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Challenges for a cross-disciplinary geoarchaeology: The intersection between environmental history and geomorphology

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ABSTRACT

Geoarchaeology is a growing subfield of cross-disciplinary research at the intersection between geomorphology, environmental history, and archaeology. This prospective essay does not aim to analyze the nature or evolution of geoarachaeology, or to review available techniques and methods. Instead it addresses *challenges*. Exciting challenges confront geoarchaeology in the form of persistent problems that demand satisfactory solutions, despite improving skills and innovative technologies. Drawing from the full record of human history, a number of practical issues can be highlighted to explicate these challenges:

(1) Open-air archaeological sites are the main object of study for the Early to Mid-Pleistocene, even though they represent open systems that raise fundamental questions about archaeo-taphonomic integrity. How were sites buried and then modified by selective preservation, horizontal or vertical disturbance, and the role of carnivores? Is it possible to determine the degree to which such sites accurately record prehistoric human behavior, prior to the Late Pleistocene when hearths and living structures lend better definition to occupation surfaces? Can non-primary open-air sites also shed light on human activities and environmental history?
(2) Cave sites have long been favored by archaeologists because of the impression that they represent relatively complete and undisturbed archaeostratigraphic sequences. But serious problems also exist here in regard to the nature of accumulation and the sources of mineral and biogenic sediments in what were open systems, liable to disturbance, despite comparatively low-energy processes.
(3) Less familiar are urban and other architectural sites, where processes of formation and degradation mimic natural sedimentation and erosion. Such a geoarchaeology can be highly informative for urban processes, demographic cycles, or the intersection between sites and their surrounding landscapes.
(4) Spatial components of geoarchaeological research need more systematic consideration, for locational strategies and with an appreciation that site presence or absence allows a more dynamic modeling of settlement and procurement strategies. Regional settlement expansion and contraction may also inform on mosaic evolution or Pleistocene dispersals, including the Out of Africa hypothesis.
(5) Finally, multiple themes connected with environmental degradation during Holocene times may open new windows to examine specific problems by objective criteria, so contributing to a wider academic discourse about long-term trends, the interfingering of climatic and land-use factors in cause-and-effect dilemmas, or the construction of future scenarios in an era of accelerating planetary change.

The focus of archaeology is shifting to later ranges of prehistory so that geoarchaeologists now have a mandate to engage more directly with urban, spatial, and degradation issues. This should be met with a broader and more inclusive agenda, one that optimizes on expertise with historical geomorphology and environmental history, but in collaboration with archaeologists and other social scientists. That would sustain a more prominent role for geoarchaeology in the university curriculum.

1. Rationales

Geoarchaeology is a growing subfield that includes many kinds of research, with different preferred methodologies, and implemented at several scales. To compound this complexity, in North America

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geoarchaeology is primarily practiced by geologists, but in Europe mainly by geographers and archaeologists. Add to that, the fields of study are different. In the New World, little geoarchaeology considers the record earlier than 15 ka, while in the Old World the archaeological record reaches back 2.6 million years. Old World geoarchaeology is also allied to paleoanthropology, which stresses early human evolution and favors multidisciplinary projects in Plio-Pleistocene depo-centers, with fossil beds and early human remains. Yet many geoarchaeologists who work in the Old World are based in North America, so that any fault lines are not national, but reflect different perspectives, interests and social circles.

Despite those contrasts, geoarchaeology is an intellectually rewarding medium of research and the commonalities are strong because the subject matter has great appeal, and archaeologists for the main part are inclusive. The devil is in the details, meaning the university structures and funding agencies that separate, divide, or marginalize the geoarchaeological enterprise, particularly in the United States. The ontological dilemma also includes whether specialists and facilities engaged primarily in dating, geochemistry, metallurgy, geophysics, or geoceramics are automatically counted to geoarchaeology or archaeometry. It consequently serves no practical purpose to seek logical, unifying structures or categories for what geoarchaeologists do.

