25	Adult
	BSS2/239-US117	< 25	1	M	35-40	Adult
	BSS2/453-US119	< 25	1	F	40-50	Mature
	BSS2/482-US119	25-50	2	M	50+	Mature

Site	Ind.	R.	P.	Sex	Age at death	Age group
Malles Burgusio S.Stefano/ Mals Burgeis St.Stephan	BSS2/483-US119	25-50	2	F	25-30	Adult
	BSS2/484-US119	25-50	3	M	40-50	Mature
	BSS2A	> 75	2	ND	4-5	Infant I
	BSS2B	< 25	2	ND	2-3	Infant I
	BSS2C	< 25	1	ND	3-5	Infant I
	BSS2D	< 25	1	ND	3-5	Infant I
	BSS2E	< 25	1	ND	8±10	Infant II
	BSS3-US100	> 75	2-3	M	35-40	Adult
	BSS5-US137	25-50	1	M	35-40	Adult
	BSS6-US126	< 25	1-2	F?	35-40	Adult
	BSS6-US127	< 25	1	M?	20+	Adult nd
	BSS7-US105a	50-75	2-3	M	40-45	Mature
	BSS7-US105b	< 25	2	M	30-35	Adult
	BSS7-US105c	< 25	1-2	M?	20-25	Adult
	BSS8-US112	25-50	1-2	M	35-40	Adult
	BSS8-US113	> 75	2-3	M	40-45	Mature
	BSS8-US120	25-50	1-2	M	25-35	Adult
	BSS8-US121	50-75	1	ND	5±1.5	Infant I
	BSS8-US125	> 75	1-2	M	35-40	Adult
	BSS-US123	< 25	1	M?	20+	Adult nd
	BSS-US128	< 25	1	ND	20+	Adult nd
	BSS-US142	25-50	1-2	F	60+	Senile

Site	Ind.	R.	P.	Sex	Age at death	Age group
Malles Burgusio S.Stefano/ Mals Burgeis St.Stephan	BSS-US144	< 25	1	F	20+	Adult nd
	BSS-US158	> 75	1-2	ND	5-7	Infant I
	BSS-US163A	25-50	2	M	30-35	Adult
	BSS-US163B	< 25	2	M	25-30	Adult
	BSS-US163C	< 25	2	ND	6-8	Infant II
	BSS-US163D	< 25	3	M	60+	Senile
	BSS-US167	< 25	1-2	M	50-60	Mature
Malles Maso Pauli/ Mals Paulihof	MHP1	25-50	1-2	M	40-60	Mature
	MHP2	50-75	1	M	30-35	Adult
	MHP3	> 75	2	M	45-50	Mature
	MHP4	50-75	1	M	45-55	Mature
	MHP5	< 25	1	ND	20+	Adult nd
	MHP6	50-75	2	ND	2 years±8 months	Infant I
	MHP7	< 25	1	ND	18±6 months	Infant I
	MHP-US902A	< 25	2	M?	20-30	Adult
	MHP-US902B	< 25	2	ND	1-2	Infant I
	MHP-US902C	< 25	2	ND	0-2 months	Newborn
	MHP-US902D	< 25	2	ND	0-2 months	Newborn
Tanas/ Tanas	TA1	< 25	1	M?	20-40	Adult
	TA2	> 75	2	M	30-35	Adult
	TA3	< 25	1	ND	13-15	Juvenile
	TA4	25-50	1	M	60+	Senile

Site	Ind.	R.	P.	Sex	Age at death	Age group
Tanas	TA5-OS	< 25	1	M	50-60	Mature
	TA6-ST	< 25	1	M	40-60	Mature

Table. 3A Sex and age at death distribution per valley and archaeological site. Legend: MNI, minimum number of individuals; Freq. frequency; *, data included also in a bachelor thesis (Unpublished data, Institute for Mummy Studies, Eurac research).

		Total		**Female (adult)**		**Male (adult)**		**n.d. (subadult)**		**n.d. (adult)**	
Valley	**Site**	MNI	Freq %	MNI	*Freq%*	MNI	*Freq %*	MNI	*Freq%*	MNI	*Freq %*
Adige/Etschtal	Appiano Castelvecchio/ Eppan Altenburg	**5**	**2.9**	3	1.7	1	0.6	1	0.6	0	0
	Montagna Pinzano/ Montan Pinzon	**6**	**3.5**	2	1.2	3	1.7	1	0.6	0	0
	Nalles/ Nals	**1**	**0.6**	1	0.6	0	0	0	0	0	0
	Terlano/ Terlan	**11**	**6.4**	3	1.7	7	4.0	0	0	1	0.6
Merano basin/Meraner Becker	Castel Tirolo/ Schloss Tirol	**41**	**23.7**	2	1.2	11	6.4	27	15.6	1	0.6
	Maia Bassa/Untermais*	**10**	**5.8**	3	1.7	4	2.3	0	0	3	1.7
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas	**47**	**27.2**	8	4.6	17	9.8	7	4.0	15	8.7
Venosta/Vinschgau	Malles Burgusio S. Stefano/ Mals Burgeis St. Stephan	**35**	**20.2**	6	3.5	20	11.6	8	4.6	1	0.6
	Malles Maso Pauli/ Mals Paulihof	**11**	**6.4**	0	0	5	2.9	5	2.9	1	0.6
	Tanas/ Tanas	**6**	**3.5**	0	0	5	2.9	1	0.6	0	0
	Total	**173**	**100**	**28**	**16.2**	**73**	**42.2**	**50**	**28.9**	**22**	**12.7**
	Adige valley/Etschtal	**23**	**13.3**	9	5.2	11	6.4	2	1.2	1	0.6
	Merano basin/ Meraner Becker	**51**	**29.5**	5	2.9	15	8.7	27	15.6	4	2.3
	Isarco valley/Eisacktal	**47**	**27.2**	8	4.6	17	9.8	7	4.0	15	8.7
	Venosta valley/Vinschgau	**52**	**30.1**	6	3.5	30	17.3	14	8.1	2	1.2

Table. 4A Paleopathological evidence (excluded the results of the trauma anaylsis that is presented in the following table, Tab.5A) and selected non-metric traits (in other remarks). Legend: CO, Cribra Orbitalia; Degen., degenerative; DJD, degenerative joint disease; sOA, spinal osteoarthritis; (), uncertain; -, not present; x present; nd, not determinable; /, few indicative bone lesions not diagnostic for a specific metabolic disease; *, data included also in a bachelor thesis (Unpublished data, Institute for Mummy Studies, Eurac research); **, due to the bad state of preservation of the majority of the skeletal remains from the site of Elvas Bressanone, the paleopathological investigation was often limited. In general, when the majority of the cells are indicated as "nd", it means that the bones preservation was very poor limiting the paleopathological investigation.

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
AP-AL1	F	Adult	x	x	x	x	-	-	-	x	x	-	periostitis	Non-metric trait: bilateral preauricular sulcus (depth > 5 mm).
AP-AL2	F	Adult	x	x	x	x	-	-	-	x	x	x	-	Non-metric trait: bilateral preauricular sulcus (depth ~5 mm).
AP-AL-INF	ND	Newborn	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
AP-AL4	F	Adult	x	x	x	x	-	-	-	x	x		periostitis	Possibile osteoma on the right femur (diameter 3.5 mm). Non-metric trait: bilateral preauricular sulcus (depth > 5 mm).

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
AP-AL5	M	Adult	x	x	x	x	-	-	-	x	x		periostitis	Non-metric trait: preauricular sulcus (depth < 5 mm) right side.
MO-P1	M	Adult	x	x	x	x	-	nd	nd	-	-	-	-	Two button osteomata on the left temporal bone.
MO-P2	M	Adult nd	nd	nd	nd	nd	-	nd	nd	x	-	-	-	-
MO-P4	M	Mature	x	x	x	-	-	nd	nd	-	x	nd	-	Non-metric trait: preauricular sulcus (depth < 5 mm) right side.
MO-P5	F?	Juvenile	x	x	-	x	hypoplasia (1.7-5.7 years, Goodman & Rose 1990)	nd	nd	nd	nd	nd	periostitis	-
MO-P6	F	Adult	x	x	-	-	-	nd	nd	x	-	-	-	-
MO-P7	F	Adult	x	x	x	x	hypoplasia (2.1-4 years, Goodman &	nd	-	nd	nd	nd	periostitis	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
							Rose 1990)							
NA1	F	Adult	x	x	x	x	-	-	-	x	x	-	-	One button osteoma on the right parietal bone.
TE1	M	Senile	-	x	x	x	-	x	x	x	x	-	-	-
TE2	M	Mature	x	-	x	x	-	-	-	x	x	-	-	-
TE3	F	Adult	edentulous				-	x	x	x	x	-		
TE4	F	Adult	x	-	x	x	-	x	x	x	x	-	osteomyelitis	Spina bifida. Craniosynostosis. Non-metric trait: bilateral preauricular sulcus (depth < 5 mm).
TE7	M	Adult	-	x	x	x	-	nd	nd	x	x	-	-	Severe coxartrosis, Perthes disease? (more analyses are required)
TE10	M	Mature	x	-	-	-	-	nd	-	x	-	-	-	-
TE12	F	Adult	x	-	-	x	-	nd	nd	x	-	-	-	Non-metric trait: bilateral preauricular sulcus (depth ~5 mm)
TE13	ND	Adult nd	nd	nd	nd	nd	-	nd	nd	x	-	-	-	-
TE-US45	M	Adult	-	x	x	nd	-	nd	nd	x	x	-	-	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
TE-Sett.A1	M?	Adult nd	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TE-Sett.A2	M	Adult nd	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT5a	M	Adult	-	nd	nd	nd	-	-	-	nd	nd	nd	periostitis	-
TCT5b	ND	Infant II	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT6a	ND	Infant II	x	nd	nd	x	/	x	x	nd	nd	nd	-	Unknown object in the crown of the left second molar of the mandible.
TCT6b	ND	Infant I	-	nd	nd	-	/	nd	nd	nd	nd	nd	periostitis	Left tibia slightly curved.
TCT7a	ND	Juvenile	-	-	nd	nd	nd	nd	nd	nd	nd	nd	nd	Teeth only.
TCT7b	ND	Infant I	-	-	nd	nd	hypoplasia (1.6-1.8 years, Goodman & Rose 1990)	nd	nd	nd	nd	nd	nd	Teeth only.

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
TCT8a	ND	Infant I	x	-	-	-	/ Hypoplastic defects in the form of pitting	nd	(x)	nd	nd	nd	periostitis	Right tibia slightly curved.
TCT8b	ND	Newborn	nd	nd	nd	nd	-	-	-	nd	nd	nd	-	-
TCT9	ND	Infant I	x	nd	nd	nd	/ Hypoplastic defects in the form of pitting	x	x	nd	nd	nd	-	-
TCT10	ND	Infant I	x	nd	nd	nd	/ Hypoplastic defects in the form of pitting	x	nd	nd	nd	nd	-	-
TCT11a	ND	Infant I	-	-	-	-	/	-	-	nd	nd	nd	-	

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
TCT11b	ND	Foetus-Perinatal	nd	nd	nd	nd	-	-	-	nd	nd	nd	-	-
TCT12	M	Adult	-	-	-	-	-	x	x	x	x	x	Periostitis; new bone formation observable on the posterior surface of two ribs; possible otitis or mastoid osteitis.	-
TCT13	ND	Infant II	-	-	-	-	scurvy	x	x	nd	nd	nd	periostitis	-
TCT14	ND	Juvenile	-	-	-	-	scurvy	x	x	nd	nd	nd	periostitis	-
TCT15a	M	Adult	x	-	-	-	-	nd	nd	x	x	x	periostitis	-
TCT15b	ND	Foetus-perinatal	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT15c	ND	Newborn	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT16a	F?	Mature	nd	nd	x	nd	-	nd	-	x	-	-	-	-
TCT16b	ND	Adult nd	nd	nd	nd	nd	-	nd	nd	-	nd	nd	-	-
TCT16c	ND	Infant II	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT17	ND	Infant II	-	-	-	-	hypoplasia (2-3.6	x	x	nd	nd	nd	possible periostitis	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
							years, Goodman & Rose 1990)							
TCT18a	M	Adult	nd	nd	nd	nd	-	x	x	x	x	x	periostitis	Arachanoid fovea on the endocranial frontal bone.
TCT18b	ND	Infant II	-	-	-	x	-	-	-	nd	nd	nd	nd	Anomalous diplöe thickness and fovee granularis frontalis.
TCT19	M	Mature	x	x	x	x	-	-	-	x	x	x	periostitis	Ridge caused by the brachialis muscle of the right humerus.
TCT19b	M	Adult	nd	nd	nd	nd	-	-	-				periostitis	-
TCT20	ND	Infant II	x	-	-	x	/	nd	nd	-	-	-	-	-
TCT21-22a	ND	Infant I	x	-	x	x	/	x	x	-	-	-	periostitis	-
TCT21-22b	M	Adult	nd	nd	nd	x	-	nd	nd	x	x	nd	periostitis	-
TCT24	ND	Infant I	nd	nd	nd	nd	-	nd	nd	-	-	-	periostis	-
TCT25a	M	Adult	nd	nd	nd	nd	-	nd	nd	x	x	-	-	3rd or 4th lumbar vertebrae: the spinous process

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
														and the lamina (right and left) are unfused.
TCT25b	ND	Infant I	-	nd	-	-	-	nd	nd	nd	nd	nd	-	-
TCT26	M	Adult	nd	nd	nd	nd	/	nd	nd	x	x	x	periostitis	-
TCT27	F	Adult	x	x	x	x	possible scurvy	-	-	x	x	nd	periostitis	Calcified object 40 mm x 34 mm (Fig.6).
TCT28	M	Adult	-	nd	x	x	/	-	-	x	nd	nd	periostitis	-
TCT30	M	Mature	-	x	-	x	-	nd	nd	x	x	nd	-	-
TCT31	ND	Foetus-Perinatal	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT-US92c.1	ND	Infant I	-	-	-	-	-	nd	x	nd	nd	nd	-	-
TCT-US92c.2	ND	Foetus-Perinatal	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT-US92c.3	ND	Foetus-Perinatal	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	-	-
TCT186	ND	Infant I	nd	nd	nd	nd	/	nd	nd	nd	nd	nd	periostitis	-
MVH1*	M	Mature	x	-	x	nd	-	-	-	x	nd	nd	periostitis	-
MVH2*	F	Mature	x	-	x	-	-	-	-	x	x	-	periostitis	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
MVH3*	F?	Senile	x	x	x	x	-	-	-	nd	nd	nd	nd	-
MVH5*	M	Mature	x	x	x	x	-	-	-	nd	nd	nd	nd	-
MVH6*	M	Mature	x	x	x	x	-	-	-	x	x	nd	periostitis	-
MVH7*	ND	Adult nd	x	x	-	x	nd	nd	nd	nd	nd	nd	periostitis	-
MVH8*	ND	Adult nd	x	x	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
MVH9*	M	Mature	x	x	x	x	-	-	-	x	x	x	periostitis	Osteochondritis Dissecans
MVH10*	F	Mature	x	-	nd	x	-	x	-	x	x	x	periostitis	-
MVH11*	ND	Adult	x	x	-	nd	-	nd	nd	nd	nd	nd	nd	-
BEN1**	ND	Adult nd	nd	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	-
BEN2a	M	Mature	nd	nd	nd	nd	nd	nd	nd	x	x	x	nd	-
BEN2b	ND	Infant II	x	nd	x	nd	hypoplasia (4.2-4.9 years, Reid and Dean 2000)	-	-	nd	nd	nd	nd	-
BEN3	M	Mature	nd	nd	nd	nd	-	nd	nd	x	x	nd	periostitis	
BEN4	M	Adult	x	x	nd	x	-	-	-	x	x	x	periostitis	-
BEN5	M	Adult	x	nd	x	x	-	nd	nd	x	x	nd	-	-
BEN6	M	Adult nd	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	new bone formation on the callus	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
													formation (trauma)	
BEN7	ND	Adult nd	nd	nd	nd	nd	-	nd	nd	nd	nd	nd	nd	-
BEN8	F	Adult	x	nd	x	x	/	x	x	x	x	-	-	-
BEN9a	ND	Juvenile	nd	nd	nd	nd	nd	nd	nd	-	-	-	-	-
BEN9b	ND	Adult nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN10	M?	Adult	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	periostitis	-
BEN11	F	Adult	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN12	M	Adult	x	nd	x	x	nd	nd	nd	nd	nd	nd	periostitis	-
BEN13	F	Adult	x	nd	-	x	nd	nd	nd	x	nd	nd	nd	-
BEN14	F	Adult	nd	nd	x?	nd	nd	nd	nd	x	nd	nd	nd	-
BEN15	M	Adult	x	x	nd	nd	nd	nd	nd	x	nd	nd	periostitis	-
BEN16	ND	Adult	x	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN17	ND	Adult nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN18	ND	Adult	nd	nd	nd	nd	/	nd	nd	nd	nd	nd	nd	-
BEN20	ND	Adult	nd	nd	nd	nd	/	nd	nd	nd	nd	nd	nd	-
BEN21	ND	Adult nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN22	M	Adult	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN23	M	Adult	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	periostitis	-
BEN24	ND	Infant I	-	-	-	-	nd	nd	nd	nd	nd	nd	nd	-
BEN26	ND	Adult	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN27	M?	Mature	-	-	-	nd	nd	nd	nd	nd	nd	nd	nd	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
BEN28	F?	Mature	x	x	x	x	/	x	x	x	nd	nd	nd	-
BEN28a	ND	Adult	nd	nd	nd	nd	nd	nd	nd	x	x	nd	-	-
BEN29	F	Mature	x	nd	x	x	/	x	x	nd	nd	nd	nd	-
BEN31	M	Adult	x	x	x	x	nd	nd	nd	x	nd	nd	periostitis	-
BEN32	F?	Adult	x	x	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN34	ND	Adult nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN35	M	Mature	-	-	nd	nd	nd	nd	nd	x	nd	nd	nd	-
BEN36	ND	Adult	-	nd	nd	nd	possible hypoplasia	nd	nd	nd	nd	nd	nd	-
BEN37	M	Senile	nd	nd	nd	nd	nd	nd	nd	x	x	nd	nd	-
BEN38	ND	Infant II	-	-	nd	d	possible hypoplasia	nd	nd	nd	nd	nd	nd	-
BEN39	ND	Adult	-	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN40	M	Adult	nd	x	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN41	M	Mature	x	x	x	x	nd	nd	nd	x	x	x	periostitis	Overbyte or extramasticatory dental wear (maxilla).

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
BEN42	M?	Adult nd	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	periostitis	-
BEN43	ND	Adult	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN44	ND	Infant I	-	-	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BEN45	ND	Infant I	-	-	nd	nd	/	nd	nd	nd	nd	nd	nd	-
BEN46	ND	Infant II	x	nd	nd	x	-	nd	nd	nd	nd	nd	nd	-
BEN47	ND	Adult nd	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	nd	-
BEN49	F	Mature	x	x	x	x	nd	-	-	x	x	nd	x	Incomplete fusion of the ecto-endocranial sutures.
BSS2-US117	F	Adult	x	x	x	x	/ hypoplasia (2.3-2.7 years, Reid and Dean 2000)	x	x	x	x	x	-	Severe DJD and bilateral coxoarthrosis, stronger on the left side. Dislocation of the left femur. Non-metric trait: bilateral preauricular sulcus (depth >0.5 cm).
BSS2-US118	M	Adult	x	x	x	x	-	-	-	x	x	x	-	Bilateral coxartrosis. Fusion of the vertebral cervical bodies. Five button osteomata (max

Ind.	Sex	Age group	Oral: caries	Oral: calculus	Oral: abscess	Oral: parodontitis	Metabolic	CO: left	CO: right	Degen.: DJD	Degen.: sOA	Degen.: Schmorl's nodules	Non-specific/ specific Infections	Other remarks
														diameter: 7mm) on the frontal, parietal and mediocoronal sutures, left side. Non-metric trait: bilateral preauricular sulcus (depth < 5 mm).
BSS2-US133	M	Adult	nd	nd	nd	nd	nd	nd	nd	x	x	x	periostitis	Right superior costal facet of T5 fused to the head of the rib. Eloganted right femur neck probably due to the trauma. Tibiae slightly laterally curved.
BSS2/239-US117	M	Adult	-	x	-	x	nd	nd	nd	nd	nd	nd	nd	Maxillary tori.
BSS2/453-US119	F	Mature	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	nd	-
BSS2/482-US119	M	Mature	-	x	x	x	nd	x	x	x	nd	nd		Mandibular tori. Deviated nasal septum. Distal epiphyses of the left tibia and fibula are

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
														almost fused together due to severe DJD.
BSS2/483-US119	F	Adult	x	x	x	x	-	-	-	x	nd	nd	nd	Non-metric trait: bilateral preauricular sulcus (depth ~5 mm).
BSS2/484-US119	M	Mature	x	x	x	x	nd	-	-	x	nd	nd	-	-
BSS2A	ND	Infant I	-	-	-	x	/	x	x	-	-	-	periostitis	-
BSS2B	ND	Infant I	-	-	-	x	/	x	x	-	-	-	-	-
BSS2C	ND	Infant I	nd	nd	nd	nd	-	x	x	-	-	-	periostitis	-
BSS2D	ND	Infant I	nd	nd	nd	nd	nd	nd	x	nd	nd	nd	nd	-
BSS2E	ND	Infant II	-	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
BSS3-US100	M	Adult	-	x	x	x	-	-	-	x	x	nd	periostitis	Severe coxarthrosis on the left side. Nasal septum deviation.
BSS5-US137	M	Adult	x	nd	x	x	-	x	x	x	nd	nd	periostitis (localized	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
													on the trauma)	
BSS6-US126	F?	Adult	x	x	x	x	nd	x	nd	x	nd	nd	periostitis	Lambdoid cranial suture thickening. General severe DJD and bilateral coxoarthtosis that probably developed ankylosis. Cribra femuri on the left femur proximal epiphysis. Widening of the distal methaphyses of both femurs and tibiae.
BSS6-US127	M?	Adult nd	-	nd	nd	x	nd	nd	nd	x	nd	nd	nd	-
BSS7-US105a	M	Mature	x	x	x	x	-	-	-	x	x	-	periostitis	Button osteoma (diameter 7mm) on the right parietal bone. Severe coxartrosis on the left side that probably developed ankylosis. Possible

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
														Perthes disease (additional analyses are required).
BSS7-US105b	M	Adult	-	x	x	x	nd	x	x	x	nd	nd	periostitis	Dental malposition (canine and first premolar maxillary left)
BSS7-US105c	M?	Adult	nd	nd	nd	nd	nd	x	nd	x	nd	nd	periostitis	Coxartrosis on the left side.
BSS8-US112	M	Adult	x	x	x	x	/ hypoplasia (4 years, Reid and Dean 2000)	x	x	x	x	x	nd	-
BSS8-US113	M	Mature	x	x	x	x	-	x	x	x	x	x	periostitis	Severe sOA, almost complete fusion of L5 and S1. Possible dislocation of the proximal epiphysis of the right femur from the acetabulum. Osteochondritis

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
														Dissecans. Cribra femuri on both proximal epiphyses of the femurs. Presence of two bone calcifications of rounded shape (diameter approx. 20 mm.)
BSS8-US120	M	Adult	x	x	x	x	-	x	x	x	x	nd	periostitis	Bone proliferation in the right nasal sinus. Maxillary tori. Absence of the left foramen transverse. Severe coxarthrosis on the left side. An ostephyte of approx. 14 mm is visible on the distal epiphysis of the right tibia (frontal). Osteochondritis Dissecans.

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
BSS8-US121	ND	Infant I	-	-	-	x	/ hypoplasia (3.6-4.2 years, Reid and Dean 2000)	x	x	nd	nd	nd	nd	-
BSS8-US125	M	Adult	x	x	x	x	hypoplasia (3.1-3.6 years, Reid and Dean 2000)	x	x	x	x	nd	new bone formation on the callus formation (trauma)	Frontal bone thickening, on the bregmatic suture. Osteochondritis Dissecans.
BSS-US123	M?	Adult nd	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	nd	-
BSS-US128	ND	Adult nd	-	nd	nd	x	nd	nd	nd	x	nd	nd	periostitis	-
BSS-US142	F	Senile	nd	nd	nd	nd	osteoporosis at the femuri	nd	nd	x	x	x	periostitis and new bone formation on the	Vertebral body fusion from L3 to S1. Ostephytes on the left auricular surface of the coxa, initial fusion stage

Ind.	Sex	Age group	Oral: caries	Oral: calculus	Oral: abscess	Oral: parodontitis	Metabolic	CO: left	CO: right	Degen.: DJD	Degen.: sOA	Degen.: Schmorl's nodules	Non-specific/ specific Infections	Other remarks
													long bone diaphyses.	with the sacroiliac joint. Non-metric trait: bilateral preauricular sulcus (depth ~5 mm).
BSS-US144	F	Adult nd	-	nd	nd	nd	nd	nd	nd	x	nd	nd	nd	Non-metric trait: preauricular sulcus (depth < 5 mm) right side (left was nd)
BSS-US158	ND	Infant I	-	-	-	-	hypoplasia (2.0-2.6 years, Reid and Dean 2000).	-	-	-	-	-	-	-
BSS-US163A	M	Adult	-	x	-	x	-	-	-	x	x	-	-	Prognathism
BSS-US163B	M	Adult	-	-	-	x	nd	nd	nd	nd	nd	nd	nd	A part of the right emimandibula is still preserved.
BSS-US163C	ND	Infant II	nd	nd	nd	nd	nd	nd	nd	-	-	-	nd	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
BSS-US163D	M	Senile	x	x	-	x	-	x	x	nd	x	nd	nd	Cranium: Edentulous mandible. *Concha nasalis medialis* bullosa. Postcranium: Advanced stadium of spondyloarthrosis and spondylosis deformance at the thoracic vertebrae.
BSS-US167	M	Mature	-	x	x	x	porotic hyperos tosis	-	-	nd	x	nd	nd	Cranial vault thickening. Non-metric trait: bipartite Acromion (right side)
MHP1	M	Mature	x	nd	x	x	-	-	-	x	x	nd	-	-
MHP2	M	Adult	x	nd	x	x	-	-	-	x	x	x	nd	-
MHP3	M	Mature	x	nd	x	x	-	-	-	x	x	nd	periostitis	-
MHP4	M	Mature	x	nd	x	x	-	x	x	x	x	nd	nd	Severe coxarthrosis on the right side; possible extramasticatory dental wear (mandible)
MHP5	ND	Adult nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
MHP6	ND	Infant I	-	-	-	-	/	nd	x	-	-	-	-	-
MHP7	ND	Infant I	-	-	-	-	nd	nd	nd	-	-	-	-	-
MHP-US902A	M?	Adult	x	nd	-	x	hypoplasia (3-4.8 years, Reid and Dean 2000)	-	-	nd	nd	nd	nd	Parietal cranial bone thickening (laterality is unclear)
MHP-US902B	ND	Infant I	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
MHP-US902C	ND	Newborn	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
MHP-US902D	ND	Newborn	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	new bone formation at the middle shaft of the right tibia	-
TA1	M?	Adult	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	nd	-

Ind.	Sex	Age group	Oral				Metabolic	CO		Degen.			Non-specific/ specific Infections	Other remarks
			caries	calculus	abscess	parodontitis		left	right	DJD	sOA	Schmorl's nodules		
TA2	M	Adult	x	x	-	x	-	-	-	x	x	nd	-	Severe coxarthrosis on the right side.
TA3	ND	Juvenile	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
TA4	M	Senile	x	x	-	x	-	-	-	x	x	nd	-	Possibile healed trauma on the rib 7th. The rib displays an osteophytic-like bone bridge (lenght: 16 mm, width: 3 mm). This ends with an articular facet that connects the body of rib 7th right (location of a trauma) to the upper one (rib 6th), where the corresponding articular facet was observed.
TA5-OS	M	Mature	-	nd	nd	nd	nd	-	-	x	nd	nd	-	-
TA6-ST	M	Mature	nd	nd	nd	nd	nd	nd	nd	x	nd	nd	nd	-

Table. 5A List of the recorded traumata at the postcranium (descriptive protocol by Lovell 1997, modified). Legend: N, quantity of recorded traumata per individual (total N=39); R, right; L, left; * direct trauma; nd, not determinable.

Ind.	Sex	Age group	N	Bone	R-L	Type	Direct* or Indirect	Secondary to	Healing stage
AP-AL2	F	Adult	**1**	Rib	R	extra-articular	Greenstick?	nd	Remodelling
TE2	M	Mature	**3**	Rib-5	R	extra-articular	Greenstick?	nd	Consolidation
				Rib-7	R	extra-articular	Greenstick?	nd	Callus formation
				Rib-8	R	extra-articular	Greenstick?	nd	Callus formation
TE4	F	Adult	**1**	Femur	L	extra-articular	Oblique	nd	Consolidation
TE10	M	Mature	**1**	Tibia	R	extra-articular	*Comminute	nd	Callus formation
MO-P4	M	Mature	**3**	Rib	nd	extra-articular	Greenstick?	nd	Consolidation
				Rib	nd	extra-articular	Greenstick?	nd	Consolidation
				Rib	nd	extra-articular	*Possible sharp force	nd	Partial consolidation
TCT12	M	Adult	**1**	Radius	L	extra-articular	nd	nd	Callus formation
TCT18A	M	Adult	**1**	Lumbar vertebra (L5)	L	intra-articular	*Compression	Spondylosis (unilateral)	nd
TCT19	M	Mature	**3**	Femur	L	extra-articular	*Sharp force	nd	Partial consolidation
				Tibia	L	extra-articular	Oblique	nd	Callus formation
				Rib	R?	extra-articular	nd	nd	Callus formation

Ind.	Sex	Age group	N	Bone	R-L	Type	Direct* or Indirect	Secondary to	Healing stage
TCT19B	M	Adult	**1**	Femur	R	extra-articular	nd	nd	Callus formation
TCT26	M	Adult	**2**	Metatarsal 4	R	extra-articular	Oblique?	nd	Consolidation
				Lumbar vertebra (L4?) inferior facet	R	intra-articular	nd	Spondylosis or physical stress	Consolidation
TCT27	F	Adult	**1**	Tibia	L	extra-articular	nd	Pathology (e.g., metabolic, tumor)	Partial consolidation
MHV2	F	Mature	**2**	Rib	L	intra-articular	nd	nd	Remodelling
				Rib	R	extra-articular	nd	nd	nd
MVH6	M	Mature	**1**	Metacarpal	nd	extra-articular	Oblique	nd	Remodelling
MVH10	F	Mature	**1**	Humerus	L	extra-articular	Spiral	nd	Remodelling
MVH7	ND	Adult nd	**1**	Tibia	R	extra-articular	Oblique	nd	Consolidation
BEN4	M	Adult	**1**	Ulna	R	extra-articular	Greenstick	nd	Consolidation
BEN6	M	Adult nd	**1**	Tibia	L	extra-articular	nd	nd	Callus formation?
BEN12	M	Adult	**1**	Tibia	L	extra-articular	Oblique	nd	Callus formation-remodelling
BEN15	M	Adult	**2**	Tibia	L	extra-articular	Greenstick?	nd	Callus formation
				Fibula	L	extra-articular	Greenstick?	nd	Callus formation

Ind.	Sex	Age group	N	Bone	R-L	Type	Direct* or Indirect	Secondary to	Healing stage
BSS5-US137	M	Adult	**2**	Tibia	L	intra-articular	Oblique?	nd	Callus formation
				Fibula	L	intra-articular	Oblique?	nd	Callus formation
BSS8-US125	M	Adult	**1**	Tibia	L	extra-articular	Oblique	nd	Consolidation
BSS8-US113	M	Mature	**2**	Fibula	R	extra-articular	Greenstick	nd	Callus formation-consolidation
BSS8-US120	M	Adult	**1**	Tibia	R	extra-articular	nd	nd	Partial consolidation
BSS2-US133	M	Adult	**2**	Femur	R	extra-articular	nd	nd	Partial consolidation
				Tibia	R	extra-articular	nd	nd	Consolidation
BSS-US142	F	Senile	**1**	Proximal hand phalange (4?)	L	extra-articular	Greenstick?	nd	Callus formation
MHP1	M	Mature	**1**	Cervical vertebra (C7)	nd	extra-articular	nd	Spondylosis or physical stress	nd
TA4	M	Senile	**1**	Rib-7?	R	extra-articular	nNd	Physical stress	Callus formation, tubercle

Article I

Received: 22 December 2017 | Revised: 7 June 2018 | Accepted: 22 June 2018
DOI: 10.1002/oa.2694

RESEARCH ARTICLE

WILEY

Evidence of probable subadult scurvy in the Early Medieval cemetery of Castel Tirolo, South Tyrol, Italy

Alice Paladin[1,2] | Joachim Wahl[2,3] | Albert Zink[1]

[1] Eurac Research, Institute for Mummy Studies, Bolzano, Italy
[2] Institute for Archaeological Sciences, WG Palaeoanthropology, University of Tübingen, Tübingen, Germany
[3] State Office for Cultural Heritage Management Baden-Württemberg, Osteology, Konstanz, Germany

Correspondence
Alice Paladin, Institute for Mummy Studies, Eurac Research, 39100, Bolzano, Italy.
Email: alice.paladin@eurac.edu

Abstract

The study of subadult scurvy (vitamin C deficiency), also known as Möller-Barlow's disease, is of growing interest in palaeopathology. However, in Italy, there is still a paucity of knowledge on nutritional stress diseases in human skeletal remains.

In the present work, the anthropological and palaeopathological study on subadults found in the Early Medieval cemetery of Castel Tirolo, in South Tyrol (Italy) is reported. Referring to the macroscopic and palaeopathological features described in the literature, abnormal pores, and abnormal new bone formations were analysed in multiple cranial and postcranial skeletal regions. Based on our study, 58% individuals (*N* = 14/24) displayed abnormal lesions: three subadults were nonspecific pathological cases; nine showed few indicative, but not diagnostic, lesions; and two cases (TCT13 and TCT14) exhibited abnormal lesions highly consistent with scurvy. As a reliable diagnosis of vitamin C deficiency is still challenging, we conducted a differential diagnosis of the recorded lesions that supported the probable presence of scurvy in the two cases.

This work presents the first documentation of scurvy in Early Medieval Italy revealing new insights into the health condition and nutritional stress in historical communities in the Eastern Italian Alps.

KEYWORDS

abnormal porosity, Alto Adige, differential diagnosis, Early Middle Ages, new bone, vitamin C

1 | INTRODUCTION

Infantile scurvy or Möller-Barlow's disease (Barlow, 1883, 1894) is a metabolic deficiency caused by the inability of the human body to synthesise the enzyme L-glucuronolactone oxidase necessary to convert glucose to vitamin C, also known as ascorbic acid (Armelagos, Siraka, Werkema, & Turner, 2014; Aufderheide & Rodríguez-Martín, 2008). This vitamin plays a fundamental role in bone collagen synthesis and in the formation of the connective tissues of blood vessel walls, as well as the blood itself. Ascorbic acid is obtained from dietary sources, such as vegetables, fresh fruits containing citrus, or breast milk. If consumption of vitamin C is limited, a pathological condition can manifest after 4–5 months, but it can be resolved after 1 week of an adequate vitamin C intake in the diet (Tamura et al., 2000). In clinical cases, 80% of patients show musculoskeletal alterations (Leone et al., 1997; Stark, 2014), which are especially linked to hemorrhages, caused by the weakening and rupture of blood vessel walls (Ortner, Kimmerle, & Diez, 1999). In particular, the principal scorbutic symptoms in children, where bone growth is rapid, are related to bleeding in the skin (Aufderheide & Rodríguez-Martín, 2008), orbits (Sloan, Kulwin, & Kersten, 1999), gums (Omori et al., 2014), gastrointestinal tract, subperiosteal surfaces, and muscles (Fain, 2005). Arthralgia, inflammation, osteopenia, and trauma are also documented (Clemetson, 2002; Duggan, Westra, & Rosenberg, 2007; Halcrow, Harris, Beavan, & Buckley, 2014; Khonsari, Grandière-Perez, & Caumes, 2005; Noordin, Baloch, Salat, Rashid Memon, & Ahmad, 2012). The consequences of chronic bleeding that manifest when physiological muscles contract and lacerate the blood vessels (Lovász et al., 2013) are fundamental pathological indicators for scurvy not only in living patients but also in human skeletal remains.

In palaeopathology, Ortner and colleagues were the pioneers of the study of scurvy on archaeological human remains, as they identified a selection of skeletal manifestations likely caused by vitamin C deficiency (Brown & Ortner, 2011; Ortner, 1984, 2003; Ortner et al., 1999; Ortner, Butler, Cafarella, & Miligan, 2001; Ortner & Ericksen, 1997; Ortner & Frohlich, 2007). Particularly, the authors proposed specific patterns of abnormal porosity and abnormal new bone formation as the pathological lesions more indicative for scurvy. Nevertheless, the nonspecific nature of the bony changes do not allow attribution of the lesions to a single aetiology. In general, a detailed investigation of the presence and distribution of the lesions within a skeleton followed by a differential diagnosis must be performed (Brickley & Ives, 2006; Klaus, 2015). Recently, the interest in the detection of infantile scurvy, in skeletal materials from various time periods and geographical regions, has significantly increased (e.g., Bourbou, 2014; Brickley & Ives, 2006, 2008; Buckley et al., 2014; Castilla, Carretero, Gracia, & Arsuaga, 2014; Halcrow et al., 2014; Klaus, 2014; Lovász et al., 2013; Mays, 2008a; Schattmann, Bertrand, Vatteoni, & Brickley, 2016; Snoddy, Halcrow, Buckley, Standen, & Arriaza, 2017; Wrobel, 2014). Moreover, different scientific methods such as histology (Schultz, 2001), radiology (Noordin et al., 2012; Popovich, McAlhany, Adewumi, & Barnes, 2009; Tamura et al., 2000), computed tomography (Zuckerman, Garofalo, Frohlich, & Ortner, 2014), and chromatography (Koon, 2010, 2012; Pendery & Koon, 2013) were applied to support the macroscopic analyses, especially in the early stages of scurvy. Despite these increasing efforts, the limited success of detecting scurvy in immature skeletons did not change. In fact, abnormal pores and new bone formation may also occur in other pathological conditions, such as anaemia, rickets, and/or infectious diseases (Brickley & Ives, 2008; Snoddy et al., 2017).

