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Review

Rapid Climate Change, Integrated Human–Environment–Historical Records and Societal Resilience in Georgia

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Abstract: In the midlatitudes of the planet, we are facing the imminent disappearance of one of our best high-resolution (pre)historic climate and anthropogenic pollution archives, namely the loss of glacial ice, through accelerated global warming. To capture these records and interpret these vanishing archives, it is imperative that we extract ice-cores from midlatitude regions where glaciers still survive and analyse them within frameworks of inter-disciplinary research. In this paper, we focus on Georgia, part of the Greater Caucasus. Results of ice-core analyses from the region have never, to date, been integrated with its other abundant palaeo-environmental, archaeological and historical sources. We review the results of international projects on palaeo-environmental/geoarchaeological sediment archives, the archaeology of metal economies and preliminary ice-core data in Georgia. Collectively, we show that the different strands need to be integrated to fully explore relationships between climate/landscape change and human societal transformations. We then introduce an inclusive interdisciplinary framework for ongoing research on these themes, with an ultimate future goal of using data from the past to inform societal resilience strategies in the present.

Keywords: climate-change; ice-cores; palaeo-environment; geoarchaeology; landscapes; (pre)historic-pollution; metal-economies; Caucasus; resilience; SDG-13

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1. Introduction

In this paper, we review current research on climate and environmental change in Georgia from the onset of the Bronze Age to the later Middle Ages, when the region was a nexus between Eurasian civilisations [1–3]. The aim is to explore the variable interactions between rapid climate change and human societal transformations, with a particular focus on the Georgian Greater Caucasus and the trans-Caucasus corridor (Figure 1a). We discuss the results of research on different palaeo–climate/environmental and geoarchaeological records and their future research potential (ice-cores; glacial moraines; coastal-, lake-, river-, peat- and settlement-sediment archives), together with archaeological research on metal production and settlement patterns. The research has been undertaken by different Georgian and Georgian–International teams. Following our summary of the nature and potential of current research, we present an inclusive interdisciplinary future research agenda that suggests several priorities designed to enable different projects to contribute to larger scale research questions. Eventually, we hope to set the evidence from integrated climate/environmental, archaeological and historic records of the Georgian Caucasus in their appropriate place between those more firmly established global midlatitude records for western and central Europe and the Mediterranean, and central and east Asia. Ultimately, our future objective is to use the evidence from the past to inform the development of strategies for social resilience to climate change in the future, contributing to the United Nations Sustainable Development Goal 13 [4,5].

The last decade has seen increasing interdisciplinary analysis of multiple strands of evidence by teams researching the impact (or not) of climate and environmental change on complex human societies in different regions. For example, the historic climate and societal change studies based on dendrochronological sequences in Europe and central Asia and volcanic eruptions recorded in polar ice cores [6–10]; those based on measurement of historic Nile floods for Egypt and the Middle East, linked to volcanic climate-forcing [11]; and the Mediterranean-wide climate studies based on pollen and marine sediment cores [12,13]. These focused regional interdisciplinary studies linking pollen, sediment-core, textual and archaeological evidence have also identified distinct regional patterns of contemporary climate differences, for example, between the western and eastern Mediterranean, raising questions over the validity of general climate-period characterisations, such as the Late Antique Little Ice Age and Medieval Climate Anomaly [14–21]. Given the recognition of the variable regional impact of climate change in the past, there is an imminent need to undertake an interdisciplinary study in Georgia, sampling from the Greater Caucasus and the trans-Caucasus corridor, to evaluate human response and resilience to exogenous influences from climate.

The regional studies above, conducted across the midlatitudes of the planet, have been augmented recently by high-resolution, interdisciplinary ice-core research projects from both polar and midlatitude mountain locations, exploring trends in (pre)historic climate change and human macroeconomic and societal markers (e.g., pandemics) from pollution records over the last two millennia. For example, seen in the Greenland ice-sheet research by McConnell and Rogerson [22,23] and in the research of the 'Historical ice core project' at Colle Gnifetti in the Swiss–Italian Alps, led by Mayewski and McCormick [24]. Other midlatitude, ice-core research is currently being undertaken in the Himalayas and the Pamirs (Figure 1b). Some have attempted to link climate trends from western/central Europe and the Mediterranean with those emerging from eastern Asia [25]. However, the absence of interdisciplinary studies from the Caucasus–Black Sea, located between the more comprehensively studied regions, is severely limiting those attempts.

High-resolution data on the impact of climate and environmental change in Georgia is currently lacking. We are also faced with the imminent loss of some of our best high-resolution (pre)historic potential climate and pollution archives, preserved in alpine glacial ice, due to accelerated global warming [26–28]. The region has a unique and currently recoverable variety of palaeo–climate, environmental and pollution (prehistoric and historic) records, together with a growing corpus of associated archaeological evidence of settlement patterns, extractive industries and landscape change. Timing is everything in regard to the extraction of the glacial ice records of at least 250 m thickness, preserved in the Greater Caucasus glaciers. They may hold 4000 years [29] or more of climate and human macroeconomic/societal history, potentially at annual resolution level, if new sampling technology is used. Hence, there is an urgent need for comprehensive data collection within coordinated climate–environment–archaeological projects using integrated interdisciplinary approaches. Global warming may make the next several years the last opportunity to recover and analyse Greater Caucasus glaciochemical records before melting destroys their integrity [30]. This review and the suggested interdisciplinary research framework will hopefully provide a foundation to catalyse this necessary research before the full spectrum of data disappears.

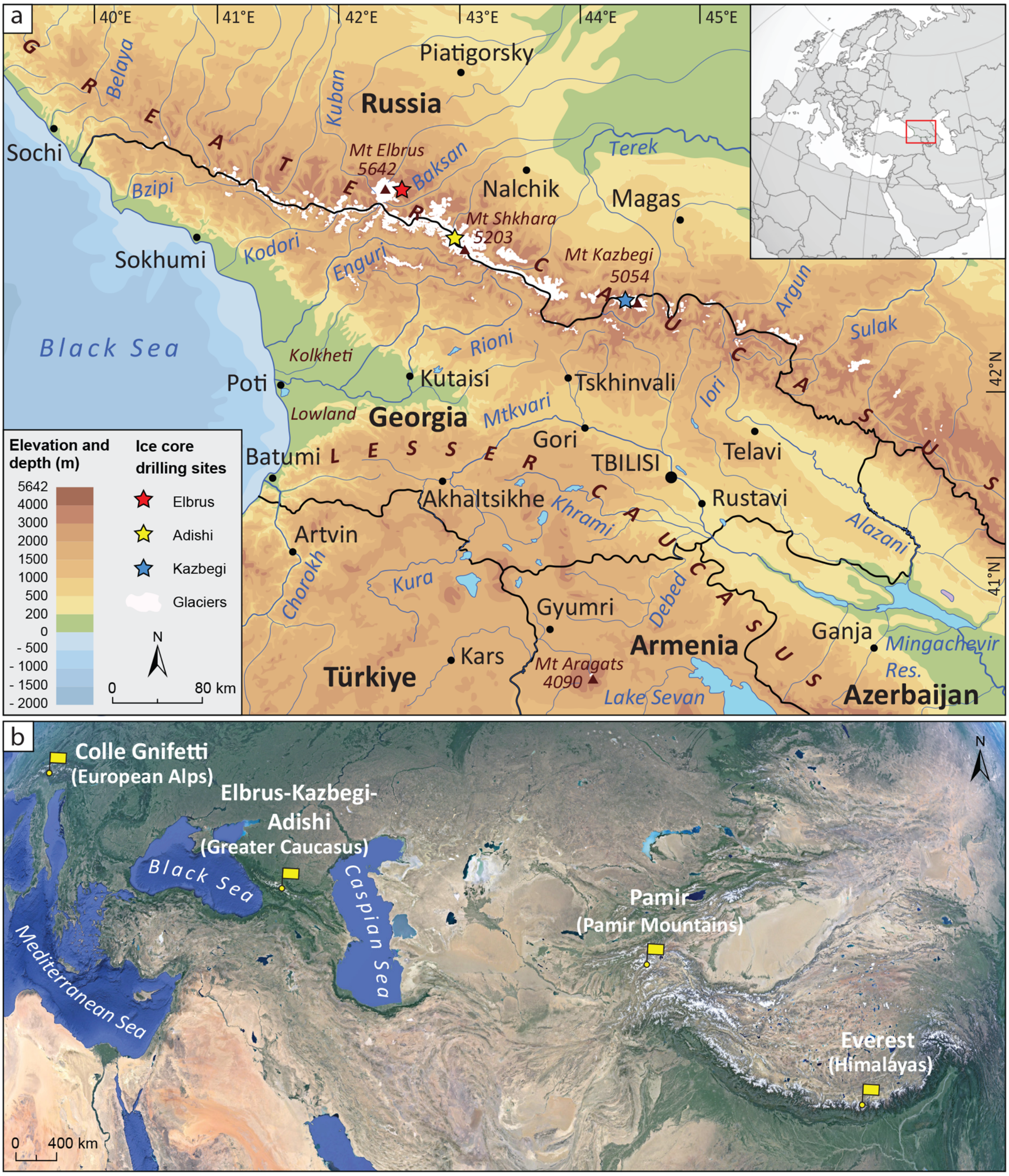

Figure 1. (**a**)—Location map of Georgia relative to the Caucasus Region and the location of the ice core drilling sites. A physical map of the Caucasus ecoregion was used and modified for the background [31]. The insert map in the upper right shows the location of Georgia relative to Eurasia. (**b**)—Midlatitude global ice-core locations. (© Google Earth).