The designation 'geoarchaeology' was first used in print in 1973 (Butzer 1973a), and a series of reviews and books followed. These include Gladfelter (1981, 1985), Butzer (1982), Brown (1997, 2008-this volume), Goldberg and Macphail (2006), and Rapp and Hill (2006), among others, which all include rewarding bibliographies. Further, the journal *Geoarchaeology* now is in its twenty-third year.

The purpose of this essay is not to review the growth or scope of the field, but to single out and explicate some of the exciting *challenges* confronting geoarchaeology today. 'Challenges' implies that solutions to some persistent problems continue to be tested, despite improving skills and innovative technologies. Under whatever name, geoarchaeology initially focused on environmental reconstruction and stratigraphic dating of sites. Over time deeper interdisciplinary links were developed with archaeology on the one hand, and several branches of the science community on the other. Attention turned to an active engagement with site micro-depositional environments, and the application of technical innovations to archaeology. But we argue here that geoarchaeology can and should be a great deal more than the application of geoscience methods to archaeology.

The archaeological record is a proxy for human biological and cultural evolution that identifies behavioral patterns, encoded in artifacts and embedded in sediments. This should call for a far more interactive collaboration between geoarchaeologists and archaeologists, in the field and laboratory, to address central archaeological issues directly. Archaeologists are good partners to jointly discuss, test, and implement geo/archaeological strategies and methods that may resolve specific problems or enhance comprehension.

In the best of possible worlds, that would be the ideal. But the reality is that most geoarchaeologists with extended careers have followed zigzagging opportunities made possible by major developments in archaeology and paleoanthropology. Despite shared interests in geomorphology, environmental history, and the human past, they find themselves doing many kinds of things, as they confront distinctive field problems in different world areas or time periods. Linear progressions are less common than in some fields, but fortunately personal growth is cumulative, and may be significantly influenced by 'field based apprenticeships' and relationships with archaeologists.

What geoarchaeologists do in long-term practice can be informative, not in the biographical sense, but in didactic terms, to highlight problems commonly encountered. To test this, I made an inventory and found that I happen to have studied and published on some 54 sites. But I was able to collaborate in ongoing excavations at only eight of these, while I excavated another four myself. Other sites were investigated after the main archaeological excavation was completed or long thereafter, in part with the original excavators, in part independently. The collaborative excavations obviously involved much longer investments of time. At more than half of the 54 sites studied, the major effort was expended on 'traditional' methods, such as site micro-depositional environments and relating these to a wider record of environmental change, in part with the goal of stratigraphic dating.

This retrospective turn was surprising and instructive, clarifying that much or most of what we do as geoarchaeologists is indeed 'archaeological geoscience.' But today we *can* transcend this strictly empirical model, to engage more directly in archaeological issues by taking initiatives in the formulation and testing of hypotheses.

The most immediate question concerns the concept of an 'archaeological site.' That may be clear for an urban mound or a cave, but not for a cluster of artifacts found embedded in a fluvial sedimentary profile. Artifacts and/or animal bones resting on a sedimentary discontinuity may or may not relate to prehistoric occupation. How does one argue the point? Some of this is in the purview of the archaeologist, but other aspects must be dealt with by the geoarchaeologist. If the preponderance of evidence does eventually favor an occupation floor, then the next issue is whether it retains its integrity, i.e., has not been disturbed and 'rearranged' by environmental processes before, during, or after burial with sediment? If undisturbed, the site would qualify as 'primary,' but if selectively 'rearranged' it might still provide useful information on human activities so as to qualify as a 'semiprimary' site.

How common are primary or semiprimary sites, as defined here? Excluding 'urban' or 'architectural sites,' and several dozen other sites with artifacts but no archaeological integrity, 17 sites that I studied lacked demonstrable occupation surfaces. These do not include 4 faunal and 3 rock art sites. Of the sites that had been systematically excavated, 22 may well have been semiprimary, and another 4 probably merited a primary status. Of these 26, some 18 were cave sites That is a reasonably large sample, but a low tally, skewed in favor of cave rather than open-air sites. That would imply that *site integrity* is or should be a prime concern for archaeology and geoarchaeology.