The study of infantile scurvy can provide insights into biological factors, sociocultural and environmental events of past populations, although a consistent diagnosis is still challenging (Brickley & Ives, 2008; Snoddy et al., 2017). One important indicator for biocultural diversity and demographic changes in a community is the evaluation of subadult health (Lewis, 2007). The bioarchaeological studies of subadults can provide insights into the relationship of children with their physical and cultural environment, their biosocial context, and the health of a studied population (Lillehammer, 1989). Therefore, the analysis of immature bones can provide us with direct evidence of the subadults' lifestyle in past communities (Lewis, 2007). In Italy, there is still a clear lack of palaeopathological studies dealing with nutritional diseases, especially with vitamin C deficiency in human skeletal remains dating to the Middle Ages. The only likely case of scurvy described in the literature is of a 3- to 5-year-old child from the Collatina necropolis in Rome dating to the Roman imperial age (Minozzi, Catalano, Caldarini, & Fornaciari, 2012).

From the cemetery of Castel Tirolo, in South Tyrol, Italy, the results on the probable scurvy cases among the subadult individuals are presented with the aim to provide new insights into the still poorly understood sociocultural and historical context of Early Medieval South Tyrol and to further develop the knowledge of the frequency and geographical distribution of vitamin C deficiency in Early Medieval Europe. With reference to the literature on scurvy, we investigate the presence of macroscopic and palaeopathological features in the medieval remains.

2 | MATERIALS AND METHODS

The study was conducted on human skeletal remains recovered from the archaeological site of Castel Tirolo, in South Tyrol, Italy. The site was named after the castle, which was built on a moraine hill in the 12th century, at the behest of the counts of Tyrol (Dal Ri, 1997; Figure 1).

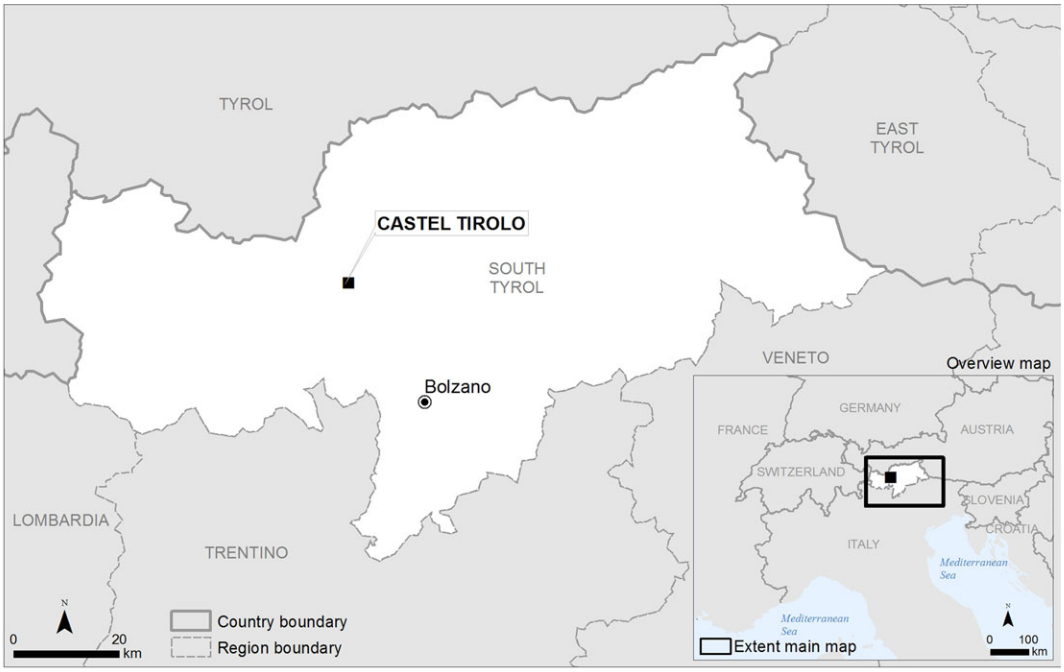


FIGURE 1 Geographical location of the archaeological site of Castel Tirolo, in South Tyrol, Italy [Colour figure can be viewed at wileyonlinelibrary.com]

The moraine hill dominates the Merano basin, a geographical area that in the Early Middle Ages was contested by Germanic populations, such as Bavarians and Longobards (Marzoli, Bombonato, & Rizzi, 2009).

The archaeological excavations conducted near the castle uncovered the stratigraphy of three early Christian churches: a three-apse church (ninth century AD), a one-apse church with a reliquary chamber (fifth–sixth centuries AD), and a single central nave building (Marzoli, 2002; Marzoli et al., 2009). In the surroundings of the three-apse church, in the south, east, and west areas, a cemetery with mostly stone-lined pits was unearthed. There were dual tombs, in which the subadult individuals were buried together with the adults. A unique example is Tomb 15: an adult male was buried as a primary deposition with a perinate in the fetal position situated at the adult's left upper limb. The cemetery was dated to the seventh–eighth centuries AD by relative chronology (Marzoli, 2002). However, radiocarbon dating of the individual in Tomb 17 yielded an age of 888–1.062 cal. AD (85.7%), which suggests a later usage of the cemetery until the ninth–11th centuries, and it was probably abandoned during the construction of the castle in the 12th century (Bombonato, Dal Rì, & Marzoli, 2003; Marzoli, 2002). Until today, the functions (e.g., religious, military, or of occupational nature) of this site remains unclear, and very little is known about the people who lived in this area.

The skeletons from a total of 25 tombs and commingled osteological assemblages, which were found in stratigraphic layers without a clear tomb structure, were analysed using anthropological and palaeopathological methods. As a first step, it was necessary to estimate the minimum number of individuals, as some adults were commingled with immature bones and in some cases, the archeological records did not allow a clear differentiation on the type of skeletal deposition. Age-at-death of immature bones was estimated through standard methods, such as dental development and eruption patterns (AlQathani, Hector, & Liversidge, 2010; Ubelaker, 1978) and the measure of diaphyseal lengths (before birth: Fazekas & Kósa, 1978; after birth: Maresh, 1970), as well as the assessment of the epiphyseal–diaphyseal fusion (Scheuer & Black, 2009). In individuals where both teeth and long bones were absent, the age was broadly estimated on the basis of the size of the preserved bones and by comparison with other infants of this site, in which the age range could be established. Sex determination was not attempted due to the ambiguity in assessing specific sexual traits in immature skeletons (Baker, Dupras, & Tocheri, 2005).

During the palaeopathological investigation, all immature bones were macroscopically investigated to record abnormal lesions, such as abnormal porosity and abnormal new bone formation. Ortner and Ericksen (1997 p. 212) defined abnormal porosity as "a localized, abnormal condition in which fine holes, visible without magnification but typically less than 1 mm in diameter, penetrate a lamellar bone surface." Moreover, the authors argued that abnormal pores can occur in scorbutic cases, as a pathological bone reaction to chronic hemorrhage.

Porous lesions at the cranium can affect both the ectocranial and/or endocranial surfaces, and in the endocranium, the pores can occur together with vascular impressions (Brown & Ortner, 2011; Lewis, 2004). Bilateral porous lesions can also manifest in the orbital roofs as well as in several bones related to muscle activity, such as chewing, which in scurvy cases can cause bleeding and related inflammatory reaction; these include the greater wings of the sphenoid bone, the zygomatic bones, the maxilla, the hard palate, the medial coronoid processes, and the ramus of the mandible (Ortner, 2003; Ortner et al., 2001).

Scurvy lesions can also occur in some postcranial bones, such as the supraspinous and infraspinous scapular processes, the costochondral junction of the ribs, and the medial and lateral surfaces of the ilium, as well as the joints and the diaphyses and metaphyses of upper and lower limbs (Ortner, 2003; Ortner et al., 2001). The limbs, especially at the level of the metaphyses and the closest diaphyseal surface, can display a greater severity of porosity compared with the cranium (Ortner, 2003 p. 390 and 392 figures 15–8 a).

Abnormal new bone formation is an additional pathological change considered in this study, most likely caused by bleeding, which can manifest in combination with abnormal porosity (e.g., Bourbou, 2014; Brickley & Ives, 2008; Klaus, 2014; Ortner, 2003; Ortner et al., 2001). In scurvy, hematomas can manifest between the periosteum and the compact bone (subperiosteal), organising into connective tissues (Ragsdale & Lehmer, 2012). Consequently, an apposition of new bone formation (periosteal bone) is formed. Such skeletal changes can be macroscopically detected in different bones, both cranial (e.g., orbital roof, ectocranial and endocranial vault, maxilla, hard palate, and coronoid process of the mandible) and postcranial bones, especially in the lower limbs (Klaus, 2015; Ortner, 2003).

Porosity associated with alveolar sockets were not documented as possible scorbutic lesions since abnormal pores in this specific bone region can be assigned to various pathological and nonpathological conditions (e.g., dental eruption and/or oral diseases; Mays, 2014). Lesions were recorded as present, absent, or nonobservable, specifying if the anatomical regions displayed bilateral lesions. Pores penetrating the bone cortex were considered pathological if the diameter was equal to or less than 1 mm (Ortner & Ericksen, 1997). The porosity of the metaphyses was considered as abnormal remodelling when it extended more than 5–10 mm (Ortner et al., 2001). The measurements were taken with an electronic digital caliper (Archtool), and a 15× magnification hand-held loupe (GOLDTOOL GCB-016) was used for microscopic examinations. For differential diagnosis of scurvy, the expanded scoring system of Snoddy et al. (2017) was applied to the cranial and postcranial bones (Table 1). This classification system reports lesions with possible etiologies and diagnostic strength for scurvy based on the initial work of Brickley and Ives (2008). Furthermore, in order to increase the accuracy of the differential diagnosis, the modified nomenclature of the Istanbul Protocol criteria (Appleby, Thomas, & Buikstra, 2015) was applied for the evaluation of consistency or inconsistency of the observed lesions with specific pathological conditions.

3 | RESULTS

3.1 | The subadult individuals of Castel Tirolo

Out of a minimum number of 27 individuals, we excluded two sets of human remains consisting of only teeth and one skeleton with an imprecise dating. The remaining 24 individuals belonged to different age groups, five perinates (36–40 weeks old), 12 infants from birth to 6 years old, and seven from 7 to 14 years old. Of the 24 skeletons analysed, 14 showed abnormal lesions indicating an underlying

TABLE 1 List of bones and their specific locations included in this study for the analyses of bone lesions indicative for vitamin C deficiency

Bone	Anatomical region	Type of lesion	Diagnostic strength	Differential diagnosis
Cranium				
Cranial vault	Ectocranial and endocranial surfaces	p, vascular impressions	D, G	Scurvy, rickets, trauma, and infection
Frontal bone	Orbital roof	nb	D	Scurvy and trauma
Sphenoid bone	Greater wing of the sphenoid bone, anterior, and posterior surfaces	p, nb	D	Scurvy
Zygomatic bone Maxilla	Orbital surface Anterior, posterior, and lateral surfaces Hard palate	p p, nb p, nb	D D	Scurvy, trauma, and infection
Mandible	Medial surface of the coronoid process Medial and lateral surfaces of the ramus	p, nb p, nb	D	Scurvy, trauma, and infection
Postcranium				
Scapula	Supraspinous and/or infraspinous fossa	p, nb	D	Scurvy
Rib	Lateral shaft and costochodral junction	nb, enlargment	G	Trauma and infection
Ilium	*Medial and lateral surfaces*	*p, nb*	–	–
Humerus, femur, and tibia	Anterior, posterior, medial, and lateral surfaces of the diaphyses and metaphyses	p, nb	D	Scurvy, rickets, trauma, infection, neoplastic disease, and autoimmune disease

Note. The type of lesion, diagnostic strength, and differential diagnosis follow the classification as in Snoddy et al., 2017. Features in italic are not included in Snoddy et al., 2017 but are mentioned by Ortner, 2003. p: porous lesions; nb: new bone formation; D: diagnostic; G: generally suggestive lesion.

pathological process (Table 2). The majority of these subadults (57%, 8/14) had at least 50% of the entire skeleton present and showed a medium/good state of preservation. In total, three individuals (TCT9, TCT17, and TCT24) displayed bone changes that could not be points to a specific pathological condition. A further nine (TCT6A, TCT6B, TCT8A, TCT10, TCT11A, TCT11B, TCT20, TCT21-22A, and TCT186) had few indicative but not diagnostic lesions. Two subadults, who were found in Tomb 13 (TCT13, 11–12 years old) and Tomb 14 (TCT14, 12–14 years old), exhibited multiple diagnostic lesions of scurvy. In the following sections, greater details on the cranial and postcranial lesions observed in TCT13 and TCT14 are presented (Table 2).

3.2 | Cranial lesions in subadults TCT13 and TCT14

The cranium of individual TCT13 displayed widespread small pores in the ectocranial surfaces of the frontal, parietal, and occipital bones. However, the exact distribution could not be distinctly identified due to the poor/medium level of bone preservation. The lesions were more clearly visible on the occipital bone and temporal bones. The endocranial surfaces were recorded, although difficult to evaluate, as small areas included dense porosity combined with irregular and multiple vascular channel-like impressions. Moreover, the left part of the frontal bone displayed a plaque-like new bone formation with a maximum length of 14.9 and 5.7-mm width (Figure 2). Possible new bone formation was also present in the internal surface of the right parietal bone while the left parietal bone showed vascular impressions and small pores. The left orbit and the fragmented right orbit exhibited abnormal pores (cribra orbitalia). Clearly visible was the porosity displayed in the central part of the orbital surface and in the supraorbital margins, while larger pores penetrating the bone cortex were observed in the medial surface. A small fragment of the right greater wing of the sphenoid bone displayed dense and large abnormal pores penetrating the bone cortex. The right zygomatic bone (left bone absent) showed minor porosity on the external orbital border, while none of the porotic lesions were detected on the orbital surface. The anterior part of the right maxilla (left bone absent) showed scattered elongated pores combined with vascular ramus-like impressions. Fine porosity was also recorded in a small area at the right medial surface of the mandibular coronoid process.

The skeleton TCT14 was less well preserved compared with TCT13, especially the cranium. The cranial vault of TCT14 was mainly represented by the fragmented frontal bone. The lesions were not clearly observable due to the poor state of conservation of the ectocranial surface of the fragmented frontal bone, which had a peel-like effect, probably caused by taphonomic processes. The right orbital roof of TCT14 displayed abnormal pores (cribra orbitalia) penetrating the cortex and various vessel impressions scattered on the orbital surface. The left orbital roof was incomplete but showed larger pores compared with the right as the pores were penetrating the outer and inner lamina in combination with fine new bone formation (Figure 3). A fragment of the right greater wing of the sphenoid bone showed abnormal vessel impressions at the posterior surface. Like in TCT13, the orbital surfaces of the zygomatic bones did not display pathological alterations. The left part of the maxilla exhibited pores penetrating the anterior and the lateral maxillary surfaces, while the hard palate (right part absent) showed extensive porosity. Also, the left medial surface of the coronoid process of the mandible (right part absent) showed abnormal pores.

3.3 | Postcranial lesions observed in subadults TCT13 and TCT14

The postcranial bones of individual TCT13 were better represented than the cranium, displaying enlarged pores penetrating the bone cortex as well as elongated abnormal vascular impressions. The supraspinous fossa of the left scapula (right one absent) presented scattered abnormal pores. In the fragmented ribs, four preserved

TABLE 2 Results of the macroscopic analyses of the subadults of Castel Tirolo, Italy

Individual	Representativity	Age-at-death	Ectocranium	Endocranium	Orbital roof	Greater wing	Facies orbitalis	Maxilla	Palatum durum	Mandible	Supraspinous fossa	Costochondral junction	Ilium	Humerus	Femur	Tibia	Collective diagnostic strength
TCT6A	0.25–0.50	8–9 years	p[a]	—	p[a]	p[a]	—	—	—	—	—	—	—	p[a]	o	—	Few indicative bone lesions but not diagnostic
TCT6B	0.25	5–6 years	—	—	—	—	—	p[a]	p[a]	—	—	—	—	p, nb	(p)	nb	Few indicative bone lesions but not diagnostic
TCT8A	0.50–0.75	3–4 years	—	—	(p[a])	—	o	o	—	o	—	—	o	p[a]	—	p, nb[a]	Few indicative bone lesions but not diagnostic
TCT9	0.25–0.50	5–6 years	o	o	p[a]	—	o	—	—	p	—	—	—	—	—	—	No diagnostic features
TCT10	0.50–0.75	3–4 years	—	—	—	—	o	—	—	—	p	—	—	—	—	p	Few indicative bone lesions but not diagnostic
TCT11A	0.75–1.0	3–9 months	—	—	o	p	p[a]	p[a]	—	o	o	o	o	(p[a])	(p[a])	o	Few indicative bone lesions but not diagnostic
TCT11B	0.50–0.75	38 weeks	o	nb[a]	nb[a]	—	—	p	—	—	—	—	o	o	o	—	Few indicative bone lesions but not diagnostic
TCT13	0.75–1.0	11–12 years	p	p[a], nb[a]	p[a]	p	o	p	o	p	p	(p[a])	p[a], nb	p	p[a], nb	nb[a]	Diagnostic for scurvy
TCT14	0.50–0.75	12–14 years	—	—	p[a], nb	p	o	p[a]	p	p	o	(p[a])	p[a]	o	nb[a]	—	Diagnostic for scurvy
TCT17	0.50–0.75	10–12 years	—	—	p	p	o	o	—	—	—	—	—	o	o	o	No diagnostic features
TCT20	0.25–0.50	11–12 years	o	o	—	p	—	p	o	p	o	o	p[a], nb[a]	o	p[a]	—	Few indicative bone lesions but not diagnostic
TCT21-22A	0.25–0.50	5–6 years	o	o	p	—	o	—	—	p	o	—	—	o	nb	nb	Few indicative bone lesions but not diagnostic
TCT24	0.50–0.75	4–5 years	—	—	—	—	—	—	—	—	o	o	—	o	(nb)	nb	No diagnostic features
TCT186	0.25	4–5 years	—	—	—	—	o	—	—	p[a]	—	—	—	—	nb[a]	—	Few indicative bone lesions but not diagnostic

Note. p: porous lesions; nb: new bone formation; o: the lesion is absent; —: not observable lesions, thus the bone is absent or it is poorly preserved; (): uncertain; 0.25–0.50: less than 50% of the skeleton is completed; 0.50–0.75: more than 50% of the skeleton is completed; 0.75–1.00: complete skeleton.

[a]The lesion is present on both right and left side.

FIGURE 2 Individual TCT13. Localised abnormal new bone formation observable in the endocranial surface of the left frontal bone (arrow) [Colour figure can be viewed at wileyonlinelibrary.com]

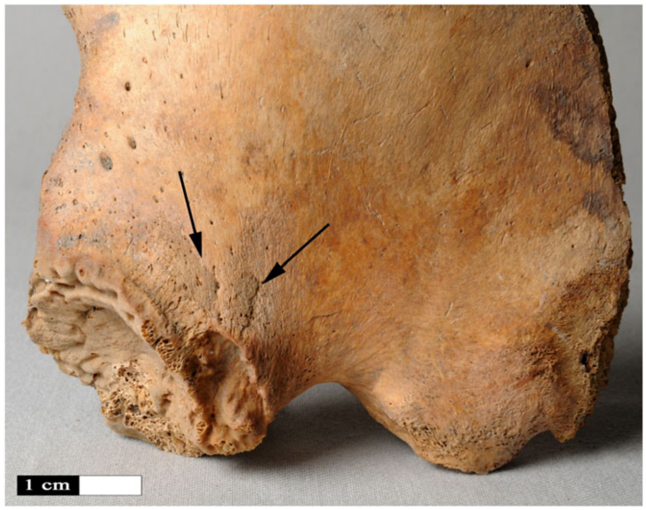


FIGURE 4 Individual TCT13. The lateral surface of the left ilium, in proximity of the acetabulum, exhibits abnormal new bone formation (arrows) [Colour figure can be viewed at wileyonlinelibrary.com]

costochondral ends were slightly enlarged with possible abnormal porosity. The posterior surfaces of the right and left ilium presented enlarged foramina associated with little vascular channels. Moreover, abnormal new bone formation was clearly identified in proximity of the left acetabulum (Figure 4). Concerning the long bones, a localised tapered oval defect with abnormal cribra orbitalia-like pores (Figure 5) was penetrating the bone cortex of the proximal part of the left humeral diaphysis. Unfortunately, it was not possible to observe if this specific lesion was also present in the right humerus, as this part of the bone was missing. Abnormal pores were observed in the right femur, especially in the distal metaphysis and in the distal end of the diaphysis. The lateral surfaces of both femurs were effected by minor new bone formation, greater in the left femur. Both femoral necks exhibited abnormal bone loss and trabeculae-like pores.

The posterior view of the metaphysis of the left femur showed an osteolytic lesion (length: 31.2 mm; width: 9.5 mm) with smooth margins (Figure 6). A similar, less profound bone change was also observed in the posterolateral surface of the same femur. The almost complete right tibia displayed active dense porosity associated with severe abnormal new bone formation on the anteromedial diaphyseal surface (Figure 7). Moreover, osteolytic lesions in the posterior surface of the proximal metaphysis were also detected in the right tibia, and the nutrient foramina of both tibiae were very elongated, and the metaphyses were slightly enlarged.

The supraspinous fossae of the scapulae of individual TCT14 were not preserved, and only a few costochondral ends of the ribs could be observed. Nevertheless, porosity was noted in the costochondral end of one rib, which was slightly enlarged. In the right and left ilium, minor porosity was recorded in the posterior view, in proximity of the nutrient foramina. The proximal metaphysis of the left humerus displayed extended porosity and abnormal vessel impressions on the medial and anterior surfaces. Both femurs of TCT14 showed pathological lesions, which had similar characteristics to TCT13. Cribra femoris was observed in both femoral necks, and abnormal trabeculae-like lesions were recorded in a nonfused epiphysis of the proximal left femur (Figure 8a). Abnormal bone loss and enlarged trabeculae-like

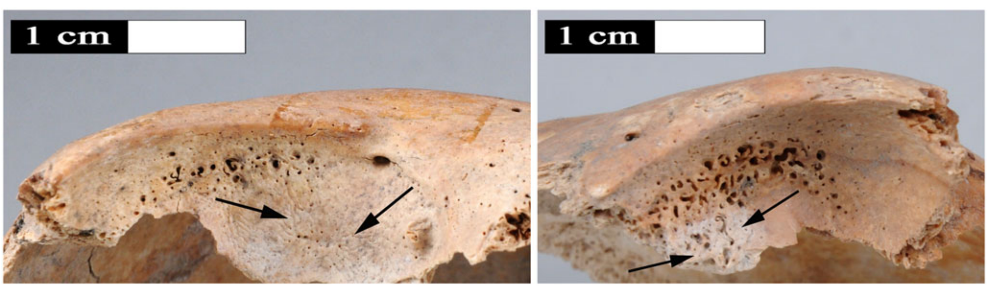


FIGURE 3 Individual TCT14. Right and left orbits displaying cribra orbitalia, multiple vascular ramus-like impressions (arrows, left image), and new bone (arrows, right image) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Left image: extended porosity in the metaphysis of a tibia of a probable infantile scurvy case documented by Ortner (2003 p. 392, figures 15–8,a: modified). Right image: the individual TCT13 displays in the left humerus, anterior surface, and one tapered oval formation similar to the one in the left image [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Individual TCT13. Left image: one osteolytic lesion and one less profound, on the posterior surface of the distal metaphysis of the left femur. Right image: microscopic detail (magnification 0.75×) illustrates the smooth margins of the distal part of the lytic lesion illustrated in the left image [Colour figure can be viewed at wileyonlinelibrary.com]

lesions were detected in the proximal and distal anteroposterior right femoral metaphysis (Figure 8b). Additionally, abnormal new bone formation on the medial surface of the right femoral diaphysis was recorded (Figure 8c), which was less recognisable on the left side, probably due to taphonomic damage. The anterior and posterior surfaces of the distal metaphyseal region of the right femur possessed two extended porous lesions. One of them was similar to the pathological lesion detected in TCT13, but smaller and less marked. None of the described lesions could be analysed in the left tibia (right tibia absent), due to postmortem processes.

FIGURE 7 Individual TCT13. The anteromedial surface of the diaphysis of the right tibia exhibits abnormal new bone formation [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION AND DIFFERENTIAL DIAGNOSIS

4.1 | Variations on normal growth

In immature bones, the distinction between nonspecific bone lesions, thus not ascribable to a certain aetiology, and normal growth variations is often challenging. Particularly, the differentiation between normal and abnormal pores is difficult, as normal pores in immature skeletal remains can be nonpathological signs typical of the growing process and remodelling of bones (Bourbou, 2014; Ortner et al., 2001). In pathological cases, porosity can be the primary skeletal lesion caused by a reduction of osteoblastic activity, subperiosteal hemorrhages, or infections (Brickley & Ives, 2008; Ortner, 2003). According to Ortner et al. (2001), the presence of abnormal pores in different anatomical sites within a skeleton can be indicative of a pathology with a single underlying cause, such as scurvy. In the subadults of Castel Tirolo, both normal and abnormal pores were recorded.

Differently from normal porosities, the abnormal ones usually appeared in conjunction with other pathological lesions within a skeleton, such as new bone formation. The latter are mainly observed in the endocranium of small children as their appearance decrease with age (Mensforth, Lovejoy, Lallo, & Armelagos, 1978). The thick and compact new bone plaque observed in the endocranial surface of the left frontal bone (TCT13, Figure 2) is inconsistent with normal neurocranial growth. The specific location of this lesion is exempt from specific dynamic processes of bone growing and remodelling, which might cause localised abnormal new bone formation. Perhaps the understanding of the cause of this abnormal alteration can be suggested by clinical cases, as it has been demonstrated that vitamin C decrease can entail spontaneous cerebral hemorrhage (Carli-Thiele, 1996; Vannier, Thomas, Jean-Christophe, Pinel, & Verin, 2014), causing lethal complications.

4.2 | Differential diagnosis

To attempt a differential diagnosis of vitamin C deficiency from other metabolic, neoplasms, and infectious diseases is an important issue raised by many authors (e.g., Brickley & Ives, 2008; Klaus, 2015; Ortner & Ericksen, 1997; Schattmann et al., 2016; Snoddy et al., 2017). Moreover, a co-occurrence of different metabolic conditions and infections can be associated with vitamin C deficiency as already noted in early medical studies on scurvy (Barlow, 1883; Cheadle, 1878).

4.2.1 | Anaemia

The bleeding that occurs in scorbutic infants can manifest as pathological lesions at the orbital roofs (Barlow, 1894), but also chronic anemia and/or a variety of other pathological conditions may lead to abnormal porosity (cribra orbitalia) in the orbits (Walker, Bathurst, Richman, Gjerdrum, & Andrushko, 2009; Wapler, Crubézy, & Schultz, 2004). In modern clinical cases, anaemia is considered a minor symptom of scurvy, more than a specific disease, because the level of iron in the

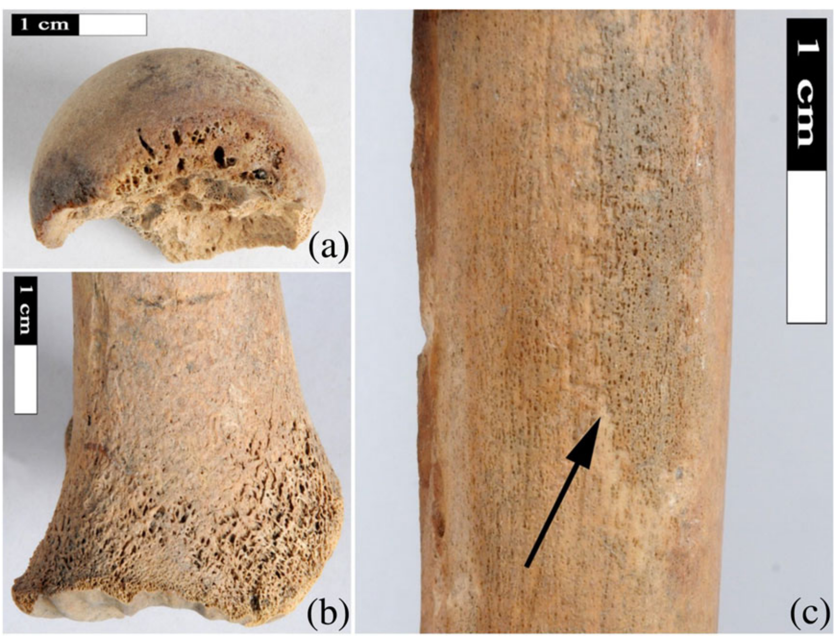


FIGURE 8 Individual TCT14. (a) the nonfused epiphysis of the proximal left femur displaying abnormal trabeculae-like lesions; (b) abnormal porosity at the distal metaphysis of the anteroposterior surface of the right femur (c) right medial part of the femoral diaphysis showing extensive new bone formation (arrow) [Colour figure can be viewed at wileyonlinelibrary.com]

body is linked to folic acid, in addition to ascorbic acid status (Halcrow et al., 2014; Larralde et al., 2007; Tamura et al., 2000; Walker et al., 2009). Therefore, it is difficult or even impossible to ascribe cribra orbitalia to a single aetiology. However, according to Klaus (2015), a detailed macroscopic investigation of the abnormal orbital pore features could help in the identification of its possible causes. Increasing marrow space thickness can be indicative for anaemic states in general, while "circular pores penetrating irregular patches of newly formed or remodeled bone atop an intact outer cortex" are more consistent with abnormal pores due to bleeding in scorbutic cases (Klaus, 2015 p. 15). In the individuals from Castel Tirolo, the subadults show a mixture of changes: bone marrow hypertrophy, asymmetrically distributed pores accompanied by channel-like lesions, and minor new bone formation (TCT14, Figure 3). Therefore, the orbital lesions observed in the individual TCT14 of Castel Tirolo might be consistent with two different pathological processes, including scurvy and anaemia (subsequent to hemorrhages) and thereby represent a case of comorbidity. Moreover, Brickley and Ives (2006) reported that it is improbable that orbital lesions in scorbutic individuals occur without other bone changes in the cranium. The Castel Tirolo cases displayed abnormal pores not only in the orbital roofs but also in several cranial bones related to muscle activity. In particular, a connection between porosity of the cranial bones and the anatomy of the muscles involved during chewing was recorded. This normal physical movement can cause bleeding and related inflammatory reactions typical of those afflicted with scurvy (Ortner et al., 2001).

4.2.2 | Haemorrhagic bleeding and correlated trauma

One of the most frequent symptoms in scorbutic clinical cases is musculoskeletal pain (Fain, 2005; Rajakumar, 2001), as the contraction of the muscles can injure the weakened blood vessels (Brown & Ortner, 2011). Hemorrhagic bleeding can manifest not only as a response to an intense muscular activity but also to regular physical movements (Carli-Thiele, 1996; Mays, 2014; Ortner & Ericksen, 1997). Thus, especially in the long bones, normal muscular contraction can cause traumatic injuries of the muscles and the consequent extravasation from hemorrhage. Ortner (2003, p. 392 figures 15–8) in a report on a scurvy case in Shannon site, Virginia, documented the manifestation of large bilateral extended porous lesions. In the subadult TCT13, the tapered oval formation patch observed on the left humerus (Figure 5) showed a clear similarity to the abnormal lesions described in Ortner et al. (2001, p. 349 figure 9 and 2003, p. 392 figures 15–8).

Asymmetrical lesions are indicative of a wide variety of pathological conditions, especially associated with trauma and infectious diseases. Furthermore, in the reported scurvy cases, lesions are often described as bilateral and symmetrical (Brickley, Schattmann, & Ingram, 2016). Interpersonal traumatic events or accidental injuries can cause external trauma, which do not necessarily break the bones but can still cause some osseous reactions (Klaus, 2015). These events can manifest in asymmetrical unilateral hematomas not only on the body externally but also at the bone level, as the skeletal system is highly vascularised (Sivaraj & Adams, 2016). The observed pathological lesions in Castel Tirolo are not consistent with accidental trauma and therefore do not support interpersonal violence as the main diagnostic criteria.

4.2.3 | Nonspecific and specific infectious diseases

In the immature bones of Castel Tirolo, periosteal new bone formation was recorded in weight-bearing long bone diaphyses in 50% of subadults. Any attempt to attribute periosteal new bone formation to a single underlying cause is very problematic (Brickley et al., 2016). In palaeopathology, this specific lesion is commonly associated with periostitis, which is one of the major changes attributed to nonspecific infections. Therefore, periosteal new bone formation alone is inadequate to support the diagnosis of vitamin C deficiency, but a detailed assessment of the skeletal location and the evaluation of other pathological evidence can provide useful information about its likely aetiology.

Evidence of new bone formation is also present in infectious diseases such as syphilis and tuberculosis. *Treponema* sp. bacteria are the causative agents of syphilis, congenital syphilis, and yaws, resulting in different bone lesions including caries sicca, abnormal thickness of the long bone shafts, gummatous osteoperiostitis, and lytic foci surrounded by sclerotic bone response (Nissanka-Jayasuriya, Odell, & Phillips, 2016; Ortner, 2003). Tuberculosis is another infectious disease that can manifest in new bone formation on the long bone shafts, reactive periostitis of the pleural surface of the ribs (Roberts, 1999), and destructive alterations at the vertebral bodies (Holloway, Henneberg, De Barros, & Henneberg, 2011). However, the pathological lesions observed in the subadults of Castel Tirolo are not consistent with the bone changes diagnostic for treponemal or mycobacterial infections.

Osteomyelitis is a severe infectious disease, common in infants that can manifest lytic lesions on the bones. This infection results from the bacteria *Staphylococcus aureus* or *Streptococcus*, which enters the blood stream infecting the periosteum and the cortex of long bones (Ortner, 2003; White & Folkens, 1999). Advanced osteolysis generally causes circumferential necrosis and cloacal openings of the infected bone, which is enveloped by a hypervascular bone shell or involucrum (Milella, Knüsel, & Haddow, 2016; Ortner, 2003). The absence of cloacal openings, localised hypervascularities, involucra, and focal periosteal bone depositions suggested a nonconsistency of osteomyelitis with the studied individuals from Castel Tirolo.

There are other causes for periostitis that have to be taken into consideration, although some of the diseases lack a clear aetiology. Hypertrophic pulmonary osteoarthropathy (Jaffe, 1972; Ortner, 2003) displays symmetrical diaphyseal periostitis and, more rarely, bone deposition at the endocranium. However, this pathology is more frequent in adult individuals and it usually exhibits additional pathological patterns (e.g., thick lumpy bone surfaces and lamellar bone formation) that were not observed in the analysed individuals.

The massive deposits of periosteal woven bone, the cortical thickening of long bone, and the fusion of adjacent bones within a skeleton are a selection of pathological skeletal evidences that can manifest in infantile cortical hyperostosis disease, also known as Caffey's disease (Caffey, 1972; Caffey & Silverman, 1945; Silverman, 1985). This pathology shows spontaneous regression by 2 years of age, although a reoccurrence has been also clinically observed in adolescent patients (Navarre, Pehlivanov, & Morin, 2013). Caffey's disease can involve single or multiple bones, but it is only rarely observed at the skull (Nistala, Mäkitie, & Jüppner, 2014; Ortner, 2003 p. 417). The pathological bone evidences reported in Caffey's diseases cases are not consistent with the abnormal bone lesions observed in the infantile skeletal remains of Castel Tirolo.

4.2.4 | Metabolic diseases

Rickets is another pathological condition that can manifest porosity and new bone formation in skeletal remains (Brickley & Ives, 2006; Buckley et al., 2014; Halcrow et al., 2014; Lovász et al., 2013). This metabolic disease, resulting from vitamin D deficiency, can cause bone defects due to osteoid mineralisation during bone formation (e.g., Follis, Jackson, & Park, 1940; Mays, 2008b). Unlike scurvy, vitamin D deficiency does not affect the vascular system (Schattmann et al., 2016). Rickets is often linked to bone distortion of weight-bearing bone elements, causing the widening and cupping of long bone metaphyses (Pettifor, 2003), as well as pelvis distortion. Abnormal porosities can also manifest in bones deficient in vitamin D, thus representing a lack of osteoid mineralisation in life. This is especially displayed in the costochondral ends of the ribs and in the growing ends of the long bones, resulting in a "strut/slit" anatomy (Ortner & Mays, 1998). Figure 8a,b displays abnormal trabeculae-like lesions at the growth plate of the individual TCT14, which could be consistent with rickets. However, none of the bones had bell-shaped metaphyses and/or distorted diaphyses. Therefore, the overall picture of the pathological changes observed in TCT13 and TCT14 are not consistent with the diagnosis of vitamin D deficiency alone.