2. Potential of Palaeo–Climate/Environmental and Archaeological Records in Georgia

2.1. Ice Core(s)—Assessment of the State of Preservation of the Ice Archives in the Georgian Caucasus

Several ice cores have been recovered from the Greater Caucasus since the mid-1980s (Figure 1). The highest site, at 5115 m a.s.l., is located on the western plateau near the active

Mt. Elbrus volcano [29,32–34]. The radiocarbon age from the bottom of this 181.8-metre ice core is 280 ± 400 CE. Older ice could potentially be found if drilling took place at the thickest part of the glacier [35]. Only one shallow 18-metre ice core record was recovered prior to the 2021 expedition to the Mt. Kazbegi plateau, 4500 m a.s.l., in 2015 [35]. In the same study, the authors reported an ice thickness of ca. 250 metres near the drill site, but problems with the drilling prevented the recovery of the entire record. An attempt to recover a pilot shallow ice core in 2021 by a Georgian-led international team from a slightly lower elevation resulted in only a 1.5-metre-long sample (Figure 2). Drilling was hampered again by the increasing presence of thick refrozen melt layers. A comparison of the 2021 stratigraphy with the 2015 ice core record clearly shows an increase in melt layer thickness.

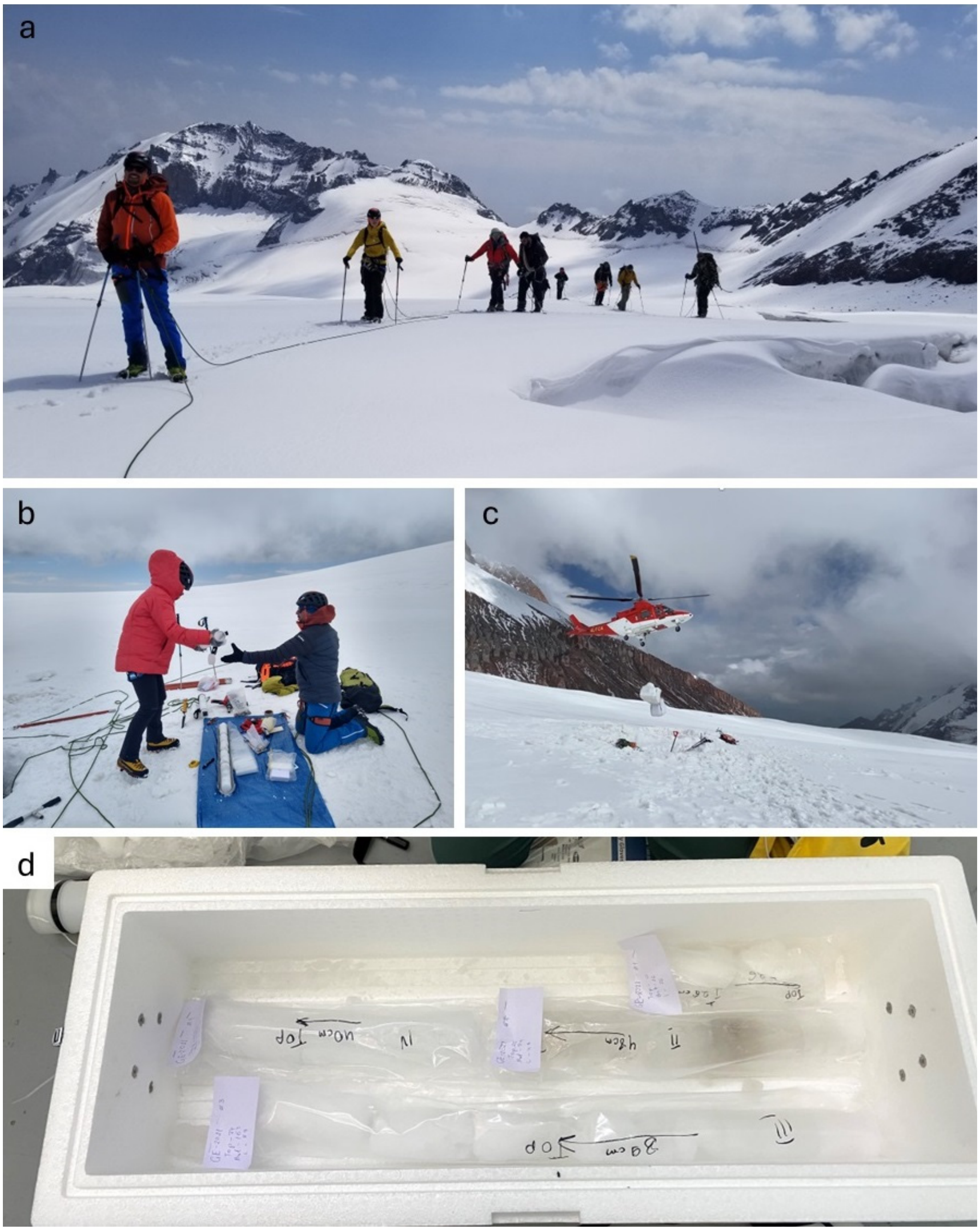

Figure 2. Mount Kazbegi 2021 ice-core pilot project. (**a**)—ascending to the camping site (4100 m a.s.l.), (**b**)—Ice sampling site 4300 m a.s.l., (**c**)—Transportation of the ice samples. (**d**)—transported ice samples in the laboratory at the Climate Change Institute, University of Maine.

This finding is corroborated by an increase in mean surface temperature in the region (Figure 3). Observed melt layers due to the increased regional temperature trend have already impacted the recovery of ice cores from several sites [36]. Fortunately, new electrothermal drilling technology [37] should be able to circumvent problems related to the presence of water in firn ice near the surface that impacts electromechanical drills. We expect that a long-term ice archive is preserved at depths below the influence of recent anthropogenic warming and that we should be able to reconstruct an entire palaeo record using comprehensive glaciochemical measurements [38]. It is not clear at this point when deeper parts of the record will be rendered unusable as warming propagates down from the surface, possibly in as little as five to ten years [39].