Finally, this essay is directed to archaeologists as well as geoarchaeologists, to outline common ground and identify issues of deeply shared interest. One goal would be to explain to archaeologists what geoarchaeologists do and why, but equally so to urge geoarchaeologists to engage more fully in common research that can move to the forefront of contemporary themes in environmental history and global change. In terms of public interest, student engagement, and funding sources, the future of our field may well depend on our willingness to participate in current discourse and debates.

2. A matter of scale

An integral perspective of most geoarchaeological investigations is scale or scale-switching, from the large to the small and back. This is all well enough known, but a brief reiteration helps to put some certain interrelationships into context before engaging in the main themes of this essay.

2.1. Macroscale environments

The initial stages of a study involve familiarization with a particular landscape in which a known site is located or unidentified sites may be located. Concurrent field reconnaissance with the study of maps, air photos and satellite imagery and so forth help define a preliminary environmental context. This exploratory stage allows for a provisional mental assessment of potential combinations of geomorphic and other processes operating in the region, and affecting sites in particular kinds of topographic settings.

2.2. Mesoscale environments

In greater proximity, investigation focuses on direct, empirical identification of the spatial patterns of geomorphic context for a proven site or for undetermined but promising locations. A combination of *on-site and off-site study* helps situate a project within a larger geomorphologic system, such as a floodplain, and also draws attention to the organizational grain of an environment as a human habitat. The on-site/off-site dichotomy relates directly to the complementarity of watershed and site. In an agropastoral context, for example, human impacts in site proximity differ in scale and intensity from those in more distant lowland or upland sectors of a much larger watershed. Ultimately what happened around the site either can or cannot be reconciled with the response of the watershed, and such concordances or divergences would be informative. Quaternary-style watershed studies may reveal little or no Holocene change, which helps assess how land-use practices within a restricted area may have effected landscape change at a larger scale (Butzer and Harris, 2007). This example, which can be modified for other archaeological settings, illustrates the direct applicability of geomorphology to geoarchaeological problems.

2.3. Depositional micro-environments

On-site geoarchaeology focuses on sediments and sedimentation, micro-stratigraphy and soil horizons, as well as evidence for alternating stability and change:

(a) Site formation, modification, and eventual destruction depend on intersecting natural and cultural processes that are viewed somewhat differently by a geoscientist or an archaeologist. That is most apparent in diverging drawn sections of an excavation face, which may require cross-disciplinary discussion and reconciliation. Sites form and are transformed within a four-dimensional matrix, as a result of interactive agencies unbeholden to disciplinary boundaries. Excavations require close cross-disciplinary collaboration in sediment interpretation and also in terms of excavation strategies, i.e., where additional trenches need to be dug.

(b) If animal bone is prominent in a site, the active participation of a qualified bioarchaeologist is indispensable. The issue is more than the identification of bone, but includes questions about the accumulation, processing, and discarding or scattering of bone fragments. This concerns human activity patterning, local biota, and micro-sedimentation, particularly in early prehistoric sites.

(c) The geoarchaeologist must sample and analyze on-site and off-site sediments and soils with all relevant techniques, to determine differences and similarities. This may seem obvious, but in practice it is not so. Analog-sampling of off-site environments is a requisite for sophisticated interpretation of sediments, using appropriate statistical procedures, much as in the case of modern palynological studies.

3. Archaeological integrity of open-air sites

3.1. Archaeo-taphonomic integrity

The basic issues of site integrity are grounded in the physical and social sciences. The obvious analog is given by taphonomy, a study mode first developed in paleontology (see Allison and Briggs, 1991) to assess the inputs, processes, and filters that transform a living community to a death assemblage and ultimately a fossil palimpsest. In part, the dead organisms are initially scattered, and then in part buried and selectively preserved. Tracking these possibilities, how does one reconstruct the living community?

For archaeology, the challenges and possibilities are much the same. The converging and diverging behavioral patterns of a particular group at a given time are abstracted as a material record, through cultural and physical filters. Part of that record is lost or destroyed, but another part is buried and preserved, to produce the archaeological record or assemblage. The logical charge for geoarchaeology is to identify and assess the role of the filters and processes that impact the 'coming together' of those material residues and their transformation into an archaeological record.

