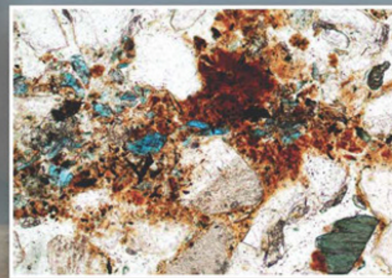
Second Edition



Practical and Theoretical Geoarchaeology

Paul Goldberg and Richard I. Macphail
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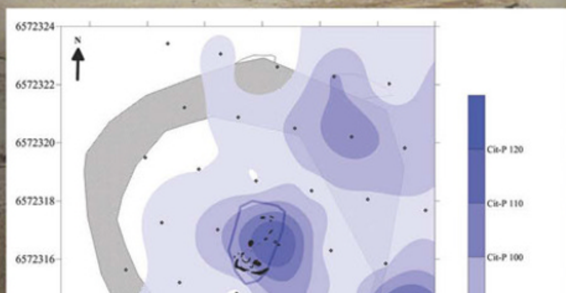

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Richard I. Macphail

With Chapter Contributions by Chris Carey and Yijie Zhuang

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PG: To all my friends and colleagues who really helped write the book.

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CC: To Sam, mum and dad, my friends and colleagues.

YZ: To my mum and family.

Contents

Preface to Revised Edition

It has been more than a decade and a half since the first edition appeared. Over this time, Geoarchaeology as a broad discipline has developed and matured significantly. Although the fundamentals of geological and pedological sciences that are employed during fieldwork and laboratory investigations essentially remain the same, the ways data are gathered and the accuracy of their interpretations have clearly advanced. In addition, we have seen an enormous expansion in the geographical and cultural scope of sites and issues now being addressed as a part of interdisciplinary investigations. The sites, countries, and methods employed by the authors are both worldwide in scope and up to date. This is because the four authors – who are based in three continents – have combined their practical experience and academic study to this end. Whilst several recent works have focused on single-technique approaches, this book has the aim of bringing all geoarchaeological methods to the table. For example, traditional fieldwork is now augmented by remote sensing techniques and three-dimensional modelling through geotechnical approaches. We also show how laboratory studies, using both traditional methods (bulk chemistry and soil micromorphology), can be enhanced by employing various new instrumental techniques. Just as importantly, we demonstrate how data can be fully integrated with other palaeoenviromental findings, and then graphically portrayed employing GIS, for example.

In particular, the past decade or so displayed a burgeoning development of geoarchaeology in Asia and Africa. Reflecting on the great achievements that have been made by colleagues working in these diverse environmental and ecological settings, we have incorporated some recent geoarchaeological studies on these regions in relevant chapters. We believe that more dialogues among geoarchaeologists working in different global regions will stimulate methodological and theoretic innovations in geoarchaeology and we hope that our preliminary effort in this book will start to provide a useful platform for such important scholarly understanding in global geoarchaeology.

After discussions over the years with fellow geoarchaeologists (e.g., Sarah Sherwood, Sewanee, USA), as well as archaeologists and palaeoenvironmentalists who equally need to be able to appreciate what Geoarchaeology can achieve for their site and projects, we have retained a similar thematic structure. In the first part, fundamental aspects of Sediments, Stratigraphy, and Soils are presented, which, with numerous case studies and examples, should prove interesting to both novices and professionals who want to brush up their skills and renew their acquaintance with these subjects. We then examine a broad series of depositional environments and their differing roles in use of the landscape and potential for archaeological site preservation. We have grouped the first three into topics associated with the hydrological cycle. Slopes, for example, includes issues of both erosion and colluviation; Rivers examines the physics of flow, sediment transport, and deposition, such as alluviation and its effects on landscapes given over to rice production in south-east Asia, for example; Lakes are important for wetland resources, and for their sediments that preserve records of early human activity. Other special environments involve wind as an agency of deposition of both sands and silts, which provide both background environments as well some typical site formation processes (Aeolian). Similarly, while Marine Coasts can be characterized by both recent and ancient dune formation, an understanding of intertidal archaeology and sea level changes can be key to interpreting site analyses and associated formation processes. Caves and Rockshelters are very special depositional environments where human use dates from Early Palaeolithic hunting and gathering to recent animal stabling; some of the earliest recognized cognitive activity is recorded in them.

After this discussion of sedimentary environments, we present five thematic chapters demonstrating the many facets of Geoarchaeology. Human Impact mainly deals with some important activities of people, such as woodland clearance and cultivation, the latter including a large variety of cultivation and manuring methods from across the globe; the effects of mining and water management in arid environments are also considered. This is followed by a chapter on The Human Use of Materials, which involves both the use of natural soils for construction and the manufacture of lime-based materials, and the investigation of residues from ferrous and non-ferrous metal working. This section then leads to Anthropogenic Deposits, which begins with a review of how these can be modelled for better understanding site formation processes and use of space, for example. In addition, we investigate mounds and mound-like deposits such as tells, utilizing examples from the New World, Eastern Europe, and the Near East. This chapter also encompasses urban and settlement archaeology, and formation of specific occupation deposits. Special topics (e.g. *terra preta*, Dark Earth, and pit houses) are also headlined. An important chapter explains how Geoarchaeologists arrive at sound interpretations of past sites and landscapes. This is presented in Experimental and Ethno-Geoarchaeology, where we discuss experiments ranging from clearance and cultivation methods, to monitoring changes to buried soils through time and how these findings have been applied to sites. In addition, we discuss experimental aspects of inundation of coastal sites, creation of reference materials, animal management, and observations of deposits that are relicts of house burning and decay. The last chapter in this thematic series, Geoarchaeology of Forensic Science and Mortuary Practices, was developed because of the increasing interest in both forensic science and the allied study of various funerary practices of cultural importance that need to be differentiated.

The last part of the book is given over to methods and the presentation of geoarchaeological findings. Fieldwork (Field Methods) can now involve coring, remote sensing, use of drones, 3D modelling, as well as careful logging of profiles and scientific sampling protocols. The chapter on Laboratory Methods discusses the use of traditional physical and chemical analyses employing instrumental techniques on bulk samples to map and characterize patterns of occupation, for example; parallel thin section studies have the advantage of contextualizing and closely linking analytical results to the microstratigraphy. For the latter, we briefly give examples of the use of associated SEM/EDS and micro-FTIR techniques to produce the kind of hard data that was only dreamt about in the past. Lastly, no matter how good the field and laboratory data are, they are not useful if they are not presented properly. In Reporting and Publishing we not only provide instances of how a variety of site findings can be documented and illustrated for the client and wider scientific audience, but we also show that the very act of preparing an article can improve the interpretation of sites when all data are integrated.