Another pathological condition that show nonspecific lesions is pellagra. This is a nutritional disease caused by a lack of niacin or vitamin B3 or vitamin PP. Pellagra is known as the sickness of the low social status people, in the 19th century AD, as this disease has commonly affected rural areas, like in the north of Italy (Ginnaio, 2011). Klaus (2015) pointed out the paucity of pellagra cases in palaeopathology, which may be due to the limited clinical descriptions on the bone alterations specific for that disease. Skeletal remains effected by pellagra can display nonspecific lesions, such as severe alveolar bone loss, strong presence of dental caries, cribra orbitalia, and irregular lesions on the cranial cortex, periostitis, and cortical loss in ribs (Paine & Brenton, 2006). In Castel Tirolo, pellagra would not explain the overall evaluation of all the recorded lesions. However, due to the lack of a systematic diagnostic framework, pellagra cannot be fully ruled out.

4.2.5 | Scurvy

Vitamin C deficiency is the remaining and most plausible diagnostic option of the skeletal remains of Castel Tirolo, particularly for TCT13 and TCT14. The described pathological lesions, such as abnormal porous lesions and localised new bone formation at multiple vascular sites within the skeletons, appear to be consistent with scurvy as also shown in previous studies (e.g., Bourbou, 2014; Brickley & Ives, 2008; Ortner, 2003; Ortner et al., 2001; Snoddy et al., 2017). Moreover, following the modified Istanbul Protocol criteria, the outlined lesions could be considered as "diagnostic of" scurvy, as they could not have been caused by any other pathological condition (Appleby et al., 2015).

4.3 | Historical account and natural events

Metabolic diseases were important causes of morbidity in antiquity (Ortner & Mays, 1998). However, in the Italian palaeopathological literature of metabolic disorders, particularly vitamin C deficiency, has been generally underreported. This may be due to the common assumption that scurvy was a rare disease in ancient Italian populations, due to the belief that favourable environmental and climatic conditions in Italy would have limited the occurrence of this pathological condition. Therefore, the indications of malnutrition in Castel Tirolo provided us with new insights into the poorly understood sociocultural and local historical context, and also on possible natural events.

The hill of Castel Tirolo is situated in an important border territory that was intensively populated in Early Middle Ages (Marzoli et al., 2009). In the historical chronicle written by Paul the Deacon, *Historia Langobardorum* is documented that in the sixth century AD; the Franks entered this region causing the devastation of various fortifications (*castra*). Particularly, it is mentioned the destructions of the *castra* located on the west hydrographic side of the main river that crosses the valley, while the east side was left undamaged. The Castel Tirolo hill is located on the east riverbank, and therefore it is not in the list of the destroyed *castra* (Nothdurfter, 1991). Consequently, the archaeologists hypothesised that the Franks did not enter the Castel Tirolo area. However, the study of the skeletal human remains seem to suggest a different scenario. Malnutrition disorders can be indicative of socioeconomic changes in populations undergoing subsistence transition (Papathanasiou, 2011; Snoddy et al., 2017). Indeed, scurvy develops in people deprived of an appropriate diet due to biocultural factors (Aufderheide & Rodríguez-Martín, 2008; Kiple, 1999). In Early Middle Ages, this territory was controlled by high status military powers and indeed highly contended for its strategic geopolitical role. Famine, improper nourishment, and pestilences are important consequences of war and siege that cause isolation and fresh food inaccessibility (Prinzing & Westergaard, 1916). Therefore, the soldiers could have restricted food resources to local lower status people, for their own nutrition and for feeding their livestock. War causes not only the destruction of the buildings but also secondarily the devastation of cultivated fields. The palaeopathological data therefore suggest that the historical facts are still not completely understood. Additionally, the location of settlement of the individuals buried in the cemetery of Castel Tirolo is still unknown and has never been excavated (Marzoli et al., 2009). Therefore, it cannot be excluded that this geographical, as well as historical, context is a likely contender for a condition of periodic food scarcity and/or reduced dietary diversity.

Variations in living conditions can also be related to natural habitat or climate changes that alter subsistence patterns or inhibit access to key nutrients. It has been observed that scurvy also occurs in environments where fresh vegetables and fruits are usually available (e.g., for Greece, Bourbou, 2014; for the Pacific islands, Buckley et al., 2014; and for Southeast Asia, Halcrow et al., 2014). In particular, periods of nutritional stress can manifest in mountain areas, as well as in regions where harsh winters can cause episodes of food scarcity, impeding access to vitamin C sources for short periods. One such example is Puy St. Pierre, in the western Alps of France, where climatic stress allowed the communities to consume fresh fruits only during a restricted time of the year (Salis, Massa Detton, Fulcheri, & Rabino, 2005). In Europe, palaeoclimatic data have documented the so-called Climatic *Pessimum* or Little Medieval Ice Period (sixth–eighth centuries AD) marked by cold damp weather with increased precipitation and lower temperature (Ortolani & Pagliuca, 2007). On the other hand, the later Medieval Warm Period corresponded to the prolonged Climatic *Optimum* phase (950–1250 AD), characterised by warm hemispheric conditions (Hughes & Diaz, 1994; Mann et al., 2009). Therefore, in the Early Middle Ages, a variety of possible climatic factors could have brought episodes of famine and reduced vitamin C availability, particularly for infants. In mountainous areas such as Castel Tirolo, seasonal-related food scarcity was common and often caused famine. Harsh winters condemned populations to starvation and epidemic events (Winckler, 2012). As a consequence, this caused an increase in infant mortality.

5 | CONCLUSIONS

This study has provided the first evidence of skeletal manifestations of vitamin C deficiency in an Early Medieval cemetery of the Eastern Italian Alps, giving insights into the health conditions of subadults in South Tyrol. The palaeopathological investigation and differential diagnosis of the subadult skeletons found in Castel Tirolo have suggested that out of 14 infants displaying abnormal bone lesions, two cases showed pathological lesions highly consistent with scurvy. The observed indicators of malnutrition could have been caused by periodic resource depletion in Early Medieval times of the area surrounding Castel Tirolo. However, a note of caution is needed when drawing a conclusion from such observations, as strides are still being made to develop a reliable diagnosis of vitamin C deficiency in palaeopathology. Furthermore, the co-occurrence of scurvy with other metabolic diseases should also be considered. Future studies will apply additional analyses (stable isotope and biomolecular analysis of dental calculus) to investigate the nutritional stress that affected the health in South Tyrol. Additionally, the aim is to extend this palaeopathological study to other archeological sites in the Eastern Italian Alps, in order to increase data consistency on the presence of metabolic bone disease in this region.

ACKNOWLEDGEMENTS

The study was achieved with the permission of Dr. Catrin Marzoli, Ufficio 13.2, Beni archeologici, Autonomous Province of Bolzano, Italy. We would also like to thank Leeanne Mundle for the language editing, Marco Samadelli for the image editing, and Kathrin Renner of the Institute for Earth Observation, Eurac Research, for image editing of Figure 1. We are also very grateful to all the reviewers, which significantly improved our work.

CONFLICT OF INTEREST

The authors declare no conflicts of interest regarding the paper to be published.

ORCID

Alice Paladin http://orcid.org/0000-0001-5397-195X

Albert Zink http://orcid.org/0000-0002-1461-747X

REFERENCES

AlQathani, S. J., Hector, M. P., & Liversidge, H. M. (2010). Brief communication: The London atlas of human tooth development and eruption. *American Journal of Physical Anthropology*, *142*, 481–490. https://doi.org/10.1002/ajpa.21258

Appleby, J., Thomas, R., & Buikstra, J. (2015). Increasing confidence in paleopathological diagnosis—Application of the Istanbul terminological framework. *International Journal of Paleopathology*, *8*, 19–21. https://doi.org/10.1016/j.ijpp.2014.07.003

Armelagos, G. J., Siraka, K., Werkema, T., & Turner, B. L. (2014). Analysis of nutritional disease in prehistory: The search for scurvy in antiquity and today. *International Journal of Paleopathology*, *5*, 9–17. https://doi.org/10.1016/j.ijpp.2013.09.007

Aufderheide, A., & Rodríguez-Martín, C. (2008). *The Cambridge encyclopedia of human paleopathology*. Cambridge: Cambridge University Press.

Baker, B. J., Dupras, T. L., & Tocheri, M. W. (2005). *The osteology of infants and children*. Texas: Texas A&M UP.

Barlow, T. (1883). On cases described as "acute rickets" which are probably a combination of scurvy and rickets, the scurvy being an essential, and the rickets a variable, element. *Medico-Chirurgical Transactions*, *66*, 159–220.

Barlow, T. (1894). Infantile scurvy and its relation to rickets. *British Medical Journal*, *2*, 1029–1034.

Bombonato, G., Dal Rì, L., & Marzoli, C. (2003). Dorf Tirol, Schlosshügel von Tirol (C25). In H. R. Sennhauser (Ed.), *Frühe kirchen im östlichen Alpengebiet, von der spätantike bis in Ottonische zeit* (pp. 607–610). München: Bayerische Akademie der Wissenschaften, Band 1.

Bourbou, C. (2014). Evidence of childhood scurvy in a Middle Byzantine Greek population from Crete, Greece (11th–12th centuries A.D.). *International Journal of Paleopathology*, *5*, 86–94. https://doi.org/10.1016/j.ijpp.2013.12.002

Brickley, M. B., & Ives, R. (2006). Skeletal manifestations of infantile scurvy. *American Journal of Physical Anthropology*, *129*, 163–172. https://doi.org/10.1002/ajpa.20265

Brickley, M. B., & Ives, R. (2008). *The bioarchaeology of metabolic bone disease*. Oxford: Academic Press.

Brickley, M. B., Schattmann, A., & Ingram, J. (2016). Possible scurvy in the prisoners of Old Quebec: A re-evaluation of evidence in adult skeletal remains. *International Journal of Paleopathology*, *15*, 92–102. https://doi.org/10.1016/j.ijpp.2016.10.001

Brown, M., & Ortner, D. J. (2011). Childhood scurvy in a medieval burial from Mačvanska Mitrovica, Serbia. *International Journal of Osteoarchaeology*, *21*, 197–207.

Buckley, H. R., Kinaston, R., Halcrow, S. E., Foster, A., Spriggs, M., & Bedford, S. (2014). Scurvy in a tropical paradise? Evaluating the possibility of infant and adult vitamin C deficiency in the Lapita skeletal sample of Teouma, Vanuatu, Pacific islands. *International Journal of Paleopathology*, *5*, 72–85. https://doi.org/10.1016/j.ijpp.2014.03.001

Caffey, J. (1972). *Pediatric X-ray diagnosis* (6th ed., Vol. 1 and 2). Chicago: The Year Books Publishers.

Caffey, J., & Silverman, W. (1945). Infantile cortical hyperostosis: Preliminary report on a new syndrome. *American Journal of Roentgenology, Radium Therapy and Nuclear Medicine*, *54*, 1–16.

Carli-Thiele, P. (1996). Spuren von Mangelerkrankungen an steinzeitlichen Kinderskeleten. *Fortschritte in der Paläopathologie und Osteoarchäologie*, Band I: Göttingen.

Castilla, M., Carretero, J. M., Gracia, A., & Arsuaga, J. L. (2014). Evidence of rickets and/or scurvy in a complete Chalcolithic child skeleton from the El Portalón site (Sierra de Atapuerca, Spain). *Journal of Anthropological Science*, *92*, 257–271. https://doi.org/10.4436/JASS.92005

Cheadle, W. B. (1878). On three cases of scurvy supervening on rickets in young children. *Lancet*, *112*, 685–687. https://doi.org/10.1016/S0140-6736(02)43922-0

Clemetson, C. A. B. (2002). Barlow's disease. *Medical Hypotheses Issue*, *1*(59), 52–56.

Dal Ri L. 1997. Testimonianze di edifici sacri di epoca carolingia e ottoniana nell'alta valle dell'Adige. Gli scavi di Castel Tirolo. In *Hortus Artium Medievalium*, Journal of the International Research Center for Late Antiquity and Middle Ages vol. 3, Jurkovíc M. (ed.). Zagreb-Motovun: Croatia; 81-100. DOI: https://doi.org/10.1484/J.HAM.2.305101.

Duggan, C. P., Westra, S. J., & Rosenberg, A. E. (2007). Case records of the Massachusetts General Hospital (Case 23-2007). A 9-year-old boy with bone pain, rash, and gingival hypertrophy. *New England Journal of Medicine*, *357*, 392–400. https://doi.org/10.1056/NEJMcpc079017

Fain, O. (2005). Musculoskeletal manifestations of scurvy. *Journal of Bone & Joint Surgery*, *72*, 124–128. https://doi.org/10.1016/j.jbspin.2004.01.007

Fazekas, I. G. Y., & Kósa, F. (1978). *Forensic fetal osteology*. Akademiai Kaido: Budapest.

Follis, R. H., Jackson, D. A., & Park, E. (1940). The problem of the association of rickets and scurvy. *American Journal of Diseases of Children*, *60*, 745–747.

Ginnaio, M. (2011). Pellagra in late nineteenth century Italy: Effects of a deficiency disease. *Population-E*, *66*(3–4), 583–610. https://doi.org/10.2307/41488615

Halcrow, S. E., Harris, N. J., Beavan, N., & Buckley, H. R. (2014). First bioarchaeological evidence of probable scurvy in Southeast Asia: Multifactorial etiologies of vitamin C deficiency in a tropical environment. *International Journal of Paleopathology*, *5*, 63–71. https://doi.org/10.1016/j.ijpp.2014.01.004

Holloway, K. L., Henneberg, R. J., De Barros, L. M., & Henneberg, M. (2011). Evolution of human tuberculosis: A systematic review and meta-analysis of paleopathological evidence. *Homo*, *62*(6), 402–458. https://doi.org/10.1016/j.jchb.2011.10.001

Hughes, M. K., & Diaz, H. F. (1994). *The Medieval Warm Period*. Netherlands: Springer. https://doi.org/10.1007/978-94-011-1186-7

Jaffe, H. (1972). *Metabolic, degenerative, and inflammatory disease of bones and joints*. Philadelphia: Lea and Febiger.

Khonsari, H., Grandière-Perez, L., & Caumes, E. (2005). Scurvy, a re-emerging disease. *La Revue de Médecine Interne*, *26*, 885–890. https://doi.org/10.1016/j.revmed.2005.03.007

Kiple, K. F. (1999). *The Cambridge world history of human disease*. (pp. 1000–1005). Cambridge: Cambridge University Press.

Klaus, H. D. (2014). Subadult scurvy in Andean South America: Evidence of vitamin C deficiency in the late pre-Hispanic and Colonial Lambayeque valley, Peru. *International Journal of Paleopathology*, *5*, 34–45. https://doi.org/10.1016/j.ijpp.2013.09.002

Klaus, H. D. (2015). Paleopathological rigor and differential diagnosis: Case studies involving terminology, description, and diagnostic frameworks for scurvy in skeletal remains. *International Journal of Paleopathology*.. https://doi.org/10.1016/j.ijpp.2015.10.002 (in press)

Koon, H. E. (2010). Scurvy bones: A collagen biomarker to detect vitamin C deficiency in archaeological bone, in: Fourth International Symposium on Biomolecular Archaeology Conference Programme and Abstracts, p. 79.

Koon, H. E. (2012). A biochemical marker for scurvy in archaeological bones. *American Journal of Physical Anthropology*, *147*, 184–185.

Larralde, M., Munoz, A. S., Boggio, P., Di Gruccio, V., Weiss, I., & Schygiel, A. (2007). Scurvy in a 10-month-old boy. *International Journal of Dermatology*, *46*, 184–198. https://doi.org/10.1111/j.1365-4632.2007.02856.x

Leone, J., Dehlinger, V., Maes, D., Scheer, C., Pennaforte, J. L., & Eschard, J. P. (1997). Manifestations rhumatologiques du scorbut. *Revue du Rhumatisme*, *64*, 502–505. https://doi.org/10.1016/j.rhum.2004.01.007

Lewis, M. (2004). Endocranial lesions in non-adult skeletons: Understanding their aetiology. *International Journal of Osteoarchaeology*, *14*, 82–97. https://doi.org/10.1002/oa.713

Lewis, M. (2007). *The bioarchaeology of children: Perspectives from biological and forensic anthropology*. Cambridge: Cambridge University Press.

Lillehammer, G. (1989). A child is born: The child's world in an archaeological perspective. *Norwegian Archaeological Review*, *22*, 89–105.

Lovász, G., Schultz, M., Gödde, J., Bereczki, Z., Pálfi, G., Marcsik, A., & Molnár, E. (2013). Skeletal manifestations of infantile scurvy in a Late Medieval anthropological series from Hungary. *Anthropological Science*, *121*, 173–185. https://doi.org/10.1537/ase.130905

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., … Ni, F. (2009). Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, *326*(5957), 1256–1260. https://doi.org/10.1126/science.1177303

Maresh, M. M. (1970). Measurements from roentgenograms, heart size, long bone lengths, bone, muscle and fat widths, skeletal maturation. In R. W. McCammon (Ed.), *Human growth and development* (pp. 155–200). Charles C. Thomas: Springfield.

Marzoli, C. (2002). Die kirchengrabung von Tirol. In L. Dal Ri, & S. Di Stefano (Eds.), *Archeologia Romana in Alto Adige, beni culturali in Alto Adige, studi e ricerche 1* (pp. 1053–1069). Bolzano/Vienna: Folio Editore.

Marzoli, C., Bombonato, G., & Rizzi, G. (2009). Nuovi dati archeologici sull'insediamento tardo antico-altomedievale della Valle dell'Adige tra la conca di Merano e Salorno. *Atti dell'Accademia Roveretana degli Agiati*. 259 ser. VIII, vol. IX, A, fasc. II, 1, 145–183.

Mays, S. (2008a). A likely case of scurvy from early Bronze Age Britain. *International Journal of Osteoarchaeology*, *18*, 178–187. https://doi.org/10.1002/oa.930

Mays, S. (2008b). Metabolic disease. In R. Pinhasi, & S. Mays (Eds.), *Advances in human palaeopathology* (pp. 215–253). Chichester: Wiley and Sons.

Mays, S. (2014). The paleopathology of scurvy in Europe. *International Journal of Paleopathology*, *5*, 55–62. https://doi.org/10.1016/j.ijpp.2013.09.001

Mensforth, R. P., Lovejoy, C. O., Lallo, J. W., & Armelagos, G. J. (1978). The role of constitutional factors, diet, and infectious disease in the etiology of porotic hyperostosis and periosteal reactions in prehistoric infants and children. *Medical Anthropology*, *2*(1), 1–59. https://doi.org/10.1080/01459740.1978.9986939

Milella, M., Knüsel, C. J., & Haddow, D. (2016). A Neolithic case of fibrous dysplasia from Çatalhöyük (Turkey). *International Journal of Paleopathology*, *15*, 10–18. https://doi.org/10.1016/j.ijpp.2016.09.001

Minozzi, S., Catalano, P., Caldarini, C., & Fornaciari, G. (2012). Palaeopathology of human remains from the Roman imperial age. *Pathobiology*, *79*, 268–283. https://doi.org/10.1159/000338097

Navarre, P., Pehlivanov, I., & Morin, B. (2013). Recurrence of infantile cortical hyperostosis: A case report and review of the literature. *Journal of Pediatric Orthopaedics*, *33*(2), e10–e17. https://doi.org/10.1097/BPO.0b013e318277d3a2

Nissanka-Jayasuriya, E. H., Odell, E. W., & Phillips, C. (2016). Dental stigmata of congenital syphilis: A historic review with present day relevance. *Head and Neck Pathology*, *10*(3), 327–331. https://doi.org/10.1007/s12105-016-0703-z

Nistala, H., Mäkitie, O., & Jüppner, H. (2014). Caffey disease: New perspectives on old questions. *Bone*, *60*, 246–251. https://doi.org/10.1016/j.bone.2013.12.030

Noordin, S., Baloch, N., Salat, M. S., Rashid Memon, A., & Ahmad, T. (2012). Skeletal manifestations of scurvy: A case report from Dubai. *Case Reports in Orthopedics*, *12*, 624–628. https://doi.org/10.1155/2012/624628

Nothdurfter, H. (1991). Das spätantike und frühmittelalterliche Bozen und sein Umfeld aus der Sicht der Archäologie, in Bozen von den Anfängen bis zur Schleifung der Stadtmauern. Bericht über die internationale Studientagung der Stadtgemeinde Bozen, Schloss Maretsch, April 1989, Bolzano, pp. 105-113.

Omori, K., Hanayama, Y., Naruishi, K., Akiyama, K., Maeda, H., Otsuka, F., & Takashiba, S. (2014). Gingival overgrowth caused by vitamin C deficiency associated with metabolic syndrome and severe periodontal infection: A case report. *Clinical Case Reports*, *2*, 286–295. https://doi.org/10.1002/ccr3.114

Ortner, D. J. (1984). Bone lesions in a probable case of scurvy from Metlatavik, Alaska. *Museum Applied Science Center for Archaeology (MASCA) Journal*, *3*, 79–81.

Ortner, D. J. (2003). *Identification of palaeopathological conditions in human skeletal remains*. San Diego: Altamira Press.

Ortner, D. J., Butler, W., Cafarella, J., & Miligan, L. (2001). Evidence of probable scurvy in subadults from archaeological sites in North America. *American Journal of Physical Anthropology*, *114*, 343–351. https://doi.org/10.1002/ajpa.1046

Ortner, D. J., & Ericksen, M. F. (1997). Bone changes in the human skull probably resulting from scurvy in infancy and childhood. *International Journal of Osteoarchaeology*, *7*, 212–220. https://doi.org/10.1002/(SICI)1099-1212(199705)7:3<212::AID-OA346>3.0.CO;2-5

Ortner, D. J., & Frohlich, B. (2007). The EB IA tombs and burials of Bâb edh-Dhrâ, Jordan: A bioarchaeological perspective on the people. *International Journal of Osteoarchaeology*, *17*, 358–368. https://doi.org/10.1002/oa.907

Ortner, D. J., Kimmerle, E. H., & Diez, M. (1999). Probable evidence of scurvy in subadults from archaeological sites in Peru. *American Journal of Physical Anthropology*, *108*, 321–331. https://doi.org/10.1002/(SICI)1096-8644(199903)108:3<321::AID-AJPA7>3.0.CO;2-7

Ortner, D. J., & Mays, S. (1998). Dry-bone manifestations of rickets in infancy and early childhood. *International Journal of Osteoarchaeology*, *8*, 45–55. https://doi.org/10.1002/ (SICI) 1099-1212(199801/02)8:1<45::AID-OA405>3.0.CO;2-D

Ortolani, F., & Pagliuca, S. (2007). Evidenze geologiche di variazioni climatico ambientali storiche nell'Area Mediterranea. In F. Wezel (Ed.), *Variabilità naturale del clima nell'Olocene ed in tempi storici: un approccio geologico* (pp. 13–17). Roma: Società Geologica Italiana.

Paine, R. R., & Brenton, B. P. (2006). The paleopathology of pellagra: Investigating the impact of prehistoric and historical dietary transitions to maize. *Journal of Anthropological Science*, *84*, 125–135.

Papathanasiou, A. (2011). Health, diet and social implications in Neolithic Greece from the study of human osteological material. In R. Pinhasi, & J. T. Stock (Eds.), *Human Bioarchaeology of the Transition to Agriculture* (pp. 87–106). Chichester: John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470670170.ch5

Pendery, S. R., & Koon, H. E. C. (2013). Scurvy's impact on european colonization in northeastern North America. In P. E. Pope, & S. Lewis-Simpson (Eds.), *Exploring Atlantic transitions, archaeologies of transience and permanence in new found lands* (pp. 57–65). Woodbridge: The Boydell Press.

Pettifor, J. M. (2003). Nutritional rickets. In F. H. Glorieux, J. M. Pettifor, & H. Jüppner (Eds.), *Pediatric bone. Biology and diseases* (pp. 541–565). San Diego: Academic Press.

Popovich, D., McAlhany, A., Adewumi, A. O., & Barnes, M. M. (2009). Scurvy: forgotten but definitely not gone. *Journal of Pediatric Health Care*, *23*, 405–415. https://doi.org/10.1016/j.pedhc.2008.10.008

Prinzing, F., & Westergaard, H. (1916). *Epidemics resulting from wars*. Oxford: Clarendon Press.

Ragsdale, B. D. M., & Lehmer, L. M. (2012). A knowledge of bone at the cellular (histological) level is essential to paleopathology. In A. L. Grauer (Ed.), *A companion to paleopathology* (pp. 227–249). Chichester, UK: Willey-Blackwell.

Rajakumar K. 2001. Infantile scurvy: A historical perspective. *Pediatrics 108* (4): E76. DOI:https://doi.org/10.1155/2010/717518, 1, 4.

Roberts, C. A. (1999). Rib lesions and tuberculosis: The current state of play. In G. Pálfi, O. Dutour, J. Deák, & I. Hutás (Eds.), *Tuberculosis: Past and present* (pp. 311–316). Budapest/Szeged: Golden Book Publishers and Tuberculosis Foundation.

Salis, N., Massa Detton, E., Fulcheri, E., & Rabino, M. E. (2005). Pathological lesions attributable to vitamin deficiency in skeletal remains from Puy St. Pierre (Briançon, France). *International Journal of Anthropology*, *20*, 325–330.

Schattmann, A., Bertrand, B., Vatteoni, S., & Brickley, M. (2016). Approaches to co-occurrence: Scurvy and rickets in infants and young children of 16–18th century Douai, France. *International Journal of Paleopathology*, *12*, 63–75. https://doi.org/10.1016/j.ijpp.2015.12.002

Scheuer, L., & Black, L. (2009). *Developmental juvenile osteology*. London: Elsevier Academic Press.

Schultz, M. (2001). Paleohistopathology of bone: A new approach to the study of ancient diseases. *American Journal of Physical Anthropology*, *44*, 106–147.

Silverman, F. N. (1985). *Caffey's pediatric X-ray diagnosis. An integrated imaging approach* (Eighth ed., Vol. 1). Chicago: Year Book Medical Publishers.

Sivaraj, K. K., & Adams, R. H. (2016). Blood vessel formation and function in bone. *Development*, *143*(15), 2706–2715. https://doi.org/10.1242/dev.136861

Sloan, B., Kulwin, D. R., & Kersten, R. C. (1999). Scurvy causing bilateral orbital hemorrhage. *Archives of Ophthalmology*, *117*, 842–843. https://doi.org/10.1001/archopht.117.6.842

Snoddy, A. M. E., Halcrow, S. E., Buckley, H. R., Standen, V. G., & Arriaza, B. T. (2017). Scurvy at the agricultural transition in the Atacama Desert (ca 3600–3200 BP): Nutritional stress at the maternal-foetal interface? *International Journal of Paleopathology*, *18*, 108–120. https://doi.org/10.1016/j.ijpp.2017.05.011

Stark, R. J. (2014). A proposed framework for the study of paleopathological cases of subadult scurvy. *International Journal of Paleopathology*, *5*, 18–26. https://doi.org/10.1016/j.ijpp.2014.01.005

Tamura, Y., Welch, D. C., Zic, J. A., Cooper, W. O., Stein, S. M., & Hummell, D. S. (2000). Scurvy presenting as painful gait with bruising in a young boy. *Archives of Pediatrics & Adolescent Medicine*, *154*, 732–735.

Ubelaker, D. H. (1978). *Human skeletal remains: Excavation, analysis and interpretation*. Washington: Taraxacum.

Vannier, S., Thomas, R., Jean-Christophe, F., Pinel, J. F., & Verin, M. (2014). Vitamin C depletion is spontaneous intracerebral hemorrhage risk factor. *Neurology*, *82*, 10.

Walker, P. L., Bathurst, R. R., Richman, R., Gjerdrum, T., & Andrushko, V. A. (2009). The causes of porotic hyperostosis and cribra orbitalia: A reappraisal of the iron-deficiency-anemia hypothesis. *American Journal of Physical Anthropology*, *139*, 109–125. https://doi.org/10.1002/ajpa.21031

Wapler, U., Crubézy, E., & Schultz, M. (2004). Is cribra orbitalia synonymous with anemia? Analysis and interpretation of cranial pathology in Sudan. *American Journal of Physical Anthropology*, *123*, 333–339. https://doi.org/10.1002/ajpa.10321

White, T. D., & Folkens, P. A. (1999). *Human osteology* (2nd ed.). Academic Press: New York.

Winckler, C. (2012). *Die Alpen im Frühmittelalter, Die Geschichte eines Raumes in den Jahren 500 bis 800*. Böhlau: Wien.

Wrobel, G. (2014). Brief communication: A likely case of scurvy in a rural early classic Maya burial from Actun Uayazba Kab, Belize. *American Journal of Physical Anthropology*, *155*, 476–481. https://doi.org/10.1002/ajpa.22592

Zuckerman, M. K., Garofalo, E. M., Frohlich, B., & Ortner, D. J. (2014). Anemia or scurvy: A pilot study on differential diagnosis of porous and hyperostotic lesions using differential cranial vault thickness in subadult humans. *International Journal of Paleopathology*, *5*, 27–33. https://doi.org/10.1016/j.ijpp.2014.02.001

How to cite this article: Paladin A, Wahl J, Zink A. Evidence of probable subadult scurvy in the Early Medieval cemetery of Castel Tirolo, South Tyrol, Italy. *Int J Osteoarchaeol*. 2018;28:714–726. https://doi.org/10.1002/oa.2694

Article II

International Journal of Paleopathology 27 (2019) 46–55

Contents lists available at ScienceDirect

International Journal of Paleopathology

journal homepage: www.elsevier.com/locate/ijpp

Perimortem sharp force trauma in an individual from the early medieval cemetery of Säben-Sabiona in South Tyrol, Italy

Daniela Tumler[a,b,1], Alice Paladin[a,c,1], Albert Zink[a,*]

[a] Institute for Mummy Studies, Eurac research, Viale Druso 1, 39100 Bolzano, Italy
[b] Faculty of Biology, Department of Biology II, Anthropology and Human Genomics, Ludwig Maximilian University of Munich, Großhaderner Str. 2, 82152 Planegg-Martinsried, Germany
[c] Institute for Archaeological Sciences, WG Palaeoanthropology, University of Tübingen, Rümelin Str. 23, 72070 Tübingen, Germany

ARTICLE INFO

Keywords:
Interpersonal conflict
Weapons
Violence
Italian alps

ABSTRACT

Objective: To provide a detailed analysis and interpretation of cranial and postcranial lesions noted on an early medieval skeleton from the Italian Alps.
Materials: Individual (SK63) was buried within the early Christian church (5th-8th centuries AD) of Säben-Sabiona in South Tyrol (Italy).
Methods: The skeleton underwent macroscopic, microscopic and metric analyses.
Results: SK63 was a 19–25 year old male, the analysis identified at least 29 lesions, consisting of three possible antemortem injuries and 26 perimortem sharp force injuries on the cranium (n = 4) and postcranium (n = 22).
Conclusions: The trauma pattern observed indicates that different bladed weapons were used and interpersonal violence rather than a large-scale conflict led to the death of SK63.
Significance: The present findings provide novel information on violent interpersonal interactions in early medieval Säben-Sabiona, Italy.
Limitations: The sequence of the inflicted injuries was not reconstructed.
Suggestions for Further Research: Future interdisciplinary investigations (i.e., 3D imaging and reconstructions) will provide a better understanding of the possible types of weapons used to inflict injuries, the required forces to create the lesions, as well as the directions of impact.

1. Introduction

Trauma analysis in anthropology provides a direct line of evidence regarding the occurrence and nature of violent conflict, as well as contributing to our understanding of care and medical treatment in human societies (e.g., Nicklisch et al. 2017; Boucherie et al. 2017; Caffell and Holst, 2012; Binder and Quade, 2018; Knüsel and Smith, 2014). Additionally, skeletal trauma can provide information on aspects of behavior at the level of social groups, such as exposure to risk associated with daily activities, the scale and frequency of conflict, interpersonal violence, and the extent to which such hazards lead to death (DiMaio and DiMaio, 2001; Gerhards, 2007; Kjellström, 2005; Nicklisch et al., 2017; Šlaus et al., 2012, 2010).

Skeletal injuries occur when blunt, projectile, or sharp forces are applied to bone. Sharp force trauma (SFT) can derive from either compression or shearing forces that are applied vigorously over a narrow area, whereby the angle of contact, the force applied, and the weapon used, determine the type of lesion observed on bone (Byers, 2017; DiMaio and DiMaio, 2001). Puncture and chop marks result from implements (e.g., knives, swords, lances and axes, machetes) that apply concentrated compression forces perpendicularly to small or narrow areas of bone, whereas incisions are associated with slashing motions that produce a lesion whose length is greater than its depth (e.g., knives, swords) (Byers, 2017; DiMaio and DiMaio, 2001). The severity of bone damage depends on many factors, including the condition of the tool, the type and quantity of soft tissue covering the bone, as well as the type of clothing worn by the victim (DiMaio and DiMaio, 2001; O´Callaghan et al., 1999).

Historical and archaeological records feature extensive evidence for interpersonal aggression (Appleby et al., 2015; Caffell and Holst, 2012; Quade and Binder, 2018; Skinner, 2015; Šlaus et al., 2012; Šlaus and Novak, 2006; Vazzana et al., 2018). However, skeletal trauma

* Corresponding author.
E-mail address: albert.zink@eurac.edu (A. Zink).
[1] Both authors contributed equally to this work.

https://doi.org/10.1016/j.ijpp.2019.07.005
Received 28 November 2018; Received in revised form 15 July 2019; Accepted 21 July 2019
Available online 24 September 2019
1879-9817/

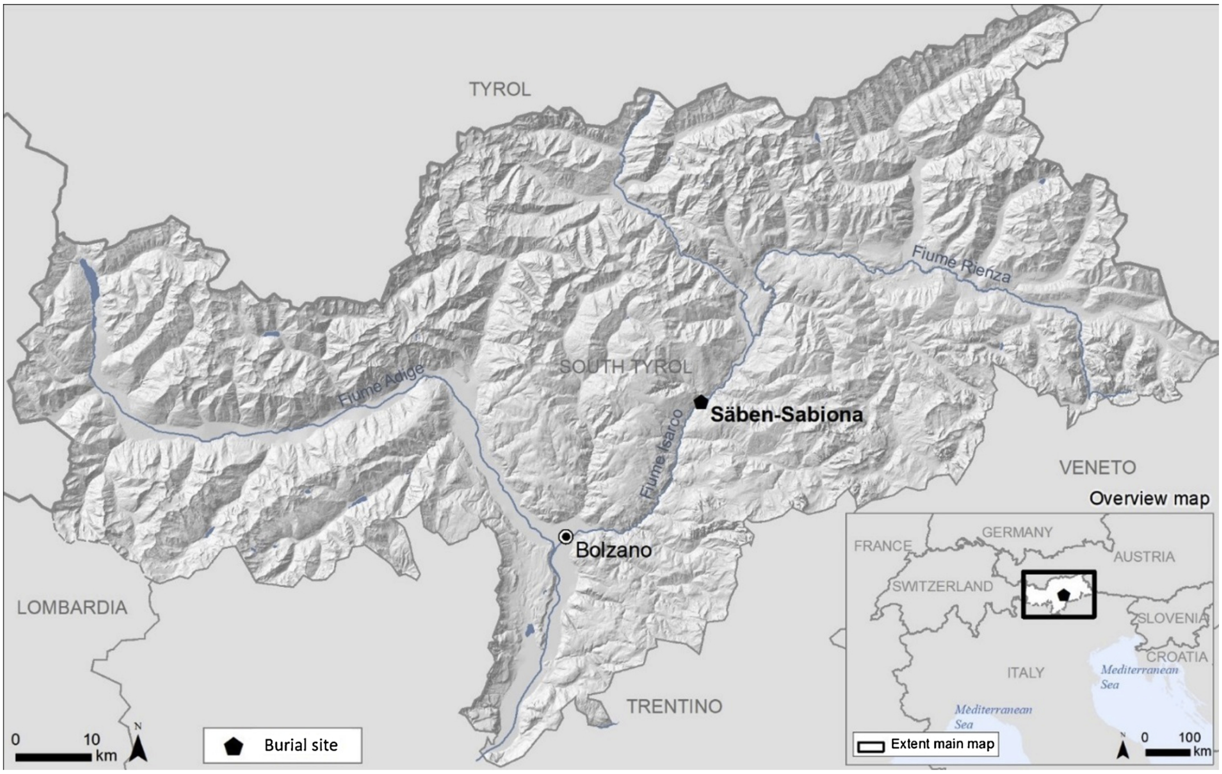


Fig. 1. Geographical location of the archaeological site of Säben-Sabiona, in South Tyrol, Italy.