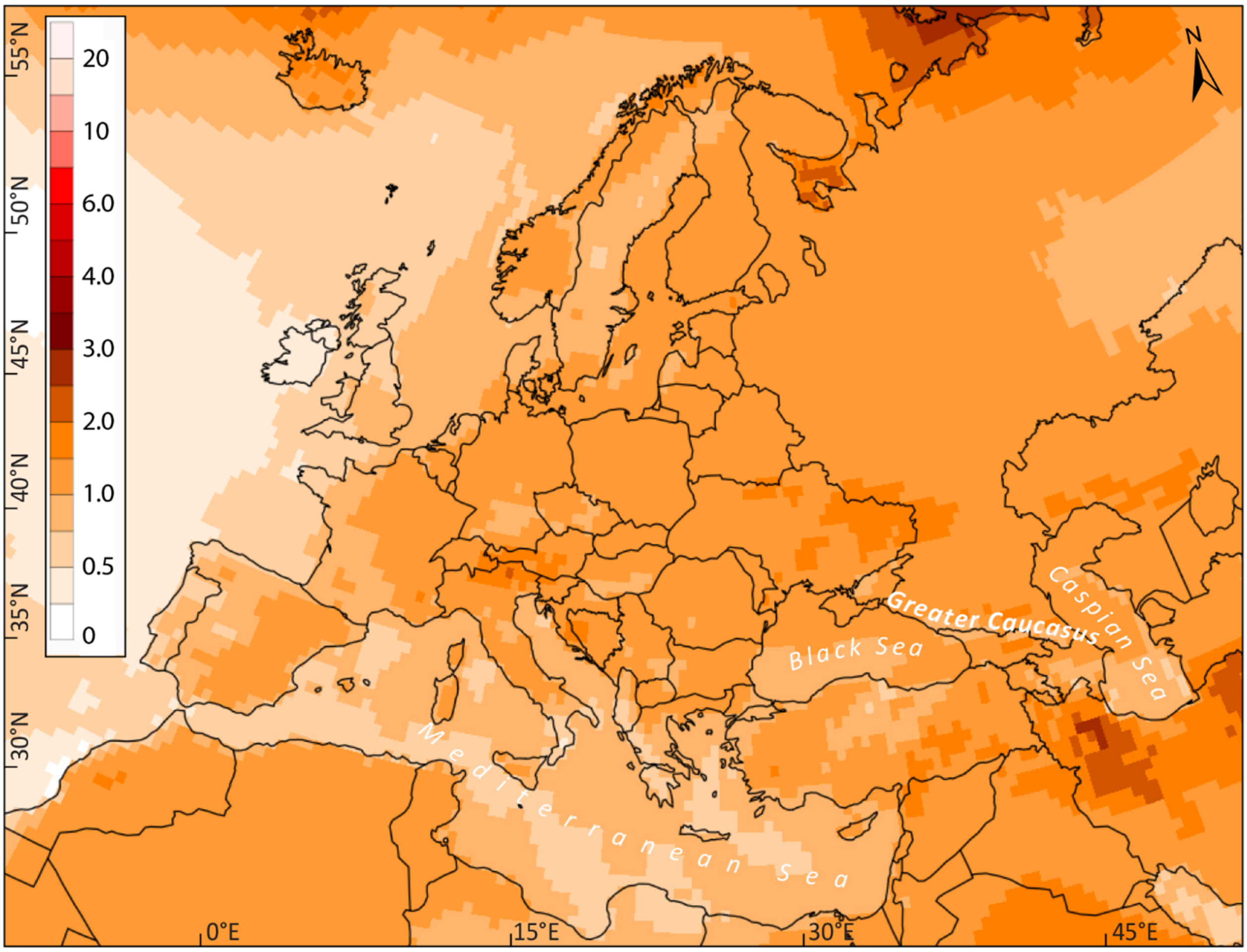

Figure 3. Temperature anomaly plot of observed surface temperature increase in western Eurasia between 2000 and 2023, which has had a very negative impact on many glaciers in the region. The ECMWF European Reanalysis V5 (ERA5) [0.25° × 0.25°] 2-m surface temperature data files were re-gridded and generated to 0.5° × 0.5° using bilinear interpolation function. Climate Reanalyzer 2024. [Monthly Reanalysis Maps]. Climate Change Institute, University of Maine. Retrieved [17 January 2024], from https://climatereanalyzer.org/.

2.2. Glacial Moraines

In the last few decades, regional glacier-related research in the Greater Caucasus focused mainly on glacier inventories, indicating a significant shrinkage in regional ice coverage during the last decades [30]. In contrast, only a few published investigations are available for the Greater Caucasus covering longer periods, based on numerical radiocarbon [40] and surface exposure ages [41]. Previously, moraine deposits and glacial stratigraphy were used for the reconstruction of past glaciations in this region [42]. However, in most cases, these studies lacked hard chronological data, so the dates of the majority of moraines are currently assumed but not proven. In this context, future work will need to implement state-of-the-art complementary methods such as terrestrial cosmogenic nuclide (TCN) dating (Beryllium-10, Aluminium-26, Chlorine-36, Carbon-14) and numerical glacier modelling to investigate past glacier-climate variability in the Greater Caucasus and to identify any regional divergences during apparent global climate shifts (Figure 4).

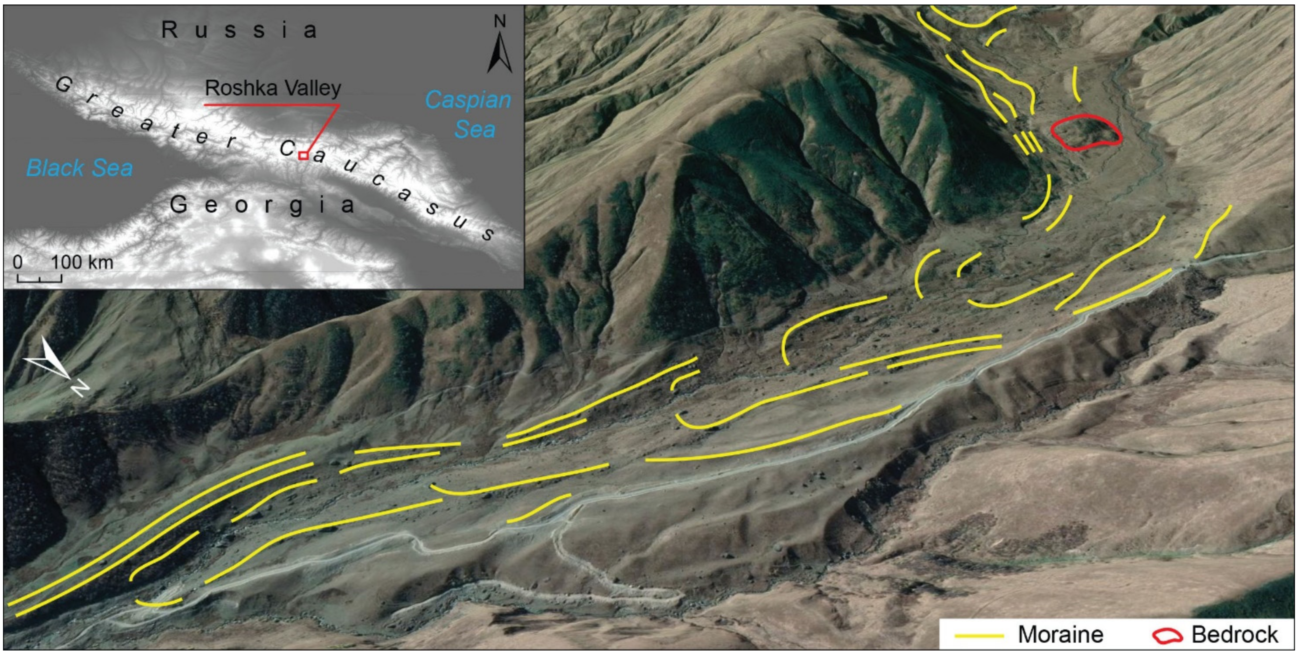

Figure 4. Moraines from the Roshka River valley. Future moraine sampling site. Google Earth image was used as a background. (© Google Earth).

2.3. River-, Peat- and Lake-Sediment Cores

The investigation of Holocene river sediments in western Georgia can provide unique information on hydrological and environmental changes in the floodplains and studied catchments caused by natural and anthropogenic factors (Figure 5). Furthermore, reconstructed sedimentation rates of the rivers (originating from the Caucasus cryosphere with the influence of snow and ice melt, as well as those without cryospheric influence only fed by rainfall) can provide unprecedented details on the regional sediment dynamics of different geo-ecological zones linked to Holocene climate changes and agriculture [43,44]. Additionally, metal-pollution levels within the river sediments can provide information about mining/smelting and pollution of waterways [45]. On the basis of former research, it is expected that the river sediments will mainly provide data from the last 5500 years [46].

Extraction of peat cores for detailed long-term analysis of climate change has been undertaken in western, coastal Georgia, notably at the Ispani peat bog, which contained a pollen record providing data on climate and landscape change extending back over 4500 years [47–49]. Currently, however, the records are poorly resolved in terms of chronology, with age-depth-models going back to the mid-Holocene constructed from relatively few radiocarbon dates. Western Georgia is perhaps the only place in the wider Middle East where sphagnum and ombrotrophic peat bogs exist. To date, no prehistoric to historic pollution studies have been undertaken on these peat records. They certainly contain ombrotrophic (blanket bog) records for the last two millennia, which coincide with landscapes that are archaeologically well-documented for metal production [47]. Analysis of elements related to metalworking and crustal proxies (e.g., lead, silver, copper, zinc, arsenic, bismuth, iron, titanium, sulphur etc.) using pXRF scans and then ICP-MS measurements of acid-digested samples, as well as lead isotope ratios of these peat records, have the potential to generate a regional picture of former industrial activity that complements and extends that provided by archaeometallurgical surveys. It may also identify the presence of pollution sources from the Mediterranean or Middle East, as prevailing winds carry aerosols from those regions (Figure 6) [50,51]. They may also contain information on macrosocietal events and trends resulting from disease pandemics, economic shifts and wider societal transformations [22–24]. Peat records from overlapping cores from the same location would also allow for the analysis of cryptotephra to refine radiocarbon chronologies [52,53] and for the detailed study of environmental change and peat accumulation rates using pollen. Reconstruction of temperature profiles could also be achieved through analysis of ^{13}Carbon, a well-established temperature proxy in peat sediments [54].

Figure 5. Approximately 3-metre-thick layered, fine-grained Rioni river sediments near Samtredia town, forming a potential Late Holocene palaeo–environmental archive.