Acknowledgments

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We benefited from numerous discussions and collaborations and retrieved a number of valued insights from the late Ofer Bar-Yosef, Takis Karkanas, Sarah Sherwood, Carolina Mallol, the late Harold Dibble, Shannon McPherron, Dennis Sandgathe, Chris Miller, Vera Aldeias, Susan Mentzer, as well as Mike Allen, Jan Bill, John Crowther, Gill Cruise, Henri Galinié, Lars Erik Gjerpe, Joachim Henning, Johan Linderholm, the late Peter Reynolds, Pat Wiltshire and Seonbok Yi. Amalia Pérez-Juez looked over a number of chapters and made several constructive and valuable comments. The staff at Wiley-Blackwell has been always there, and Andrew Harrison and Rosie Hayden, and Antony Sami have been very helpful and understanding throughout the course of the revisions.

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Over the years, the interaction with many geoarchaeologists similarly shaped our thinking. At the outset, the late Henri Laville served as an inspiration for cave sediments. Marie-Agnès Courty has carried on this tradition of scholarship and friendship and has set the bar for geoarchaeological standards. Our first collaboration with her was invigorating and subsequent geoarchaeological interactions have helped us all develop and profit. We continue to be indebted to her.

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1

Introduction to Practical and Theoretical Geoarchaeology

1.1 Introduction

People were doing geoarchaeology long before this term was invented for earth sciences applied to archaeology. One of the authors (PG) can remember a lecture in his first year at the University (1961) by Sheldon Judson on stream erosion in Italy (Judson, 1961, 1963). Shortly after that, he discovered others in the Old World who had carried out or summarized what would be considered "modern" geoarchaeology. These were published as major books that include, for example, works by Cornwall (1953), Zeuner (1946, 1958, 1959), and Butzer (1960, 1964; Butzer and Cuerda, 1962). It gained proper name recognition with the publication of an edited volume: *Geoarchaeology: Earth Science and the Past* (Davidson and Shackley, 1976).

Since that time, geoarchaeology has become highly prominent and almost common parlance on archaeological sites. Geoarchaeological investigations, either as independent research or tied to archaeological projects, appear in reports, monographs, books, and journal articles, and they may be either within a specific section of an article or as a stand-alone publication. The namesake geoarchaeological journal is simply *Geoarchaeology* (Wiley), but the discipline receives some attention in other, more broadly science-focused publications, such as *Journal of Archaeological Science* and *Archaeological and Anthropological Science, Quaternary International*, *Quaternary Science Reviews*, *Quaternary Research*, and others. Finally, geoarchaeological subjects make it into other publications that touch on more mainstream archaeological, anthropological, or geological subjects: *Journal of Human Evolution*, *American Antiquity*, *Journal of Sedimentary Research*, *Antiquity*, and *Sedimentary Geology*. There have also been inclusions in high-end science journals, *Nature* and *Science*.

In the United States, annual meetings of both the Geological Society of America (GSA) and the Society for American Archaeology (SAA), generally have at least one session or poster session, in addition to society-sponsored symposia on the subject. The GSA has an Archaeological Geology Division, and the SAA has the Geoarchaeology Interest Group. It can be noted here that two of the authors are recipients of the GSA's *Rip Rapp Award for Archaeological Geology*. The Association of American Geographers (AAG) commonly has geoarchaeology sessions at their annual meetings. In Europe, more and more scientific meetings (e.g. Association for Environmental Archaeology, European Association of Archaeologists, European Geosciences Union, UISPP, and International Union of Soil Science (IUSS), Paleopedology Commission) include some aspect of geoarchaeology, including paleopedology, past agricultural practices and other human influences on the landscape, stratigraphy/microstratigraphy, and micromorphology of archaeological soil-sedimentary sequences and living floors.

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Likewise, the most exciting archaeological sites that one reads about today, either in the popular press or professional literature, commonly have a substantial geoarchaeological component. The reader has only to be reminded about the significance of the geoarchaeological aspect of sites that are concerned with major issues relating to human development and culture. Some high profile issues and sites include: the use and evidence of the controlled use of fire (Zhoukoudian, China; Wonderwerk, South Africa; Schöningen, Germany); the sedimentary context and the origin of various hominins (Dmanisi, Republic of Georgia; Denisova, Russia; Liang Bua, Indonesia; Boxgrove, UK; Atapuerca, Spain; Mediterranean and South African caves – Gorham's Cave, Gibraltar; Hayonim Cave, Israel, Blombos Cave, South Africa; Olduvai Gorge, Tanzania); peopling of the New World (Gault/Buttermilk Creek sites, Texas); Asian rice cultivation (Huizui, China); large Eastern European and Near Eastern settlements (Borduşani-Popină, Romania; Çatal Höyük, and Aşıklı Höyük, Turkey; Tel Dor, Israel); early management of domestic animals (L'abri Pendimoun à Castellar, France; Arene Candide, Italy; Negev Desert, Israel); tropical and European Dark Earth (Marco Gonzalez, Belize; London Guildhall, UK); and worldwide settlement morphology and funerary practices (Heimdalsjordet and Gokstad Mound, Norway).

These well-known landmark sites have really drawn attention to the contribution that geoarchaeology can make to, and its necessity in, modern archaeological studies. This situation was not the case only a few decades ago when only a handful of archaeological projects utilized the skills of the geoarchaeologist. Still, the best results have come from highly focused geoarchaeological investigations, which have employed the appropriate techniques, and which have been intimately linked to multidisciplinary studies that provide consensus interpretations.

This totally revised book is about how to approach geoarchaeology and use it effectively in the study of archaeological sites and contexts (see Preface). We shall not enter into any detailed discussion of the origins and etymology of "Geoarchaeology" vs. "Archaeological Geology" (full discussions of this irrelevant debate can be found in Butzer, 1982; Courty et al., 1989; Rapp, 1975; Rapp and Hill, 1998; Waters, 1992). In a prescient, no-frills view of the subject Renfrew (1976: 2) summed it up concisely and provided these insights into the nature of geoarchaeology:

> This discipline employs the skills of the geological scientist, using his concern for soils, sediments, and landforms to focus these upon the archaeological "site", and to investigate the circumstances which governed its location, its formation as a deposit and its subsequent preservation and life history. This new discipline of geoarchaeology is primarily concerned with the context in which archaeological remains are found. And since archaeology, or at least prehistoric archaeology, recovers almost all its basic data by excavation, every archaeological problem starts as a problem in geoarchaeology.

These issues of context, and what today would be called "Site Formation Processes" in its broadest sense, can and should be integrated regionally to assess concerns of site locations and distributions, and geomorphic filters that might have controlled their visibility on the landscape.