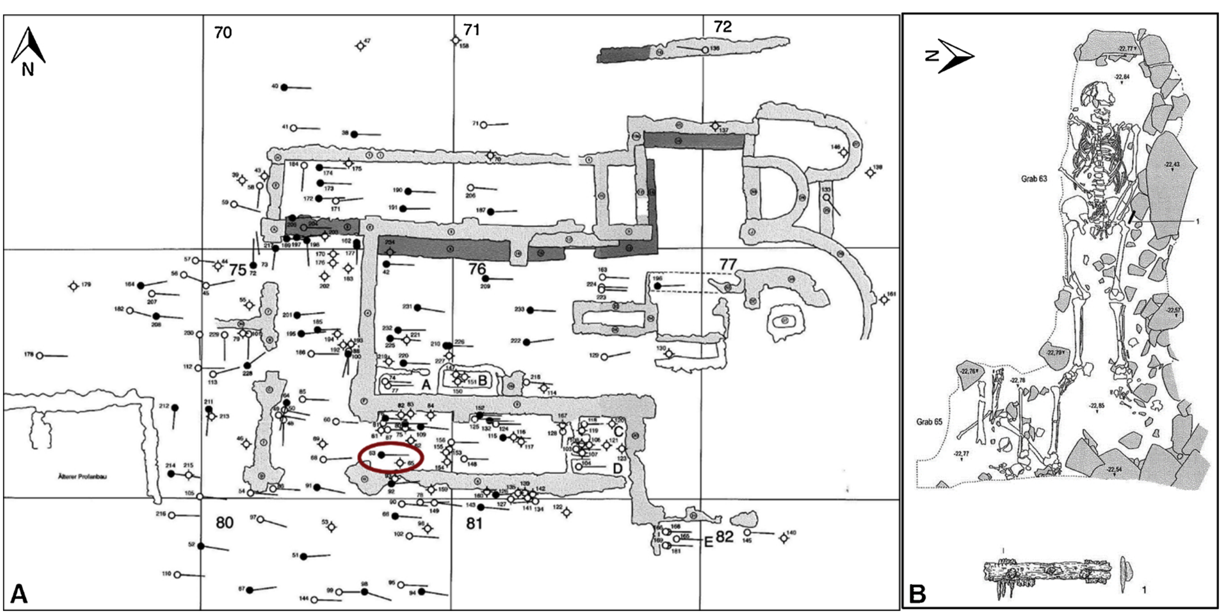


Fig. 2. a) The early medieval cemetery of Säben-Sabiona, indicating the location of grave T.63 (circled); b) Archaeological documentation of tomb T.63.

Table 1
Features distinguishing ante-, peri- and postmortem trauma (adopted from Kimmerle and Baraybar, 2008; Byers, 2017).

	Antemortem	Perimortem	Postmortem
Edges	Rounded, loss of sharpness, porosity near lesion (bone activity and resorption), callus formation.	Sharp, no rounding/remodelling.	Sharp, no rounding/remodelling, can appear jagged and irregular.
Coloration	Uniform coloration of the lesion.	Presence of occasional staining of the bone surface caused by haematoma formation.	Broken surface is lighter in color than the rest of the bone.
Fracture lines	Osteogenic reactions or appear like V-shaped grooves.	Radiate outward from the point of impact.	Radiating and greenstick fractures uncommon.
Hinging	Absent	Present	Rarely present

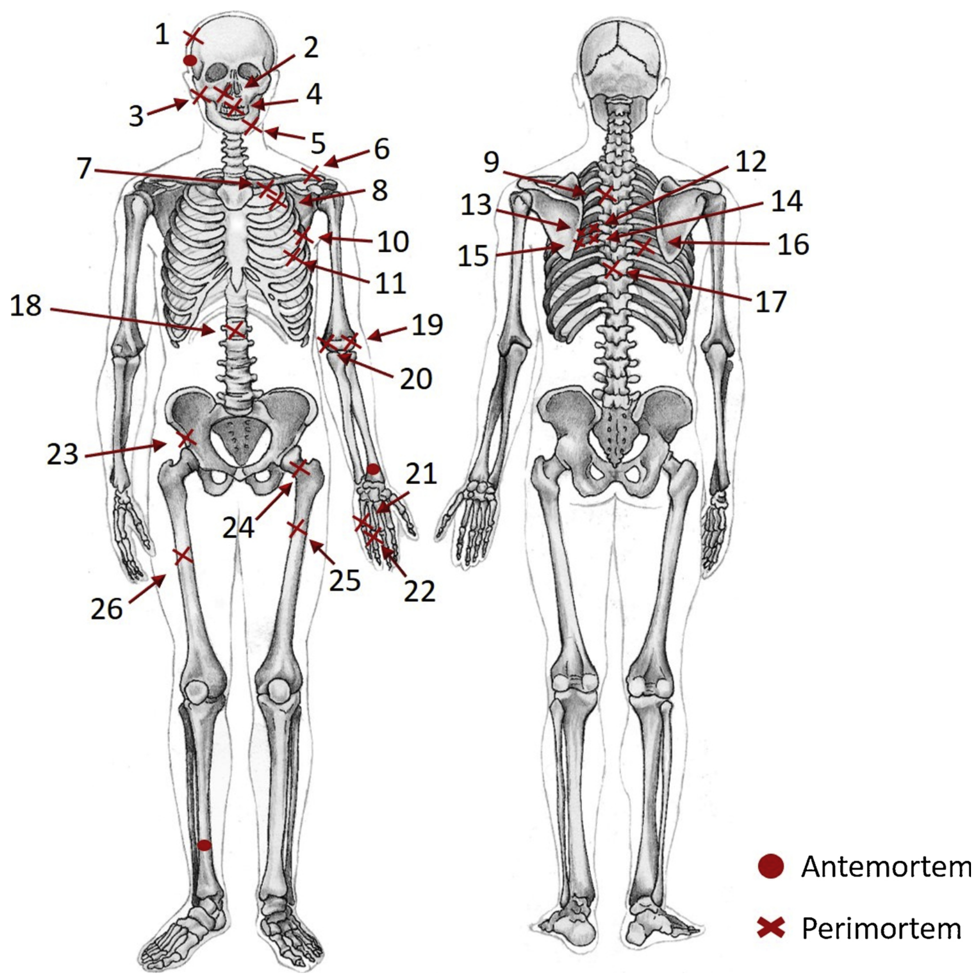


Fig. 3. Location of antemortem (dots) and perimortem (crosses) trauma of SK63. The numbers refer to the perimortem injuries.

documented from early medieval Italy is limited to a few studies (Facchini et al., 2008; Rubini and Zaio, 2011). In South Tyrol (Italy), the only available research is from the cemetery of San Procolo in Naturno (Renhart, 1991).

Our work aims to provide a detailed analysis of perimortem SFT in an individual from the early medieval cemetery of Säben-Sabiona in South Tyrol, Italy. Moreover, the circumstances of the violent event as well as the type of weapon(s) used are investigated.

2. Materials and methods

Säben-Sabiona is located on a mount in the Isarco valley in South Tyrol, Italy (Fig. 1).

Grave T.63 was excavated within the early medieval church of Säben-Sabiona (Fig. 2a) (Bierbrauer and Nothdurfter, 2015). T.63 was a single grave in a stone-lined earth pit (Fig. 2b) and, based on the stratigraphy, was dated to the 7th -8th century AD (Bierbrauer and Nothdurfter, 2015). The skeletal remains (SK63) were in almost complete articulation and showed no signs of disturbance. SK63 was buried in Christian tradition with a fragmented comb next to the left os coxae (Fig. 2b).

Standard morphological and osteometric methods were used for sex (Acsádi and Nemeskéri, 1970; Ferembach et al., 1979; Murail et al., 2005) and age at death estimation (AlQahtani et al., 2010; Buckberry and Chamberlain, 2002; Katz and Suchey, 1986; Meindl and Lovejoy, 1985; Rouge-Maillart et al., 2009; Schaefer et al., 2009).

Trauma analysis included the identification, localization and description of each injury. The type of trauma was defined based on four trauma categories i.e., blunt force, sharp force, projectile and miscellaneous trauma (Byers, 2017; DiMaio and DiMaio, 2001; Mahoney et al., 2005). Trauma timing was assessed based on the modifications as shown in Table 1. The lesions were characterised based on eight traits proposed in the experimental study of Lewis (2008): length, shape, flaking, feathering, cracking, breaking, shards and aspect, whereby flaking and feathering refers to chipping and hinging respectively. Lewis' study aids to describe the lesions and to assess what type of weapon was potentially used to create them. To complement the macroscopic investigation, all lesions were examined microscopically (Leica M205A) and photographed (Nikon DS300).

3. Results

SK63 was a 19–25 year old male. The skeleton displayed 29 lesions; five on the cranium and twenty-four on the postcranium (Fig. 3). Twenty-three of 29 alterations were highly likely of traumatic origin; the remaining six lesions were recorded as possible trauma.

Three lesions (10%, 3/29) displayed bone remodelling, thus were registered as possible antemortem lesions. These were located on the right side of the cranium, the left radius and the right tibia. The remaining lesions (26/29) were identified as perimortem SFT, as none of them showed signs of healing.

3.1. Antemortem lesions

Three injuries displayed an advanced stage of remodelling and were likely antemortem injuries. The cranial lesion was located near the right

Fig. 4. Right ectocranial view of the frontal bone; arrows indicate the antemortem lesion on the sphenofrontal suture.

sphenofrontal and frontozygomatic suture (Fig. 4). An irregularly spiked osseous protrusion was discernible on the ectocranium and a less pronounced osteoblastic reaction was observed endocranially.

Postcranial lesions include enlargement of the distal diaphysis of the left radius and localized thickening on the anterior crest of the diaphysis of the right tibia, indicating a progressive stage of healing.

3.2. Perimortem lesions

The 26 lesions were recognised as consistent with perimortem sharp force injuries due to the presence of distinct kerfs with sharp walls and margins. Descriptions, including information on trauma location, size, shape, fracturing and aspect of the injuries are provided in Table 2.

The lengths of all cranial lesions (lesions 1) and most postcranial (5–21, 24–25) injuries were indicative of incisions, rather than chop marks or punctures. However, the length of the SFT on the left 4th proximal phalanx (22, Fig. 5a), the right os coxae (23, Fig. 6) and the left and right femora (24, 26; Figs. 7 and 8) featured characteristics of chop marks. The shapes of the incisions were predominantly an ellipse (46%, 12/26) or a line (19%, 5/26). The lesions on the left 4th proximal phalanx (22, Fig. 5a), the right femur (26, Fig. 8), and the neck of the left femur (24), exhibited clear elliptical outlines. In contrast, the cut on the anterior inferior iliac spine of the right os coxae (23) appeared linear.

Unilateral flaking was found on 62% (16/26) of the cases, as seen in the maxilla (4, Fig. 9a). Less frequently noted was the presence of unilateral feathering (38%, 10/26) and cracking (58%, 15/26), as seen on the right os coxae (23, Fig. 6) as well as on the 1 st and 2nd ribs (7, 8, Fig. 10).

Breakage (15%, 4/26), visible on the mandible (5, Fig. 11), and shards (35%, 9/26), were noted to a less frequently.

The lesions of the maxillae (2, 4, Fig. 9) and the left 5th metacarpal (21, Fig. 5b), appear to have been separated completely by the blade rather than breaking off after the blow. In all, 77% (20/26) of the cut marks appear to be glancing, while 23% (6/26) appear to be perpendicular. The left femur displayed both types of impact angles (Fig. 7a): a perpendicular cut at the femoral neck (24) and a glancing trauma on the proximal diaphysis (25, Fig. 7b). Direction of impact could not be reconstructed for 27% (7/26) of the cut marks due to taphonomic alterations (3, 6, 19, 20), fragmentation (2, 4, Fig. 9), or angle of impact (1, 21, Fig. 5b). The glancing injury on the mandible (5, Fig.11) displayed a sharp border at the posterior end, as well as a roughened border with bone chipping at the anterior end, suggesting that the blade cut was oriented from posterior to anterior. The lesions of the left 1st and 2nd ribs (7, 8), and possibly also the glancing cut on the left clavicle (6), resulted from a single stroke delivered from above, which may have continued to the left 5th rib causing the internal cut mark (11). The magnified image of the lesion on the left femur (25, Fig. 7b) displays a smooth mediodistal border, roughened proximolateral border, and striation marks within the surface, suggesting that the blow was delivered from the mediodistal to the proximolateral aspect of the bone.

Eighty percent (4/5) of the cut marks on the skull were located on the right side. More than half of the injuries were located on the left side (73%, 19/26). The ribs and vertebrae were most often affected (47%, 9/19), followed by the bones of the upper limbs and shoulder girdle (26%, 5/19) (Fig. 3).

4. Discussion

4.1. Antemortem and perimortem lesions

The antemortem modifications of this individual were sufficiently well healed to be considered as ´old injuries´ at the time of death (Jurmain, 1999; Byers, 2017; Kimmerle and Baraybar, 2008; Sauer, 1998). The texture and shape of the antemortem cranial lesion was not consistent with neoplastic lesions, such as an osteoma (Ortner, 2003; Waldron, 2009), since it was rough and irregular in shape. The texture appeared to consist of multiple small bone splinters remodelled together, rather than osteogenic cortical bone. Thus, the combination of texture and shape of the alteration appeared to be highly consistent with antemortem trauma. Neither healed fracture lines nor any other direct signs of trauma were observed on the zygomatic, sphenoid, or

Table 2
List and descriptions of perimortem trauma noted in SK63 (ND refers to not determinable).

Lesion	Bone	Laterality	Location	Length (mm)	Shape	Flaking	Feathering	Cracking	Breakage	Shards	Aspect
1	Parietal	Right	Between the parietal tuber and the squamous suture, superior to parietal striae	23.9	Line	Bilateral	Absent	Absent	Absent	Absent	Glancing
2	Maxilla	Right	Right nasal aperture (Alare)	ND	ND	Unilateral	Absent	Present	ND	Absent	Glancing
3	Zygomatic	Right	Inferior border of the zygomatic at masseteric origin	ND	ND	Unilateral	Absent	Absent	ND	Absent	Glancing
4	Maxilla	Left and right	From the alveolus of the left 1st incisor to the right 2nd premolar	ND	ND	Bilateral	Absent	Present	ND	Absent	Glancing
5	Mandible	Left	Inferior border of mandible	36.4	Ellipse	Unilateral	Absent	Present	Present	Absent	Glancing
6	Clavicle	Left	Posterior border of the acromial end	26.2	Ellipse	Unilateral	Absent	Absent	ND	Absent	Glancing
7	1 st rib	Left	Mid-shaft, external border	superior: 5.4, inferior: 4	Ellipse	Unilateral	Unilateral	Present	Absent	Present	Glancing
8	2nd rib	Left	Distal end, internal border	superior: 1.8, inferior: 3.4	Ellipse	Unilateral	Unilateral	Present	Absent	Present	Glancing
9	3rd thoracic vertebrae	Left	Inferior, posterior body	11.3	Trapezoid	Unilateral	Absent	Absent	Present	Absent	Glancing
10	5th rib	Left	Mid-shaft, external border	superior: 5.7, inferior: 4.7	Ellipse	Absent	Unilateral	Present	Absent	Absent	Glancing
11	5th rib	Left	Mid-shaft, internal border	superior: 3.7, inferior: 2.8	Ellipse	Unilateral	Unilateral	Present	Absent	Present	Glancing
12	6th rib	Left	Inferior of articular facet	7.1	Rhombus	Bilateral	Bilateral	Present	Absent	Present	Perpendicular
13	6th rib	Left	Inferior border at angle	3.6	Triangle	Bilateral	Absent	Present	Absent	Present	Perpendicular
14	7th rib	Left	Superior border at tubercle	8.6	Line	Absent	Unilateral	Present	Absent	Absent	Perpendicular
15	7th rib	Left	Superior border near angle	6.4	Line	Bilateral	Bilateral	Absent	Absent	Present	Glancing
16	7th rib	Right	Inferior border at angle	external: 7.8, internal 8.2	Ellipse	Unilateral	Unilateral	Present	Absent	Present	Glancing
17	9th thoracic vertebrae	Left	Inferior lamina	16.0	Triangle	Unilateral	Unilateral	Absent	Present	Absent	Glancing
18	1 st lumbar vertebrae	NA	Anterior body	16.5	Line	Unilateral	Absent	Present	Absent	Present	Glancing
19	Humerus	Left	Capitulum	17.2	Circle	Absent	Absent	Absent	ND	Absent	Glancing
20	Humerus	Left	Medial epicondyle	15.7	Ellipse	Unilateral	Unilateral	Absent	ND	Absent	Glancing
21	5th metacarpal	Left	Distal epiphysis, palmar articular surface	11.9	Trapezoid	Absent	Absent	Absent	ND	Absent	Glancing
22	4th proximal phalanx	Left	Proximal epiphysis, palmar surface	8.1	Ellipse	Unilateral	Unilateral	Absent	Absent	Absent	Perpendicular
23	Os coxae	Right	Mid-point, anterior inferior illiac spine	18.2	Line	Unilateral	Unilateral	Present	Absent	Absent	Glancing
24	Femur	Left	Antero-medial neck (between head and intertrochanteric line)	15.6	Ellipse	Unilateral	Absent	Present	Absent	Absent	Perpendicular
25	Femur	Left	Anterior surface of proximal-mid diaphysis	26.3	Ellipse	Unilateral	Absent	Absent	Present	Absent	Glancing
26	Femur	Right	Antero-medial mid-diaphysis	18.9	Ellipse	Bilateral	Bilateral	Present	Absent	Present	Perpendicular

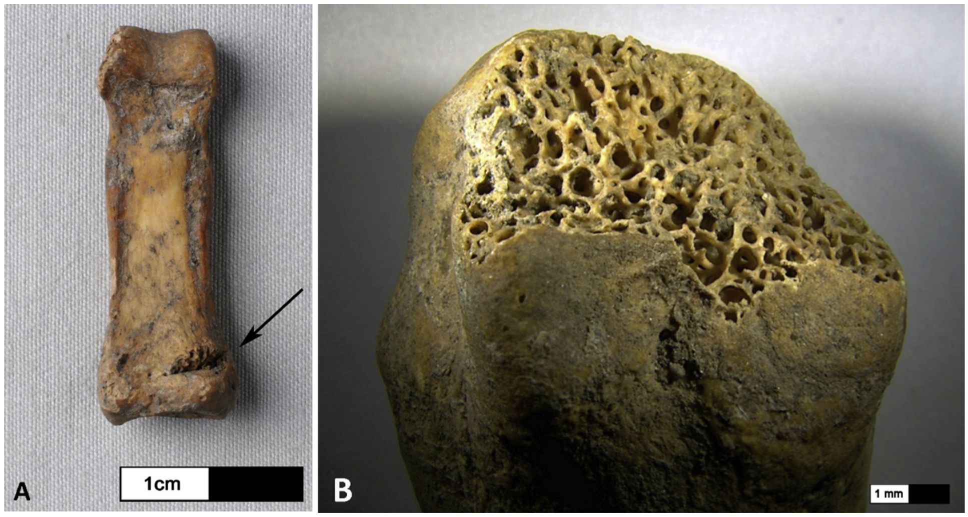


Fig. 5. a) Palmar view of the diagonal cut on the base of the left 4th proximal phalanx (22); b) Palmar view of the lesion on the head of the left 5th metacarpal (21).

Fig. 6. Anterior-medial view of the incision on the anterior inferior iliac spine of the right os coxae (23).

parietal bone fragments. Considering that the side of the cranium is frequently targeted during events involving interpersonal aggression (Afshar et al., 2018; Meyer et al., 2014; Nicklisch et al., 2017; Novak, 2007; Šlaus and Novak, 2006), this lesion may indicate the survival of a previous injury caused by an unknown event.

The fracture on the distal diaphysis of the left radius is typical for Smith's or Colle's fractures that can result when trying to break a fall (Nicklisch et al., 2017; Novak and Šlaus, 2010; Šlaus et al., 2012). However, as the fracture is well aligned and lacks signs of angulation, the cause of the fracture could not be determined. The lesion on the anterior crest of the tibia was well-defined and localised with no osteogenic activity, so could, as Ortner (2003) and Roberts and Manchester (2010) point out, be due to periostitis or osteitis. Research by Gerhards (2007); Myszka et al. (2012) and Šlaus et al. (2012) suggest that such injuries are often associated with accidents rather than conflicts.

Twenty six of the 29 lesions featured sharp margins with a homogenous coloration and fracture lines, none of which displayed signs of healing. Perimortem body modifications that involve SFT can be due to dismemberment and defleshing (Black et al., 2017; Dye, 2016; Holst et al., 2018; Robb et al., 2015; Wallduck and Bello, 2016). However, due to the position and depth of the lesions on this skeleton, none of which were located at major joints or included multiple small cuts indicative of soft tissue removal, both dismemberment and defleshing were excluded. Further, the completeness and articulation of the skeleton indicates that the body of the deceased was not manipulated after his death.

4.2. Injury interpretations

The cut mark on the right maxilla at the nasal opening (2) appears in alignment with the lesion on the right zygomatic bone (3), suggesting that they were caused by a single stroke across the face of SK63. The wounds to the left 4th proximal phalanx and the 5th metacarpal (21, 22) resulted most likely from a single cut while the hand was flexed, often associated with defensive wounds found in stab victims (Bohnert

Fig. 7. a) Medial view of the left femur exhibiting two SFT at the inferior-medial portion of the femoral neck (24) and on the proximal diaphysis (25); b) High-magnification image of the glancing lesion on the proximal diaphysis of the left femur (25).

Fig. 8. Anterior view of the cut mark on the mid-diaphysis of the right femur (26).

et al., 2006; Schmidt and Pollak, 2006). Research by Bohnert et al. (2006) and Pal Singh et al. (2004) has shown that stab wounds to the thorax affect vital organs and major blood vessels and may be life threatening. In skeleton SK 63, most of the stab wounds to the chest appear to have been inflicted from the front and include the 1st, 2nd (7, 8) and 5th ribs (10, 11). The external lesion of the left 5th rib (10) appears to be the result of a slashing action from anterior to posterior without penetrating the ribcage. In contrast, the location of both injuries on the left 6th and left and right 7th ribs (12–16) suggest infliction from behind. Depending on the depth of the stab wound, the lesions on the left clavicle (6), left 1st (7), 2nd (8), 6th (12, 13) and both 7th (14–16) ribs, probably caused severe damage to major blood vessels (e.g., axillary artery, the aortic arch). Furthermore, the cut marks on the 3rd and 9th thoracic vertebrae (9, 17) and the 1 st lumbar vertebra (18) also caused substantial injuries to the nerves and internal organs of the chest and the abdominal cavity. Both thoracic vertebrae presented traumatic lesions on their posterior aspect, implying an impact from behind. The 1st lumbar vertebra (18), on the contrary, appears to have received the injury from the front, which may have penetrated several muscles and major blood vessels including the inferior vena cava and aorta, as well as the diaphragm, pancreas and stomach.

Overall, the trauma pattern noted in SK63 is consistent with stabbing injuries. Since the injuries were most commonly found on the left side of the body and on the thorax, respectively, it is possible that they were inflicted by a right-handed assailant (Bohnert et al., 2006; Pal Singh et al., 2004). The fact that only bone injuries can be evaluated here considerably limits the interpretation of the injuries (Binder and Quade, 2018; Croft and Ferllini, 2007; Nicklisch et al., 2017). All incisions observed on the lower part of the body (23–26) probably caused serious damage to the muscles (e.g., the M. iliacus, M. psoas major, M. sartorius) and the circulatory system (e.g., A. circumflexa femoris, A.

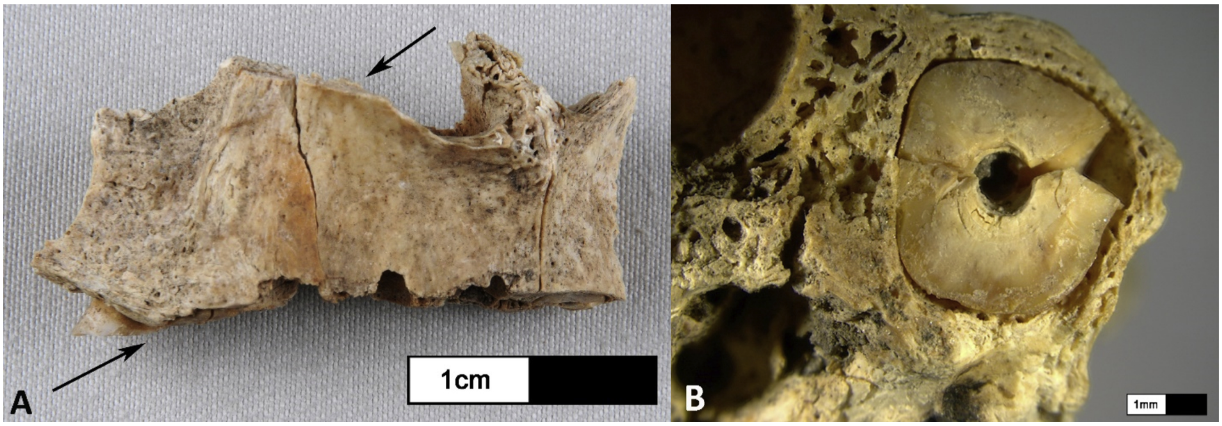


Fig. 9. a) Maxillae fragment featuring two cut marks (arrows, 2, 4); b) High-resolution image of the inferior view of the alveolus of the left permanent first maxillary incisor (4).

Fig. 10. Superior view of the incisions on the 1st and 2nd left ribs (7, 8).

femoralis).

4.3. Evaluation of trauma patterns

Numerous studies on European sites dating from the Medieval to Early Modern Periods, which involve intentional violence, show that different kinds of aggressive encounters leave distinct lesion patterns on the deceased (Boucherie et al., 2017; Constantinescu et al., 2017; Ingelmark, 1939; Nicklisch et al., 2017). Kjellström (2005) and Novak (2007) suggest that injuries resulting from large scale conflicts, i.e., organised warfare, are concentrated predominantly on the front and back of the skull, whereas Ingelmark (1939) found higher prevalence of postcranial trauma in skeletons from Wisby (Sweden). Both targeting the head of the opponent, implying the lethal intentionality of a dispute, and blows to the lower limbs were suggested to be useful strategies to immobilise the opponent and then to deliver the *coup de grace* (Boucherie et al., 2017; Constantinescu et al., 2017; Forsom et al., 2017; Ingelmark, 1939). Gassmann (2018) argues that field battles were relatively rare in the Early Middle Ages, whereas raids on enemy infrastructure and subsistence supplies were common in this period. Disputes linked to honor or vengeance were resolved through duelling or ´trial by combat´ (Elema, 2012; Shoemaker, 2002; Smith, 2017). In contrast to trauma patterns associated with large scale conflicts, the postcranial cuts on SK63 clearly outnumber the cranial ones. The trauma distribution of SK63 deviates from cases found in Medieval battle sites (Bennike et al., 2006; Boucherie et al., 2017; Kjellström, 2005; Novak, 2007). However, the injuries to the legs are similar to the findings at Wisby and are plausibly interpreted as a tactic designed to bring down the opponent in order to facilitate the killing blow.

The battlefield dead were seldomly buried, thus rendering corpses accessible to scavengers (Holst et al., 2018; Smith, 2017). The lack of scavenging activities on SK63 imply that he was interred soon after his death.

The injuries of SK63 did not correspond with trauma patterns associated with large scale violence, but they were more consistent with small scale face-to-face conflict. The left side of the skeleton presented a clear predominance of cut marks, which corresponds with the patterns observed in direct hand-to-hand frontal attacks between right-handed opponents (Boucherie et al., 2017; Fiorato et al., 2007). Conversely, the majority of cranial wounds of SK63 were located on the right side.

Fig. 11. Left inferior view of the mandible, displaying a glancing traumatic lesion on the body (5).

However, due to the degree of fragmentation of the cranium, the osteological analysis was limited since much of the left side was missing. Moreover, SK63 featured numerous (35%, 9/26) lesions on the left posterior and anterior thorax, possibly indicating that he was attacked by more than one assailant or that SK63 changed position during the assault. The infliction of these injuries over the course of multiple events was ruled out since the microscopic analysis showed no osteogenic reactions. The number and positions of perimortem lesions observed on SK63 appears to exceed the amount of injuries necessary to kill a victim. This is referred to as overkilling (Bohnert et al., 2006; Geber, 2015; Nikolic and Zivkovic, 2015; Šlaus et al., 2010). Overkilling has been associated with strong emotional conflict (Bohnert et al., 2006; Karlsson, 1998; Nikolic and Zivkovic, 2015; Ormstad et al., 1986).

4.4. Assessment of possible weapons

Following Lewis' (2008) criteria, possible weapons used to inflict the injuries on SK63 are proposed. The majority of incisions (81%, 21/26) were consistent with a sword, featuring an elliptical shape, breakage, shards and cracking, as well as a glancing aspect. About 11% (3/26) of the lesions showed unilateral flaking and feathering, and a perpendicular aspect that is seen in various blade injuries. Further, 8% (2/26) of the injuries were indicative of a lesion caused by a knife, such as the cuts at the 6th and 7th left ribs (12, 15). All lesions on bones other than the long bones diaphyses could not be associated with the weapon types offered by Lewis (2008). Despite this, research by Giuffra et al. (2015) suggests that the most common weapons in early medieval Italy were swords and axes. Some injuries on SK63 are consistent with those left by long bladed weapons, i.e., swords. The trauma afflicted to the thorax of SK63, which was more indicative of stabbing rather than slashing, would correspond with research by Prieto (2007), who found a positive association between SFT to the thorax and short tools, i.e., knives. Considering the grave goods recovered from Säben-Sabiona, the implements found could be used in close combat, such as multiple knives (8.5–20 cm), a *scramasax* (36.3 cm) and a *spatha* (89 cm) (Bierbrauer and Nothdurfter, 2015). These were typical Early Medieval Period weapons associated with Germanic cultures, e.g., Bavarians and Lombards (Bierbrauer and Nothdurfter, 2015; Kustatscher and Romeo, 2010; Rigoni and Bruttomesso, 2011). All weaponry recovered from this area are consistent with the trauma patterns of SK63. However, in order to make a positive match between the weapons and the lesions, further research is required.

5. Conclusion

The systematic analysis of multiple lesions on a young adult male found in the cemetery of Säben- Sabiona (Italy) enabled a detailed investigation on Early Medieval Period interpersonal violence in the Italian Alps. Trauma analyses showed that bladed weapons, probably sword- and knife- type instruments were used. The overall trauma pattern was suggestive of injuries inflicted during interpersonal violence rather than large scale conflict.

Future studies will consist of a detailed scientific examination of other human skeletal remains displaying traumatic lesions from the Early Medieval Period cemetery of Säben-Sabiona, along with radiocarbon dating, stable isotope and ancient DNA analyses, 3D imaging, and reconstructions of the bone injuries. All this information will provide a unique opportunity to develop a more comprehensive picture of violent encounters in the Italian Alps.

Acknowledgements

The study was achieved with the permission of Catrin Marzoli, 13.2 Amt für Bodendenkmäler, Autonomous Province of Bozen, Italy. Special thanks are due to Robert Mann, who was supportive and has given much advice in the trauma analysis. Further, the authors would like to thank Kathrin Renner of the Institute for Earth Observation, Eurac Research and Valentina Fameli for the figures Fig. 1 and Fig. 3, as well as Benno Baumgarten from the South Tyrol Museum of Natural History in Bozen for the permission to utilise the electronic microscope and Marco Samadelli of the Institute for Mummy Studies, Eurac Research for editing the pictures.

References

Acsádi, G.Y., Nemeskéri, J., 1970. History of Human Life Span and Mortality. Akademiai Kiado, Budapest.
Afshar, Z., Roberts, C., Millard, A., 2018. Interpersonal violence among the Chalcolithic and Bronze Ages inhabitants living on the Central Plateau of Iran: A voice from Tepe Hissar. Anthropol. Anz. 75, 49–66. https://doi.org/10.1127/anthranz/2018/0723.
AlQahtani, S.J., Hector, M.P., Liversidge, H.M., 2010. Brief communication: The London atlas of human tooth development and eruption. Am. J. Phys. Anthropol. 142, 481–490. https://doi.org/10.1002/ajpa.21258.
Appleby, J., Rutty, G.N., Hainsworth, S.V., Woosnam-Savage, R.C., Morgan, B., Brough, A., Earp, R.W., Robinson, C., King, T.E., Morris, M., Buckley, R., 2015. Perimortem trauma in King Richard III: A skeletal analysis. Lancet. https://doi.org/10.1016/S0140-6736(14)60804-7.
Bennike, P., Otto, T., Thrane, H., Vandkilde, H., 2006. Rebellion, combat and massacre: a medieval mass grave at Sandbjerg near Naestved in Denmark. Warfare and Society. Archaeological and Social Anthropological Perspectives. Aarhus Universitetsforlag,