Pollution profiles from peat cores and river sediments can also be contextualised against existing modern pollution studies of different agricultural soils undertaken in the post-Soviet era to assess any contamination risks for upper historical peat and river sediments [55]. This would enable the assessment of the cumulative impact of the potential release of toxic metal pollution from the Bronze Age to the early modern period, alongside the pollution from the twentieth century.

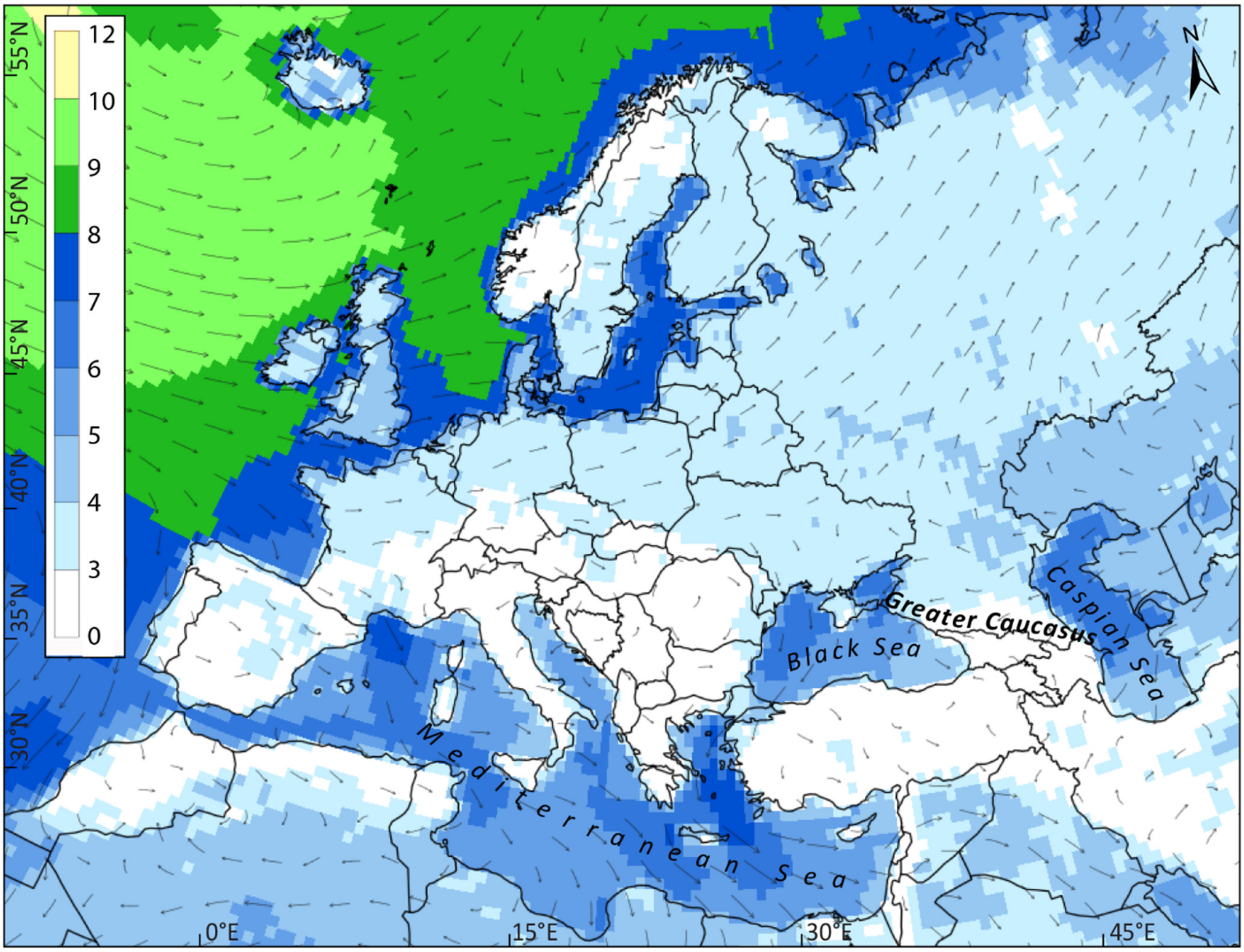

Figure 6. Plot visualising predominant wind directions and wind speed (m/s) in western Eurasia between 2000 and 2023, governing air-mass movement. The ECMWF European Reanalysis V5 (ERA5) [0.5° × 0.5°] annual data. Climate Reanalyzer™, Climate Change Institute, University of Maine.

Analyses of lake- and palaeo-lake sediment cores for their potential to illustrate changing climate and environmental conditions and anthropogenic impact through time has, to date, only been undertaken in central-southern Georgia, in the Lesser Caucasus. Particularly notable pollen records extending beyond the Last Glacial Maximum, with dating models based on between 17 and 21 radiocarbon dates, have been retrieved from Lake Paravani [56]. The Paravani records form part of a cluster of detailed lake sediment studies in the Georgian Lesser Caucasus, in Armenia and eastern Türkiye [57–59]. Currently, however, there are no high-resolution lake records in the Georgian Greater Caucasus or in coastal western Georgia. As with current peat records, there are no regional studies of anthropogenic heavy metal pollution (lead, mercury, copper, arsenic, et al.) from lake sediment cores at present. A series of lakes could provide optimal records, notably in the Svaneti region, northwestern Georgia, for example, Lake Ugviri (Figure 7). Regional histories of anthropogenic pollution derived from lake, fluvial and peat sediments, with sufficiently high-resolution, age-depth models based on multiple radiocarbon and luminescence dates, could be compared to ice-core pollution histories from the Greater Caucasus. Such comparison could facilitate, alongside the use of lead isotope analysis, differentiation of local/regional pollution signals from those that arrived as aerosol from more distant sources in other parts of the Black Sea region, Anatolia or the Mediterranean.

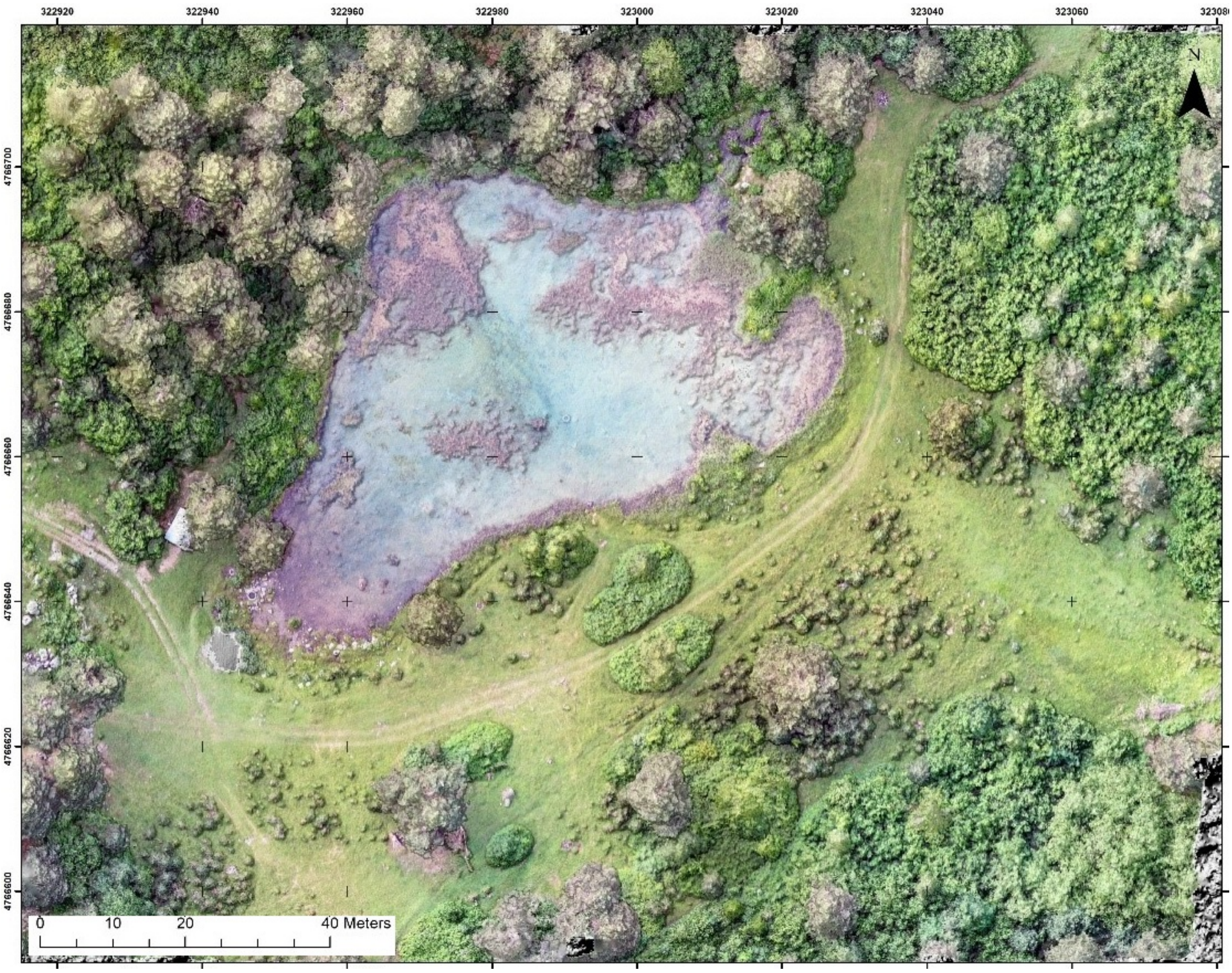

Figure 7. Lake Ugviri (Svaneti region, western Georgia) is one of the possible sources of lake sediment cores. Aerial orthophoto taken from a drone.