Geoarchaeology exists and is performed at different scales (Stein and Linse, 1993). Its usage and practice vary according to the training of the people involved and the goal of their study. For example, geologists and geographers may well emphasize the mapping of large-scale geological and geomorphological features, such as the location of a site within a drainage system or other regional landscape feature, and some may call this the geotechnical approach. This perspective is at a regional scale that exists in three dimensions, with relative relief possibly being measured in 1,000s of meters, especially if working in the Alps and Andes. Much of the geoarchaeological research carried out in North America is focused at this landscape scale, while it is more of a preliminary study approach in Europe. Geologists would also be interested in the overall *stratigraphy* of a site (including sediments, soils, features, etc.) and how these aspects might interrelate with major landforms, such as stream terraces, glacial features, and loess plateaus.

Pedologists, on the other hand, would be more concentrated on the parent materials, the surfaces upon which soils formed, and how both have evolved in conjunction with the landscape; these materials can be buried by subsequent deposition or occur on the present-day surface. In either case, pedologists' focus tends to be on the scale of the soil pit, i.e., on the order of meters.

Archaeologists themselves may want to focus geoarchaeological attention upon microscale, cm-thick occupation deposits: what they are, and how they reflect specific or generalized past human activities, and how they may fit into larger behavioral patterns. In the case of rescue/mitigation archaeology, in the USA commonly termed Cultural Resource Management (CRM), geoarchaeology is tailored to the nature of the "job specifications" proscribed by the developer under the guidelines of salvage operations. In Europe, the whole funding remit is to extract as much geoarchaeological and associated paleoenvironmental information as possible, and specialists have urged the importance of site visits, and advising and training of site staff even before machining and excavation commences. Thus, the geoarchaeologist may well be just one member of an environmental team whose task is to reconstruct the full biotic/geomorphic/pedologic character of a site and its setting, and how these environments were interrelated with past human occupations. All the above approaches can be relevant depending on the research questions involved; holistically they could be subsumed under the term "site formation processes" (Schiffer, 1987).

Archaeologists come from a variety of backgrounds. As stated above, in North America, archaeology is taught predominantly in anthropology programs, although very rarely, some universities (e.g. Simon Fraser University in Canada) actually have archaeology departments; Classical and Near Eastern Archaeology programs are not rare, but these tend to emphasize written sources over excavation. In Europe, archaeology is included within Programs, or in Departments and Institutes, and not necessarily as an extension of anthropology. Many archaeologists there have no science background, and come from History or Art History.

Although in the UK geoarchaeology is taught in a number of archaeological departments, it is not taught in all archaeology degrees and this is the same across Europe as a whole. In France for example, this subject may only be taught to prehistorians and not to classical or medieval archaeologists. Commonly, even in the UK and elsewhere in the world, geoarchaeology is often an "optional module" or is found as an *ad hoc* offshoot of geology and geography. In North America, it is not anchored in any particular department and may be cross listed among Anthropology, Archaeology, Geology, and Geography. Despite good intentions and good training, many geoscientists tend to be naïve in their approach to solving archaeological problems, and therefore they effectively reduce their potential in advancing this application of their science. This situation often diminishes or even negates their contributions to interdisciplinary projects. The opposite situation can be found, where an archaeologist does not know what questions to ask of a deposit sequence or feature (Goldberg, 1988; Thorson, 1990). Recognition of these educational constraints to what geoarchaeology can achieve for both the site and the researcher is the main *raison d'être* for this 2nd edition.

Thus, as Renfrew (1976) so cogently demonstrated, geoarchaeology provides the ultimate context for all aspects of archaeology from understanding the position of a site in a landscape setting to a comprehension of the context of individual finds and features. As such, it serves as the lowest common denominator to all archaeological sites worldwide. Without such knowledge, even the most sophisticated isotope study has limited meaning and interpretability. As banal as it might sound, the adage, "garbage in, garbage out" is wholly pertinent if the geoarchaeological aspects of a site are ignored.

In the past, geoarchaeology was carried out very much by individual innovators. In North America, the names Claude Albritton Jr., Kirk Bryan, E. Antevs, E.H. Sellards, and C. Vance

Haynes immediately come to mind as the early and prominent leaders in incorporating the geosciences into the framework of archaeology (see Holliday (1997) and Mandel (2000a) for details). In fact, Mandel concisely points out that for the Great Plains, geoarchaeology, or at least geological collaboration, locally constituted an active part of archaeological survey for several areas, although it was patchy in space and time. Much of the emphasis was focused on evaluating the context of Paleoindian sites and how these occurrences figured into the peopling of the New World (Mandel, 2000b).

In Europe during the 1930s to the 1950s, Zeuner at the Institute of Archaeology (now part of University College London), developed worldwide expertise in the study of the geological settings of numerous Quaternary and Holocene sites that ranged from India to Gibraltar (Zeuner, 1946; Zeuner, 1953; Zeuner, 1959). After Kubiëna called the world's attention to soil micromorphology (Kubiëna, 1938, 1953; Kubiëna, 1970; Zeuner, 1946, 1953, 1959), Cornwall, also at the Institute of Archaeology, applied this technique to archaeology for the first time (Cornwall, 1953) (see below). At the same time, Dimbleby (and later, J. G. Evans) developed the link between archaeology and environmental studies, and produced one of the first detailed investigations of past vegetation and monument-buried soils for Bronze Age England (Dimbleby, 1962; Evans, 1972). Duchaufour in France also systematically studied environmental change and pedogenesis (Duchaufour, 1982), and some of the earliest paleo-pastoralism rock shelter studies were developed in France (Binder et al., 1993; Brochier, 1983). In mainland Europe, the legendary French prehistorian François Bordes, whose doctorate in geology was concerned with the study of loess, paleosols, and archaeological sites, principally in Northern France (Bordes, 1954), placed the French Paleolithic within its geomorphologic setting. Vita-Finzi, working in the Mediterranean Basin, used archaeological sites to suggest the chronology of Mediterranean valley fills, which he related to both climatic and anthropogenic factors (Vita-Finzi, 1969). Cremaschi (1987) investigated paleosols and prehistoric archaeology in Italy.

Although some geoarchaeological research is funded by granting agencies (NSF, NGS, NERC, CNRS, DFG, ARC), much, if not most, of modern geoarchaeological work, in both the New and Old Worlds, is fostered and sponsored by CRM projects, ultimately related to human development throughout the world. Approaches and job specifications vary according to whether investigations are at one end of the spectrum, short-term one-off studies, or long-term research projects at the other. Geoarchaeological work can be done by single private contractors or by huge international teams, which may well include specialists who also act as private contractors. Nowadays, local authorities, government agencies (e.g. State Departments of Transportation in the USA; National Cultural Heritage Administration, China) and national research funding agencies (e.g. NSF in the USA, AHRC and Historic England in the UK, and AFAN and the CNRS in France; Nara National Institute, Japan; Cultural History Museum, University of Oslo, NiKU and NTNU, Norway) may all be involved in commissioning geoarchaeological investigations. It is currently a very flexible field. It is also one where there is an increasing need for formal training, but where relatively few practitioners have been in receipt of one.