Aarhus, pp. 305–318.
Bierbrauer, V., Nothdurfter, H., 2015. Säben I- Die Ausgrabungen im Spätantik-Frühmittelalterlichen Bischofssitz Sabiona-Säben in Südtirol I. Verlag C.H. Beck München, München.
Binder, M., Quade, L., 2018. Death on a Napoleonic battlefield – Peri-mortem trauma in soldiers from the Battle of Aspern 1809. Int. J. Paleopathol. 22, 66–77. https://doi.org/10.1016/j.ijpp.2018.05.007.
Black, S., Rutty, G., Hainsworth, S., Thomson, G., 2017. Criminal Dismemberment Forensic and Investigative Analysis. CRC Press, Boca Raton.
Bohnert, M., Hüttemann, H., Schmidt, U., 2006. Homicide by sharp force. In: Tsokos, M. (Ed.), Forensic Pathology Reviews. Humana Press Inc, Totowa.
Boucherie, A., Jørkov, S., M.L, Smith, M, 2017. Wounded to the bone: digital microscopic analysis of traumas in a medieval mass grave assemblage (Sandbjerget, Denmark, AD 1300–1350). Int. J. Paleopathol. 19, 66–79. https://doi.org/10.1016/j.ijpp.2017.10.005.
Buckberry, J.L., Chamberlain, A.T., 2002. Age estimation from the auricular surface of the ilium: a revised method. Am. J. Phys. Anthropol. 119, 231–239. https://doi.org/10.1002/ajpa.10130.
Byers, S.N., 2017. Introduction to Forensic Anthropology, 5th editio. Routledge, Boston.
Caffell, A., Holst, M., 2012. Osteological Analysis 3 and 6 Driffield Terrace York North Yorkshire. York. .
Constantinescu, M., Gavrilă, E., Greer, S., Soficaru, A., Ungureanu, D., 2017. Fighting to the Death: Weapon Injuries in a Mass Grave (16th–17th Century) from Bucharest, Romania. Int. J. Osteoarchaeol. 27, 106–118. https://doi.org/10.1002/oa.2450.
Croft, A.M., Ferllini, R., 2007. Macroscopic characteristics of screwdriver trauma. J. Forensic Sci. 52, 1243–1251. https://doi.org/10.1111/j.1556-4029.2007.00552.x.
DiMaio, V.J., DiMaio, D., 2001. Forensic Pathology, 2nd ed. CRC Press, New York.
Dye, D.H., 2016. Ancient Mississippian Trophy-Taking. Oxford University Presshttps://doi.org/10.1093/oxfordhb/9780199935420.013.30.
Elema, A., 2012. Trial by Battle in France and England. University of Toronto.
Facchini, F., Rastelli, E., Belcastro, M.G., 2008. *Peri mortem* cranial injuries from a medieval grave in Saint Peter's Cathedral, Bologna, Italy. Int. J. Osteoarchaeol. 18, 421–430. https://doi.org/10.1002/oa.949.
Ferembach, D., Schwidetzky, I., Stloukal, M., 1979. Empfehlungen für die Alters- und Geschlechtsdiagnose am Skelett. Homo 30, 1–32.
Fiorato, V., Boylston, A., Knüsel, C., 2007. Blood Red Roses the Archaeology of a Mass Grave From the Battle of Towton AD 1461, 2nd ed. Oxbow Books, Oxford.
Forsom, E., Thorup, Warner, Boel, L., Jaque, B., Mollerup, L., 2017. The death of a medieval Danish warrior. A case of bone trauma interpretation. Scand. J. Forensic Sci. Nord. rettsmedisin 23, 1–8. https://doi.org/10.1515/sifs-2017-0001.
Gassmann, J., 2018. Combat Training for Horse and Rider in the Early Middle Ages. Acta Period. Duellatorum 6, 63–98. https://doi.org/10.2478/apd-2018-0003.
Geber, J., 2015. Comparative Study of Perimortem Weapon Trauma in Two Early Medieval Skeletal Populations (AD 400-1200) from Ireland. Int. J. Osteoarchaeol. 25, 253–264. https://doi.org/10.1002/oa.2281.
Gerhards, G., 2007. Traumatic lesions in human osteological remains from the Daugava area (7th to 17th centuries AD). Archaeol. Balt. 8, 360–367.
Giuffra, V., Pejrani Baricco, L., Subbrizio, M., Fornaciari, G., 2015. Weapon-related Cranial Lesions from Medieval and Renaissance Turin, Italy. Int. J. Osteoarchaeol. 25, 690–700. https://doi.org/10.1002/oa.2334.
Holst, M.K., Heinemeier, J., Hertz, E., Jensen, P., Løvschal, M., Mollerup, L., Odgaard, B.V., Olsen, J., Søe, N.E., Kristiansen, S.M., 2018. Direct evidence of a large Northern European Roman period martial event and postbattle corpse manipulation. Proc. Natl. Acad. Sci. 115, 5920–5925. https://doi.org/10.1073/pnas.1721372115.
Ingelmark, B.E., 1939. The skeletons. In: Thordeman, B. (Ed.), Armour from the Battle of Wisby 1361. Kungliga Vitterhets historie och anikvitets akademien, Stockholm, pp. 149–209.
Jurmain, R., 1999. Stories from the Skeleton: Behavioural Reconstruction in Human Osteology. Gordon and Breach, Amsterdam.
Karlsson, T., 1998. Sharp force homicides in the Stockholm area, 1983-2992. Forensic Sci. Int. 94, 129–139.
Katz, D., Suchey, J.M., 1986. Age determination of the male Os pubis. Am. J. Phys. Anthropol. 69, 427–435. https://doi.org/10.1002/ajpa.1330690402.
Kimmerle, E.H., Baraybar, J.P., 2008. Skeletal Trauma Identification of Injuries Resulting From Human Rights Abuse and Armed Conflict. CRC Press, New York.
Kjellström, A., 2005. A sixteenth-century warrior grave from Uppsala, Sweden: the battle of good Friday. Int. J. Osteoarchaeol. 15, 23–50. https://doi.org/10.1002/oa.746.
Knüsel, C.J., Smith, M.J., 2014. The Routledge Handbook of the Bioarchaeology of Human Conflict. Routledge Taylor & Francis Group, London.
Kustatscher, E., Romeo, C., 2010. Passaggi E Prospettive, Lineamenti Di Storia Locale (L´area Tirolese Della Preistoria Al Tardo Medioevo), 1st ed. Athesia, Bozen.
Lewis, J.E., 2008. Identifying sword marks on bone: criteria for distinguishing between cut marks made by different classes of bladed weapons. J. Archaeol. Sci. 35, 2001–2008. https://doi.org/10.1016/j.jas.2008.01.016.
Mahoney, P.F., Ryan, J., Brooks, A.J., Schwab, C.W., 2005. Ballistic Trauma- a Practical Guide, 2nd editio. Springer, Leonard Cheshire.
Meindl, R.S., Lovejoy, C.O., 1985. Ectocranial suture closure: a revised method for the determination of skeletal age at death based on the lateral-anterior sutures. Am. J. Phys. Anthropol. 68, 57–66. https://doi.org/10.1002/ajpa.1330680106.
Meyer, C., Wirth, K., Alt, K.W., 2014. Gold, Gewalt und Gebrechen. Die Beziehung zwischen sozialem Status und traumatischen Skelettbefund im frühen Mittelalter am Beispiel des Hermsheimer Bösfelds, Mannheim-Seckenheim, in: Gewalt und Gesellschaft. Dimensionen Der Gewalt in Ur- Und Frügeschichtlicher Zeit. Bonn.
Murail, P., Bruzek, J., Houët, F., Cunha, E., 2005. DSP: A tool for probabilistic sex diagnosis using worldwide variability in hip-bone measurements. Bull. Mémoires la Société d'Anthropologie Paris 17, 167–176.
Myszka, A., Piontek, J., Milosz, E., 2012. Traumatic injuries in the late medieval and early modern population from Lekno. Poland. Interdiscip. Archaeol. Nat. Sci. Archaeol. 3, 237–243.
Nicklisch, N., Ramsthaler, F., Meller, H., Friedrich, S., Alt, K.W., 2017. The face of war: Trauma analysis of a mass grave from the Battle of Lützen (1632). PLoS One 12, 1–30. https://doi.org/10.1371/journal.pone.0178252.
Nikolic, S., Zivkovic, V., 2015. Multiple sharp force injuries to the head - the crime of passion. Srp. Arh. Celok. Lek. 143, 494–499. https://doi.org/10.2298/SARH1508494N.
Novak, A.S., 2007. Battle-related trauma. In: Fiorato, V., Boylston, A., Knüsel, C. (Eds.), Blood Red Roses. Oxbow Books, Oxford.
Novak, M., Šlaus, M., 2010. Bone traumas in late antique populations from Croatia. Coll. Antropol. 34, 1239–1248.
O´Callaghan, P.T., Jones, M.D., James, D.S., Leadbeatter, S., Holt, C.A., Nokes, L.D., 1999. Dynamics of stab wounds: force required for penetration of various cadaveric human tissues. Forensic Sci. Int. 104, 173–174.
Ormstad, K., Karlsson, T., Enkler, L., Law, B., Rajs, J., 1986. Patterns in sharp force fatalities- a comprehensive forensic medical study. J. Forensic Sci. 31, 529–542.
Ortner, D., 2003. Identification of pathological conditions in human skeletal remains. Identification of Pathological Conditions in Human Skeletal Remains, 2nd ed. Academic Press, New York.
Pal Singh, V., Sharma, B.R., Harish, D., Vij, K., 2004. A Critical Analysis of Stab Wound on the Chest a Case Report. J. Indian Acad. Forensic Med. 26, 77–79.
Prieto, J.L., 2007. Stab wounds: the contribution of forensic anthropology- a case study. In: Brickley, M., Ferllini, R. (Eds.), Forensic Anthropology: Case Studies in Europe. Charles C. Thomas Publisher, Springfield.
Quade, L., Binder, M., 2018. Life on a Napoleonic battlefield: A bioarchaeological analysis of soldiers from the Battle of Aspern, Austria. Int. J. Paleopathol. 22, 23–38. https://doi.org/10.1016/j.ijpp.2018.03.006.
Renhart, S., 1991. Anthropologie: den Menschen von St. Prokulus auf der Spur. In: Nothdurfter, H. (Ed.), Sonderaustellung in Schloß Tirol-St. Prokulus in Naturns-Ergrabene Geschichte von den Menschen des Frühmittelalters und der Pestzeit. Südtiroler Landesmuseum für Archäologie, Schloß Tirol, pp. 153–190.
Rigoni, M., Bruttomesso, A., 2011. Materiali Di Etá Longobarda Nel Museo "G. Zannato " Di Montecchio Maggiore. All`insegna del Giglio, S. Lorenzo.
Robb, J., Elster, E.S., Isetti, E., Knüsel, C.J., Tafuri, M.A., Antonella, T., 2015. Cleaning the dead: Neolithic ritual processing of human bone at Scaloria Cave, Italy. Antiquity 89, 39–54.
Roberts, C., Manchester, K., 2010. The Archaeology of Disease, 3rd ed. The History Press, Stroud.
Rouge-Maillart, C., Vielle, B., Jousset, N., Chappard, D., Telmon, N., Cunha, E., 2009. Development of a method to estimate skeletal age at deat in adults using the acetabulum and the auricular surface on a Portuguese population. Forensic Sci. Int. 188, 91–95. https://doi.org/10.1016/j.forsciint.2009.03.019.
Rubini, M., Zaio, P., 2011. Warriors from the East. Skeletal evidence of warfare from a Lombard-Avar cemetery in Central Italy (Campochiaro, Molise, 6th-8th Century AD). J. Archaeol. Sci. https://doi.org/10.1016/j.jas.2011.02.020.
Sauer, N.J., 1998. The timing of injuries and manner of death: distinguishing among antemortem, perimortem and postmortem trauma. In: Reich, K. (Ed.), Forensic Osteology: Advances in the Identification of Human Remains. Charles C Thomas, Springfield, pp. 321–332.
Schaefer, M., Black, S., Scheuer, L., 2009. Juvenile Osteology: A Laboratory and Field Manual. Academic Press- Elsevier, London.
Schmidt, U., Pollak, S., 2006. Sharp force injuries in clinical forensic medicine—Findings in victims and perpetrators. Forensic Sci. Int. 159, 113–118. https://doi.org/10.1016/j.forsciint.2005.07.003.
Shoemaker, R.B., 2002. The taming of the duel: masculinity, honour and ritual violence in London, 1660-1800. Hist. J. 45, 525–545. https://doi.org/10.1017/S0018246X02002534.
Skinner, P., 2015. Visible prowess?:Reading men´s head and face wounds in early medieval Europe to 1000CE. In: Tracy, L., DeVries, K. (Eds.), Wounds and Wound Repair in Medieval Culture. Brill, Leiden.
Šlaus, M., Novak, M., 2006. An analysis of traumas in medieval samples from Kliskovac and Crkvari. Pril. Instituta za Arheol. u Zagreb. 23, 213–228.
Šlaus, M., Novak, M., Bedic, Z., Strinovic, D., 2012. Bone Fractures as Indicators of Intentional Violence in the Eastern Adriatic From the Antique to the Late Medieval Period (2nd-16th century AD). Am. J. Phys. Anthropol. 149, 26–38.
Šlaus, M., Novak, M., Vyroubal, V., Bedic, Z., 2010. The harsh life of the 15th century Croatia-Ottoman Empire Military Border: Analyzing and Identifying the Reasons for the Massacre in Cepin. Am. J. Phys. Anthropol. 141, 358–372.
Smith, M., 2017. Mortal Wounds- the Human Skeleton As Evidence for Conflict in the Past. Pen & Sword Military, Barnsley.
Vazzana, A., Scalise, L.M., Traversari, M., Figus, C., Apicella, S.A., Buti, L., Oxilia, G., Sorrentino, R., Pellegrini, S., Matteucci, C., Calcagnile, L., Savigni, R., Feeney, R.N.M., Gruppioni, G., Benazzi, S., 2018. A multianalytic investigation of weapon-related injuries in a Late Antiquity necropolis, Mutina, Italy. J. Archaeol. Sci. Reports 17, 550–559. https://doi.org/10.1016/j.jasrep.2017.12.009.
Waldron, T., 2009. Paleopathology. Cambridge University Press, Cambridge.
Wallduck, R., Bello, S.M., 2016. Cutting decaying bodies: micro-morphometric analysis of cut-marks on Mesolithic-Neolithic human remains from Lepenski Vir and Vlasac. Serbia. J. Archaeol. Sci. Reports 10, 703–714. https://doi.org/10.1016/j.jasrep.2016.06.036.

Article III

Archaeological and Anthropological Sciences (2020) 12:82
https://doi.org/10.1007/s12520-019-00982-6

ORIGINAL PAPER

Early medieval Italian Alps: reconstructing diet and mobility in the valleys

Alice Paladin[1,2] · Negahnaz Moghaddam[3,4] · Agnieszka Elzbieta Stawinoga[5] · Inga Siebke[3] · Valentina Depellegrin[6] · Umberto Tecchiati[7] · Sandra Lösch[3] · Albert Zink[1]

Received: 21 August 2018 / Accepted: 29 October 2019

Abstract

In Early Middle Ages (sixth–eleventh centuries AD), South Tyrol (Italian Alps) played a key role for geographical and military reasons. Historical sources document that allochthonous groups (*germani*) entered the territory, and the material culture shows mutual cultural exchanges between autochthonous and *germani*. Besides the nature of the migration, the demographic and socio-cultural impacts on the local population are still unknown. Stable isotope analyses were performed to provide insights into dietary patterns, subsistence strategies, changes in socio-economic structures, and mobility, according to spatial (e.g. valleys, altitudes) and chronological (centuries) parameters. Bone collagen of 32 faunal and 91 human bone samples from nine sites, located at different altitudes, was extracted for stable carbon, nitrogen, and sulphur isotope analyses. In total, 94% (30/32) of the faunal remains were of good quality, while the humans displayed 93% (85/91) of good quality samples for $\delta^{13}C$ and $\delta^{15}N$ and 44% (40/91) for $\delta^{34}S$ stable isotopes. The isotopic results of the animals reflected a terrestrial-based diet. Statistical differences were observed within and among the humans of the different valleys. The $\delta^{13}C$ values of individuals sampled from higher altitudes indicated a mainly C_3 plant-based diet compared to areas at lower altitudes, where more positive $\delta^{13}C$ values showed an intake of C_4 plants. The $\delta^{15}N$ values suggested a terrestrial-based diet with a greater consumption of animal proteins at higher altitudes. The data revealed higher variability in $\delta^{34}S$ values in the Adige valley, with individuals probably migrating and/or changing dietary habits.

Keywords Stable isotopes · Migration · Diet · Early middle ages · Italian Alps

Sandra Lösch and Albert Zink should be considered as joint senior authors.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12520-019-00982-6) contains supplementary material, which is available to authorized users.

✉ Alice Paladin
alice.paladin@eurac.edu

1 Institute for Mummy Studies, Eurac Research, Viale Druso 1, 39100 Bolzano, Italy

2 Institute for Archaeological Sciences, WG: Paleoanthropology, University of Tübingen, 72070 Tubingen, Germany

3 Department of Physical Anthropology, Institute of Forensic Medicine, University of Bern, Sulgenauweg 40, 3007 Bern, Switzerland

4 Unit of Forensic Imaging and Anthropology, University Center of Legal Medicine Lausanne-Geneva, Chemin de la Vulliette 4, CH-1000, 25 Lausanne, Switzerland

5 Management and Committees, Eurac Research, Viale Druso 1, 39100 Bolzano, Italy

6 Institut für Vor-und Frühgeschichtliche Archäologie & ArchaeoBioCenter, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 Munich, Germany

7 Dipartimento di Beni Culturali e Ambientali, PrEcLab – Laboratorio di Preistoria, Protostoria ed Ecologia Preistorica, Università degli studi di Milano, Via Festa del Perdono 7, 20122 Milan, Italy

Published online: 04 March 2020

Introduction

Early medieval South Tyrol: historical and archaeological context

South Tyrol (Trentino-Alto Adige) is an Alpine region in northern Italy. After the fall of the Western Roman Empire, South Tyrol was the scene of power struggles and dynastic disputes due to the change of military forces, such as the Byzantines (Eastern Roman Empire) and the *germani* or *barbari* (e.g. Goths, Franks, Bavarians, Langobards). The written records of such events are limited and mainly derive from the account of Paul the Deacon, *Historia Langobardorum* (eighth century AD) and a few other historical documents (Cavada 2004). The archaeological findings document a prolonged usage of the Roman defensive constructions, at least until the late fifth century AD (Heitmeier 2005; Marzoli et al. 2009). Starting from the sixth century AD, the Alemannic and Frank military elites entered the region from the northwest (Venosta valley). The Langobards first crossed *Noricum* from the east and then into the territory of Bolzano in 568 AD (Kustatscher and Romeo 2010). Moreover, Bavarians came from the northeast (Inntal and Alta Isarco valley), whereas the Slavic groups entered South Tyrol from the eastern Pusteria valley (Giostra and Lusuardi Siena 2004; Haas-Gebhard 2004). In this scenario, alliances for the domain of the territory between high status families subjected the valleys to continuously changing borders and presumably led to the migration of people. Toponymy and archaeological discoveries do not allow for any conclusions to be drawn regarding the possible settlement of the *germani* groups (Bierbrauer 1991; Marzoli et al. 2009). Additionally, the Early medieval burial sites in South Tyrol have been only partially investigated (Albertoni 2005) and, until recently, a limited number of individuals have been studied anthropologically. This leads to gaps in our knowledge about the past populations in this territory. The material culture from the funerary contexts exemplifies a mutual mixing of cultural habits due to a slow but broad hybridity between autochthonous and allochthonous practices (Albertoni 2005; Gasparri and La Rocca 2013). However, it remains unclear whether these changes were limited to the introduction of foreign cultural goods or accompanied by an admixture of newly arrived groups with the local population (Dal Ri and Rizzi 1995).

For the Middle Ages, the paleoclimatic data document a climatic *pessimum* during the sixth–eighth centuries AD, which was marked by cold, humid weather with increased precipitation and lower temperatures (Ortolani and Pagliuca 2007). Some warmer periods are supported by pollen analyses from the Swiss Alps during the fourth–fifth century AD and the eighth–eleventh century AD (Tinner et al. 2003). The later medieval Warm Period corresponded to the prolonged climatic *optimum* phase (approx. 950–1250 AD), which was characterised by warm hemispheric conditions (Hughes and Diaz 1994; Mann et al. 2009), that could have intensified the cultivation of C_4 plant, such as different millet species, which fix carbon more efficiently at higher temperature (Ehleringer et al. 1991, 2002). Isotopic studies regarding northern Italy Bronze Age bones showed that C_4 plants, such as broomcorn millet (*Panicum miliaceum*) and/or foxtail millet (*Setaria italica*) already provided an important dietary contribution for both humans and animals (Tafuri et al. 2009, 2018; Varalli et al. 2016). Additionally, a paleodietary study on Celtic population (approx. 2100 years BP) from northeast Italy documented a predominant consumption of cultivated C_4 plants (Laffranchi et al. 2016).

In the present study, isotopic analyses were conducted to gain information on dietary and mobility patterns of Early medieval populations in the Italian Alps for the first time. Carbon ($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$), and sulphur ($^{34}S/^{32}S$) isotope ratios of human and animal bone collagen were analysed from skeletal remains found at nine archaeological sites located in the alpine areas. Considering the significant distance of the studied territory from the coastal zones, the sea spray effect is not supposed to influence the data. The objectives of this project are to (i) gain insight into the inter- and intra-isotopic variability throughout both areas (sites, valleys, altitudes) and time to understand the human subsistence strategies, changes in socio-economic structures and possible adaptation to the environment and (ii) provide information about mobility, according to spatial (valleys) and chronological (centuries) parameters.

Stable isotope measurements: reconstructing diet and mobility

Stable isotope analysis is an established scientific method in bioarchaeology for the evaluation of dietary and migration patterns of past populations (e.g. Ambrose 1993; Fuller et al. 2012; Lösch et al. 2006, 2014). Today, isotopic studies on Early medieval skeletal remains are of growing interest (e.g. Hakenbeck et al. 2010, 2017; Hemer et al. 2013; Knipper et al. 2012; Lösch 2009; McGlynn 2007; Iacumin et al. 2014; Reitsema and Vercellotti 2012). With the Copper Age Iceman being an exception (Hoogewerff and Papesch 2001; Macko et al. 1999), in South Tyrol, there is a lack of comparative framework, and almost no isotope analyses on human bones have been performed.

Stable carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) isotope ratios are usually examined to study the diet of past humans and/or animals (e.g. Craig et al. 2009; Halffman and Velemínský 2015). In particular, the analysis of $\delta^{13}C$ values is necessary for the distinction between C_3 or C_4 plant sources, as C_3 plants (e.g. wheat and barley) provide more negative $\delta^{13}C$ values (approx. − 35 to − 19‰) than C_4 plants (approx. − 15 to − 9‰) (Lee-Thorp 2008; Meier-Augenstein 2010). The analysis of $\delta^{15}N$ values refers to animal protein consumption, both marine and/or terrestrial sources (Richards et al. 1998). An increase of $\delta^{15}N$ values provides information on the trophic level, as prey-predator collagen enrichment accounts for $\delta^{15}N$ values of + 3 to + 5‰ (Ambrose 1993; Hedges and Reynard 2007; Lee-Thorp et al. 1989). The trophic level enrichment for $\delta^{13}C$ is less increased with approximately + 1‰ (DeNiro and Epstein 1978; Minagawa and Wada 1984). Analyses from faunal bones are fundamental to reconstruct the faunal–human trophic relationship (Van Klinken et al. 2000). This serves as a reference for the general status of a population and for the reconstruction of the dietary sources in an archaeological context. Furthermore, this study presents sulphur ($\delta^{34}S$) isotope data for the reconstruction of the human diet (e.g. freshwater sources), and particularly for its application on mobility. The values of $\delta^{34}S$ are of growing interest in numerous archaeological studies (e.g. Bollongino et al. 2013; Craig et al. 2006; Lösch et al. 2014; Moghaddam et al. 2016, 2018; Nehlich et al. 2011, 2012, 2014; Oelze et al. 2012; Privat et al. 2007; Richards et al. 2001, 2003; Tafuri et al. 2018; Varalli et al. 2016; Vika 2009). Regarding the oceanic effects, the local geological context and the atmospheric precipitations are mainly influencing the $\delta^{34}S$ values. Hence, the isotopic signature in human and animal bones reflects the diet as well as the habitat (Nehlich et al. 2011; Vika 2009). Little is known about the $\delta^{34}S$ trophic level shift; however, studies showed that a slight increase of + 0.5‰ ± 2.4‰ is observed between consumers and their diet (Nehlich 2015). In terrestrial environments, rivers generally exhibit $\delta^{34}S$ values between − 5 and + 15‰; however, they are dependent on the local geology. Therefore, the values can vary greatly (Nehlich 2015). Thus, individuals living in terrestrial riverine landscapes would be expected to show $\delta^{34}S$ values within the stated range, or slightly above, due to a trophic shift in general.

Materials and methods

The study was performed on human and faunal skeletal remains from nine archaeological sites (Fig. 1a), located in three valleys and one basin in South Tyrol (Italy), which are crossed by two main rivers, the Adige in the west, and the Isarco in the northeast. The sites have been excavated over the last 30 years and are located in various ecological environments of those valleys (e.g. valley floor, hill and mountain) (Table S1). All sites are from a small territory with different levels of precipitations and temperatures (Winckler 2012), especially with regard to the altitude differences (Fig. 1b). In the Adige valley, sites are located at the lowest altitudes (mean 348 m a.s.l.), while the highest are in the Venosta valley (mean 1279 m a.s.l.). The site in Merano basin is at 641 m a.s.l. and the Isarco valley site is at 817 m a.s.l. (Fig. 1b).

About 121 Early medieval tombs (Adige valley: 21 tombs; Merano basin: 31; Isarco valley: 49 and Venosta valley: 20) were recovered. Nevertheless, some of the human remains came from archaeological stratigraphic units without a clear tomb structure. At the burial sites of Castel Tirolo (Merano basin) and Malles Burgusio St. Stefano (Verosta valley), the tombs were found inside and/or around a church or, as in Terlano, surrounding a Paleochristian baptistery. The latter site was located next to areas of worships, maybe due to the presence of sulphurous water springs (Lunz 1974; Tecchiati and Zanforlin 2010). When available, the archaeological data on grave goods were obtained from the original archaeological survey documentation (unpublished data) or from published sources (e.g. Marzoli et al. 2009; Marzoli 2002; Reuß 2016) (Table S1). The greatest quantity of grave goods was found in Bressanone Elvas: knives, scramasax (weapon), parts of belts, necklaces with amber and/or glass beads, earrings and bracelets dating (relative dating) approximately to the seventh century AD (Kaufmann and Demetz 2004: 76).

In this study, 91 human (Table S1) and 32 faunal remains (Table S2) were obtained for the isotopic analyses. The faunal bone samples, 11 (34%) from Adige, 7 (22%) from Merano basin, 3 (9%) from Isarco and 11 (34%) from Venosta, were contemporary to the human samples. Out of the 91 humans, 23 (25%) samples were selected from skeletons found in Adige valley, 24 (26%) from Merano basin, 21 (23%) from Isarco valley and 23 (25%) from Venosta valley.

Osteological analyses

Age at death and sex were estimated using established anthropological methods. For the age at death of adults, the pubic symphysis, the epiphyseal-diaphyseal fusions and the ectocranial suture closures were evaluated (Acsádi and Nemeskéri 1970; Meindl and Lovejoy 1985; Schaefer et al 2009; Brooks and Suchey 1990). The age at death for subadults was based on the eruption of the deciduous and permanent dentition (AlQathani et al. 2010; Ubelaker 1978), the measure of diaphyseal lengths, and the assessment of the epiphyseal-diaphyseal fusions (Fazekas and Kósa 1978; Maresh 1970; Schaefer et al 2009). Individuals were attributed to the following age groups: perinatal (38–40 weeks); newborn (0–2 months); infant 1st (3 months-6 years); infant 2nd (7–12 years); juvenile (13–19 years); adult (20–40 years); adult not determinable (n.d.; > 20 years); mature (40–59 years); and senile (> 60 years). The sex of adult individuals (> 20 years) was estimated based on sexual dimorphism of various skeletal elements as described by Buikstra and Ubelaker (1994); Ferembach et al. (1979) and Murail et al. (2005). In subadults (< 20 years), the sex was not determined due to the ambiguity of specific sexual traits (Baker et al. 2005).

Archaeozoological analyses

In South Tyrol, a limited number of archaeozoological studies on Early medieval faunal remains have been conducted (e.g.

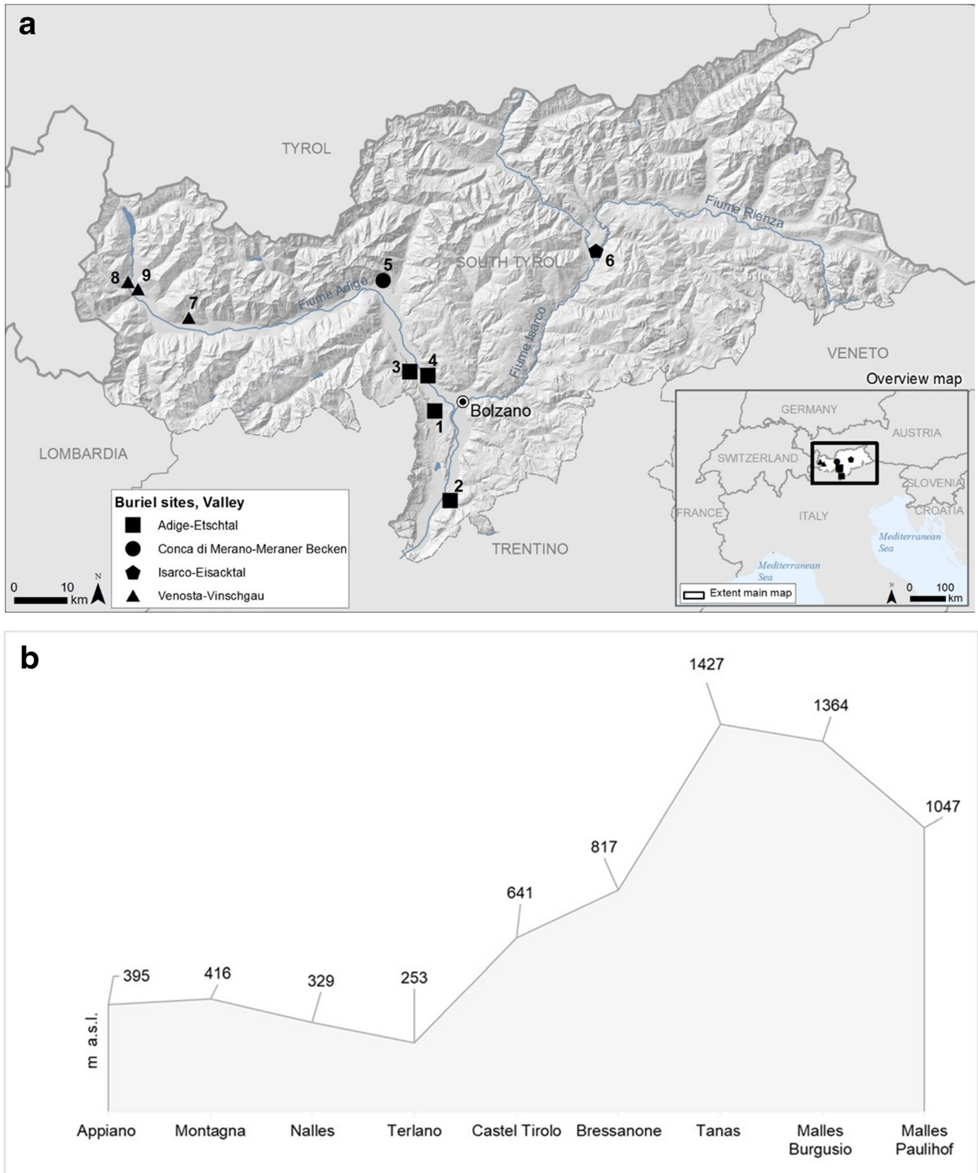


Fig. 1 **a** Map of South Tyrol, Italy, displaying the locations of the archaeological sites and valleys. Adige valley (Etschtal): (1) Appiano, S. Paolo Castelvecchio (Eppan, St. Paul Altenburg), (2) Montagna, Pinzano (Montan, Pinzon), (3) Nalles (Nals), (4) Terlano (Terlan); Merano basin (Meraner Becken): (5) Castel Tirolo (Schloss Tirol); Isarco valley (Eisacktal): (6) Bressanone Elvas necropoli 17 (Brixen, Elvas); Venosta valley (Vinschgau): (7) Tanas (St. Peter's path), (8) Malles, Burgusio S. Stefano (Mals, Burgeis St. Stephan), (9) Malles, Maso Pauli (Mals, Paulihof). **b** The altitudes of the nine sites are indicated in meters above sea level (m a.s.l.)

Riedel 1979; Dallago 2016; Sardagna and Tecchiati 2010). Faunal bone materials ($n = 32$), from the same sites and possibly from the same stratigraphic units as the human remains, were sampled. The determination of the taxonomy and the anatomical identification of the faunal remains were undertaken, referring to Schmid (1972) and Barone (1980), as well as to the osteological collection of the laboratory for Archaeozoology of the Archaeological Heritages Office of the Autonomous Province of Bolzano-Bozen.

Stable isotope analyses: analytical method and quality criteria

For $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ analyses, human bone samples were collected from cranial bones; if these were unavailable, the diaphysis of long bones were used (Table S1). The extraction of bone collagen was performed following an acid–base extraction modified after Longin (1971) and Ambrose (1990). After cleaning with distilled water, all samples were pulverized. Then, 500 mg of bone powder was demineralized with 10 ml of 1 M hydrochloric acid (HCl) for 20 min. The solution was then neutralized (pH ~ 6–7) and treated with 10 ml of 0.125 M of sodium hydroxide (NaOH) for 20 h to remove humic acids. After a neutralization phase, 10 ml of 0.001 M HCl (ideally pH 3) was added and placed in a water bath for incubation at 90 °C (10–17 h). The solubilized collagen was filtered (VitraPOR filter-funnel, porosity 16–40 µm) and lyophilized (0.42 mbar) for a minimum of 48 h. From each sample, 3.0 mg ± 0.3 mg collagen was weighted into tin capsules three times per specimen. The measurements of carbon

($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$) and sulphur ($^{34}S/^{32}S$) were performed by isotope ratio mass spectrometry (IRMS) at the Isolab GmbH of Schweitenkirchen, Germany. The average of the three measurements was calculated and used for the subsequent analyses. Results were reported in δ-notation in units of *per mil* (‰), according to the international standards: Vienna Pee Dee Belemnite (VPDB) for carbon, Ambient Inhalable Reservoir (AIR) for nitrogen and Vienna Canyon Diablo Troilite (V-CDT) for sulphur (Fry 2006; Hoefs 2009; Schoeniger and DeNiro 1984) and a laboratory internal collagen standard STD R (collagen from cowhide) from the EU project TRACE, such as $\delta^{13}C$ vs V-PDB [‰] = − 18.00 ± 0.12; $\delta^{15}N$ vs. AIR [‰] = + 5.97 ± 0.09; $\delta^{34}S$ vs. V-CDT [‰] = + 5.45 ± 0.37 (N = 46; one value consists of 3 to 4 averaged measurements). The analytical errors were recorded as less than ± 0.1‰ for $\delta^{13}C$, ± 0.2‰ for $\delta^{15}N$ and ± 0.3‰ for $\delta^{34}S$. Samples with a value of > 1% collagen portion of dry bone were selected. In addition, samples were selected for statistical evaluation when the C:N ([%C/%N] × [14.007/12.011]) ratio were between 2.9–3.6 (DeNiro 1985), the C:S ([%C/%S] × [32.064/12.011]) ratio between 300 and 900, and the N:S ([%N/%S] × [32.064/14.007]) ratio between 100 and 300 (Nehlich and Richards 2009).

Good quality was also considered, when %C was in the range of 30 to 47% and %N in the range of 11 to 17.3% (Ambrose 1990, 1993; Van Klinken 1999). When one specimen was slightly out of the range, but wt% collagen, the C:N range, and either %C or %N was within the stated criteria, the sample was still considered for statistical analyses. For sulphur, the %S values were taken when within the range of 0.15 to 0.35% (Nehlich and Richards 2009). Additionally, sulphur values were considered when the quality criteria for $\delta^{13}C$ and $\delta^{15}N$ values were acceptable and %S values of all samples followed a similar trend. The outliers were discharged due to the limited sources of verified sulphur values.

Statistical tests

The faunal data was grouped depending on valleys and sites, on species, and on dietary habits (Table 1). The human data was organized according to the geographical locations (sites and valleys), sex and age at death and to the presence or absence of grave goods in the graves (Tables 1 and 2). Since most of the grave goods were recovered in the Isarco valley at Bressanone Elvas, statistical analyses were additionally conducted on this site. Moreover, the individuals were grouped in the following chronological intervals: phase 1: fifth-seventh centuries AD, phase 2: seventh–eighth centuries AD, phase 3: eighth–tenth centuries AD, phase 4: ninth–twelfth centuries AD and the individuals not ascribable to a specific phase were clustered into "Early Middle Ages" (sixth–eleventh centuries AD) group (Tables 1 and 2).

The data was recorded in an Excel spreadsheet (Microsoft, Redmond, WA), and statistical analysis was performed using IBM® SPSS® Statistics 23 for Windows. After the analysis of distributions, the outliers in every valley (Tables S1 and S2) were excluded. Given the normality of the distributions (Shapiro-Wilk test), in order to compare the means of different groups, parametric statistical tests were applied. In the case of two groups, an independent-samples t test was performed; otherwise, for more than two groups, the one-way ANOVA with post-hoc tests were applied.

For all tests, the significance level was set at 0.05, and a p value below 0.05 was considered significant.

Results

Archaeozoological and osteological analyses

The archaeozoological investigation resulted in 32 faunal remains. Bone samples were collected from 21 terrestrial herbivores (eight cattle *Bos taurus*, seven goats and/or sheep *Capra hircus*/*Ovis aries*, three deer *Cervus elaphus* and three horses *Equus caballus*; 66%), two (6%) carnivores (two dogs *Canis lupus*) and six (19%) omnivores (one brown bear *Ursus arctos* and five pigs *Sus scrofa*). Moreover, three (9%) *Aves* sp. were also sampled (Table S2). One unique case was the sample TE SSD selected from an entire skeleton of a pig found lying on its right side in a single stoned-lined pit grave (tomb 11) at the site of Terlano in Adige valley.

The age estimation revealed 62 (68%) adults and 29 (32%) subadults of the 91 human samples. The latter were two perinatal (2%), three newborn (3%), 14 infants 1st (15%), seven infants 2nd (8%) and three juveniles (3%) (Fig. 2). The sex estimation of the adult individuals revealed 38 (42%) males, 20 (22%) females and four (4%) individuals that could not be confidently sexed (n.d.), (Fig. 2). Grave goods were recorded in 22 graves of 12 males, six females, one adult of unknown sex and three subadults (Table S1).

Sample quality and descriptive statistics

Collagen of good quality, according to the criteria for $\delta^{13}C$ and $\delta^{15}N$ values, was recorded in 85 (93%) human samples. For $\delta^{34}S$ values, 40 (44%) of the humans were considered as good collagen samples (Table S1), and thus, the samples from Nalles and Tanas had to be discarded before statistical analyses, due to their bad quality. The majority of the animals (30/32, 94%) were of good quality and were evaluated for all the stable isotope analyses (Table S2). Descriptive statistics for the faunal and human dataset, without the aforementioned outliers, are presented in Table 1.