Archaeo-taphonomy is at the crux of the intersection between the human past and the processes of geomorphology.

3.2. Situating open-air sites

Although the public imagination of Pleistocene archaeology is focused on Neanderthals, cave art, and hunters of woolly mammoths, most of the history of human biological evolution played out not in caves but in open-air sites. On a global scale, caves and rock shelters are comparatively rare, owing their origin and preservation to particular geologic circumstances, which introduces a significant bias to Paleolithic archaeology. For better or worse that is the reality we must cope with as we attempt to document most of prehistoric time.

Recently discovered sites in Ethiopia that are dated 2.3 to 2.6 million years ago have produced artifacts that are relatively abundant and essentially indistinguishable in form from much longer known ones that postdate 2 million years (Klein, 2008). But their links to a particular advanced hominin fossil remain controversial, since fossil phylogenies are unclear. Long lists of faunal assemblages from this time range have been studied, but they are rarely connected to hominin predation or butchery. Such faunas serve stratigraphic ends and environmental reconstruction, although they are biased by mainly coming from low-energy deltaic or lacustrine beds (e.g., Butzer, 1970). In combination with good lithostratigraphic resolution and some palynology, the faunal record allows ecological modeling of potential, early hominin niches or adaptive radiation (e.g., Butzer, 1977a,b).

By mid-Pleistocene times one would hope to find a more nuanced understanding of changing human behavior to emerge from the record. But serious methodological problems were encountered in transferring the archaeo-taphonomic record into a valid window on such behavior. For a time, supported by detailed mapping of excavation floors, a basic association of animal bone and lithics was believed to indicate human butchery activities (Freeman 1978). But as questions about the epistemology of archaeological interpretation arose (Schiffer, 1987, and earlier), it became clearer that early, optimistic assumptions about associations and activity surfaces were debatable.

Alternative explanations were then suggested, requiring a fundamental re-thinking of once accepted truths (Potts, 1988). Some sites were re-excavated but, more commonly, the engagement of multidisciplinary teams required much larger grants and longer periods of on-site analysis, not to mention complex analog studies — such as modern bone-accumulation by carnivores (Brain, 1981; Faith and Gordon, 2007), the outcomes of modern tool manufacture (Schick, 1986), and use-wear analyses of modern lithic artifacts in relation to potential human activities (Keeley, 1980). This all threw the archaeology of open-air sites into disarray, requiring a re-thinking of the enterprise and a much more sophisticated and interdisciplinary approach.

Geoarchaeology is, or should be, a critical component of this effort. At question is whether an artifactual or bone assemblage, uncovered by excavation of an open-air site, offers a reasonably accurate freeze-frame picture of human activities while such materials were used or abandoned?

3.3. Site burial

Was burial by sediment almost immediate or much later than abandonment of bone or artifacts? Were the sediments deposited by low or high-energy processes? Is it likely that an initial cover of sediment was later removed by erosion, to expose the bone/artifacts, prior to subsequent removal? This requires special attention by the geoarchaeologist and the excavator to the details of micro-stratification and sedimentary contacts. Such work can provide a better approximation of effective processes but, in isolation, will seldom offer certainty.

3.4. Horizontal movements

A first test of site integrity is the sedimentary matrix in which such materials are formed. Processes such as sheetwash, stream flow, gravity, frost-sorting, wave action, and animal disturbance may be involved (Rick, 1976), setting their own energy parameters. They can overprint or disrupt an original focus of human activity to create new patterns. For example, sheetwash can release dispersed artifacts from a friable sediment, to redistribute them as a single level on the floor of an erosional scar (Butzer, 1982, pp. 101–103; Johansson, 1976). This can happen after every rainstorm, and the displaced artifacts are later reburied, to simulate an occupational 'level.' Streams also move artifacts or bone that may jump from one point-bar to the next; some such point-bar collections have actually been claimed as 'occupation floors.' Frost-heaving creates periglacial patterned ground, rearranging large stones to simulate circular or elliptical, stone-bordered hearths (Butzer, 1982, pp. 103–105; Benedict and Olson, 1978). Light can be shed on such problems by fabric analyses of dip, orientation, and size of artifacts or bone (Lenoble and Bertran, 2004). But further analyses are also offered by archaeological and bioarchaeological procedures.