Geoarchaeological work is now often broken up into several phases, with desktop investigations, fieldwork survey, excavation, sample assessment and laboratory study, all being likely precursors to full analysis and final publication. This is all part of modern funding and operational procedures.

Single-job or site-specific studies may be as straightforward as finding out "What is this fill?" On the other hand, problem-based research could involve the gathering of geoarchaeological data on the possible controlled use of fire, as at Zhoukoudian, China (Goldberg et al., 2001a; Weiner, 1998) or origin of salt working coastal "redhills" in England (Biddulph et al., 2012). Sites are investigated at different scales and sometimes, for very different reasons. At one time, "Dark Earth", the dark colored Roman-medieval urban deposits found in urban sites across northern Europe, engaged the particular interest of geoarchaeologists because these enigmatic deposits commonly span the "Dark Ages", and human activities at this time have been poorly understood (Macphail et al., 2003a; Nicosia et al., 2017), while South and meso-American tropical Dark Earth (*terra preta*) recorded pre-conquest settlements in some cases (Arroyo-Kalin, 2017). Analysis of "Dark Earth" therefore, became a research-funded topic for urban development sites (CRM projects in urban areas) across Belgium, France, and the UK, for example, Brussels being a particularly well-studied urban area (Devos et al., 2020a).

On the other hand, attention can be focused on individual middens and midden formation because they provide a wealth of material remains, particularly organic, that are normally poorly preserved and complex to understand and interpret (Stein, 1992). Regional studies of the intertidal zone, for example, may include the investigation of middens as one single component, an early interdisciplinary study being Mesolithic Westward Ho! (UK) (Balaam et al., 1987); more recently, South American middens and an Antarctic seal-hunting site have come under scrutiny (Villagran et al., 2009; Villagran et al., 2013). Submerged sites (Grøn et al., 2021) and deeply stratified deposits can be found, and in some cases accessed through cofferdams or coring (Linderholm et al., Submitted) (Macphail and Goldberg, 2018a: 15–20). Equally, studies of alluvial deposits and associated floodplains (Brown, 1997; French, 2003) have involved the search for buried sites, within the overall realm of evaluating the distribution and history of archaeological sites and past land uses such as herding (Macphail, 2011a); in Norway there can be the added complication of landslides (Macphail et al., 2016). The Po plain of Italy (Cremaschi, 1987; Cremaschi and Nicosia, 2012) and the Yellow River of China (Kidder and Liu, 2017) both feature a series of late prehistoric settlements; water management and wet rice paddy fields are also phenomena of prehistoric east Asia (Lee et al., 2014; Zhuang, 2018). Many of the most significant Paleoindian and Archaic sites in the USA are situated within alluvial sequences (Ferring, 1992; Mandel, 2000a; Mandel, 2008; Mandel et al., 2018).

Modern geoarchaeological research makes use of a vast number of techniques that either have been used in geology and pedology or have been developed or refined for geoarchaeological purposes. Early geoarchaeological research until the latter part of the last century, at least in North America, was predominantly field based and made use of both natural exposures and excavated areas. More recently, field techniques have become more improved and technologically sophisticated. Natural exposures can be supplemented with surface satellite remote sensing data, as well as subsurface data derived from machine-cut backhoe trenches, augering, coring, and advanced geophysical techniques (e.g. magnetometry, electrical resistivity and ground-penetrating radar; see references in Gilbert et al., 2017). Moreover, such data can be assembled and interrogated using Geographic Information Systems (GIS) (Landeschi, 2019; Wheatley and Gillings, 2002) that produce deposit models and which can be used to generate and test hypotheses (Carey et al., 2018).

Laboratory techniques have similarly become more varied and sophisticated. At the outset, many geoarchaeological studies adopted techniques from geology and pedology that were aimed at sediment/soil characterization. Thus traditional techniques characteristically consisted of grain size analysis (granulometry), coupled with other physical attributes (e.g. particle shape, bulk density, bulk mineralogy), as well as basic chemical analyses of organic matter, calcium carbonate content, extractable iron, etc. The analysis of phosphate to elucidate activity areas or demarcate site limits has a longer history spanning over 70 years (Arrhenius, 1931, 1934; Parnell et al., 2001). Conventional techniques with long historical pedigrees, such as x-ray diffraction (XRD; now supplemented with micro-XRD), electron microprobe, x-ray fluorescence (XRF and micro-XRF), and instrumental neutron activation analysis (INAA), atomic absorption (AA) have been enhanced by rapid chemical, elemental, and mineralogical analyses of samples through the use of Fourier transform infrared spectrometry (FTIR and micro-FTIR), Raman spectrometry, and by inductively coupled plasma-atomic emission spectrometry (ICP-AES) or mass spectrometry (ICP-MS) (Artioli, 2010; Gilbert et al., 2017; Weiner, 2010).

In addition, a notable advance in geoarchaeology has been the application of soil micromorphology to illuminate a wide variety of geoarchaeological issues (Courty et al., 1989; French, 2003). These earlier works have been enhanced with new books reflecting the evolution and maturity of the discipline (French, 2015; Karkanas and Goldberg, 2018; Macphail and Goldberg, 2018a; Nicosia and Stoops, 2017; Stoops et al., 2018a). Important topics range from the development of soil and landscape use (French, 2015; Gebhardt et al., 2014; Zhuang et al., 2013), the formation of anthropogenic deposits (Banerjea et al., 2015a; Cammas et al., 1996b; Macphail, 1994a; Macphail et al., 2007a; Matthews et al., 1997), to the evaluation of the first uses of fire (Berna et al., 2012; Goldberg et al., 2001, 2017b; Stahlschmidt et al., 2015b), and the use of experiments and ethnoarchaeology to produce such insights (Banerjea et al., 2015b; Cammas, 2018; Carey et al., 2014; Friesem et al., 2014a; Macphail et al., 2004). The science has also been strengthened by geoarchaeologists standing by their analyses (Goldberg et al., 2009a; Macphail, 1998; Macphail et al., 2006).

Finally, geoarchaeological research has been facilitated by the development of numerous dating techniques just within the past two to three decades. Now, sites within the span beyond the widely accessible limits of radiocarbon are potentially datable with techniques, such as thermoluminescence (TL) (Mercier et al., 2007), optically stimulated luminescence (OSL) (Jacobs et al., 2019; Jankowski et al., 2020), and electron spin resonance (ESR) (Duval et al., 2018; Rink and Schwarcz, 2005).