Table 1 Descriptive statistics for carbon, nitrogen and sulphur stable isotope ratios (n, mean, standard deviation, median, minimum, maximum). The samples considered as outliers were excluded

		$\delta^{13}C$						$\delta^{15}N$						$\delta^{34}S$					
Valley/basin	Site	*n*	Mean	SD	Median	Min.	Max.	*n*	Mean	SD	Median	Min	Max.	*n*	Mean	SD	Median	Min.	Max.
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg	4	− 17.69	0.38	− 17.66	− 18.16	− 17.30	4	9.88	0.52	9.90	9.33	10.40	2	10.43	0.18	10.43	10.30	10.55
Adige/Etschtal	Montagna Pinzano/Montan Pinzon	5	− 17.61	0.88	− 17.80	− 18.51	− 16.26	5	9.65	0.38	9.73	9.08	10.14	2	9.12	0.80	9.12	8.55	9.63
Adige/Etschtal	Nalles/Nals	1	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–
Adige/Etschtal	Terlano/Terlan	10	− 18.29	1.18	− 18.38	− 19.89	− 16.32	10	9.69	0.61	9.90	8.53	10.54	6	6.72	2.10	6.07	5.04	10.66
Total (Adige/Etschtal)		20	− 18.01	0.98	− 17.99	− 19.89	− 16.26	20	9.70	0.51	9.73	8.53	10.54	10	7.94	2.28	7.89	5.04	10.66
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	23	− 18.43	1.05	− 18.48	− 20.25	− 15.84	20	9.94	0.65	9.90	8.53	11.22	6	4.49	1.38	4.27	3.05	6.76
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas	20	− 18.72	0.89	− 18.97	− 19.85	− 16.82	19	10.16	0.90	10.17	8.06	11.58	20	7.10	1.06	7.22	4.84	9.61
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan	13	− 19.23	0.33	− 19.30	− 19.70	− 18.58	14	10.49	0.76	10.57	9.09	11.52	2	4.76	1.13	4.76	3.96	5.56
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof	6	− 19.40	0.31	− 19.41	− 19.86	− 18.98	6	10.88	1.22	10.84	9.17	12.79	2	5.00	0.96	5.00	4.32	5.68
Venosta/Vinschgau	Tanas/Tanas	1	–	–	–	–	–	2	9.70	0.15	9.70	9.59	9.81	–	–	–	–	–	–
Total (Venosta/Vinschgau)		20	− 19.29	0.31	− 19.31	− 19.86	− 18.58	22	10.52	0.90	10.57	9.09	12.79	4	4.88	0.87	4.94	3.96	5.68
Overall total		83	− 18.59	0.97	− 18.76	− 20.25	− 15.84	81	10.09	0.81	9.99	8.06	12.79	40	6.69	1.90	6.81	3.05	10.66
Sex	Male (adult)	35	− 18.74	0.95	− 19.04	− 20.08	− 15.8	37	10.10	0.74	10.18	8.53	11.52	16	6.62	2.06	6.86	3.25	10.66
	Male (20–40 years old)	19	− 18.64	1.19	− 19.15	− 20.08	− 15.8	20	9.99	0.69	9.89	8.53	11.11	10	6.40	2.03	6.47	3.25	10.55
	Female (adult)	17	− 18.66	1.13	− 18.97	− 20.25	− 16.3	16	9.85	0.58	9.81	9.08	11.06	10	6.55	2.03	7.02	3.05	9.61
	Female (20–40 years old)	15	− 18.54	11.50	− 18.53	− 20.25	− 16.3	14	9.80	0.52	9.82	9.08	10.83	8	6.73	2.03	7.02	3.05	9.61
	N.d. (adult)	3	− 18.39	0.86	− 18.46	− 19.78	− 16.4	2	9.59	1.71	9.29	8.06	11.44	3	6.42	0.73	6.54	5.64	7.08
	N.d. (subadult)	28	− 18.70	1.39	− 19.03	− 19.89	− 17.2	25	10.28	0.88	10.10	9.03	12.79	11	7.01	1.93	6.76	4.37	10.30
Age at death (nine classes)	Perinatal (38–40 weeks)	2	− 18.08	0.11	− 18.08	− 18.16	− 18.0	2	10.39	0.86	10.39	9.78	11.01	–	–	–	–	–	–
	Newborn (0–2 months)	3	− 17.54	1.12	− 17.50	− 18.68	− 16.44	3	10.23	0.41	10.40	9.76	10.55	2	7.34	4.19	7.34	4.37	10.30
	Infant 1st (3 months–6 years)	14	− 18.55	0.79	− 18.60	− 19.70	− 17.50	11	10.75	1.03	10.91	9.03	12.79	5	6.73	1.27	6.76	5.34	8.42
	Infant 2nd (7–12 years)	6	− 18.68	0.97	− 19.00	− 19.78	− 17.31	6	9.81	0.51	10.35	9.04	10.51	2	7.13	0.88	7.13	6.50	7.75
	Juvenile (13–19 years)	3	− 18.10	0.72	− 18.37	− 18.65	− 17.28	3	9.48	0.21	9.37	9.35	9.73	2	7.26	3.42	7.26	4.84	9.68
	Adult (20–40 years)	35	− 18.61	1.14	− 19.13	− 20.25	− 15.84	35	9.95	0.66	9.90	8.53	11.44	19	6.56	1.93	6.81	3.05	10.55
	Adult N.d. (> 20 years)	2	− 19.09	1.12	− 19.09	− 19.89	− 18.30	2	9.67	0.54	9.67	9.29	10.06	2	5.89	0.92	5.89	5.24	6.54
	Mature (40–60 years)	16	− 18.83	0.70	− 18.99	− 19.86	− 17.17	16	10.14	0.97	10.28	8.06	11.52	6	7.10	2.18	7.22	4.17	10.66
	Senile (> 60 years)	2	− 19.16	0.65	− 19.16	− 19.62	− 18.70	3	10.11	1.03	9.59	9.45	11.31	2	5.85	2.67	5.85	3.96	7.74
Age at death (two classes)	Adults (males and females)	55	− 18.71	1.01	− 19.03	− 20.25	− 15.84	56	10.00	0.76	9.95	8.06	11.52	26	6.59	2.01	6.86	3.05	10.66
	Subadults	28	− 18.39	0.86	− 18.46	− 19.78	− 16.44	25	10.28	0.88	10.10	9.03	12.79	11	7.01	1.93	6.76	4.37	10.30
Grave goods	Individuals with grave goods	20	− 18.80	0.67	− 18.84	− 19.85	− 17.28	20	10.35	0.70	10.35	9.08	11.58	14	7.48	1.27	7.53	5.04	9.68
	Individuals without grave goods	63	− 18.54	1.04	− 18.80	− 20.25	− 15.84	61	10.12	0.83	9.92	8.06	12.79	26	6.27	2.07	5.90	3.05	10.66

Table 1 (continued)

Valley/basin	Site	δ13C *n*	Mean	SD	Median	Min.	Max.	δ15N *n*	Mean	SD	Median	Min	Max.	δ34S *n*	Mean	SD	Median	Min.	Max.
	Individuals with accessory	11	−18.82	0.80	−18.67	−19.85	−17.28	11	9.97	0.57	9.90	9.08	10.67	6	7.73	1.63	7.35	5.51	9.68
	Individuals with accessory and weapon	6	−18.80	0.40	−18.84	−19.13	−18.18	6	10.73	0.61	10.58	10.14	11.58	5	7.71	0.43	7.59	7.29	8.42
	Individuals with weapon	3	−18.75	0.89	−19.03	−19.46	−17.75	3	11.01	0.45	11.06	10.54	11.44	3	6.60	1.38	7.08	5.04	7.68
	With grave goods (Ísarco only)	12	−19.15	0.39	−19.08	−19.85	−18.67	12	10.63	0.66	10.61	9.39	11.58	12	7.50	0.96	7.53	5.51	9.61
	Without grave goods (Ísarco only)	8	−18.08	1.06	−17.82	−19.78	−16.82	7	9.37	0.69	9.37	9.09	12.79	8	6.49	0.95	6.66	4.84	7.75
Chronological phases	Phase1: 5th–7th	22	−18.75	0.86	−18.97	−19.85	−16.82	21	10.15	0.86	10.17	8.06	11.58	20	7.10	1.06	7.22	4.84	9.61
	Phase 2: 7th–8th	23	−18.58	0.91	−18.80	−19.70	−16.26	24	10.21	0.79	10.32	9.08	11.52	7	7.75	2.65	8.55	3.96	10.55
	Phase 3: 8th–10th	8	−18.14	1.24	−18.11	−19.89	−16.32	8	9.62	0.67	9.60	8.53	10.54	4	7.37	2.38	6.88	5.04	10.66
	Phase 4: 9th–12th	6	−19.35	0.30	−19.34	−105.00	−18.98	7	10.46	1.21	10.18	9.17	12.79	1	–	–	–	–	–
	Early medieval (6th–11th)	24	−18.46	1.05	−18.46	−20.25	−15.84	21	9.96	0.63	9.92	8.53	11.22	8	4.72	1.25	4.81	3.05	6.76
Animals per valley and sites																			
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg	2	−20.95	0.37	−20.95	−21.21	−20.69	3	5.59	2.42	4.34	4.06	8.38	3	8.37	2.08	7.39	6.95	10.76
Adige/Etschtal	Montagna Pinzano/Montan Pinzon	1	–	–	–	–	–	1	–	–	–	–	–	1	–	–	–	–	–
Adige/Etschtal	Nalles/Nals	3	−20.89	0.52	−20.77	−21.46	−20.43	3	4.66	2.33	4.19	2.60	7.18	3	10.54	1.47	11.07	8.87	11.67
Adige/Etschtal	Terlano/Terlan	3	−20.12	0.49	−20.40	−20.40	19.55	3	5.98	1.84	5.53	4.41	8.01	3	4.05	2.16	3.57	2.17	4.67
Total (Adige/Etschtal)		9	−20.49	0.67	−20.43	−21.46	−19.46	10	5.41	1.89	4.90	2.60	8.38	10	7.95	3.26	8.13	2.17	11.67
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	7	−19.90	1.03	−20.05	−20.87	−18.01	7	5.80	2.93	4.76	2.73	10.65	6	6.10	1.27	6.17	3.95	7.61
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas	3	−19.55	0.75	−19.21	−20.41	−19.02	3	6.33	1.42	6.80	4.73	7.45	3	7.58	0.83	7.60	6.75	8.40
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan	3	−20.52	0.40	−20.29	−20.99	−20.29	3	5.29	2.71	5.00	2.73	8.13	3	6.73	0.86	6.48	6.03	7.69
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof	5	−20.56	0.72	−20.60	−21.52	−19.70	5	4.93	2.26	4.17	2.74	8.38	5	6.99	1.86	7.70	4.93	9.29
Venosta/Vinschgau	Tanas/Tanas	2	−20.95	0.64	−20.95	−21.40	−20.50	2	7.13	1.65	7.13	5.96	8.30	2	6.48	0.08	6.48	6.42	6.54
Total (Venosta/Vinschgau)		10	−20.63	0.58	−20.55	−21.52	−19.70	10	5.48	2.23	5.45	2.73	5.38	10	6.81	1.32	6.51	4.93	9.29
Overall total		29	−20.29	0.81	−20.41	−21.52	−18.01	30	5.61	2.16	5.19	2.60	10.65	29	7.14	2.20	6.95	2.17	11.67
Animal species	*Aves*	3	−20.15	0.53	−20.29	−20.60	−19.57	3	5.85	3.10	5.90	2.73	9.61	3	6.88	0.80	6.48	6.35	7.80
	Bos primigenius f. taurus	7	−19.90	1.10	−20.29	−21.40	−18.01	7	6.01	1.38	5.59	4.41	8.30	7	6.76	2.23	6.42	3.57	10.66
	Canis lupus f.familiaris	1	–	–	–	–	–	2	8.38	0.00	8.38	8.38	8.38	2	9.23	2.16	9.23	7.70	10.76
	Cervus elaphus	3	−20.79	0.72	−20.87	−21.46	−20.03	3	2.89	0.39	2.74	2.60	3.34	2	7.05	2.57	7.05	5.23	8.87
	Equus ferus f. caballus	3	−21.08	0.39	−20.93	−21.52	−20.79	3	4.08	0.59	4.17	3.45	4.61	3	7.08	2.18	7.03	4.93	9.29
	Capra hircus/*Ovis aries*	6	−20.60	0.58	−20.72	−21.21	−19.55	6	5.28	1.47	4.75	4.19	8.13	6	6.99	2.89	7.49	2.17	11.07
	Sus scrofa f. domestica	5	−19.97	0.75	−20.40	−20.69	−19.02	5	7.34	2.37	7.18	4.06	10.65	5	7.15	2.80	6.75	3.95	11.67

Table 1 (continued)

Valley/basin	Site	$\delta^{13}C$						$\delta^{15}N$						$\delta^{34}S$					
		n	Mean	SD	Median	Min.	Max.	*n*	Mean	SD	Median	Min	Max.	*n*	Mean	SD	Median	Min.	Max.
	Ursus arctos	1	–	–	–	–	–	1	–	–	–	–	–	1	–	–	–	–	–
Classification (*n* = 3 *Aves* excluded)	Herbivores	19	−20.45	0.89	−20.67	−21.52	−18.01	19	4.98	1.61	4.73	2.60	8.30	18	6.92	2.28	6.78	2.17	11.07
	Omnivores	6	−19.98	0.67	−20.23	−20.69	−19.02	6	6.57	2.83	6.99	2.73	7.92	6	7.22	2.51	6.85	3.95	11.67
	Carnivores	1	–	–	–	–	–	2	8.38	0.00	8.38	8.38	8.38	2	9.23	2.16	9.23	7.70	10.76

The $\delta^{13}C$ values for herbivores ranged from − 21.52 to − 18.01‰ (mean − 20.45 ± 0.89‰); $\delta^{15}N$ values ranged from + 2.60 to + 8.30‰ (mean + 4.98 ± 1.61‰), and $\delta^{34}S$ values ranged from + 2.17 to + 11.07‰ (mean + 6.92 ± 2.28‰). The omnivores ranged between − 20.69 and − 19.02‰ for $\delta^{13}C$ values (mean − 19.98 ± 0.67‰); $\delta^{15}N$ values between + 2.73 and + 7.92‰ (mean + 6.57 ± 2.83‰) and $\delta^{34}S$ values between 3.95 and + 11.67‰ (mean + 7.22 ± 2.51‰). Only one dog (MHP CF) represented the carnivores for $\delta^{13}C$ values (− 19.00‰; the outlier for $\delta^{13}C$ values is AP-AL CF, as displayed in Table S2). For $\delta^{15}N$ values, both dogs provided the same results (+ 8.38‰), while $\delta^{34}S$ values ranged between + 7.70 and + 10.76‰ (mean + 9.23 ± 2.16‰).

The $\delta^{13}C$ values of all human samples ranged from − 20.25 to − 15.84‰, with a mean of − 18.59 ± 0.97‰. The $\delta^{15}N$ values ranged from + 8.06 to + 12.79‰ (mean of + 10.09 ± 0.81‰) and $\delta^{34}S$ values ranged from + 3.05 to + 10.66‰ (mean of + 6.69 ± 1.90‰). The highest mean value for $\delta^{13}C$ in humans was observed in Adige valley (Table 1; Fig. 3a, b), the highest $\delta^{15}N$ mean value was in Venosta valley (Table 1; Fig. 3a, b), and the $\delta^{34}S$ data showed the highest mean in Adige valley (Table 1, Fig. 3c, d). Figure 4a–c show the stable isotope variations based on altitudes in more detail. The highest mean values for $\delta^{13}C$ were detected at lower altitudes around 400 m a.s.l. (Fig. 4a), as well as for $\delta^{34}S$ data (Fig. 4b). This was different for the $\delta^{15}N$ values, where the highest means corresponded to altitudes around 1000–1300 m a.s.l. (Fig. 4c).

All adults (males and females) of the different valleys ranged from − 20.25 to − 15.84‰, with a mean of − 18.71 ± 1.01‰ for $\delta^{13}C$ values (Table 1). In Venosta valley, the females (− 19.59 ± 0.28‰) displayed slightly lower $\delta^{13}C$ values compared to the males (− 19.20 ± 0.28‰) (Fig. 5a). Concerning the $\delta^{15}N$ mean values, the females represented the lowest means compared to males and subadults. The subadults from Isarco valley, differently from the other areas, showed a lower $\delta^{15}N$ mean values (+ 10.04 ± 1.13‰) compared to the males (+ 10.34 ± 0.68‰) (Fig. 5a). The $\delta^{34}S$ data showed that females in Adige valleys had higher values than males, while in Isarco valley, the values were more equal. However, no comparisons among sexes could be considered for Merano basin and Venosta valley due to the limited number of samples with collagen of good quality for $\delta^{34}S$ values (Fig. 5b).

Four different groups, according to the presence of grave goods, were also clustered (Table 1; Fig. 6a, b): (1) individuals buried with accessory (e.g. parts of belt, jewelry), (2) accessory and weapon, (3) weapon only and (4) without any grave goods. The mean of the $\delta^{13}C$ values between groups showed little variations with the means ranging between − 18.82 and − 18.75‰. However, individuals buried with weapons showed the highest mean values for $\delta^{15}N$ (Fig. 6 a), while

Table 2 List of *p* values of one-way ANOVA and independent sample *t* tests. The significance level set at 0.05 and significant values are shown in italics

	$\delta^{13}C$		$\delta^{15}N$		$\delta^{34}S$	
	p value		*p* value		*p* value	
	ANOVA	Independent *t* test	ANOVA	Independent *t* test	ANOVA	Independent *t* test
Valleys	*0.000*	–	*0.007*	–	*0.000*	–
Adige vs Merano basin	0.548	–	0.744	–	*0.000*	–
Adige vs Isarco	0.097	–	0.242	–	0.474	–
Adige vs Venosta	*0.000*	–	*0.005*	–	*0.007*	–
Merano vs Isarco	0.754	–	0.810	–	*0.003*	–
Merano vs Venosta	*0.005*	–	0.077	–	0.977	–
Isarco vs Venosta	0.056	–	0.440	–	*0.047*	–
Sites (Nalles and Tanas excluded)	*0.000*	–	*0.028*	–	*0.000*	–
Sexes (males, females and n.d. subadults)	0.343	–	0.221	–	0.845	–
Males vs females	–	0.799	–	0.235	–	0.931
Males (adults 20–40 years) vs females (adults 20–40 years)	–	0.819	–	0.375	–	0.712
Males (adults 20–40 years) vs females (adults 20–40 years) Adige	–	0.963	–	*0.030*	–	0.746
Males (adults 20–40 years) vs females (adults 20–40 years) Isarco		0.691		0.571		0.653
Males (adults 20–40 years) vs females (adults 20–40 years) Venosta		0.459		0.483		Insufficient data quantity
Males (matures) vs females (matures)	–	Insufficient data quantity	–	Insufficient data quantity	–	Insufficient data quantity
Males (seniles) vs females (seniles)	–	Insufficient data quantity	–	Insufficient data quantity	–	Insufficient data quantity
Age classes (adults vs subadults)	–	0.149	–	0.156	–	0.526
Grave goods present vs absent	–	0.297	–	0.105	–	0.054
Grave goods present vs absent (Isarco only)	–	*0.025*	–	*0.001*	–	*0.033*
Chronological phases	*0.004*	–	0.270	–	0.982	–
Phase 1 vs phase 2	0.918	–	–	–	–	–
Phase 1 vs phase 3	0.594	–	–	–	–	–
Phase 1 vs phase 4	0.055	–	–	–	–	–
Phase 2 vs phase 3	0.794	–	–	–	–	–
Phase 2 vs phase 4	*0.011*	–	–	–	–	–
Phase 3 vs phase 4	0.108	–	–	–	–	–

the two groups “accessory” and “accessory and weapon” resulted in higher $\delta^{34}S$ mean values compared to the other clusters (Fig. 6b).

A clustering based on the chronological phases was also evaluated (Fig. 7a, b). The highest mean value of $\delta^{13}C$ was represented by the group of phase 3 (Table 1; Fig. 7a, b); the highest mean value for $\delta^{15}N$ by the group of phase 4 (Table 1; Fig. 7a), while the highest $\delta^{34}S$ mean value was displayed for the human individuals of phase 2 (Table 1; Fig. 7b).

Non-migratory animals, such as domestic pigs (Scheeres et al. 2013), were used as a faunal baseline to detect the presence of possible allochthonous individuals in Adige valley as displayed in Fig. 8.

Statistical tests

The valleys and the archaeological sites showed significant differences in all stable isotope elements (Table 2). Moreover, the results showed differences in $\delta^{13}C$ between Adige and Venosta valley (post-hoc ANOVA, p value = 0.000) and Merano basin vs Venosta valley (post-hoc ANOVA, p value = 0.005). Differences in $\delta^{15}N$ values were significant in Adige vs Venosta valley (post-hoc ANOVA, p value = 0.005). The $\delta^{34}S$ values were significantly different in Adige valley vs Merano basin (post-hoc ANOVA, p value = 0.000) and Venosta (post-hoc ANOVA, p value = 0.007) as well as in Merano basin vs Isarco valley (post-hoc

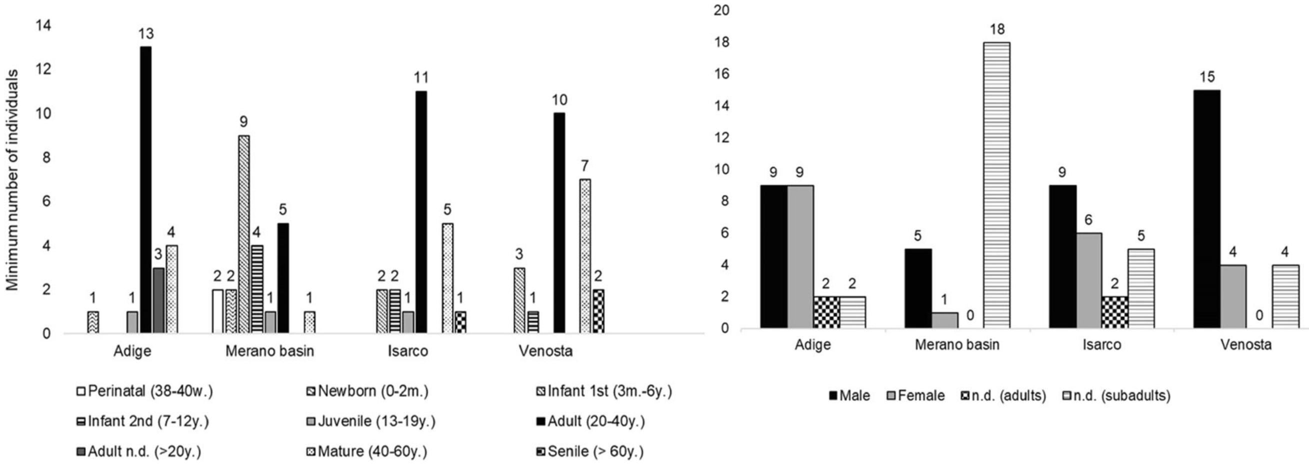


Fig. 2 Age at death (left) and sex (right) distribution of all the human individuals ($n = 91$) grouped by valleys/basin

ANOVA, p value = 0.003) and the latter vs Venosta valley (post-hoc ANOVA, p value = 0.047). There were no differences of all stable isotopes elements between males, females and subadults overall. However, statistical differences were observed for δ^{15}N values of males and females (adults 20–40 years) from Adige valley (independent t test, p value = 0.030) only.

The individuals buried with or without grave goods did not displayed statistical differences (Table 2). However, if only the site of Bressanone Elvas was tested, significant differences among the two groups in all the analysed isotope values were observed (independent t test, for δ^{13}C p value = 0.025; for δ^{15}N p value = 0.001; for δ^{34}S p value = 0.033).

The chronological phases displayed differences only in the δ^{13}C values for phase 2 vs phase 4 (post-hoc ANOVA, p value = 0.011).

Discussion

Fauna in Early medieval South Tyrol

The isotopic results reflected a terrestrial based diet with a C_3 plant intake. In order to obtain a proper baseline for δ^{13}C and δ^{15}N stable isotopes, different animal remains, including domesticated and wild animals, were considered (Katzenberg 2008; Bonafini et al. 2013). Both forested species (bear and deer) showed relatively negative δ^{13}C values as expected, although no significant differences in the other herbivores were detected. The reason for this ^{13}C-depletion can be explained by the so-called canopy effect, which is caused by ^{13}C-depleted plants and a gradient of leaf δ^{13}C values from ground to canopy in a dense woodland ecosystem (Bonafini et al. 2013; Drucker et al. 2008, 2011; Ferrio et al. 2003; Van der Merwe and Medina 1991). Interestingly, the horses presented the most negative δ^{13}C mean (− 21.08 ± 0.39‰; Fig. 3b) together with the most representative forest animals, such as deers (− 20.79‰ ± 0.72‰; Fig. 3a, b), suggesting that they were fed in forested enviroments or other places depleted in ^{13}C. This is comparable with the low δ^{13}C mean value (− 22.1 ± 0.4‰) of the horses from central medieval Germany, probably due to environmental factors (e.g. mixed habitats) as well as metabolic differences (Knipper et al. 2012). As expected, the δ^{15}N values of all faunal remains showed the highest variation (from + 2.60 to + 10.65‰). The δ^{15}N mean value of the dogs was enriched by Δ3.4‰ compared to the herbivore average. However, the dogs had lower nitrogen values (+ 8.38 ± 0.00‰) compared to the humans (+ 10.09 ± 0.81‰), suggesting an omnivore diet. An explanation for this could be that dogs, as human companions, were likely provisioned with human refuses. Indeed, stable isotopes from dogs remains can offer indication of their owners' dietary habits (Guiry 2012). This might also be confirmed by the δ^{13}C values, with a clear C_4 signal (− 16.36‰) for the dog sample (AP-AL CF, a statistical outlier) found in Adige. Differently to the dogs, the pigs in Adige valley might have been fed not only with leftovers, but also with a greater ammount of C_3 plants (e.g. oakwood, acorn). Anagously, the pigs' nitrogen values (+ 6.91 ± 1.9‰) from the medieval site of Petersberg in South Germany, showed an herbivore diet (Lösch 2009). This is in accordance with Early medieval farming practices, as domesticated pigs were possible allowed out to grass in open lands and/or forests (Montanari and Baruzzi 1981). The highest δ^{15}N value (+ 10.65‰) of a young pig (TCT SSD) indicated that it was buchered or it died before weaning. Another relatively high δ^{15}N value (+ 8.01‰) was observed from a pig (TE SSD), which was found in a single stoned-lined pit grave (tomb 11) in Terlano. The trophic level is similar to the local humans, and this pig's single burial might have had a ritualistic purpose, as already documented in the second century BC (Marcus Porcius Cato, *De Agri Cultura*). The lowest δ^{15}N

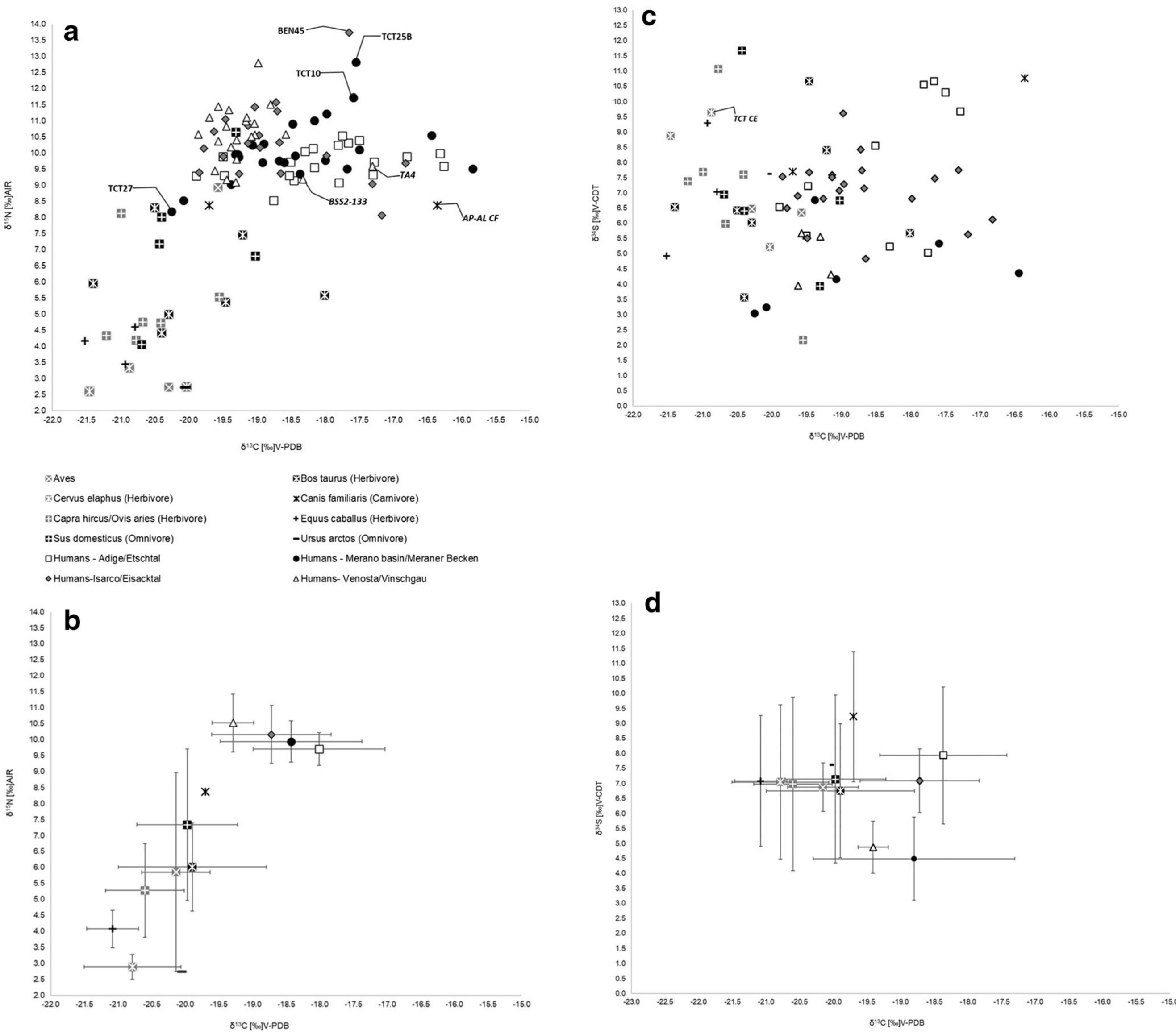


Fig. 3 **a** Plotted results of δ^{13}C and δ^{15}N values of all human ($n = 85$) and animal samples ($n = 30$) with collagen of good quality. The statistical outliers are indicated (Italics = outliers for the δ^{14}C values only). **b** Mean δ^{13}C and δ^{15}N values, excluding the outliers, with SD. **c** Plotted results of δ^{13}C and δ^{34}S values of all human ($n = 40$) and animal ($n = 30$) with collagen of good quality. The statistical outlier for δ^{34}S value is indicated in italics. **d** Mean δ^{13}C and δ^{34}S values, excluding the outliers, with SD

values were observed from samples of red deer and brown bear, such as + 2.60 and + 2.73‰ respectively. Regarding the isotopic signature of the bear, the hybernatic metabolic process could explain the isotopic depleted nitrogen value which was also reported for a medieval brown bear (+ 1.10‰) by Lösch (2009). A significant difference in the metabolism of modern black bears (*Ursus americanus*) and grizzly bear (*A. arctos*) compared to other animals has been documented (Nelson et al. 1998). During that process, the bears maintain their body temperature with no defecation nor urination. According to Bocherens et al. (2006), depleted δ^{15}N values could also indicate a herbivore diet or that the bear suffered long cold climatic conditons.

Varying dietary patterns in Early medieval valleys in South Tyrol

The overall stable isotope data indicated a terrestrial diet with a subsistence base of mainly C_3 plants for all human samples across the different valleys. The C_3-signal is in accordance with published studies of medieval populations in western and central Europe (e.g. Hakenbeck et al. 2010, 2017; Knipper et al. 2012;

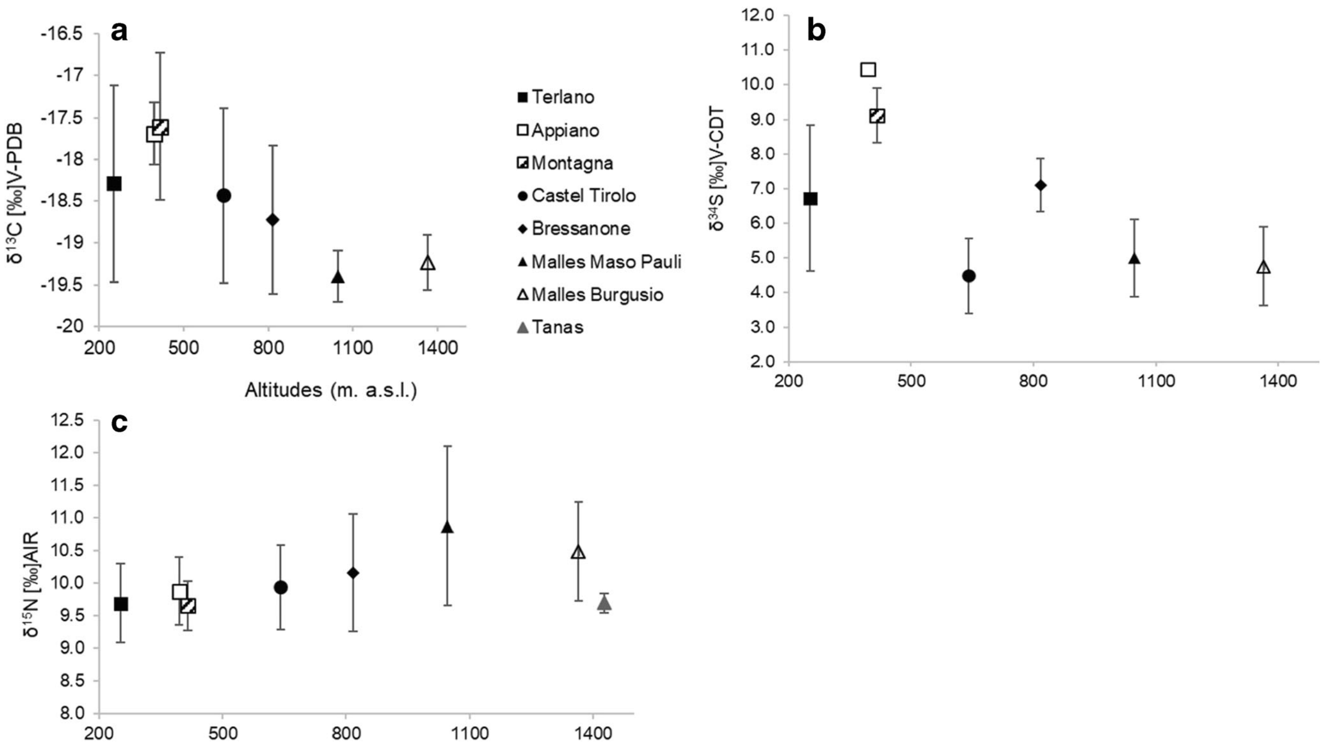


Fig. 4 **a** Plotted δ^{13}C mean values (including SD) in relation to altitudes (m a.s.l) for the archaeological sites (excluding Nalles and Tanas) and valleys (squares = Adige valley, circles = Merano basin, diamonds = Isarco valley, and triangle = Venosta valley). **b** Plotted δ^{34}S mean values (including SD) in relation to altitudes (m a.s.l.) for the archaeological sites (excluding Nalles and Tanas) and valleys. **c** Plotted δ^{15}N mean values (including SD) in relation to altitudes (m a.s.l.) for the archaeological sites (excluding Nalles) and valleys

Prevedorou et al. 2010; Polet and Katzenberg 2003; Reitsema et al. 2010; Reitsema and Vercellotti 2012; Schutkowski and Herrmann 1999). The data showed significant differences in diet among the populations from the valleys, whereby the δ^{13}C and δ^{15}N data differed most between the individuals from Adige valley and those from Venosta valley (Fig. 3a, b). The Italian Alps consist of highly diverse geological areas, including these two valleys in particular, which are located in different regional zones and at various altitudes (Figs. 1b and 4a, c). The results showed depleted δ^{13}C values (mean Δ1.3‰) and enriched δ^{15}N values (mean Δ0.8‰) in Venosta valley compared to Adige valley (Table 1). The observed values could be due to the availability and use of different food sources at different altitudes; however, anthropogenic effects such as manuring or admixing food sources from different geographical locations have to be considered. Moreover, the data could also indicate that the cultivation of C_4 plants played an important role. Remains of C_4 cereals dating to Copper Age were already recovered at sites located at 700–850 m a.s.l. in Isarco valley (Castiglioni and Tecchiati 2005; Festi et al. 2011; Nisbet 2008). At the burial site

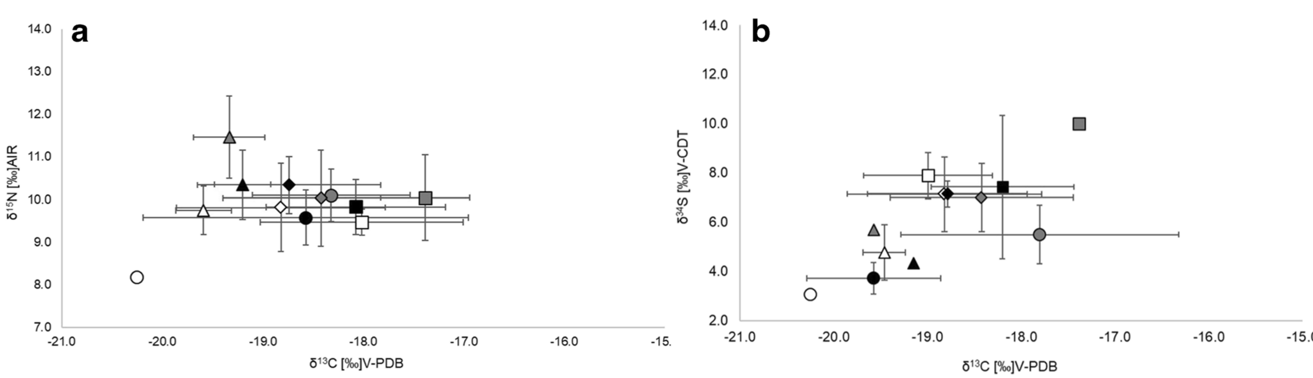


Fig. 5 **a** Plotted δ^{13}C and δ^{15}N mean values (total $n = 79$ excluding the six outliers as shown in Table S1) and SD for males, females, and subadults grouped by valleys. **b** Plotted δ^{13}C and δ^{34}S mean values (including SD) for males, females, and subadults (total $n = 40$) grouped by valleys. White = females, black = males, and gray = subadults. Squares = Adige valley, circles = Merano basin, diamonds = Isarco valley, and triangle = Venosta valley

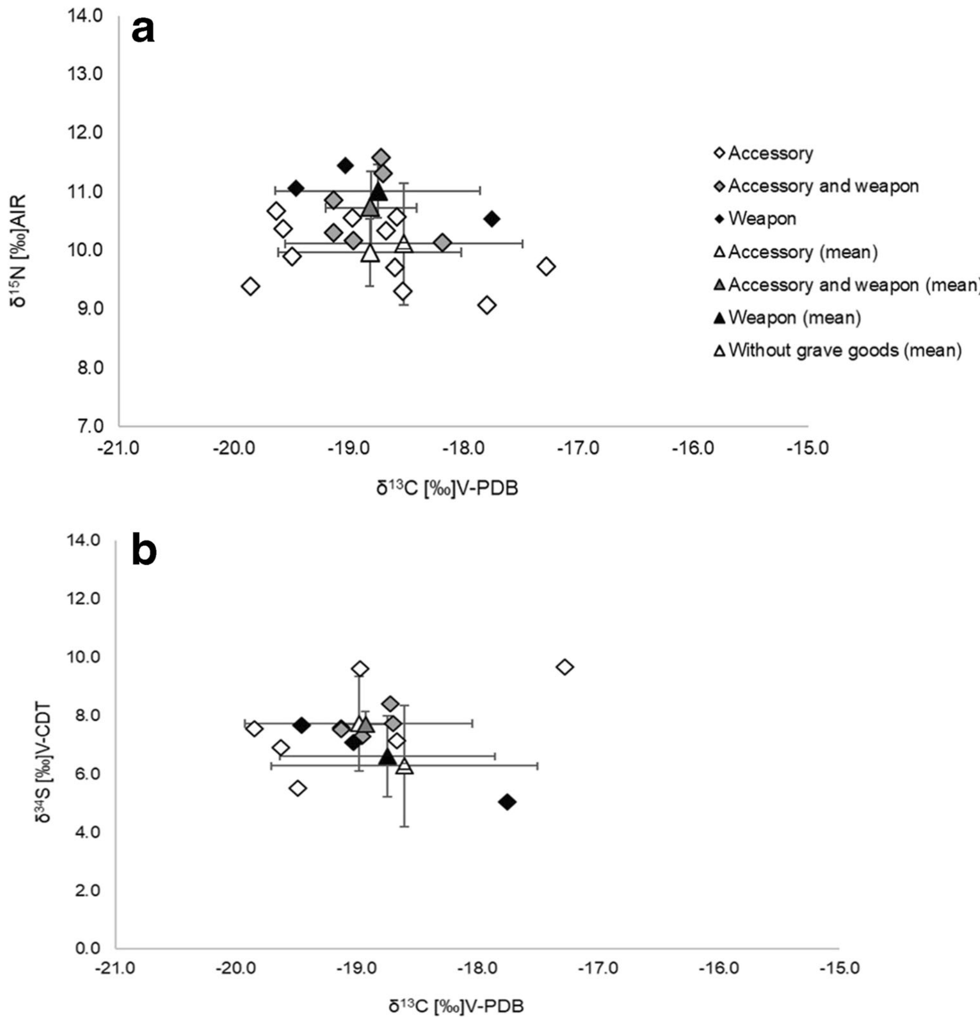


Fig. 6 **a** Plotted $\delta^{13}C$ and $\delta^{15}N$ mean values (including SD) of the samples grouped according to the four groups of graves goods. Graves without goods are only represented by their mean value (including SD). **b** Plotted $\delta^{13}C$ and $\delta^{34}S$ mean values (including SD) of the samples grouped according to the four groups of graves goods. Graves without goods are only represented by their mean value (including SD)

of Naz, next to Bressanone Elvas in the Isarco valley, carbonized cereals were found in graves (Kaufmann and Demetz 2004) including spelt (*Triticum spelta*), barley (*Hordeum vulgare*) but also few remains of C_4 plants like millet as well as fruit seeds and grapevine (*Vitis vinifera*) (Öggl 1993). In the present study, the C_4 plant intake had a bigger influence on the diet at lower altitudes (Adige valley) compared to higher altitudes. In total, 53% ($n = 10/19$) of the individuals from Adige valley expressed $\delta^{13}C$ values more positive than − 18‰ and thus a signal of an intake of C_4 plants, such as millet or sorghum (Le Huray and Schutkowski 2005). Given the important contribution of fruits and seeds in the nowadays diet in South Tyrol, the isotopic variability among different botanical species has to be considered. Indeed, the observed $\delta^{13}C$ values may also indicate a contribution of, e.g. fruits, seeds, roots and woody stems, which are ^{13}C-enriched compared to leaves and thus lead to more positive $\delta^{13}C$ values in the consumers' tissue (Cernusak et al. 2009). In Merano basin 25% ($n = 6/24$), in Isarco valley 20% ($n = 4/20$) and in Venosta valley only 5% ($n = 1/22$) of the individulas indicate a C_4-signal. This suggests an increased significance of C_4 plant cultivation at lower altitudes compared to settlements at higher areas. However, trading might have played a key role in nutrition preferences and communications among valleys influencing cultivation patterns of neighbouring regions. Indeed, since Roman times, transalpine trading routes, such as Via *Claudia Augusta*, crossed this territory between northern Italy and the transalpine areas into *Augusta Vindelicorum* (Augsburg) in southern Germany and thus connecting the valleys from the southern to northern areas of the region and favouring goods exchanges (Banzi 2005; Kustatscher and Romeo 2010). Therefore, trading and communication between the valleys, as well as within neighbouring territories, could have led to human adaptation and changes in agriculture. In addition, mobility pattern could also be an explanation for the C_4 signal of two individuals found at higher altitudes (BSS2-133 and TA4), although a general decrease of the C_4 signal at higher areas was recorded.