2.4. Archaeological Surveys and Dating Programmes

2.4.1. Metal Economies

Western Georgia (ancient Colchis) has had well-documented human occupation since the Middle Palaeolithic [60,61] and has one of the richest Bronze and Iron Age metallurgical traditions in the world. The fame of its metalworking industries was recorded in early Assyrian, Urartian, Greek, Roman, and Armenian written sources, as well as Greek mythology. Strabo considered and analysed this tradition and concluded: 'The richness of this country (Colchis) in gold, silver, iron, and copper explains the true reason for the Argonaut campaign' [62]. In addition to thousands of metal artefacts recovered in hoards and graves [63], hundreds of metal production sites (both primary smelting sites and secondary casting workshops) have been reported, providing an exceptional picture of the region's 'crafting landscape' [64,65]. These metal production sites were initially investigated during the Soviet period [66,67], but the technology, chronology, and organisation of production have been greatly clarified over the last decade of archaeometallurgical research [68,69]. While metallurgical production debris is attested already in third-millennium BCE sites, a massive expansion in copper and bronze production is well-documented in the late second and early first millennium BCE [68,69]. This expansion coincides with the peak of the 'Colchis Bronze Culture' [60]. Iron was probably smelted locally as early as the eighth–seventh centuries BCE, but the earliest iron smelting sites identified so far date to the fifth–third centuries BCE; and further concentrations of iron production followed in the medieval period (Figure 8).

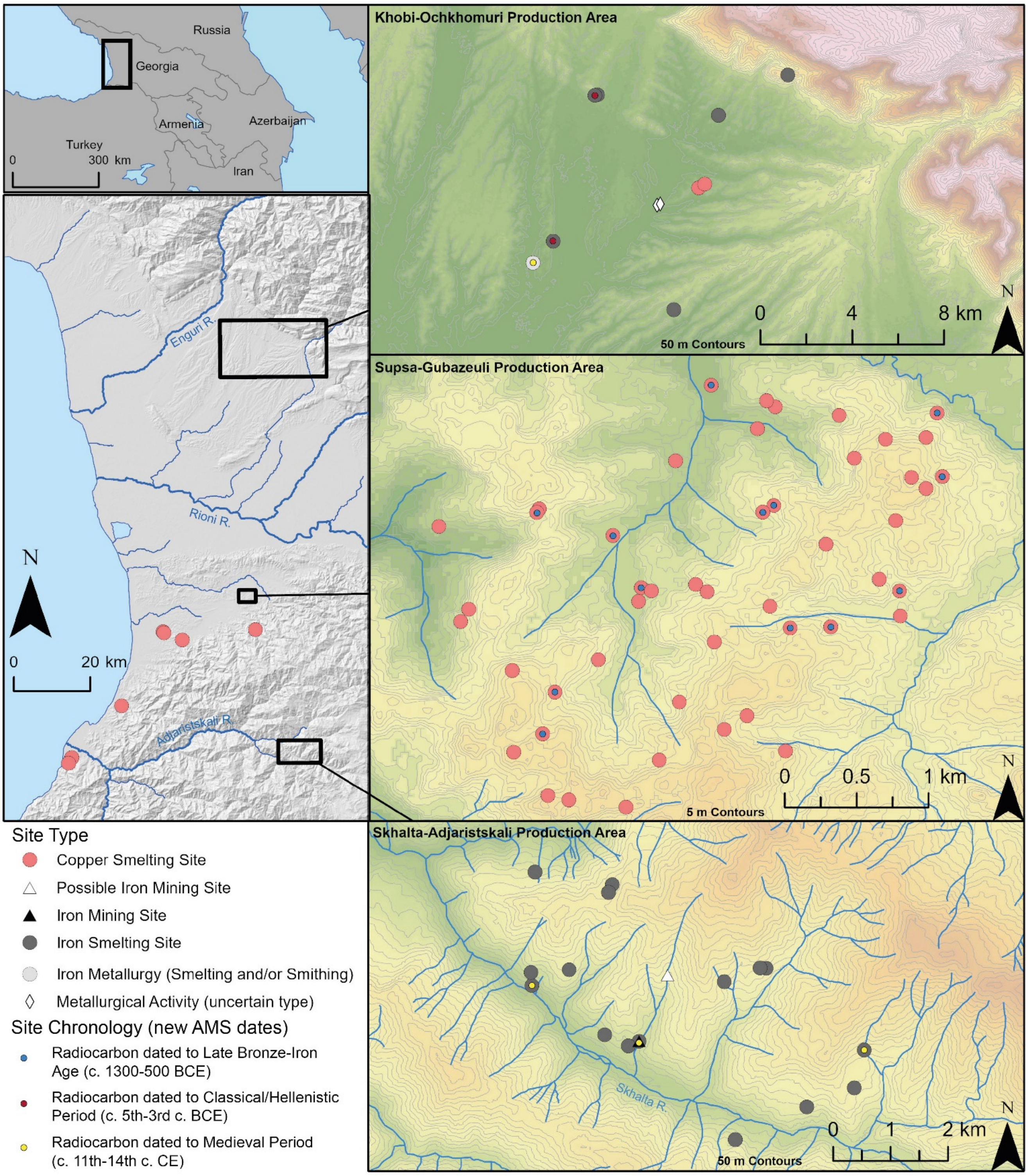

Figure 8. Map of prehistoric and historic metal production sites in western Georgia. Digital elevation data is from the Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (a product of METI and NASA) (developed from Erb-Satullo et al. [68]).

Though extremely rich, the documented archaeometallurgical record is uneven, both geographically and chronologically, with some areas and periods well-documented and others virtually unexplored. The densely vegetated landscape, as well as the swampy and mountainous terrain, mean that surveys are challenging, and there are major differences in comprehensiveness of data collection and quality between intensive and extensive surveys. For instance, it is unclear what happened to the Late Bronze Age–Early Iron Age copper smelting industry in the mid-first millennium BCE, as few copper smelting sites belonging to that period have been identified so far (for a rare exception, see Nadiradze, [70]). Did the industry collapse, or did it relocate to higher elevations more inaccessible to modern archaeological surveys? The answer requires further research. There is also the possibility of a contraction of iron production in the 14th century CE. Was this a consequence of the recorded pandemics in the mid-fourteenth century—anthrax, bubonic plague—or the combined result of the pandemics and the wars of the mid-fourteenth century in Georgia, culminating in the invasions of Timur the Lame from 1386 [3] (145–147) To address these questions and others, a combined approach involving further radiocarbon/luminescence dating of smelting sites in the mountain (e.g., Svaneti region, Lechkhumi) river catchment and coastal locations is necessary, allied to studies of glacial ice and sediment pollution proxies for metallurgical activity.

2.4.2. Settlement and Connection Dynamics

Hippocrates, the father of medicine (ca. 460–370 BCE), wrote in his only authentic treatise preserved to us—*On Airs, Waters and Places*—that in the 'fenny, warm, humid, and wooded' lowlands of the Phasis (modern Rioni River, western Georgia), with a warm climate dominated by 'copious and severe rains. . . at all seasons' the inhabitants were living 'among the fens', in 'dwellings constructed of wood and reeds, . . . erected amidst the waters'. Therefore, 'they seldom practice walking either to the city or the market, but sail about, up and down, in canoes constructed out of single trees, for there are many canals there'. This has been confirmed by Georgian archaeologists and the geomorphological team of the University of Cologne. The latter showed that in the lower part of the Enguri floodplain, round or ellipsoidal artificial mounds of several dozens of metres in diameter were raised from the late third and throughout the second millennium BCE in the middle of marshes drained by channels and that some of them were inhabited until the Roman period [46,71,72]. By contrast, along the lower Rioni River, archaeologists have observed Bronze and Iron age settlements on natural hills. Sometimes terraced, these hill settlements were protected by ditches, wooden palisades and even walls built with stones, wood and clay [1,73]. However, although some sites are reputed to contain archaeological traces (like Namarnu), the settlements situated downstream from Kutaisi, on the ancient estuary which developed into the Paliastomi lake, have not yet been fully mapped, dated, or systematically investigated. Also, the location of the major Greek city, Phasis, remains unknown, like almost all of the other sites mentioned in the ancient texts or inscribed on the Peutinger map (Figure 9) [74–77].