In this book we aim to present a fundamental, wide-ranging perspective of the essentials of modern geoarchaeology in order to demonstrate the breadth of the approaches and the depth of problems that can be proposed and tackled. Additionally, it is aimed to promote a basic and straightforward line of communication and understanding among all multi-disciplinarians. We cover a variety of topics that discuss thematic issues, as well as practical skills. The former encompasses such broad concepts as stratigraphy, Quaternary and environmental studies, sediments, and soils. We then present a survey of some of the most common geological terrains that provide the natural settings for most archaeological sites, and expanded into chapters on "slopes", "rivers", "lakes, "aeolian settings", "marine coasts", and "caves". These are established geoarchaeological topics into which we have incorporated some new findings. Unlike many books on geoarchaeology, we have dedicated a major portion of the volume to topics that were normally not treated in many geoarchaeological texts. While the first edition (2006) pioneered chapters on "human impact", "occupation deposits", "human materials", and "applications to forensic science", for example, these have been revised into "clearance, cultivation and other soil modifications" (e.g. from mining), "human use of materials", "anthropogenic deposits", "experimental and ethnogeoarchaeology", and "forensic and mortuary geoarchaeology". The topics span the course of human history from early hominins in African caves, major food production developments across south-east Asia to settlement patterns and urban sites across Europe and south-west Asia.

Similarly, it is important also to obtain some insights into practical aspects of geoarchaeology, including how geoarchaeologists should specifically fit in to a project. Similarly, two chapters are devoted to a presentation of pragmatic and theoretical methods currently used in geoarchaeology. These include not only field techniques (e.g. from remote sensing, satellite and drone imagery, coring, to describing a profile and collecting samples), but also those techniques that are used in the laboratory (varying from bulk, microscope to instrumental approaches). Although we summarize the "what" and "how", we also try to emphasize the "why" and provide several example-based caveats for important techniques. A final facet deals with the practical aspects of manipulating and reporting geoarchaeological results (e.g. with GIS) while keeping in mind that material presented in reports differs from that in articles. Reports essentially present the full database and arguments, whereas articles are commonly more thematic and focused, and by necessity are constrained to present results more concisely. Reports, which are seldom published in full, constitute the "gray literature" and make up an important part of the scientific database. They are too commonly overlooked, ignored, or simply are not readily accessible. We suggest electronic archives can be best accessed online, but these websites need to have been built and be under continual maintenance.

As a final point, we maintain that geoarchaeology in its broadest sense, must be made understandable to all players involved, be they archaeologists with strong training in anthropology, or the geophysicist, with minimal exposure to archaeological issues. All participants should have enough of a background to understand what each participant is doing, why they are doing it, and most importantly, what the implications of the geoarchaeological results are for all team members. Too often we hear about the geo-specialist simply turning over results to the archaeologist, essentially being unaware of the archaeological problem(s), both during the planning stages and later, after execution of the project. Hence, they cannot correctly put their results to use. On the other hand, many archaeologists tacitly accept results produced by specialists with few notions on how to evaluate them. This book attempts to level the playing field by providing a cross-disciplinary background to both ends of the spectrum. Such basic material is needed to establish a dialogue among the participants so that problems can be mutually defined, mutually understood, and best interpreted.

2

Sediments

2.1 Introduction

Sediments – and their alteration products, soils (see Chapter 4) – are the backbone of most archaeological sites (see Figure 2.1 for example). They are the glue that hold the rest of the archaeological record (lithics, bones, ceramics, even architecture) in place, and they are what archaeologists "dig". In most sites, archaeological objects are articulated with the sediments, and are commonly transported with the natural/geological components. Furthermore, the site itself and its deposits can be integrated with sediments that occur on the landscape scale, such as a building situated on a floodplain and perhaps buried by stream deposits (Figure 2.1). So, it is important that we provide some of the basic aspects of what sediments are, how we describe them, and how we can use them to extract information about their history and their relationship to archaeological materials, contexts, and past environments.

Geologists describe sediments, loose or indurated (sedimentary rocks), as materials deposited at the earth's surface under low temperatures and pressures (Pettijohn, 1975). They are found all over the globe – typically Pleistocene and younger (<2.5 my). Sedimentology, the study of sediments, also takes into consideration pores, the void spaces between the sediments that help reveal the history of the sediments.

Sediments differ from soils (treated in Chapter 4) in that sediments we observe today are not formed in place. Instead, in the case of clastic/detrital sediments (see below), they consist of individual particles that can greatly vary in size and organization. Particles such as gravel or sand originate from a source, are transported (e.g. by water, wind, or gravity), and then are deposited. Thus, there is a physical displacement from point A to point B that can be reconstructed using specific parameters of the sediment (discussed below) and the attributes of the deposit, or the three-dimensional unit distinguished in the field on the basis of observable changes in some physical properties (e.g. color, sediment size or composition) (discussed in Chapter 3).

In this section we examine some of the basic characteristics of sediments. Since many soils develop from the *in situ* weathering of sedimentary deposits, many of these characteristics are applicable to soils as well (Chapter 4). We have two principal goals. Since sediments largely guide the framework for archaeological site interpretation, it is necessary to have at least a working knowledge of their basic characteristics and the terminology used to describe them. Essentially, these descriptive characteristics constitute a lexicon: the term "sand", for example, corresponds to a defined size range, irrespective of composition. Secondly, and perhaps more important, is that many of the descriptive parameters that we observe in sediments commonly reflect – either

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(a) (b) (c) (d)