3.5. Selective preservation

Differential preservation of bone and other organic features, with respect to decomposition or fossilization, is an obvious concern and not unexpected in many chemical environments (Butzer, 1982: Figs. 7–16). More fundamental would be the absence or underrepresentation of finer size-classes of lithic débitage or bone (Fladmark, 1982; Hoch, 1983; Lenoble et al., 2008). This can signal erosional winnowing of smaller lithics or bone, which would raise questions about the clustering and patterning of the surviving larger artifacts. A good test would be to try to retrofit the flakes struck from a particular core during the original stone knapping (Cahen et al., 1979). If retrofitting is possible, it is probable that a measure of original patterning has been preserved, on what is likely to be an 'occupation floor.' The geoarchaeologist is qualified to test size-classes for artifacts and flaking debris, and may be able to recognize flaking debris in the sand or grit fraction under magnification. But he/she is dependent on a lithics specialist for results on retrofitting and artifactual associations.

3.6. Bone and carnivores

An early question at Olduvai was whether the concentrations of animal bone in lake beds represented kill sites, or whether people had simply scavenged carnivore kills or taken advantage of animals bemired in the mud, or recently died of natural causes (Potts, 1988). This does not directly fit a geoarchaeological job description, but it is a question so central to basic site interpretation that its pursuit is essential. Excavators commonly are quite competent to examine archaeofaunas for cut-marks, impact-damage from thrown rocks or javelins/spears, or gnaw- and breakage-marks from other predators. Bioarchaeologists may be better trained to inventory which bone parts are present or absent, and articulated or not, so as to apply modern analog studies to determine which body parts were selected and consumed by which predator, and whether they were dragged from a kill-site as opposed to processed in place (Brain, 1981; Klein, 1987, 1989; Allison and Briggs, 1991; Outram et al., 2005). Such methods should narrow down the possibilities, but may never be conclusive. The inferences drawn must of course be consistent with the microsedimentology.

3.7. Vertical movements

A number of processes can disturb the horizontality of an occupation level, by selectively moving objects up or down in a profile. In wet, clayey deposits, artifacts or potsherds can sink downwards for many meters, as for example in the Nile Valley or Delta (Butzer, 2002). On the other hand, alternating soaking and parching of expandable clays can promote soil heaving, to eject artifacts to the surface (Butzer, 1982: Figs. 7–9, 7–10) or, in cracking heavy clays, dislocate them downwards. Sheetflow can remove sand from underneath an object, so that artifacts or bone appear to sink down to the top of a denser or harder level. Because of differential conductivity, needle ice and frost-heaving can raise rocks or artifacts at variable rates, to displace components of a once horizontal occupation level. Bioturbation by ants in Africa or earthworms in higher latitudes can disperse artifacts through considerable depth of sediment (Bocek, 1986; Balek, 2002; Johnson, 2002; Canti, 2003); sometimes rock and artifacts 'reassemble' as stone lines a meter or more below, on what have occasionally been identified as archaeological horizons (Cahen and Moeyersons, 1977). Wind can have a similar effect by deflating friable but complex strata that incorporate archaeological sites. Subsequently the artifacts may reappear within interdunal swales (Butzer, 1982: Figs. 7–5), and several cycles later the eolian bedforms may be partly obscured. Through-flow can then produce lines of groundwater ferruginization that, in combination with bits of preserved humus horizons, can simulate multiple soils and occupation levels (Butzer, 2004). Trampling by people or elephants may disrupt or simulate an archaeological level (Stockton, 1973), while trampling by hooves can simulate bone damage by butchery (Behrensmeyer et al., 1986).

3.8. Challenges?

This litany of possibilities is at the heart of what geoarchaeologists study, and such complications are common enough, and not only in Africa or Europe. Artifacts do move, and at some point they may be exposed long enough to become patinated with desert varnish or ferruginous solutions, so as to make use-wear analyses inoperative.