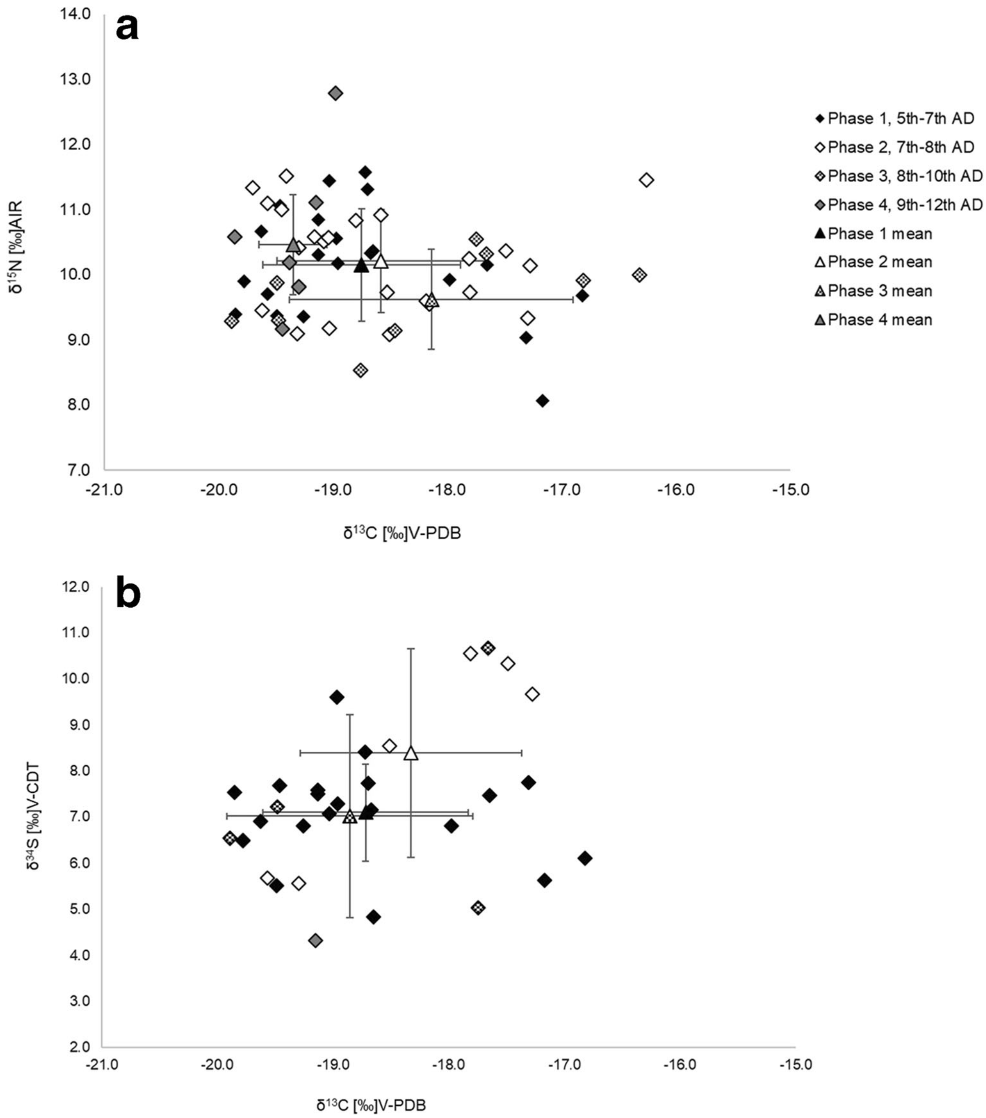


Fig. 7 **a** Plotted $\delta^{13}C$ and $\delta^{15}N$ mean values (including SD) of the samples grouped according to the four chronological phases. **b** Plotted $\delta^{13}C$ and $\delta^{34}S$ mean values (including SD) of the samples grouped according to the four chronological phases

Unfortunately, the carbon stable isotope data presented in this work cannot be compared with other local datasets; as to the authors' knowledge, there is a clear lack of available comparative data from Trentino-South Tyrol. Published comparable data from southern German medieval Petersberg (Lösch 2009) and Austrian Early medieval Volders (McGlynn 2007) were used for comparisons. As expected, our data showed higher variation in $\delta^{13}C$, compared not only to Volders (males − 20 ± 0.4‰ and females − 20 ± 0.4‰) but also to Petersberg (males − 20.5‰ and females − 20.5‰), and to other sites in Bavaria (Knipper et al. 2012). This is mainly due to the variety of geographical areas considered in this paper, whereas Petersberg and Volders represent samples from a single site. The diversity of the carbon values can also be explained by climatic variations in South Tyrol that allow differences of plant cultivation and human adaptation to the enviroment. The enviromental and climatic conditions influenced the types of cultivation during the different chronological phases within the valleys. The highest $\delta^{13}C$ mean value (− 18.14 ± 1.24‰) corresponded to the chronological phase 3 (eighth–tenth centuries AD) (Table 1; Fig. 7a). This result could indicate a possibile increased consuption of C_4 plants due to favourable climatic conditions, since this period corresponded to a climatic *optimum* characterized by warmer climat (Hughes and Diaz 1994; Mann et al. 2009).

The stable nitrogen isotopic data indicated a higher intake of animal protein, such as meat and dairy products, at higher altitudes, with the highest mean value of $\delta^{15}N$ (+ 10.52 ± 0.90‰) in Venosta, followed by Isarco valley ($\delta^{15}N$ + 10.16 ± 0.90‰). Overall, the $\delta^{15}N$ averages of the humans were enriched by Δ5.1‰ compared to herbivores, displaying a difference of one trophic level (Hedges and Reynard 2007). Two adults, one from Venosta (BSS7-105A) and one from

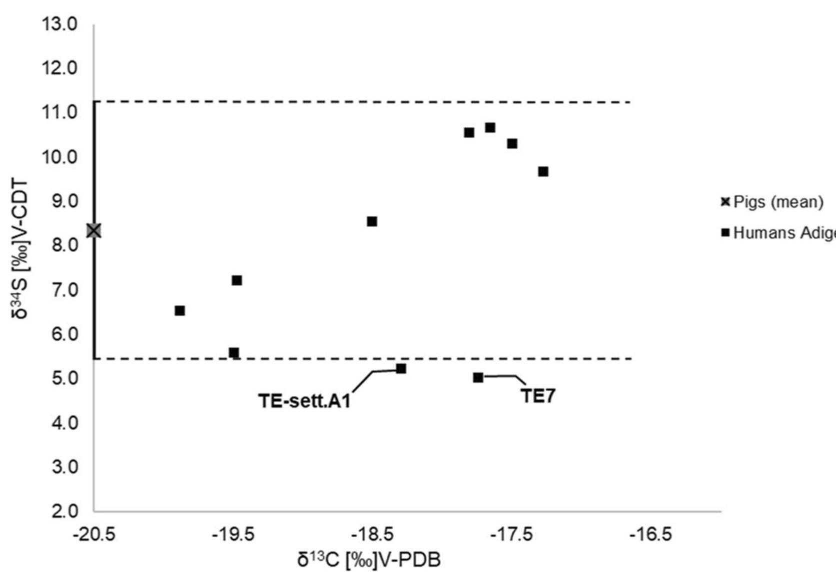
Isarco valley (BEN18) showed enriched δ^{15}N values (Table S1), which could be due to a lower proportion of herbivore meats (Δ6.4‰) in favour of omnivore meats, as also suggested by Knipper et al. (2012). Another explanation could be that these individuals (one male and one n.d.) had more in general a significant higher proportion of animal proteins in their diet compared to the other individuals of the same sites. Therefore, this could be an indicator of higher social status, as animal ressources were much more expensive to produce. Consumption of dairy products is the other possible cause of higher δ^{15}N values in humans. In Northern Italy, cheese was traditionally made with sheep or goats' milk (Flandrin and Montanari 2007). In the Alpine areas, cow milk was also used, as documented by the earlier evidences of dairy lipids in Iron Age vessels (Carrer et al. 2016).

Geological differences and mobility patterns in Early medieval South Tyrol

The isotopic variation of the δ^{34}S values of humans ($n = 40$) ranged from + 3.05 to + 10.66‰ (mean + 6.69 ± 1.90‰). In Adige valley, the human δ^{34}S values ranged from + 5.04 to + 10.66‰ (mean + 7.94 ± 2.28‰) displaying the higher standard deviation (± 2.28‰) compared to the other territories (Table 1). This might be explained by different hypotheses, such as (i) variation in dietary habits, (ii) different geological factors, (iii) mobility patterns. (i) A certain proportion of freshwater fish as a food source might be considered, due to the proximity to freshwater sources, and the finding of archaeological materials (e.g. hooks) would also suggest fishing in this area (Dal Ri 2009; Tecchiati 2009). However, at the present, there are still no available freshwater fish data from that area; thus, further conclusion on fish consumption in Early medieval South Tyrol cannot be made. (ii) The drinking water, as well as other nutritional sources, could have been enriched in sulphur, due to the presence of the aforementioned sulphurous water springs (Lunz 1974; Tecchiati and Zanforlin 2010). Nevertheless, other analyses are needed to better understand the implication of those springs to the local sulphur values. (iii) Based on the human values, there are some distinct differences between Adige and the other sites with enriched and varying δ^{34}S values in Adige. An explanation might be some mobility pattern (Vika 2009; Richards et al. 2001). The study of Coia et al. (2012) reported already a higher genetic diversity in modern populations in Adige compared to other valleys in Trentino, probably indicating that different populations went through Adige valley since prehistory. This was also documented by local archaeological data (Lanzinger et al. 2000). Due to the different sample sizes of the faunal remains per valley, the local baseline for Adige valley could be established based on non-migratory animals (pigs) (Fig. 8). The δ^{34}S mean value of the three pigs from Adige (+ 8.34‰ ± 2.89‰) showed a slightly more positive rate compared to the humans (Δ0.4‰). However, two individuals from the site of Terlano (TE7 and TE-sett.A1) showed lower values to the faunal baseline (5.04‰ and 5.24‰ respectively) and a difference of Δ3.2‰, and thus a possible different origin and/or a change in dietary habits is suggested. Of particular interest is the adult male TE7, as he was the only Early medieval individual in Terlano inhumated with a grave good (i.e. sharp object). However, the low sample size of non-migratory animals has to be considered and further baseline samples are required to verify the observations on possible migration.

Regarding the chronological phases, the highest δ^{34}S standard deviation (± 2.65‰) was recorded for phase 2 (seventh–eighth centuries AD), suggestive of greater human mobility during those centuries (Fig. 7b), and this would be in accordance with the few historical and

Fig. 8 Plotted δ^{13}C and δ^{34}S values of the humans from Adige valley. The δ^{34}S mean and SD of the pigs from the same site are indicated by the dashed lines representing the local baseline



archaeological sources. Particularly from the seventh century, allochthonous cultures (e.g. Langobards, Bavarians) were well-established in the territory, and the archaeological material indicates a cultural hybridity among autochthonous (christianized) and allochthonous traditions (Bierbrauer 2005). However, the tests did not show statistical differences when considering all phases (Table 2). Moreover, the radiocarbon dating was limited to 10% ($n = 4/40$) of the samples with good quality collagen for $\delta^{34}S$ analyses (Table S1).

Varying social status and grave goods

The higher $\delta^{15}N$ mean values in males compared to females (Table 1) could suggest sex related restrictions in the access to animal proteins, such as meat and dairy products with males as main consumers. This could also reflect diverse social positions, such as higher social ranks for male individuals (e.g. Czermak et al. 2006; Schutkowski and Herrmann 1999; Moghaddam et al. 2016). However, the nitrogen values of all males against females, independently from their age group, were not statistically significant (Table 2). Differences were observed when $\delta^{15}N$ values were tested based on sex in correlation with age classes, but only for Adige valley. In fact, the difference between males and females aged 20–40 years was statistically significant ($p = 0.030$; Table 2). This could be indicative of sex-specific dietary differences in this area, with males (20–40 years old) having a diet more rich in animal proteins (mean + 9.99 ± 0.69‰) compared to females (+ 9.80 ± 0.52‰). This is also in accordance with studies on prehistoric and historic populations, suggesting that males had a larger amount of meat and dairy product components in their diets (Moghaddam et al. 2016, 2018; Reitsema et al. 2010; Baldoni et al. 2016). However, when looking at isotopic differences between sexes, the metabolic variations as well as the different bone turnover rates in skeletal elements need to be considered (Fahy et al. 2017; Olsen et al. 2014).

The presence and the type of grave goods might also provide information about sex-specific dietary differences and/or social status (Le Huray and Schutkowski 2005). In the present study, the cemetery of Bressanone Elvas displayed the highest amount of grave goods compared to the other sites. Six males, four females, one adult n.d. and one infant were buried with goods and showed significantly increased $\delta^{15}N$ values (+ 10.63 ± 0.66‰) compared to those without any grave goods (two males, one females, one possibile female, three subadults; mean + 9.37 ± 0.69‰) (Table 1). This may be due to a higher number of males, with in general higher $\delta^{15}N$ mean values (+ 10.10 ± 0.74‰) in respect to females (+ 9.85 ± 0.58‰). Indeed, in Bressone Elvas, the majority of the individuals buried with weapons (e.g. knife, dagger) were males (57%, 4/7), and this could suggest not only sex specific dietary differences, with males having a more prestigious role, as reported in other studies (e.g. Le Huray and Schutkowski 2005, Moghaddam et al. 2018), but also a division based on social status, with the "weaponry group" having an increased amount of animal protein in their diet.

Conclusions

The analyses of $\delta^{15}N$, $\delta^{13}C$ and $\delta^{34}S$ data of human and faunal remains from three different valleys and one basin in South Tyrol were an effective approach to study, for the first time, the subsistence strategies, dietary behaviour and, for preliminary insights, mobility in Early medieval populations from the Italian Alps. The $\delta^{13}C$ values showed, for all individuals, a terrestrial diet based on C_3 plants with increasing proportions of C_4 plants (e.g. millet, sorghum) at lower altitudes. The data clearly indicated that differences in the subsistence are more dependent on the environmental context, mainly on altitudes, rather than on cultural influences. When comparing the sites and valleys, with regard to their geographical location and altitudes (m a.s.l.), enriched $\delta^{15}N$ values are noted at higher altitudes (Venosta valley), probably due to a diet richer in animal proteins and dairy products. Differences in $\delta^{15}N$ values might also be attributed to social status when considered in combination with recovered grave goods. The $\delta^{34}S$ data indicated higher variability in Adige valley compared to the other areas, suggesting greater mobility in Adige. In order to strengthen these findings, additional analyses are required. Future studies will include analyses of $\delta^{18}O$ and partially $^{87}Sr/^{86}Sr$, and the isotopic data will be crosschecked with genetic data, which is within the framework of the ongoing interdisciplinary project (BioArchEM).

Acknowledgements The study was achieved with the permission of Catrin Marzoli (*Ufficio 13.2 Beni archeologici*, Autonomous Province of Bolzano, Italy), who approved the sampling of the human and animal bone remains as well as the consultation of unpublished data. We wish to acknowledge the help provided by Wilfried Rosendahl (REM, Germany) for support of radiocarbon dating, Andreas Rossmann (IsoLab, Germany) for stable isotope measurements, Katrin Renner (Eurac Research) for Fig. 1 editing and George Logan for language editing. We thank the anonymous reviewers for their precious advices and support.

Funding Information Open Access funding provided by Projekt DEAL.

References

Acsádi G, Nemeskéri J (1970) History of human life span and mortality. Akadémiai Kiadó, Budapest

Albertoni G (2005) Romani e Germani come questione storiografica. In: Landi W (ed) Romani e Germani nel cuore delle Alpi tra V e VIII secolo. Athesia, Bolzano, pp 17–27

AlQathani SJ, Hector MP, Liversidge HM (2010) Brief communication: the London atlas of human tooth development and eruption. Am J Phys Anthropol 142:481–490. https://doi.org/10.1002/ajpa.21258

Ambrose SH (1990) Preparation and characterization of bone and tooth collagen for isotopic analysis. J Archaeol Sci 17:431–451. https://doi.org/10.1016/0305-4403(90)90007-R

Ambrose SH (1993) Isotopic analysis of Paleodiets: methodological and interpretive considerations. In: Sandford MK (ed) Investigations of ancient human tissue: chemical analyses in anthropology. Food and nutrition in history and anthropology. Gordon and Breach Science Publisher Ltd, New York

Baker BJ, Dupras TL, Tocheri MW (2005) The osteology of infants and children. Texas A&M UP, Texas

Baldoni M, Nardi A, Müldner G, Lelli R, Gnes M, Ferraresi F, Meloni V, Cerino P, Greco S, Manenti G, Angle M, Rickards O, Martínez-Labarga C (2016) Archaeobiological reconstruction of the Italian medieval population of Colonna (8th–10th centuries CE). J Archaeol Sci Rep 10:483–494. https://doi.org/10.1016/j.jasrep.2016.11.013

Banzi E (2005) Sistema daziario sulla rete viaria romana nel territorio altoatesino: vecchi e nuovi dati epigrafici. In: Ciurletti G, Pisu N (eds) I territori della Via Claudia Augusta. incontri di archeologia, Trento, pp 173–189

Barone R (1980) Anatomia comparata dei mammiferi domestici. In: Osteologia, vol I. Edagricole, Bologna

Bierbrauer V (1991) L'insediamento del Tardo Antico e alto Medioevo in Trentino-Alto Adige (V-VII secolo). Fondamentali caratteristiche archeologiche e notazioni per una carta sulla diffusione degli insediamenti. In: Menis GC (ed) Italia Longobarda. Marisilio editori, Venezia, pp 121–173

Bierbrauer V (2005) Romani e Germani fra V e VIII secolo dal punto di vista della ricerca archeologica. In: Landi W (ed) Romani e Germani nel cuore delle Alpi tra V e VIII secolo. Athesia, Bolzano, pp 213–239

Bocherens H, Drucker DG, Billiou D, Geneste JM, van der Plicht J (2006) Bears and humans in Chauvet cave (Vallon-Pont-d'Arc, Ardèche, France): insights from stable isotopes and radiocarbon dating of bone collagen. J Hum Evol 50(3):370–376. https://doi.org/10.1016/j.jhevol.2005.12.002

Bollongino R, Nehlich O, Richards MP, Orschiedt J, Thomas MG, Sell C, Fajkosova Z, Powell A, BurgeR J (2013) 2000 years of parallel societies in stone age Central Europe. Science 342(6157):479–481. https://doi.org/10.1126/science.1245049

Bonafini M, Pellegrini M, Ditchfield P, Pollard AM (2013) Investigation of the "canopy effect" in the isotope ecology of temperate woodlands. J Archaeol Sci 40(11):3926–3935

Brooks ST and Suchey JM (1990) Skeletal age determination based on the os pubis: a comparison of the Acsadi-Nemeskéri and Suchey-Brooks methods. Human Evolution 5:227–238

Buikstra JE, Ubelaker DH (1994) Standards of data collection from human skeletal remains, 44. Arkansas Archeological Survey Research, Fayetteville

Carrer F, Colonese AC, Lucquin A, Petersen Guedes E, Thompson A, Walsh K, Reitmaier T, Craig OE (2016) Chemical analysis of pottery demonstrates prehistoric origin for high-altitude Alpine dairying. PLoS One 11:ARTN e0151442. https://doi.org/10.1371/journal.pone.0151442

Castiglioni E, Tecchiati U (2005) Ricerche archeobotaniche nei livelli della tarda età del Rame di Velturno-Tanzgasse in val d'Isarco (BZ). Atti Acc Rov Agiati 255(5B):505–528

Cavada E (2004) Città territorio nell'alto medioevo alla luce delle fonti archeologiche. In: Castagnetti A, Varanin GM (eds) Storia del Trentino III, L'età medievale. Il Mulino, Bologna, pp 195–223

Cernusak LA, Tcherkez G, Keitel C, Cornwell WK et al (2009) Why are non-photosynthetic tissues generally 13C enriched compared to leaves in C3 plants? Review and synthesis of current hypotheses. Funct Plant Biol 36:199–213. https://doi.org/10.1071/Fp08216

Coia V, Boschi I, Trombetta F, Cavulli F, Montinaro F, Destro-Bisol G, Grimaldi S, Pedrotti A (2012) Evidence of high genetic variation among linguistically diverse populations on a micro-geographic scale: a case study of the Italian Alps. J Hum Genet 57(4):254–260. https://doi.org/10.1038/jhg.2012.14

Craig OE, Ross R, Andersen SH, Milner N, Bailey GN (2006) Focus: sulphur isotope variation in archaeological marine fauna from northern Europe. J Archaeol Sci 33:1642–1646

Craig OE, Biazzo M, O'Connell TC, Garnsey P, Martinez-Labarga C, Lelli R, Salvadei L, Tartaglia G, Nava A, Renó L, Fiammenghi A, Rickards O, Bondioli L (2009) Stable isotopic evidence for diet at the Imperial Roman coastal site of Velia (1st and 2nd centuries AD) in southern Italy. Am J Phys Anthropol 139:572–583. https://doi.org/10.1002/ajpa.21021

Czermak A, Ledderose A, Strott N, Meier T, Grupe G (2006) Social structures and social relations–an archaeological and anthropological examination of three early medieval separate burial sites in Bavaria. Anthropol Anz 64(3):297–310

Dal Ri L (2009) L'insediamento fortificato di Lamprecht nel comune di Appiano (Bolzano). Atti Acc. Rov. Agiati, a. 259, ser. VIII, vol IX, A, fasc. II, 1: 97–129

Dal Ri L, Rizzi G (1995) Il territorio atesino alla fine del VI e nel VII secolo d.C. In G.P. Brogiolo (Ed.). Città, castelli, campagne nei territori di frontiera (secoli VI-VII). 5° seminario sul tardoantico e l'alto medioevo in Italia centro-settentrionale. Monte Barro, 9-10 giugno 1994 (Documenti di archeologia, 6), Mantova 1995, pp 87–114

Dallago S (2016) Resti dell'abitato altomedievale di Villandro Plunacker (Bolzano): i reperti faunistici. Dissertation, University of Bologna, Italy

DeNiro MJ (1985) Postmortem preservation and alteration of invivo bone-collagen isotope ratios in relation to paleodietary reconstruction. Nature. 317:806–809. https://doi.org/10.1038/317806a0

DeNiro MJ, Epstein S (1978) Influence of diet on the distribution of carbon isotopes in animals. Geochim Cosmochim Acta 42:495–506. https://doi.org/10.1016/0016-7037(78)90199-0

Drucker DG, Bridault A, Hobson KA, Szuma E, Bocherens H (2008) Can carbon-13 in large herbivores reflect the canopy effect in temperate and boreal ecosystems? Evidence from modern and ancient ungulates. Palaeogeogr Palaeoclimatol Palaeoecol 266:69–82

Drucker DG, Bridault A, Cupillard C, Hujic A, Bocherens H (2011) Evolution of habitat and environment of red deer (Cervus elaphus) during the late-glacial and early Holocene in eastern France (French Jura and the western Alps) using multi-isotope analysis ($\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, $\delta^{34}S$) of archaeological remains. Quat Int 245:268–278

Ehleringer JR, Sage RF, Flanagan LB, Pearcy RW (1991) Climate change and the evolution of C4 photosynthesis. Trends Ecol Evol 6:95–99. https://doi.org/10.1016/0169-5347(91)90183-X

Ehleringer JR, Bowling DR, Flanagan LB, Fessenden J, Helliker B, Martinelli A, Ometto P (2002) Stable isotopes and carbon cycle processes in forests and grasslands. Plant Biol 4:181–189

Fahy GE, Deter C, Pitfield R, Miszkiewicz JJ, Mahoney P (2017) Bone deep: variation in stable isotope ratios and histomorphometric measurements of bone remodelling within adult humans. J Archaeol Sci 87:10–16. https://doi.org/10.1016/j.jas.2017.09.009

Fazekas IGY, Kósa F (1978) Forensic fetal osteology. Akademiai Kaido, Budapest

Ferembach D, Schwidetzky I, Stloukal M (1979) Empfehlungen für die Alters- und Geschlechtsdiagnose am Skelett. Homo 30:1–32

Ferrio JP, Voltas J, Araus JL (2003) Use of carbon isotope composition in monitoring environmental changes. Manag Environ Qual 14:82–98. https://doi.org/10.1108/14777830310460405

Festi D, Tecchiati U, Steiner H, Oeggl K (2011) The copper age settlement of Latsch: archaeobotanical and archaeozoological results from a valley settlement coeval to the alpine iceman and located in his valley of origin. Veget Hist Archaeobot 20(5):367–379. https://doi.org/10.1007/s00334-011-0308-0

Flandrin JL, Montanari M (2007) Storia dell'alimentazione. Editori Laterza, Roma

Fry B (2006) Stable isotope ecology. Springer-Verlag, New York

Fuller BT, De Cupere B, Marinova E, Van Neer W, Waelkens M, Richards MP (2012) Isotopic reconstruction of human diet and animal husbandry practices during the classical-Hellenistic, imperial, and byzantine periods at Sagalassos, Turkey. Am J Phys Anthropol 149:57–171

Gasparri S, La Rocca C (2013) Tempi barbarici. In: L'Europa occidentale tra antichità e medioevo 300-900. Carrocci Editore, Roma

Giostra C, Lusuardi Siena S (2004) Le popolazioni germaniche in Italia: le testimonianze di epoca altomedievale a sud dello spartiacque alpino. In: Gleirscher P, Marzatico F (eds) Guerrieri Principi ed Eroi fra il Danubio e il Po dalla preistoria all'alto Medioevo. Museo Castello Buonconsiglio, Trento, pp 513–527

Guiry EJ (2012) Dogs as analogs in stable isotope-based human palaeodietary reconstruction. J Archaeol Method Theory 19(3): 351–376. https://doi.org/10.1007/s10816-011-9118-z

Haas-Gebhard B (2004) A Nord delle Alpi: Franchi, Alamanni e Baiuvari. In: Gleirscher P, Marzatico F (eds) Guerrieri Principi ed Eroi fra il Danubio e il Po dalla preistoria all'alto Medioevo. Museo Castello Buonconsiglio, Trento, pp 529–540

Hakenbeck S, McManus E, Geisler H, Grupe G, O'Connell T (2010) Diet and mobility in early medieval Bavaria: a study of carbon and nitrogen stable isotopes. Am J Phys Anthropol 143(2):235–249. https://doi.org/10.1002/ajpa.21309

Hakenbeck SE, Evans J, Chapman H, Fóthi E (2017) Practicing pastoralism in an agricultural environment: an isotopic analysis of the impact of the Hunnic incursions on Pannonian populations. PLoS One 12(3):e0173079. https://doi.org/10.1371/journal.pone.0173079

Halffman CM, Velemínský P (2015) Stable isotope evidence for diet in early medieval great Moravia (Czech Republic). J Archaeol Sci 2:1–8. https://doi.org/10.1016/j.jasrep.2014.12.006

Hedges REM, Reynard LM (2007) Nitrogen isotopes and the trophic level of humans in archaeology. J Archaeol Sci 34:1240–1125

Heitmeier I (2005) Das Inntal. Siedlungs-und Raumentwicklung eines Alpentales im Scnittpunkt der politischen Interessen von der römischen Okkupation bis in die Zeit Karls des Großen. Studien zur Frühgeschichte des historischen Tiroler Raumes I. (Schlern-Schriften). Wagner Innsbruck, Innsbruck

Hemer KA, Evans JA, Chenery CA, Lamb AL (2013) Evidence of early medieval trade and migration between Wales and the Mediterranean Sea region. J Archaeol Sci 40:2352–2359

Hoefs J (2009) Stable isotope geochemistry. Springer-Verlag, Berlin, Heidelberg

Hoogewerff J, Papesch W (2001) The last domicile of the iceman from Hauslabjoch: a geochemical approach using Sr, C and O isotopes and Trace element signatures. J Archaeol Sci 28:983–989. https://doi.org/10.1006/jasc.2001.0659

Hughes MK, Diaz HF (1994) The medieval warm period. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-1186-7

Iacumin P, Galli E, Cavalli F, Cecere L (2014) C4-consumers in southern Europe: the case of Friuli V.G. (NE-Italy) during early and central Middle Ages. Am J Phys Anthropol 154:561–574. https://doi.org/10.1002/ajpa.22553

Katzenberg MA (2008) Stable isotope analysis: a tool for studying past diet, demography, and life history. In: Katzenberg MA, Saunders SR (eds) Biological anthropology of the human skeleton. Wiley-Liss, Hoboken, pp 413–441

Kaufmann G, Demetz S (2004) Dal riparo alla città. Cenni sulla preistoria e sulla prima storia di Bressanone. In: Fuchs B, Heiss H, Milesi C, Pfeifer G (eds) Bressanone. I. La storia. Athesia, Lana, pp 29–88

Knipper C, Peters D, Meyer C, Maurer AF, Muhl A, Schöne BR, Alt KW (2012) Dietary reconstruction in migration period Central Germany: a carbon and nitrogen isotope study. Archaeol Anthropol Sci 5(1): 17–35. https://doi.org/10.1007/s12520-012-0106-3

Kustatscher E, Romeo C (2010) Passaggi e prospettive, lineamenti di storia locale 1. In: L'area tirolese dalla preistoria al tardo Medioevo. Athesia, Bolzano

Laffranchi Z, Delgado-Huertas A, Jiménez-Brobeil SA, Granado-Torres A, Riquelme-Cantal JA (2016) Stable C & N isotopes in 2100 year-B.P. human bone collagen indicate rare dietary dominance of C4 plants in NE-Italy. Sci Rep 6:38817. https://doi.org/10.1038/srep38817

Lanzinger M, Marzatico F, Pedrotti A (2000) Storia del Trentino I. In: La preistoria e la protostoria. Il Mulino, Bologna

Le Huray JD, Schutkowski H (2005) Diet and social status during the La Tène period in Bohemia: carbon and nitrogen stable isotope analysis of bone collagen from Kutná Hora-Karlov and Radovesice. J Anthropol Archaeol 24:135–147. https://doi.org/10.1016/j.jaa.2004.09.002

Lee-Thorp JA (2008) On isotopes and old bones. Archaeometry 50:925–950. https://doi.org/10.1111/j.1475-4754.2008.00441.x

Lee-Thorp JA, Sealy JC, Van der Merwe NJ (1989) Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. J Archaeol Sci 16:585–599

Longin R (1971) New method of collagen extraction for radiocarbon dating. Nature 230:241–242. https://doi.org/10.1038/230241a0

Lösch S (2009) Paläopathologisch-anthropologische und molekulare Untersuchungen an mittelalterlichen und frühneuzeitlichen Bevölkerungsgruppen Ernährung und Gesundheitszustand süd- und nordbayerischer Bevölkerungsstichproben. Dissertation, Universität München, Germany. Available at https://edoc.ub.uni-muenchen.de/9899/

Lösch S, Gruppe G, Peters J (2006) Stable isotopes and dietary adaptations in humans and animals at pre-pottery Neolithic Nevalli Cori, Southeast Anatolia. Am J Phys Anthropol 131:181–193. https://doi.org/10.1002/ajpa.20395

Lösch S, Moghaddam N, Grossschmidt K, Risser DU, Kanz F (2014) Stable isotope and Trace element studies on gladiators and contemporary romans from Ephesus (Turkey, 2nd and 3rd Ct. AD) - implications for differences in diet. PLoS One 9(10). https://doi.org/10.1371/journal.pone.0110489

Lunz R (1974) Studien zur End-Bronzezeit und älteren Eisenzeit im Südalpenraum. Sansoni, Firenze