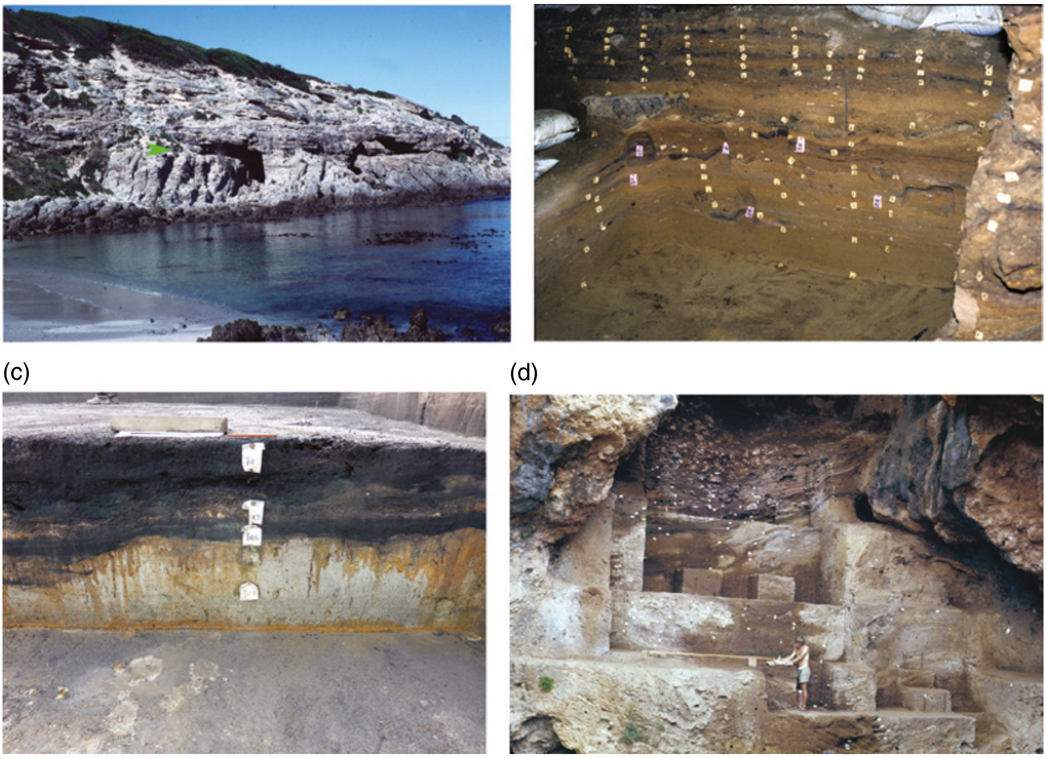

Figure 2.1 Examples of sediment types associated with archaeological sites. (a) Die Kelders Cave, South Africa, one of the best-studied Middle Stone Age (MSA) sites in the region. The cave (green arrow) is formed along the unconformable contact between Paleozoic quartzite (Table Mountain Sandstone) below and sandy limestone above (arrow); it is covered with a drape of bedded Quaternary calcareous sandstone of aeolian origin (aeolianite) (Marean, et al., 2000). (b) Die Kelders Cave interior that shows profile of bedded sand, ashes, and organic-rich occupation material that has been partially redistributed by wind; note the shift from the predominantly geogenic lower part to the increasingly anthropogenic-rich upper part. The profile is 2 m across. (c) Profile of part of the Lower Paleolithic site of Schöningen, Germany, a site known for its wooden spears, butchered horses, and stone tools. Shown here is extensively iron-stained lacustrine marls (calcareous muds) overlain and truncated by organic-rich lake deposits (Stahlschmidt, et al., 2015a, Stahlschmidt, et al., 2015b). Red scale is 20 cm. (d) Uppermost sediment of the cave site of Tabun, Mt. Carmel, Israel, one of the baseline sites for the Lower and Middle Paleolithic of the Near East. Gary Rollefson is standing on diagenetically altered silty sands (of marine and aeolian origin), which grade upward into siltier deposits capped by red and white banded clayey and ashy deposits and ultimately, red clay that accumulated through a chimney hole at the back of the cave. (Jelinek, et al., 1973, Shimelmitz, et al., 2016, Tsatskin, et al., 1992).

individually or collectively – the history of the deposit, including its (1) origin, (2) transport agent, and (3) the types of depositional processes where it was put down, its *environment of deposition* (see Stein, 1987 for a geoarchaeological perspective). Figuring out these aspects of a sediment's history constitutes a mental structure for every sedimentologist, whether they are studying a 100 m-thick sequence of Carboniferous sandstones in Nova Scotia, a 10 cm-thick sandy layer within a Late Pleistocene prehistoric cave in the Mediterranean, or a "destruction layer" from a tell in the Middle East. In sum, by observing and recording the attributes of a sediment we not only provide an objective set of criteria to describe and communicate those attributes, but also a means towards reconstructing its history.

In what follows, we attempt to provide an overview of the essential aspects of sediments themselves. The emphasis here is sediments of essentially geological/natural origin (geogenic). Archaeological sediments (anthropogenic) – those related to human activities – are discussed in other chapters (10, 13) where we provide examples and more specific details about their application and interpretation in geoarchaeological settings.

2.2 Types of Sediments

Sediments can be classified into three basic types, clastic (*or* detrital), chemical, and organic, all of which are pertinent to geoarchaeology. *Clastic* sediments are the most abundant. They are composed of fragments (clasts) of rock or minerals, other sediment, or soil material. Natural clastic sediments that are most relevant to archaeology are terrigenous sediments (*vs*. marine sediments) deposited by agents such as wind (e.g. sand dunes), running water (e.g. streams, beaches), and gravity (e.g. landslides, slumps, colluvium). Anthropogenic sediments (Ch. 10, 12, and 13) are largely composed of clastic material. An example of a typical clastic sediment is quartz sand on a beach in some vacation wilderness like Cape Cod, USA. Intertidal fine sediments, sometimes known as marine alluvium, can both bury marine inundated coastal sites or form terrestrial landscapes when post-glacial uplift has occurred (Chapter 9).

Volcaniclastic sediments (Table 2.1) are those associated with volcanic activity and include volcanic ash, blocks, bombs, and pyroclastic flow debris (Fisher and Schmincke, 2012). These types of sediments appear in geoarchaeological contexts with geologically relatively young volcanic activity where the finer debris can weather into highly fertile soils. Many of these regions have been important areas of human activity in the past (e.g. Polynesia, Central Basin of Mexico, Mediterranean, addressed in Chapter 4) (James et al., 2000). Volcaniclastic sediments have additional importance in archaeological contexts where they have been catastrophically ejected, burying Bronze Age villages (Matarazzo, 2015; Matarazzo et al., 2010) and better known sites such as Pompeii and Herculaneum, Roman towns buried on the Bay of Naples in Southern Italy when Vesuvius erupted

Table 2.1 Types of sediments; consolidated (lithified), rock equivalents for clastic sediments are given in parentheses and *italics*. Note that *bioclastic* limestones, composed of biologically precipitated shell fragments (e.g. coquina), can be thought to be both clastic and biochemical in origin.