Currently, there is no explanation for the abandonment of the wetland settlements during the Greek and Roman periods in the region, nor for the disappearance of the famous city of Phasis between the Roman–Sasanian wars and the Arabic invasion during the Late Antique Little Ice Age (?), when destructive flooding events were also recorded in northwestern Iran [20]. The current hypotheses about successive relocations of Phasis were invented due to the impossibility of correlating the actual present-day landscape and archaeological finds with the literary sources. It has been suggested that the 'Lazi', inhabitants of all Colchis between the fourth and seventh centuries CE withdrew into the southern mountains by the end of that period [2,78]. Nevertheless, the maritime settlements on the shores of the Lesser Caucasus (Pontos) and the Greater Caucasus (Abkhazeti) Black Sea coasts continued to be occupied throughout the Middle Ages [79,80]. Geospatial (satellite, aerial) and geophysical surveys, geoarchaeological coring and dating of settlement mounds and hill-top settlements, followed by targeted excavations, will establish the palaeo–environmental and palaeo–climatic reconstruction of the Georgian lowlands (Figure 10). They will confirm or contradict the general versus regional climatic scenarios of the Eastern Mediterranean. For example, can we relate the Roman Climatic Optimum (possibly seen by de Klerk et al. [49]) in the Colchian pollen record, dated 1773 ± 34 cal BP, to the increase of Roman imperial material culture in Colchis? How did the cooler and wetter periods in the Late Antique Little Ice Age and the Medieval Little Ice Age impact the lowlands and their settlements?

Figure 9. Map of the Caucasus (Tabula III Asiae) and its position on the world map, in Nicolaus Germanus' Latin edition of Claudius Ptolemy's Geography, Florence, 1467.

These integrated studies are the necessary basis for understanding new scenarios in the social, economic and cultural history of the region to give greater context to settlements subjected to sample excavation on different scales from the Neolithic to the Middle Ages [81–84], and to provide greater chronological resolution to preliminary attempts at modelling changes in long-term demographic patterns linked to major climate shifts in the wider Middle East from the Late Holocene [85]. Recording the location, date and general characterisation of the settlements (construction techniques, food production, measures of sustainability/resilience in a difficult environment) will be the first step in reconstructing the dynamic networks connecting the Caucasus through its 'Caucasian', 'Caspian', 'Sarmatian' and 'Albanian gates', with the Near East, Asia—via the so-called 'Silk roads'—the northern Eurasian steppe, and the Black Sea.

Figure 10. Geoarchaeological coring survey in the coastal plain of western Georgia, conducted by the University of Cologne and Ilia State University, Tbilisi, to establish a new palaeo–climate/palaeo–environment reconstruction.

3. Establishing an Interdisciplinary Climate–Environment–Archaeological–Historical Research Framework for Georgia

The unique circumstances of Georgia and the Greater Caucasus region, with an estimated glacial ice record stretching back between two and four thousand years, a wide variety of different palaeo–climatic and palaeo–environmental archives, abundant evidence of human presence since the mid-Palaeolithic, and complex societies with extractive industries since the Neolithic–early Bronze Age, provide an unprecedented opportunity to explore the past interplay (or lack of it) between climate change, landscape dynamics and human action. Future comparative studies of multiple types of geo-archives and archaeological evidence will enable the analysis of diverse climatic, environmental and anthropogenic markers both over the long durée and during shorter periods of rapid climate and social change [86]. On the basis of the review undertaken in this paper, we suggest below an interdisciplinary framework for the future to promote the integration of research on climate/environmental change and its relationship to human societal developments in Georgia since the Late Neolithic–Bronze Age. We hope that it may provide an inclusive structure enabling Georgian and Georgian–International teams undertaking research with different disciplinary combinations and at different spatial and temporal scales to contribute results on relationships between climate–environment and human societal dynamics.

The framework seeks to enable the provision of groundbreaking perspectives on:

- The impact (or not) of both slow and rapid climate and environmental change on the landscape dynamics and human populations in Georgia, the Greater Caucasus and the eastern Black Sea region (and possibly also the eastern Mediterranean regions for selected periods).
- Human transformation of the environment through agriculture and metal economies from the Neolithic and Bronze Age to the present.
- Key moments of human societal change through population movement, technological innovation, connection/trade, war and disease pandemics.

- The (pre)historic impact of climate change and human-induced environmental pollution on ecosystems and its consequences in our own time (for food, environment and infrastructure security) through comparison with rapid warming and cooling periods in the past and the realisation of the toxic impact of the release of historic 'legacy pollution' into modern ecosystems.

This interdisciplinary framework will lead to a new, integrated palaeo–climate–environmental/pollution/archaeological/historical research cluster in Georgia, joining others around the midlatitudes of the planet (see Figure 1b). The Colle Gnifetti Historical ice core project held records from the region of northwest/western Europe and northwest Africa, and its analysis was linked to palaeo–environmental, historical and archaeological archives from those regions [24]. The Caucasus interdisciplinary framework, hopefully linking ice cores with other palaeo–climate/palaeo–environmental records, could incorporate climate, volcanic eruption and pollution evidence from the central–eastern Mediterranean, the Black Sea, Anatolia and the Middle East and will integrate archaeological and historical evidence from the outset. Other ice cores (extracted by the Climate Change Institute, University of Maine and other institutions) from Mount Everest and the Pamirs incorporate evidence from Central Asia, the Himalayas and the northern Indian subcontinent [87,88].

Ice-core records from the Greater Caucasus mountains, sampled at ultra-high (annual) resolution, will be able to provide an unprecedented, detailed record of both historic climate change and the role of human macroeconomic (metal-related) and societal trends on the environment for the Caucasus region. Learning from preliminary ice-core drilling at Mount Kazbegi in 2021, future electrothermal drilling campaigns in that location are a priority, as are drill-site selection campaigns in the Svaneti region (Figure 11). The aim is to recover and develop several comparable regional glacial ice-core records. This will require glaciological studies of snow accumulation rates, temperature observations, glacial flow modelling and ice thickness mapping using ground penetrating radar [89,90].

The individual ice core records will need to be sampled for stable water isotopes and element concentrations using ion chromatography solution-based ICP-MS. Layer detection will be conducted using a hyperspectral imaging technique. A unique LA-ICP-MS instrumentation for ice [91] will allow the establishment of annual layer markers in deep parts of the ice core records [92]. Using glacio–chemical, physical and optical properties of the ice cores will enable the identification and careful differentiation of volcanic, dust storms and human pollution events. A developed time scale will be corroborated using microparticulate radiocarbon-dating; correlation of temperature and precipitation proxies, and prehistoric and historic pollution evidence as proxies for human macrosocietal/economic/pandemic impact on the environment with other regional archives. Climate reanalysis datasets (e.g., ECMWF ERA5, NCEP/NCAR) will be used to drive Flexpart/HYSPLIT models to establish modern-day analogue scenarios for the calculation of source emission parameters for prehistoric and historic pollution (Figure 6).

In order to differentiate (pre)historic local/regional metalworking/macrosocietal events in Georgia from pollution arriving from more distant regions (e.g., the Balkans, Cyprus, Anatolia), we need to be able to match ice core records with those from regional peat-, lake- and fluvial-sediment cores, which usually (but not always) captured local pollution sources. Importantly, however, the peat and lake core bulk samples should also be large enough to allow for comprehensive analysis of a suite of elemental isotopes required to identify local and foreign pollution signals, especially from lead/silver production [93,94].

Peat, lake and fluvial sediments will also provide pollen profiles, information on longer term fluvial sedimentation phases, and highly resolved palaeo-flood data. The latter will enable the investigation of (pre)historic landscape change and trends in cultivation/landscape management so that agricultural evidence can be analysed alongside the data from metal economies/pollution [46,95]. Building on the pioneering work of Kuparadze [96], Sulava [69], Erb-Satullo et al. [68], an enlarged survey and dating programme of the metalworking sites in western Georgia is necessary to gain further chronological resolution on trends in the scale and date of mining and smelting of different metals [68,69,96].

Also, this will allow the differentiation of pollution derived from local or longer distance sources within sediment and ice core records through isotope and concentration analyses [94].