The skills and experience of the geoarchaeologist can be critical to distinguish 'sites' from 'non-sites.' Major projects such as in the African Rift – the Omo and Awash valleys, Koobi Fora, and Olduvai Gorge, for example – were spared from premature conclusions by long-term, cross-disciplinary collaboration that offered reasonably cautious interpretations of hominin behavior.

Despite initial optimism, mid-Pleistocene open-air sites, such as Torralba and Ambrona (MIS 16 ?), on the plateau of Central Spain, have been disappointing, even after six seasons of excavation and meticulous recording. The faunal assemblages here are inconclusive as to widespread hominin butchery activities; use-wear analyses were unproductive, in part because of subtle abrasion of bone by sediment movement (Butzer, unpublished); and artifacts could not be retrofitted. Despite close to 4000 Acheulian artifacts (Freeman, 1978; Howell et al., 1991), it remains unclear whether these were primary occupation sites. By contrast, the Late Pleistocene (MIS 4) open-air site of Salzgitter-Lebenstedt in northern Germany had masses of reindeer bone that were diagnosed to be redistributed by spring floods, but displayed abundant butchery damage and significant small-scale associations with Mousterian artifacts, supported by Neanderthal fossils (Tode et al., 1953; Gaudzinski and Roebroeks, 2000). The significant differences between these sites appear to be greater spatial concentration and less abusive sedimentation processes at the younger site. Only little later (MIS 2) the case becomes even more conclusive at Hamburg-Ahrensburg (Rust, 1962) and in eastern Europe (Klein, 1973), by virtue of abundant evidence for structures and other features. Open-air sites continue to pose a major challenge, so that we cannot yet test whether mid-Pleistocene settlement systems were qualitatively different from those after ~20 kyr.

3.9. Merits of open-air "non-sites"

For most geoarchaeologists, the search for the 'perfect site' may seem specious. The presence of stratigraphically dated artifacts in off-site locations is indeed informative. So, the presence of some handaxes embedded in cemented screes on the upland above Torralba provided a spatial and ecological perspective on people in that cold-climate landscape (Butzer, 1982, pp. 235–238). These are indeed alternative goals, and priorities need not be identical. The presence of Paleo-Indian artifacts in good lithostratigraphic contexts is useful and lends meaning to a research project. Cumulatively, such sites document human presence as well as human activities within the environment, and the need exists for more, rather than fewer efforts of this kind.

Some excavators working in very early time ranges do not engage in survey work, and disdain what might be called 'incidental' sites (rather than non-sites). The apparent obsession with point-wise research may seem myopic, despite the likelihood that the big picture in the social sciences will come together from a collage of inhomogeneous case studies. In the UK, geoarchaeology has been revolutionized, by the challenges and infusion of money from the Aggregate Levy Sustainability Fund, i.e., the proceeds of a tax on the output of gravel quarries (Brown, 2008-this volume). Rather than the second-guessing of grant applications by entrenched panels of research foundations, Pleistocene archaeology and geoarchaeology in Britain are now part of the public sector and freed from disciplinary infighting. This has sparked a wave of fresh attention by a growing body of young scholars to incidental sites at the surface and below it. Interesting research is underway on a whole range of themes such as the spatial and temporal interactions of processes that disperse or sweep together prehistoric artifacts in particular meso- or micro-environments. This leads to follow-up questions about the presence or absence of incidental sites, and what that may mean for environmental preferences and settlement discontinuities of prehistoric people in the UK. In the USA, Guccione (2008-this volume) has systematically analyzed the spatial distribution of sites of varying ages along the Missouri, Red, and Mississippi river valleys, focusing on the impact of different alluvial styles upon terrace development and preservation.

Such synthetic-analytical study of surface sites is as important for prehistoric ecology as are the choice textbook sites. They simply embody different information. Given the relevant dormancy of attention to the spatial dimensions of prehistoric archaeology in some parts of the community, this is a welcome challenge for geoarchaeology.