Clastic and bioclastic		Non-clastic	
Volcaniclastic	**Terrigenous, marine, and lacustrine**	**Chemical**	**Biological**
lapilli, blocks, bombs	Cobbles, boulder; gravel (*conglomerate*)	Carbonates (*limestones*)	peat (lignite, coal)
ash (*welded tuff*)	sand (*sandstone*)	Evaporates (chlorides, sulfates, silicates; phosphates)	
	silt (*siltstone*)	Travertines and flowstones (cave and karst settings)	Algae, bacteria, diatoms, ostracodes, foraminifera
	clay (*shale*)		
	Bioclastic (carbonate): coarse (*coquina*); fine (*chalk*)		
	Bioclastic (siliceous): *diatomite*		

in AD79. Pompeii is considered the type site for the preservation of instances in archaeological time (the so-called "Pompeii Premise" (Binford, 1981) (further discussion on Pompeii is presented in Chapters 12–13). These sites are covered by meters of volcaniclastic debris (tephra), consisting of pumice, volcanic sand, lapilli (2–64 mm), and ash less than 2 mm (Giuntoli, 1994). Tephra marker horizons provided dating opportunities at Upper Paleolithic Kostenki, Russia and Viking Age Landnám – or first occupation – in Iceland (Holliday et al., 2007; Sigurgeirsson et al., 2013). The site of Ceren in San Salvador represents a similar setting, where structures and agricultural fields were buried under several meters of ash and tephra resulting in a rare snapshot of daily life among rural commoners during the Late Classic Mayan period (Sheets, 2002; Slotten et al., 2020).

Volcaniclastic deposits are widespread in rift valleys and because they are materials that can be dated, they play critical roles in the dating and stratigraphy of Pliocene and Pleistocene deposits from sites in East Africa, the Jordan Rift, and Turkey and Georgia. Rift settings and sites such as Olduvai Gorge, Koobi Fora, Gesher Benot Ya'akov, and Dmanisi figure strongly in the study of human origins, and they are just a few of the sites where archaeological deposits and hominin remains are associated or intercalated with volcanic rocks and tephra (Ashley and Driese, 2000; Blegen et al., 2016; Blumenschine et al., 2012; Ferring et al., 2011; Gabunia et al., 2000; Goren-Inbar et al., 2018; Stern et al., 2002).

Bioclastic sediments can exhibit a wide range of sediment types and sizes from both marine or terrigenous sources. Marine organisms such as mollusks and corals produce shells of calcium carbonate that can remain whole when buried. On the other hand, in cases where these hard body parts are subjected to wave action the shell can be broken into small cm- to mm-size particles, that when cemented result in the formation of a bioclastic limestone, for example (Table 2.2; see Ørlandet, Norway in Chapter 18). Coquina is an example of a coarse bioclastic sediment composed of such particles. Alternatively, a fine-grained calcareous equivalent is chalk, which is composed of silt- and fine sand-size tests of marine organisms (foraminifera); in other instances, organisms with siliceous skeletons, such as diatoms, result in the formation of diatomite. Bioclastic sediments, *per se*, are relatively rare. However, these minute biological remains, such as ostracodes, diatoms, and foraminifera, can be preserved within otherwise mostly mineralogenic deposits, such as in lake sediments (see Figure 18.23b) (Cruise et al., 2009). The moat deposits from the Tower of London, for example, contain numerous diatoms, which point to shallow, turbid water in disturbed sediments

Table 2.2 Common minerals and rock fragments in sediments (modified from Boggs, 2012).

Major minerals
Quartz
Potassium and plagioclase feldspars
Clay minerals
Accessory minerals
Micas: muscovite and biotite
Heavy minerals (those with specific gravity >2.9):
• Zircon, tourmaline, rutile
• Amphiboles, pyroxenes, chlorite, garnet, epidote, olivine
• Iron oxides: Hematite, limonite, magnetite
Rock fragments
Igneous
Metamorphic
Sedimentary

(Keevill, 2004). These conditions were inferred to be a result of inputs into the moat of waste disposal, surface water, and water from the Thames and the City Ditch. Foraminifera analyses were key to reconstructing the early hominin (Middle Pleistocene) coastal environment at Boxgrove and early Holocene inundated coastal sites in Essex, UK (Macphail et al., 2010; Pope et al., 2020).

Chemical sediments are those produced by direct precipitation from solution. Lakes in semi-arid areas with strong evaporation, for example, can exhibit a number of precipitated minerals, such as halite (table salt), gypsum (calcium sulfate), or calcite or aragonite (both forms of calcium carbonate). On occasion, these are visible in the field (Chapter 4) and recognizable under the petrological microscope (Durand et al., 2018; Mees and Tursina, 2018; Poch et al., 2018). In cave environments, chemical sediments are widespread and typically produce sheets of calcium carbonate (e.g. *travertine* or *flowstone*), or a variety of ornamental forms such as stalactites and stalagmites that are usually composed of calcite or aragonite (White and Culver, 2012). In addition, other minerals can form as a result of direct precipitation or transformation of previously present minerals; new minerals can include phosphates, nitrates, or sulfates, for example (Hill and Fortí, 1997; Karkanas and Goldberg, 2018a).

The third group, *biological* sediments, is composed mostly of organic materials, typically plant matter. Peat, lignite, or organic-rich clays in swampy areas and depressions are characteristic examples. These type of sediments, peats in particular, are key components of archaeological studies reconstructing changes in water levels, including sea levels (e.g. Smith, 2020), lake levels (e.g. Jackson et al., 2000), and even freshwater springs (e.g. Toffolo et al., 2017) where peat can represent now inundated extant surfaces that can contain evidence of human occupation.

2.2.1 Clastic Sediments

Clastic sediments (Table 2.1) have been the object of study by sedimentologists for decades and so they have a firm basis for understanding them. Clastic sediments present a number of attributes (also studied by pedologists) that can be readily described. When examined individually or together they can lead to often robust interpretations of their source, transport, and environment of deposition. These attributes generally include composition, texture (grain size and shape), fabric, and sedimentary structures.

Composition – Sediments can exhibit a wide variety of composition of mineral and rock types, and normally this is a function of the source of the material (Tables 2.2 and 2.3). As a consequence, geologists have been able to reconstruct geological landscapes (e.g. former landmasses; Table 2.3) that have long since been eroded. In spite of their wide variety, certain rocks and minerals occur repeatedly in

Table 2.3 Heavy mineral associations and related geological sources (modified from Pettijohn et al., 1975).

Mineral association	Typical geological source
Apatite, biotite, brookite, hornblende, monazite, muscovite, rutile, titanite, tourmaline, zircon	Acid igneous rocks
Augite, chromite, diopside, hypersthene, ilmenite, magnetite, olivine	Basic igneous rocks
Andalusite, corundum, garnet, phlogopite, staurolite, topaz, vesuvianite, wollastonite, zoisite	Contact metamorphic rocks
Andalusite, chloritioid, epidote, garnet, glaucophane, kyanite, sillimanite, staurolite, titanite, zoisite-clinozoisite	Dynamothermal metamorphic rocks
Barite, iron ores, leucoxene, rutile, tourmaline (rounded grains), garnet, illmanite, magnetite, zircon (rounded grains)	Reworked sediments

sediments ("major minerals" in Table 2.2). Their relative abundance in a sediment can vary with location and age. In the case of the latter, some minerals (e.g. olivine) are more susceptible to alteration/destruction than others (e.g. quartz), and thus they can be less persistent in older sediments. Furthermore, overall sediment composition can be influenced by secondary processes (e.g. soil formation and *diagenesis*), which result in the precipitation of minerals that either cement the skeletal grains of the sediment, or that precipitate as concentrations within the sedimentary mass (e.g. *nodules and concretions*). Secondary mineralization may involve different chemical groups, including carbonates (e.g. calcite, aragonite), silicates (e.g. opal, microcrystalline quartz/chert); sulfates (e.g. gypsum, barite), phosphates (e.g. apatite, leucophosphite), and iron oxides (e.g. limonite, goethite).