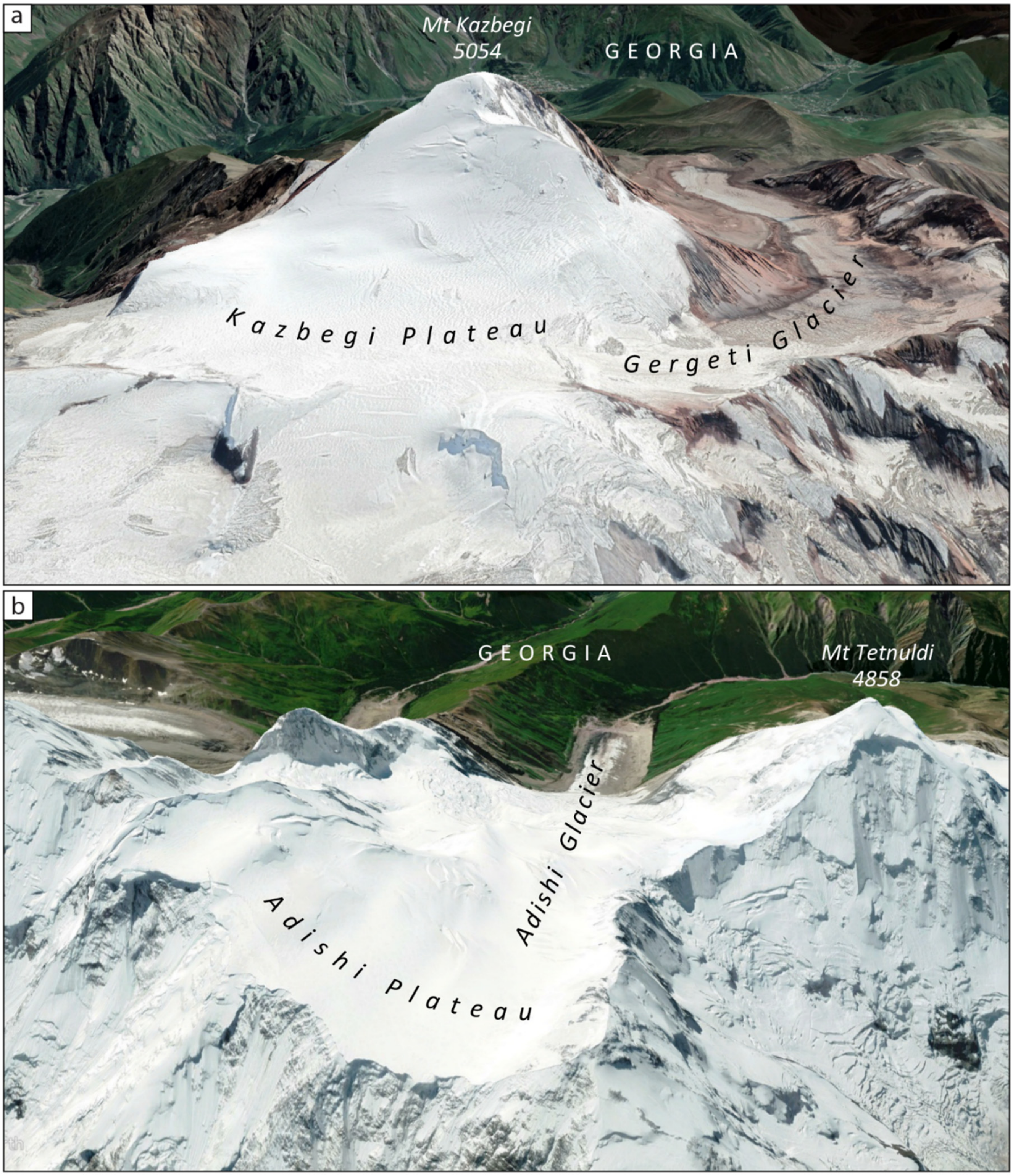

Figure 11. (**a**)—Kazbegi Plateau—preliminary ice-core drilling site in 2021. (**b**)—Adishi Plateau—future electrothermal drilling site. Google Earth images were used for backgrounds. (© Google Earth).

Geoarchaeological data from the Georgian coast of the Black Sea and the Colchis Plain will document landscape changes during the late Holocene, influenced by sea level change, tectonics and change in the sedimentation levels of major rivers (Enguri, Rioni), building on existing research in those and neighbouring areas (Figure 12) [46,95]. Reconstruction of changes in the palaeo-historic landscape can reveal patterns totally different from today. For example, in the last decade, the study of the lower Kuban River in the northern Caucasus, revealed the existence of an archipelago in the middle of the Cimmerian Bosporus/Kertch Strait [97]. Much larger than previously thought by modern scholars, and with multiple channels between the islands occupied since the Bronze Age and the Greek archaic period, this strait suffered major transformations comparable with those supposed for the lower Rioni river in Georgia (the ancient Phasis—the famous river travelled by the Argonauts searching for the Colchian Golden Fleece). However, nothing is known at present about the progradation of this delta. Geoarchaeological research is essential for reconstructing the former landscape topography, the delta advance, and the local sea-level evolution compared to other parts of the Black Sea coasts [98]. Therefore, such palaeo–environmental reconstructions will form the key component—in fact, the very first step—for understanding the human settlement pattern, local economy and wider human social networks through time, from the Bronze Age to the present. A subsequent synthetic analysis and interpretation phase, incorporating all known contexts from archaeological and historical sources, will be essential to provide meaning and context to the various proxy data, whether for known historical volcanic eruptions, disease events, sociopolitical events/periods and economic innovations.

Ideally, these multidisciplinary analyses can be structured within a broad spatial transect from the central Greater Caucasus mountains in the northeast, following major river valleys (Enguri, Rioni) to the Black Sea coast in the southwest (Rioni delta, Poti) (Figure 13).

Within such a transect, research can be focused on specific subregional case-studies:

- A **Greater Caucasus Mountain case study**, whether in the Svaneti region, the upper Enguri valley, or Kazbegi, comprising extraction and analyses of ice cores (for climate and pollution-related research) and lake sediment cores (including anthropogenic pollution profiles), glacial moraines and radiocarbon/luminescence dating of known archaeological metal smelting/working sites.
- A **Rioni river valley case study** in the central zone of the transect, comprising fluvial and alluvial geomorphology and sediment analyses, as well as minor element/metal pollution analyses, radiocarbon-dating of known metalworking sites, and synthesis of the settlement history from archaeological remains. This would need to combine the use of geomorphological (study of natural outcrops and drill cores, analysis of high-resolution DEMs), geophysical (electrical resistivity tomography, electromagnetic induction), geochronological (radiocarbon, luminescence), sedimentological-geochemical (grain size, rock magnetic, CNS and heavy mineral element analysis) and palaeobotanical (biomarker, phytolith or pollen) analyses (Figure 5) [95].
- A **Black Sea coastal plain and delta case study** can expand on the research by Ilia State University and Cologne University already undertaken in this area for micro-topographical and landscape reconstruction linked to the Bronze Age to modern settlement evidence. New research needs to focus on known ombrotrophic peat bog analysis for prehistoric and historic pollution studies. A second dimension can be added through the geoarchaeological study of the Rioni delta, following the approaches of the international project lead by the German Archaeological Institute (DAI) with French and local partners in the northern Caucasus and the Kuban delta (Figure 12). The reconstruction of the geobioarchaeological landscapes over the longue durée will allow an assessment of changing delta topography, influenced by human alteration of the landscape and climate change.