Macko SA, Lubec G, Teschler-Nicola M, Andrusevich V, Engel MH (1999) The ice man's diet as reflected by the stable nitrogen and carbon isotopic composition of his hair. FASEB J 13:559–562
Mann ME, Zhang Z, Rutherford S, Bradley RS, Hughes MK, Shindell D, Ammann C, Faluvegi G, Ni F (2009) Global signatures and dynamical origins of the little ice age and medieval climate anomaly. Science 326(5957):1256–1260. https://doi.org/10.1126/science.1177303
Maresh MM (1970) Measurements from roentgenograms, heart size, long bone lengths, bone, muscle and fat widths, skeletal maturation. In: McCammon RW (ed) Human growth and development. Charles C. Thomas, Springfield, pp 155–200
Marzoli C (2002) Die Kirchengrabung von Tirol. In: Dal Ri L, Di Stefano S (eds) Archeologia romana in Alto Adige, Beni Culturali in Alto Adige, Studi e ricerche 1. Folio Editore, Bolzano, pp 1053–1069
Marzoli C, Bombonato G, Rizzi G (2009) Nuovi dati archeologici sull'insediamento tardo antico-altomedievale della Valle dell'Adige tra la Merano basin e Salorno. Atti Acc. Rov. Agiati, 259 ser. VIII, vol IX, A, fasc. II, 1: 145–183
McGlynn G (2007) Using ^{13}C-, ^{15}N- and ^{18}O stable isotope analysis of human bone tissue to identify transhumance, high altitude habitation and reconstruct palaeodiet for the early medieval Alpine population at Volders, Austria. Dissertation, Universität München, Germany. Available at http://edoc.ub.uni-muenchen.de/7327/1/McGlynn_George.pdf.pdf
Meier-Augenstein W (2010) Stable isotope forensics. An introduction to the forensic application of stable isotope analysis. Wiley, Chichester
Meindl RS, Lovejoy CO (1985) Ectocranial suture closure: a revised method of age determination of skeletal age at death based on the lateral-anterior sutures. Am J Phys Anthropol 68:57–66
Minagawa M, Wada E (1984) Stepwise enrichment of ^{15}N along food chains. Geochim Cosmochim Acta 48:1135–1140. https://doi.org/10.1016/0016-7037(84)90204-7
Moghaddam N, Müller F, Hafner A, Lösch S (2016) Social stratigraphy in late Iron age Switzerland: stable carbon, nitrogen and sulphur isotope analysis of human remains from Münsingen. Archaeol Anthropol Sci 8:149–160. https://doi.org/10.1007/s12520-014-0221-4
Moghaddam N, Müller F, Lösch S (2018) A bioarchaeological approach to the Iron age in Switzerland: stable isotope analyses (δ^{13}C, δ^{15}N, δ^{34}S) of human remains. Archaeol Anthropol Sci 10(5):1067–1085. https://doi.org/10.1007/s12520-016-0441-x
Montanari M, Baruzzi M (1981) Porci e porcari nel Medioevo: paesaggio, economia, alimentazione. CLUEB, Bologna
Murail P, Bruzek J, Houët F, Cunha E (2005) DSP: a tool for probabilistic sex diagnosis using worldwide variability in hip-bone measurements. Bul Mém Soc Anthrop Paris 17(3–4):167–176
Nehlich O (2015) The application of sulphur isotope analyses in archaeological research: a review. Earth Sci Rev 142:1–17. https://doi.org/10.1016/j.earscirev.2014.12.002
Nehlich O, Richards MP (2009) Establishing collagen quality criteria for sulphur isotope analysis of archaeological bone collagen. Archaeol Anthropol Sci 1:59–75
Nehlich O, Fuller BT, Jay M, Mora A, Nicholson RA, Smith CI, Richards MP (2011) Applications of sulphur isotope ratios to examine weaning patterns and freshwater fish consumption in Roman Oxfordshire, UK. Geochim Cosmochim Acta 75:4963–4977. https://doi.org/10.1016/j.gca.2011.06.009
Nehlich O, Fuller BT, Márquez-Grant N, Richards MP (2012) Investigation of diachronic dietary patterns on the islands of Ibiza and Formentera, Spain: evidence from sulfur stable isotope ratio analysis. Am J Phys Anthropol 149:115–124. https://doi.org/10.1002/ajpa.22104
Nehlich O, Oelze V, Jay M, Conrad M, Stäuble H, Teegen W, Richards MP (2014) Sulphur isotope ratios of multi-period archaeological skeletal remains from Central Germany: a dietary and mobility study. Anthropologie (BRNO) LII:15–33
Nelson DE, Angerbjörn A, Lidén K, Turk I (1998) Stable isotopes and the metabolism of the European cave bear. Oecologia 116:177–181. https://doi.org/10.1007/s004420050577
Nisbet R (2008) Wood use and agriculture at Villandro/Villanders (Bolzano/Bozen, alto Adige/South Tyrol): the charred remains from Mesolithic to middle ages. Atti Soc Preist Protost Friuli- V.G., Trieste, pp 75–131
Oelze V, Koch JK, Kupke K, Nehlich O, Zäuner S, Wahl J, Weise SM, Rieckhoff S, Richards MP (2012) Multi-isotopic analysis reveals individual mobility and diet at the early Iron age monumental tumulus of Magdalenenberg, Germany. Am J Phys Anthropol 148:406–421. https://doi.org/10.1002/ajpa.22063
Öggl KD (1993) Die Planzenreste aus der Ausgrabung bei der Kirche Sankt Laurentius, in Der Vinschgau und seine Nachbarräume. Vorträge des landeskundlichen Symposiums veranstaltet vom Südtiroler Kulturinstitut in Verbindung mit dem Bildunghaus Schloss Goldrain: Schloss Goldrain 27. Bolzen pp 65–69
Olsen KC, White CD, Longstaffe FJ, von Heyking K, McGlynn G, Grupe G, Rühli FJ (2014) Intraskeletal isotopic compositions (δ(13) C, δ(15) N) of bone collagen: nonpathological and pathological variation. Am J Phys Anthropol 153(4):598–604. https://doi.org/10.1002/ajpa.22459
Ortolani F, Pagliuca S (2007) Evidenze geologiche di variazioni climatico-ambientalistoriche nell'Area Mediterranea. In: Wezel F (ed) Variabilità naturale del clima nell'Olocene ed in tempi storici: un approccio geologico. Società Geologica Italiana, Roma, pp 13–17
Polet C, Katzenberg MA (2003) Reconstruction of the diet in a mediaeval monastic community from the coast of Belgium. J Archaeol Sci 30:525–533. https://doi.org/10.1016/S0305-4403(02)00183-8
Prevedorou E, Díaz-Zorita Bonilla M, Romero A, Buikstra J, Paz de Miguel Ibáñez M, Knudson KJ (2010) Residential mobility and dental decoration in early medieval Spain: results from the eighth century site of plaza del Castillo, Pamplona. Dent Anthropol 23(2):42–52
Privat K, O'Connell TC, Hedges REM (2007) The distinction between freshwater and terrestrial-based diets: methodological concerns and archaeological applications of sulphur stable isotope analysis. J Archaeol Sci 34:1197–1204. https://doi.org/10.1016/j.jas.2006.10.008
Reitsema LJ, Vercellotti G (2012) Stable isotope evidence for sex- and status-based variations in diet and life history at medieval Trino Vercellese, Italy. Am J Phys Anthropol 148:589–600. https://doi.org/10.1002/ajpa.22085
Reitsema LJ, Crews DE, Polcyn M (2010) Preliminary evidence for medieval polish diet from carbon and nitrogen. J Archaeol Sci 37:1413–1423. https://doi.org/10.1016/j.jas.2010.01.001
Reuß OM (2016) St. Stephan ob Burgeis im Kontext des mittelalterlichen Kirchenbaus im Alpenraum. In: Auswertung der Grabungen und historische Kontextualisierung. Verlag Dr.Kovač, Hamburg
Richards MP, Hedges REM, Molleson TI, Vogel JC (1998) Stable isotope analysis reveals variations in human diet at the Poundbury camp cemetery site. J Archaeol Sci 25:1247–1252. https://doi.org/10.1006/jasc.1998.0307
Richards MP, Fuller BT, Hedges REM (2001) Sulphur isotopic variation in ancient bone collagen from Europe: implications for human paleodiet, residence mobility and modern pollutant studies. Earth Planet Sci Lett 191:185–190. https://doi.org/10.1016/S0012-821X(01)00427-7
Richards MP, Pearson JA, Molleson TI, Russell N, Martin L (2003) Stable isotope evidence of diet at Neolithic Çatalhöyük, Turkey. J Archaeol Sci 30(1):67–76. https://doi.org/10.1006/jasc.2001.0825
Riedel A (1979) Die Fauna einer frühmittelalterlichen Siedlung in Stufels bei Brixen. Der Schlern 53(7):3–23

Sardagna M, Tecchiati U (2010) La fauna dell'abitato del primo Medioevo di San Genesio, Loc. SS. Cosma e Damiano (Bolzano). Scavi 2005, in Atti del 5° Convegno Nazionale di Archeozoologia, Rovereto

Schaefer M, Black S, Scheuer L (2009) Developmental juvenile osteology: A Laboratory and Field Manual. Elsevier Academic Press, London

Scheeres M, Knipper C, Hauschild M, Schönfelder M, Siebel W, Vitali D et al (2013) Evidence for "Celtic migrations"? Strontium isotope analysis at the early La Tène (LT B) cemeteries of Nebringen (Germany) and Monte Bibele (Italy). J Archaeol Sci 40(10):3614–3625

Schmid E (1972) Atlas of animal bones: for prehistorians. Archaeologists and Quaternary Geologists. Elsevier Pub. Co, New York

Schoeniger MJ, DeNiro MJ (1984) Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. Geochim Cosmochim Acta 43:625–638. https://doi.org/10.1016/0016-7037(84)90091-7

Schutkowski H, Herrmann B (1999) Diet, status and decomposition at Weingarten: trace element and isotope analyses on early mediaeval skeletal material. J Archaeol Sci 26:675–685. https://doi.org/10.1006/jasc.1998.0384

Suchey JM, Katz D (1986) Skeletal age standards derived from an extensive multiracial sample of modern Americans. Paper presented at the 55th annual meeting of the American Association of Physical Anthropologists, Albuquerque, NM

Tafuri MA, Graig OE, Canci A (2009) Stable isotope evidence for the consumption of millet and other plants in bronze age Italy. Am J Phys Anthropol 139:146–153. https://doi.org/10.1002/ajpa.20955

Tafuri MA, Goude G, Manzi G (2018) Isotopic evidence of diet variation at the transition between classical and post-classical times in Central Italy. J Archaeol Sci Rep 21:496–503. https://doi.org/10.1016/j.jasrep.2018.08.034

Tecchiati U (2009) I resti faunistici dell'abitato tardoantico e del primo Medioevo di Lamprecht presso Appiano. Atti Acc. Rov. Agiati, 259, ser. VIII, vol IX, A, fasc. II, 1: 131–143

Tecchiati U, Zanforlin L (2010) Topografia archeologica della Bassa Atesina (Prov. di Bolzano). In: Dal Ri L, Gamper P, Steiner H (eds). Höhensiedlungen der Bronze- und Eisenzeit. Kontrolle der Verbindungswege über die Alpen – Abitati d'altura dell'età del Bronzo e del Ferro. Controllo delle vie di comunicazione attraverso le Alpi. Forschungen zur Denkmalpflege in Südtirol, VI, Beni culturali in Alto Adige. Studi e ricerche, pp 597–646

Tinner W, Lotter AF, Ammann B (2003) Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to 800 AD. Quat Sci Rev 22:1447–1460. https://doi.org/10.1016/S0277-3791(03)00083-0

Ubelaker DH (1978) Human skeletal remains: excavation, analysis and interpretation. Taraxacum, Washington

Van der Merwe NJ, Medina E (1991) The canopy effect, carbon isotope ratios and foodwebs in Amazonia. J Archaeol Sci 18:249–259. https://doi.org/10.1016/0305-4403(91)90064-V

Van Klinken GJ (1999) Bone collagen quality indicators for Palaeodietary and radiocarbon measurements. J Archaeol Sci 26(6):687–695. https://doi.org/10.1006/jasc.1998.0385

Van Klinken GJ, Richards MP, Hedges REM (2000) An overview of causes for stable isotopic variations in past European human populations: environmental, Ecophysiological, and cultural effects. In: Ambrose SH, Katzenberg MA (eds) Biogeochemical approaches to Paleodietary analysis. Kluwer Academic/Plenum Publisher, New York, pp 39–63

Varalli A, Moggi-Cecchi J, Dori I, Boccone S, Bortoluzzi S, Salzani P, Tafuri MA (2016) Dietary continuity vs. discontinuity in bronze age Italy. The isotopic evidence from Arano di Cellore (Illasi, Verona, Italy). J Archaeol Sci Rep 7:104–113. https://doi.org/10.1016/j.jasrep.2016.03.047

Vika E (2009) Strangers in the grave? Investigating local provenance in a Greek bronze age mass burial using delta S_{34} analysis. J Archaeol Sci 36:2024–2028. https://doi.org/10.1016/j.jas.2009.05.022

Winckler C (2012) Die Alpen im Frühmittelalter, Die Geschichte eines Raumes in den Jahren 500 bis 800. Böhlau, Wien

Supplementary Tables (Article III)

Table S1. Animal samples description and bone collagen $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values. Underline = samples excluded from the statistical analyses due to insufficient collagen quality; grey shaded = individual is an outlier for this value and was not considered for the statistical analysis; italicized and underlined value = this one quality criteria is just not within the stated range, but the sample was considered for the statistical test.

Table S2. Human samples description, relative and radiocarbon dating as well as the $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ isotopic results. Bold = good quality samples for $\delta^{34}S$ data inaddition to $\delta^{13}C$, $\delta^{15}N$ values; underline = samples excluded from the statistical analyses due to insufficient collagen quality; gray shaded = outliers notconsidered for the statistical analysis; italicized and underlined value = the quality criteria is not within the stated range, but this sample was considered forthe statistical test. The asterisk (*) indicates relative chronologies. Unpublished calibrated radiocarbon dates are marked with a double asterisks (**), whereasthe dates of Appiano and Montagna Pinzano were published by Marzoli et al. (2009), Castel Tirolo by Marzoli (2002) and Malles Burgusio S. Stefano by Reuß (2016). Chronological phase 1: fifth–seventh c. AD, phase 2: seventh–eighth c. AD, phase 3: eighth–tenth c. AD, phase 4: ninth–twelfth c. AD.

Table S1

Valley or Basin	Site	Burial's location	Sample ID	Bone	^{14}C (BP)/2 sigma cal. AD (probability %) or Relative dating (in centuries)	Chronological Phase	Grave goods	Sex	Age class	Yield (%)	$\delta^{13}C_{V-PDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	$\delta^{34}S_{V-CDT}$ (‰)	%C	%N	%S	C:N ratio	C:S ratio	N:S ratio
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenbur	hill	AP-AL1	femur	7th-8th AD	Phase 2	-	F	Adult	9.7	-18.16	9.55	12.31	45.1	16.4	0.10	3.2	1204	375
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg		AP-AL2	femur	1290±35 BP/650-780 AD (93.8%)	Phase 2	-	F	Adult	9.4	-17.30	9.33	9.72	46.8	17.2	0.11	3.2	1136	358
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg		AP-AL-INF	skull	7th-8th AD	Phase 2	-	ND	Newborn	6.1	-17.49	10.36	10.34	44.8	15.9	0.17	3.3	704	214
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenbur		AP-AL4	humerus	7th-8th AD	Phase 2	-	F	Adult	9.4	-17.20	9.77	11.10	47.8	17.5	0.17	3.2	751	236
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg		AP-AL5	skull	7th-8th AD	Phase 2	-	M	Adult	2.6	-17.81	10.25	10.55	42.4	15.3	0.18	3.2	629	195
Adige/Etschtal	Montagna Pinzano/Montan Pinzo		MO-P1	skull	7th-8th AD	Phase 2	-	M	Adult	2.4	-16.26	9.59	8.41	43.5	15.8	0.11	3.2	1056	329
Adige/Etschtal	Montagna Pinzano/Montan Pinzo		MO-P2	humerus	1295±40 BP/656-782 AD (95.9%)	Phase 2	-	M	Adult	0.0			insufficient collagen preservatio						
Adige/Etschtal	Montagna Pinzano/Montan Pinzo		MO-P4	skull	7th-8th AD	Phase 2	accessory and knife	M	Mature	2.7	-18.18	10.14	10.51	42.9	15.6	0.12	3.2	954	298
Adige/Etschtal	Montagna Pinzano/Montan Pinzon		MO-P5	long bone	1350±40 BP/637-725 AD (82.8%	Phase 2	accessories	ND	Juvenile	4.9	-17.28	9.73	9.68	43.1	15.7	0.17	3.2	677	211
Adige/Etschtal	Montagna Pinzano/Montan Pinzo		MO-P6	femur	7th-8th AD	Phase 2	accessories	F	Adult	3.3	-17.80	9.08	8.07	43.8	16.1	0.12	3.2	974	307
Adige/Etschtal	Montagna Pinzano/Montan Pinzon		MO-P7	skull	7th-8th AD	Phase 2	-	F	Adult	3.7	-18.51	9.73	8.55	40.0	14.5	0.15	3.2	712	221
Adige/Etschtal	Nalles/Nals		NA1	femur	1259±26 BP/671-858 AD (95.4%)**	Phase 2	accessories	F	Adult	5.1	-18.53	9.30	10.70	*47.1*	17.2	0.12	3.2	1048	328
Adige/Etschtal	Terlano/Terlar	valley floor, church	TE1	femur	8th-10th AD	Phase 3	-	M	Mature	2.1	-18.76	8.53	7.63	41.9	15.2	0.13	3.2	860	268
Adige/Etschtal	Terlano/Terlan		TE2	skull	8th-10th AD	Phase 3	-	M	Mature	3.7	-17.66	10.32	10.66	45.2	16.4	0.18	3.2	670	209
Adige/Etschtal	Terlano/Terlar		TE3	femur	8th-10th AD	Phase 3	-	F	Adult	1.0	-16.81	9.91	7.63	36.7	12.7	0.11	3.4	891	264
Adige/Etschtal	Terlano/Terlar		TE4	skull	8th-10th AD	Phase 3	-	F	Adult	1.2	-16.32	9.99	7.54	39.6	14.7	0.12	3.1	881	280
Adige/Etschtal	Terlano/Terlan		TE7	skull	1157±40 BP/770-990 AD (95.4%)*	Phase 3	sharp object	M	Adult	2.4	-17.75	10.54	5.04	41.9	15.1	0.18	3.2	621	192
Adige/Etschtal	Terlano/Terlar		TE10	femur	8th-10th AD	Phase 3	-	M	Mature	3.5	-18.46	9.14	6.54	42.5	15.5	0.12	3.2	945	296
Adige/Etschtal	Terlano/Terlan		TE12	humerus	8th-10th AD	Phase 3	-	F	Adult	4.0	-19.48	9.30	7.22	44.0	16.1	0.18	3.2	653	205
Adige/Etschtal	Terlano/Terlan		TE13	femur	8th-10th AD	Phase 3	-	ND	Adult	9.1	-19.89	9.29	6.54	45.3	16.5	0.17	3.2	711	222
Adige/Etschtal	Terlano/Terlan		TE-sett.A1	skull	-	-	-	M?	Adult	6.1	-18.30	10.06	5.24	46.0	16.9	0.17	3.2	722	228
Adige/Etschtal	Terlano/Terlan		TE-US45	skull	-	-	-	M	Adult	1.6	-19.49	9.87	5.62	39.6	14.2	0.18	3.3	587	181
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro	hill, church	TCT6A	femur	-	-	-	ND	Infant 2nd	4.6	-19.32	9.96	3.28	43.1	16.0	0.13	3.1	885	282
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT6B	femur	-	-	-	ND	Infant 1st	2.8	-19.28	9.96	5.18	44.5	16.3	0.12	3.2	990	311
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT8A	skull	-	-	-	ND	Infant 1st	4.9	-17.98	11.22	5.25	41.5	15.2	0.12	3.2	923	290
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol		TCT8B	humerus	-	-	-	ND	Newborn	5.1	-16.44	10.55	4.37	46.0	16.9	0.17	3.2	722	228
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT9	skull	-	-	-	ND	Infant 1st	6.9	-18.44	9.92	5.35	45.9	16.9	0.12	3.2	1021	322
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol		TCT10	skull	-	-	-	ND	Infant 1st	2.0	-17.59	11.72	5.34	43.8	15.7	0.16	3.3	731	225
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT11A	skull	-	-	-	ND	Infant 1st	2.8	-17.50	10.10	3.84	40.2	14.3	0.14	3.3	767	234
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT12	femur	-	-	-	M	Adult	3.2	-19.27	9.88	3.25	43.6	15.9	0.14	3.2	831	260
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT13	skull	-	-	-	ND	Infant 2nd	7.7	-17.68	9.51	5.06	44.8	16.5	0.10	3.2	1196	378
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT14	skull	-	-	-	ND	Juvenile	5.1	-18.37	9.35	6.20	44.5	16.5	0.13	3.1	914	291
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT15A	skull	-	-	-	M	Adult	7.5	-15.84	9.52	8.06	44.2	16.3	0.12	3.2	983	311
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT15B	femur	-	-	-	ND	Perinata	7.5	-18.00	9.78	4.83	44.0	16.1	0.12	3.2	979	307
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT15C	femur	-	-	-	ND	Newborn	3.1	-18.68	9.76	6.67	40.4	14.6	0.11	3.2	980	304
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT17	skull	1040±55 BP/888-1062 AD (85.7%)	Phase 4	accessories	ND	Infant 2nd	2.0	-19.23	9.99	4.49	47.4	17.4	0.15	3.2	844	266
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT18A	skull	1438±45 BP/540-670 AD (95.4%)**	Phase 1	accessory	M	Adult	5.3	-18.60	9.71	5.98	41.9	15.4	0.11	3.2	1017	320
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol		TCT19	humerus	-	-	-	M	Mature	1.8	-19.07	10.25	4.17	43.1	16.0	0.15	3.1	767	244
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT20	skull	-	-	-	ND	Infant 2nd	3.7	-18.92	9.71	4.73	44.4	16.3	0.12	3.2	988	311
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol		TCT21-22A	skull	-	-	-	ND	Infant 1st	6.3	-18.90	10.29	6.02	43.8	16.1	0.11	3.2	1063	335
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol		TCT24	tibia	-	-	-	ND	Infant 1st	1.4	-19.38	9.03	6.76	40.8	14.9	0.18	3.2	605	189
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT25B	skull	-	-	-	ND	Infant 1st	2.5	-17.55	12.82	4.99	43.0	15.7	0.13	3.2	883	276
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol		TCT26	femur	-	-	-	M	Adult	1.2	-20.08	8.53	3.25	42.8	15.2	0.18	3.3	635	193
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol		TCT27	femur	-	-	-	F	Adult	1.5	-20.25	8.18	3.05	42.0	15.0	0.17	3.3	660	202
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT31	tibia	-	-	-	ND	Perinata	3.0	-18.16	11.01	4.60	43.9	15.8	0.12	3.2	977	301
Merano basin/Meraner Becke	Castel Tirolo/Schloss Tiro		TCT92c.1	skull	-	-	-	ND	Infant 1st	5.0	-18.48	10.91	4.34	45.4	16.5	0.12	3.2	1010	315
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas	hill	BEN2B	skull	end 6th - half 7th AD	Phase 1	-	ND	Infant 2nd	9.1	-17.31	9.04	7.75	*47.1*	17.2	0.19	3.2	662	207
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN4	skull	end 6th - half 7th AD	Phase 1	-	M	Adult	5.5	-19.26	9.36	6.81	45.5	16.0	0.18	3.3	675	203
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elva		BEN5	skull	end 6th - half 7th AD	Phase 1	accessories	M	Adult	5.4	-19.24	10.73	7.29	48.0	17.4	0.18	3.2	712	221
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN8	skull	end 6th - half 7th AD	Phase 1	accessory	F	Adult	4.6	-19.49	9.90	5.51	45.5	16.4	0.18	3.2	675	209
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN9A	femur	end 6th - half 7th AD	Phase 1	-	ND	Juvenile	9.6	-18.65	9.37	4.84	45.6	16.6	0.17	3.2	716	224
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN11	skull	end 6th - half 7th AD	Phase 1	accessory	F	Adult	7.1	-18.97	10.56	9.61	45.8	16.5	0.19	3.2	644	199
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN12	skull	end 6th - half 7th AD	Phase 1	accessory	M	Adult	8.9	-19.63	10.67	6.90	43.7	15.7	0.18	3.2	648	200
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN13	tibia	end 6th - half 7th AD	Phase 1	accessories	F	Adult	9.4	-19.85	9.39	7.54	46.0	16.8	0.20	3.2	614	192
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN14	skull	end 6th - half 7th AD	Phase 1	-	F	Adult	7.3	-17.98	9.92	6.81	44.1	15.8	0.16	3.3	736	226
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN18	skull	end 6th - half 7th AD	Phase 1	knife	ND	Adult	7.4	-19.03	11.44	7.08	44.4	16.2	0.19	3.2	624	195
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN22	skull	end 6th - half 7th AD	Phase 1	accessories and sax	M	Adult	9.7	-19.13	10.30	7.59	45.5	16.6	0.15	3.2	810	253
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN24	skull	end 6th - half 7th AD	Phase 1	accessories and knife	ND	Infant 1st	4.8	-18.72	11.58	8.42	43.7	15.5	0.16	3.3	729	222
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN27	skull	end 6th - half 7th AD	Phase 1	accessories and knife	M	Adult	7.0	-19.13	10.85	7.51	45.8	16.5	0.18	3.2	679	210
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN28	skull	end 6th - half 7th AD	Phase 1	-	F?	Mature	7.1	-17.17	8.06	5.64	45.4	16.5	0.17	3.2	713	222
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN29	skull	end 6th - half 7th AD	Phase 1	knife	F	Mature	6.0	-19.46	11.06	7.68	42.3	15.0	0.19	3.3	594	181
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN31	skull	end 6th - half 7th AD	Phase 1	-	M	Adult	4.3	-16.82	9.68	6.12	44.5	15.6	0.20	3.3	594	179
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN35	skull	end 6th - half 7th AD	Phase 1	accessory and scramasax	M	Mature	6.8	-18.96	10.17	7.29	44.4	16.0	0.18	3.2	658	203
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN37	skull	end 6th - half 7th AD	Phase 1	accessories and knife	M	Senile	4.7	-18.70	11.31	7.74	46.4	16.5	0.20	3.3	619	189
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN41	skull	end 6th - half 7th AD	Phase 1	accessory	M	Mature	6.4	-18.67	10.33	7.15	45.8	16.6	0.17	3.2	719	224
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN45	skull	end 6th - half 7th AD	Phase 1	-	ND	Infant 1st	9.3	-17.65	13.74	7.47	43.1	15.8	0.16	3.2	719	226
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas		BEN46	skull	end 6th - half 7th AD	Phase 1	-	ND	Infant 2nd	7.0	-19.78	10.15	6.50	42.0	15.2	0.16	3.2	701	217
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elva		BEN49	skull	end 6th - half 7th AD	Phase 1	-	F	Mature	9.5	-19.62	10.22	7.30	47.3	17.4	0.16	3.2	789	249
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan	mountainous area, church	BSS142	femur	660-700 AD*	Phase 2	-	F	Senile	4.0	-19.62	9.45	3.96	43.1	15.9	0.15	3.2	767	243
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS163A	humerus	640-660 AD*	Phase 2	-	M	Adult	7.0	-19.31	9.09	3.32	45.4	16.8	0.14	3.2	866	275
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS163C	skull	640-660 AD*	Phase 2	-	ND	Infant 2nd	9.6	-19.08	10.51	3.87	46.6	17.1	0.14	3.2	889	280
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan		BSS2-117	femur	660-700 AD*	Phase 2	-	F	Adult	4.5	-19.30	10.41	5.56	44.7	16.5	0.15	3.2	796	252
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS2-118	tibia	1414±84 BP/428-770 AD (95.4%)	Phase 1	accessory	M	Adult	3.1	-19.57	10.37	5.46	44.8	16.5	0.13	3.2	920	291
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS2-133	humerus	660-700 AD*	Phase 2	-	M	Adult	3.7	-18.33	9.18	5.46	43.3	15.9	0.14	3.2	826	260
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS2-482	tibia	660-700 AD*	Phase 2	-	M	Mature	6.5	-19.03	10.57	5.99	46.6	17.3	0.14	3.1	889	283
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS2-483	femur	660-700 AD*	Phase 2	-	F	Adult	7.8	-18.61	9.02	6.42	47.1	17.4	0.12	3.2	1048	332
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS2-484	femur	660-700 AD*	Phase 2	-	M	Mature	5.2	-19.04	10.92	7.25	45.8	16.7	0.12	3.2	1019	319
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS3-100	femur	640-660 AD*	Phase 2	accessory	M	Adult	5.8	-18.58	10.58	6.45	46.0	17.1	0.13	3.1	945	301
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS5-137	femur	640 AD*	Phase 2	-	M	Adult	4.3	-19.16	11.00	6.35	44.6	16.4	0.14	3.2	850	268
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS6-126	tibia	640-660 AD*	Phase 2	-	F	Adult	9.2	-19.45	10.83	6.27	42.5	15.6	0.10	3.2	1135	357
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS7-105A	femur	640-660 AD*	Phase 2	-	M	Mature	7.9	-18.80	11.52	6.44	45.6	16.5	0.12	3.2	1014	315
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS8-113	skull	640-660 AD*	Phase 2	-	M	Mature	3.6	-19.41	11.34	6.58	42.8	16.0	0.12	3.1	952	305
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefa		BSS8-121	skull	640 AD*	Phase 2	-	ND	Infant 1st	2.5	-19.70	11.10	7.21	39.2	14.4	0.13	3.2	805	254
Venosta/Vinschgau	Malles Maso Pauli/Mals Pauliho	mountainous area	MHP1	skull	970±30 BP/1020-1160 AD (95%)**	Phase 4	-	M	Mature	2.7	-19.38	10.18	3.61	40.9	14.9	0.14	3.2	780	244
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof		MHP2	skull	1020±30 BP/980-1030 AD (95%)*	Phase 4	-	M	Adult	2.3	-19.15	11.11	4.32	39.0	14.1	0.16	3.2	651	202
Venosta/Vinschgau	Malles Maso Pauli/Mals Pauliho		MHP3	skull	1070±30 BP/900-920, 940-1020 AD (95%)**	Phase 4	-	M	Mature	3.8	-19.44	9.17	0.54	43.3	15.9	0.13	3.2	889	280
Venosta/Vinschgau	Malles Maso Pauli/Mals Pauliho		MHP4	skull	970±30 BP/1020-1160 AD (95%)**	Phase 4	-	M	Mature	5.9	-19.86	10.58	5.39	40.7	14.2	0.14	3.3	776	232
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof		MHP6	skull	1380±30 BP/620-670 AD (95%)*	Phase 2	-	ND	Infant 1st	2.9	-19.57	11.45	5.68	43.0	15.1	0.15	3.3	765	230
Venosta/Vinschgau	Malles Maso Pauli/Mals Pauliho		MHP7	skull	1000±30 BP/990-1040;1100-1120;1140-1150 AD (95%)*	Phase 4	-	ND	Infant 1st	5.1	-18.98	12.79	6.39	39.5	14.2	0.11	3.2	959	296
Venosta/Vinschgau	Tanas/Tanas	mountainous area	TA2	femur	9th-11th AD	Phase 4	-	M	Adult	8.5	-19.30	9.81	7.37	44.3	16.4	0.11	3.2	1075	341
Venosta/Vinschgau	Tanas/Tanas		TA4	humerus	1112±45 BP/800-1020 AD (94.2%)**	Phase 4	-	M	Senile	7.2	-17.31	9.59	7.18	43.3	15.8	0.14	3.2	826	258

Table S2

Valley or Basin	Site	Sample ID	Species	Classification	Age class	Yield (%)	$\delta^{13}C_{V\text{-}PDB}$ (‰)	$\delta^{15}N_{AIR}$ (‰)	$\delta^{34}S_{V\text{-}CDT}$ (‰)	%C	%N	%S	C:N ratio	C:S ratio	N:S ratio
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg	AP-AL CF	Canis lupus f. familiaris	carnivore	Adult	1.58	-16.36	8.38	10.76	40.1	14.2	0.18	3.3	595	181
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg	AP-AL SSD	Sus scrofa f. domestica	omnivore	Adult	4.10	-20.69	4.06	6.95	43.0	15.4	0.17	3.3	675	207
Adige/Etschtal	Appiano Castelvecchio/Eppan Altenburg	AP-AL C.O.	Capra aegagrus f. hircus/Ovis orientalis f. aries	herbivore	Adult	1.54	-21.21	4.34	7.39	*49.1*	17.2	0.23	3.3	570	171
Adige/Etschtal	Montagna Pinzano/Montan Pinzon	MO-P BT	Bos primigenius f. taurus	herbivore	Adult	9.36	-19.46	5.38	10.66	46.1	16.9	0.18	3.2	684	215
Adige/Etschtal	Nalles/Nals	NA BT	Bos primigenius f. taurus	herbivore	Adult	8.52	-20.81	6.61	8.50	49.0	18.1	0.18	3.2	727	230
Adige/Etschtal	Nalles/Nals	NA OA	Ovis orientalis f. aries	herbivore	Adult	11.44	-20.77	4.19	11.07	44.0	16.2	0.15	3.2	783	247
Adige/Etschtal	Nalles/Nals	NA SSD	Sus scrofa f. domestica	omnivore	Adult	8.92	-20.43	7.18	11.67	45.2	16.7	0.17	3.2	710	225
Adige/Etschtal	Nalles/Nals	NA CE	Cervus elaphus	wild herbivore	Adult	12.19	-21.46	2.60	8.87	46.2	17.0	0.18	3.2	685	216
Adige/Etschtal	Terlano/Terlan	TE BT	Bos primigenius f. taurus	herbivore	Adult	7.18	-20.40	4.41	3.57	44.1	16.0	0.17	3.2	693	215
Adige/Etschtal	Terlano/Terlan	TE SSD	Sus scrofa f. domestica	omnivore	Young	6.40	-20.40	8.01	6.41	42.2	15.1	0.17	3.3	663	203
Adige/Etschtal	Terlano/Terlan	TE C.O.	Capra aegagrus f. hircus/Ovis orientalis f. aries	herbivore	Adult	6.34	-19.55	5.53	2.17	43.7	15.8	0.19	3.2	614	190
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	TCT SSD	Sus scrofa f. domestica	omnivore	Adult	3.00	-19.31	10.65	3.95	45.7	16.7	0.19	3.2	642	201
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	TCT UA	Ursus arctos	wild omnivore	Adult	5.60	-20.05	2.73	7.61	46.8	17.2	0.17	3.2	735	232
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	TCT C.O.	Capra aegagrus f. hircus/Ovis orientalis f. aries	herbivore	Adult	5.34	-20.67	4.76	5.99	45.5	16.6	0.16	3.2	759	237
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	TCT CE	Cervus elaphus	wild herbivore	Adult	4.26	-20.87	3.34	9.64	45.1	16.4	0.18	3.2	669	209
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	TCT AVES	Aves sp.	-	Adult	7.94	-19.57	8.93	6.35	43.2	15.5	0.20	3.3	577	177
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	TCT BT	Bos primigenius f. taurus	herbivore	Adult	3.44	-18.01	5.59	5.68	45.6	16.6	0.19	3.2	641	200
Merano basin/Meraner Becker	Castel Tirolo/Schloss Tirol	TCT EC	Equus ferus caballus	herbivore	Adult	2.82	-20.79	4.61	7.03	42.2	15.4	0.16	3.2	704	220
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas	BEN C.O.	Capra aegagrus f. hircus/Ovis orientalis f. aries	herbivore	Adult	7.60	-20.41	4.73	7.60	46.0	16.6	0.19	3.2	646	200
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas	BEN BT	Bos primigenius f. taurus	herbivore	Adult	6.04	-19.21	7.45	8.40	44.0	15.4	0.17	3.3	691	207
Isarco/Eisacktal	Bressanone Elvas necropoli 17/Brixen Elvas	BEN SSD	Sus scrofa f. domestica	omnivore	Adult	6.02	-19.02	6.80	6.75	43.3	15.6	0.15	3.2	771	238
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan	BSS BT	Bos primigenius f. taurus	herbivore	Adult	14.84	-20.29	5.00	6.03	44.0	16.2	0.16	3.2	734	232
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan	BSS AVES	Gallus gallus	fowl	Adult	9.12	-20.29	2.73	6.48	41.6	15.0	0.19	3.2	584	181
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan	BSS C.O.2	Capra aegagrus f. hircus/Ovis orientalis f. aries	herbivore	Adult	14.59	-20.99	8.13	7.69	46.7	16.8	0.15	3.2	831	256
Venosta/Vinschgau	Malles Burgusio S.Stefano/Mals Burgeis St.Stefan	BSS C.O.1	Capra aegagrus f. hircus/Ovis orientalis f. aries	herbivore	Adult	11.06	-20.01	7.81	3.82	48.3	17.7	0.19	3.2	679	213
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof	MHP EC1	Equus ferus caballus	herbivore	Adult	3.42	-20.93	3.45	9.29	46.8	16.5	0.17	3.3	735	222
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof	MHP EC2	Equus ferus caballus	herbivore	Adult	3.24	-21.52	4.17	4.93	44.9	16.4	0.18	3.2	666	209
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof	MHP AVES	Aves sp.	-	Adult	5.62	-20.55	5.91	7.84	39.3	14.0	0.19	3.3	552	169
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof	MHP CF	Canis lupus f. familiaris	carnivore	Adult	2.72	-19.70	8.38	7.70	45.0	15.9	0.20	3.3	601	182
Venosta/Vinschgau	Malles Maso Pauli/Mals Paulihof	MHP CE	Cervus elaphus	wild herbivore	Adult	5.02	-20.03	2.74	5.23	45.1	16.4	0.18	3.2	669	209
Venosta/Vinschgau	Tanas/Tanas	TA CALF	Bos primigenius f. taurus	herbivore	Young	4.16	-21.40	5.96	6.54	*47.6*	16.8	0.17	3.3	747	226
Venosta/Vinschgau	Tanas/Tanas	TA BT	Bos primigenius f. taurus	herbivore	Adult	6.86	-20.50	8.30	6.42	45.2	16.2	0.18	3.3	670	206