Texture – Texture involves attributes of individual grains or clasts, and these like other traits, have both descriptive and interpretative value. One of the most basic and widespread attributes is that of grain size (Table 2.4), and it is one that both earth scientists (geologists and pedologists) and archaeologists use and intuitively understand: "this deposit is fine-grained, while the one above is coarser and sandier." Clearly, we need to be more precise than this example, and both geologists and pedologists employ formal names and size limits to describe the classes of particle sizes that

Table 2.4 Common grain size scales used in geology and pedology.

Wentworth class (geology)[1]	Size range	Phi (Φ) units[2]	UK soil science class equivalent[3]	Size range	USA soil science class equivalent[4]	Size range
Boulder	>256 mm	−8	Boulders	>600 mm	Boulders	>600 mm
			Very large stones	200–600 mm	Stones	250–600 mm
Cobble	64–256 mm	−6 to −8	Large stones	60–200 mm	Cobbles	76–250 mm
Pebble	4–64 mm	−2 to −6	Medium stones	20–60 mm	Coarse Gravel	20–76 mm
			Small stones	6–20 mm	Medium Gravel	5–20 mm
Granule	2–4 mm	−1 to −2	Very small stones	2–6 mm	Fine Gravel	2–5 mm
Very coarse sand	1–2 mm	0–1			Very coarse sand	1–2 mm
Coarse sand	0.5–1 mm	1–0	Coarse sand	0.6–2 mm	Coarse sand	0.5–1 mm
Medium sand	250–500 μm	2–1	Medium sand	212–600 μm	Medium sand	250–500 μm
Fine sand	125–250 μm	3–2	Fine sand	63–212 μm	Fine sand	100–250 μm
Very fine sand	63–125 μm	4–3			Very fine sand	50–100 μm
Coarse silt	31–63 μm	5–4	Coarse silt	20–63 μm	Coarse silt	20–50 μm
Medium silt	16–31 μm	6–5	Medium silt	6–20 μm	—	
Fine silt	8–16 μm	7–6	Fine silt	2–6 μm	Fine silt	2 to 5 μm
Very fine silt	4–8 μm	8–7				
Clay	<4 μm	>8	Clay	<2 μm	Clay	< 2 μm

[1] After Nichols (1999)
[2] $\Phi = -\log_2 d$ (d = grain diameter)
[3] Avery, 1990; Hodgson, 1997
[4] Schoeneberger, et al., 2012

range from fine, micron-size (1 μm = 0.001 mm) grains of dust, up to large boulders several meters across (Table 2.4).

The *grain size scale* commonly used by geologists in the United States is that developed by (Wentworth, 1922) (Table 2.4); note that this scale is a geometric grade scale with the limits between classes having a constant ratio of 1/2 (Krumbein and Sloss, 1963). Geologists have later modified this by introducing the *phi (Φ) scale*, which is a logarithmic transformation of the grain size to the base 2 ($\Phi = -\log_2 d$, where d is the grain size in mm). These arithmetic intervals are convenient for the graphical presentation of grain size data, such as histograms (see Chapter 17), and for performing statistical analyses. In any case, as can be seen in Table 2.4, the limit between silt and clay is 3.9 μm in the Wentworth scale, and the limit between silt and sand is 62.5 μm. Furthermore, we highlight that soil scientists (in both the U.S. and UK) employ different limits between sand/silt and silt/clay: for soils in the U.S, silt includes material between 50 μm and 2 μm, whereas in the UK, it is 63 μm to 2 μm (Table 2.4). These differences are particularly significant when evaluating data in reports and maps, and whether the descriptions have been done by a geologist or pedologist: the same sediment can have different percentages of silt or sand, depending if it were analyzed by a geologist or pedologist and the geographic location of the laboratory.

Methods used in grain size analysis are discussed in Chapter 17. Nevertheless, we need to point out here that sediments (and soils) are usually mixtures of different sizes of particles, as for example, sand, silt, and clay for finer materials. Graphic representation of such mixtures are commonly presented in triangular diagrams (Figure 2.2), which have three major end members, each representing 100% sand, silt, or clay. As can be seen, different mixtures are partitioned into grouped and given names to characterize each group, depending on the proportions of the different end members. Note that the boundaries/proportions between groups can vary considerably within geology (Figure 2.2 a, b) and between disciplines (geology vs. pedology; Figure 2.2c). Soil scientists use the additional term, loam, that is a mixture of predominantly sand and silt with some clay (Schoeneberger et al., 2012); a mixture of say, 40% silt, 30% sand and 30% clay would be called a clay loam.

Loam is commonly used in the geoarchaeological literature but it should be remembered that it is a term from pedology with the mindset of soil, and is out of place for describing geological sediments. The point is that, again, when evaluating grain size analyses of a given study, one should be aware of its goals, as well as the background and country of origin of the author, if the nomenclatural system is not presented. Field methods for estimating particle size are given in Chapter 16.

Sorting – Sorting is a term applied to the proportion and number of different size classes comprising the grain populations. In particular, it relates to the statistical distribution of sizes around the mean (the standard deviation; see Tucker (1988) for ways to measure and evaluate it). Sorting can be readily visualized in Figure 2.3. The predominance of one size of particle indicates a well-sorted sediment. Beach and dune sands, for example, are characteristically well sorted, as are windblown dust deposits, known as *loess* (see Chapter 8). A poorly sorted sediment consists of varying particle sizes. Slope deposits, where a mass of sediment has been moved down hill (the process of *colluviation*: see Chapter 5) and glacial till are typically poorly sorted deposits due to the lack of selectivity of the transport agent: glaciers simply pick up, grind, transport, and deposit the substrate material along their paths.

Particle shape is usually considered for gravel, pebbles, and sand-size particles. It is another descriptive parameter and indicator of the history of the sediment. Three related features of shape are generally considered. *Form* refers to the general outline of the grain and ranges from equant grains (with roughly equal length, width, and thickness dimensions approaching the shape of a sphere), to platy or disc-shaped grains, in which the thickness is markedly less than the length or