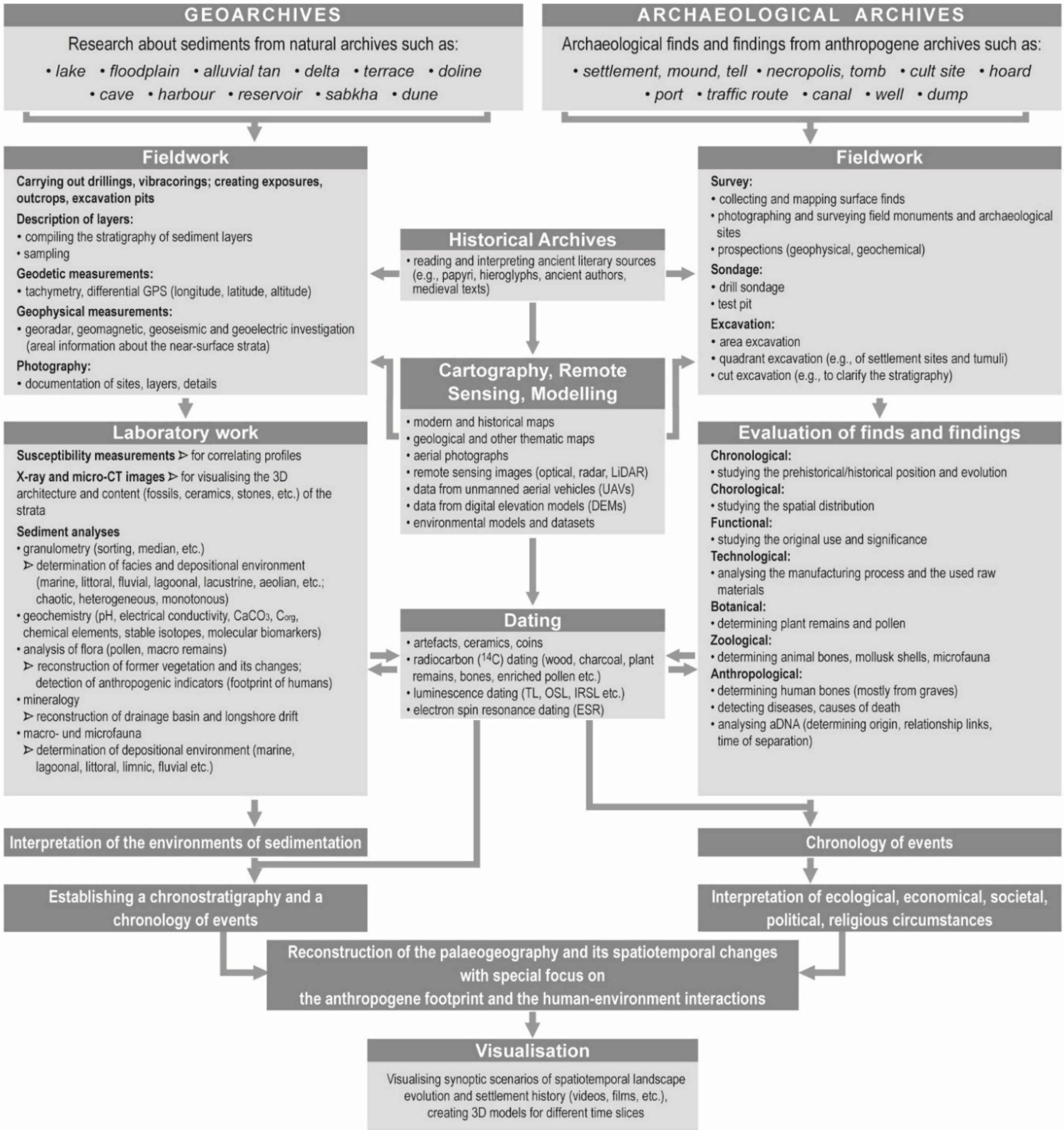

Figure 12. Flowchart of the integrated palaeo–environmental–archaeological–historical research design (after Brückner [99], Table 1).

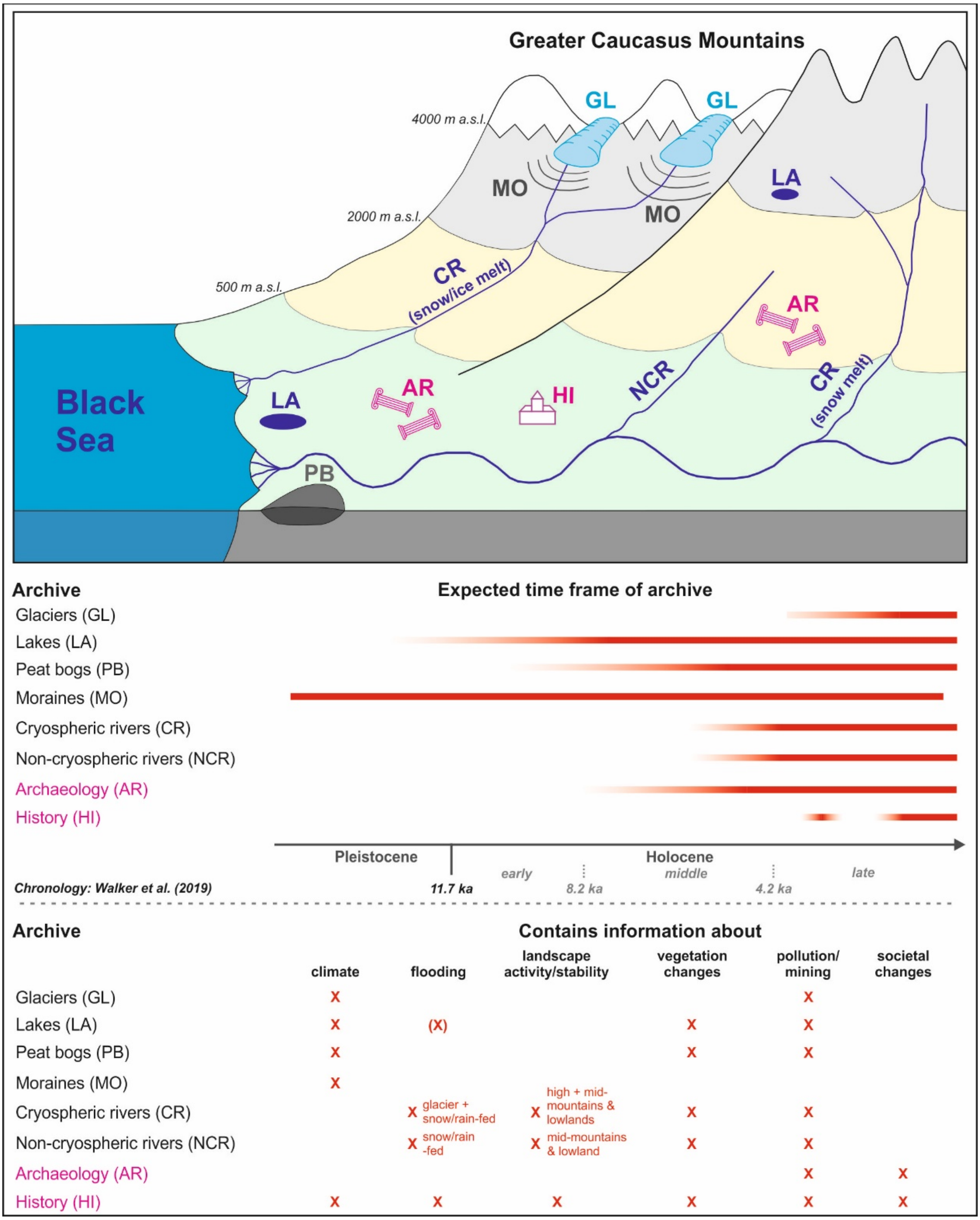

Figure 13. Composite graphic of a transect from the Georgian Greater Caucasus to the Black Sea coast, showing images of the different records at their locations along the transect.

4. Conclusions and Prospects

Given the close entanglement of human societal dynamics with climate and environment [100] and the growing picture of regional variations and responses to external shocks, the proposed interdisciplinary research framework seeks to take advantage of the unique range of climate–environment and archaeological records reviewed in this paper, to enable a systematic and integrated study of human resilience in Georgia in the face of changing climate and social challenges over the last four millennia. The strategic location of this research in Georgia, at the crossroads of prehistoric and historical connections between western and eastern Eurasia [101–103], will provide a key comparative dataset to confront current western and central European and Mediterranean biases in the clustering of high-resolution evidence. It will also directly address the relationship between regional and global climate change and human societal development in the midlatitudes of the planet. The suggested transect of records from the Greater Caucasus to the Black Sea coast will allow for the investigation of the regional impact of rapid solar- and volcanic-climate forcing, as well as cycles of economic growth/collapse, warfare, conquests and pandemics, between the Caspian and Black seas.

The framework can also enable the provision of a series of analogues from the past to aid societal resilience in the present and future [104]. Firstly, it will allow exploration of societal responses to rapid climate change and volatility in the past, such as the suggested destructive flooding of the later sixth and seventh centuries CE, and the rapid regional warming events between the mid-tenth and mid-thirteenth centuries CE. Data from the past could also help to predict future changes in hydrological/stream-flow patterns, land surface erosion, and linked changes in atmospheric circulation, which will have pronounced impacts on human settlement patterns and food supply and security. Furthermore, it will inform potential resilience measures necessary to mitigate risk from the legacies of past industrial activities. With the accelerated pace of global climate- and related landscape change in recent decades, significant levels of toxic pollution created in the past are being released into modern ecosystems. Large-scale copper-, iron-, gold- and silver-extraction from the Bronze Age onwards released toxic contaminants such as lead, arsenic and mercury from smelting ores and metal-purification processes [46,55]. Analyses of ice core and peat records in western Europe have shown that the levels of pollution from the past, such as the Roman and medieval periods, were sometimes greater than levels in the 'Industrial' era of the last two centuries. Rapidly melting glaciers and more dynamic rivers fed by them will both release and erode antique to modern pollution into current ecosystems. Assessing and measuring the scale of toxic activities from the past and the impact of their release in the present due to modern rapid climate change will enable the identification of where mitigating controls are necessary [105]. The ultimate goal, therefore, is to put the past to work for us in attempting to address the existential societal challenges of our own time and the future.

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