4. Are cave sites a Panacea?

Cave sites are the substance of 19th century archaeology directed to human origins. Excavations of French caves in the Perigord (Laville et al. 1980) drew the first geoscientists, and the basic principles of collaboration among prehistorians and paleontologists came to fruition in such projects. Anchored in the public interest for cave art, excavation in Late Pleistocene cave strata of Western Europe continues to hold an iconic role for perception of the evolution that yielded modern people. Many archaeologists have also been attracted to cave sites in the belief that they can here circumvent most problems of taphonomic integrity, to yield quasi-continuous records of cultural evolution. Nonetheless, even though highly informative, published cave sequences are not without major problems of interpretation.

4.1. What is missing in cave lithostratigraphies?

Certainly, some caves preserve unrivalled lithostratigraphic columns that may suggest clear-cut changes of archaeological assemblages. Preservation is favored by a bounded micro-environment, in what are rock shelters or deeper caverns. But caves are also flushed out, at long intervals (Butzer, 1981a), judging by vestiges of older deposits or the first appearance of cultural units on top of clean, bedrock floors. Disconformities occur below, within, or on top of cave strata that are not always readily explained by cultural intervention or absence of occupation. Floods of course can inundate valleys, but many caves are connected to the outside by fissures and vents that periodically introduce quantities of water through the roof, the back, or the floor of a cave (Butzer, 1984, pp. 57–60).

The second potential problem arises from the incongruence of (a) time, (b) net sediment accumulation, and (c) the micro-stratigraphic record of cyclic human activities. In carefully excavated 'dry' caves in South Africa, a very few centimeters of sediment may record a single phase of occupation; a dozen or more such micro-levels may be grouped into a single lithic assemblage (Butzer, 1984, Table 27). But in 'wet' caves of Biscayan Spain, the micro-bedding of some levels, 10 to 20 cm thick, may give the impression of a homogenous body of sediment, marked by little or no change of spatial and temporal activities. Yet the chronostratigraphy may posit a multi-century or millennial block of time (Butzer, 1986). Such inconsistencies suggest either a lag remaining after countless episodes of human occupation, periodic trampling and mixing of a sticky sediment mass, or cryo turbate distortion of beds. It is, therefore, not at all given that an archaeological level will provide an accurate palimpsest of numerous, sequential occupation cycles. By extension, the integrity of inferred archaeological assemblages or tool-kits may be seriously suspected.

Careful attention to the micro-stratification of cave horizons is called for, to tease out more complex and detailed sequences of occupation and sedimentation, that could hopefully reflect the mainly seasonal occupation of caves within a mobile and much larger settlement system. The contingencies of cave occupancy are such that repeated episodes of micro-erosion and deposition should be expected within a distinctive level. Features such as hearths, pits or post-molds can provide reference points.

4.2. Caves are not closed systems

A common misunderstanding is that much of the mineral sediment within a cave sequence was generated in a closed system. That is rarely true, quite apart from caves where deposits extend out beyond the entrance. Water and sediment wash into a cave from the entrance or through fissures and sinkholes. Such material normally is most similar to the sediments and soils forming outside, above the roof, and may even include material of eolian origin (Butzer, 1981a, 1986). Beyond that, people and animals will track mud in and out of caves in wet environments. Once inside, this clay, silt, and sand will mix in with the cave sediment matrix and also contribute to complex, cultural products. A strong potential relationship exists between soil/sediment forming outside of a cave and that collecting inside. Most cave-analytical methods have ignored that potentially direct link to the external paleoclimatic record (so Laville et al., 1980). It calls for regular sampling of external soils and sediments for laboratory processing, by standard methods, including clay mineral identification.

4.3. Endogenic cave sediments

In appropriate environments and lithologies, caves may produce autochthonous sediments (Butzer, 1986), especially roof spall or wall-rock. This may result from solution by percolating water along fissures, joints and bedding planes in limestone. But during episodes of cold Pleistocene climate, frost-shattering can accelerate such processes to form cryoclastic components (*éboulis secs*) that thin from next to the entrance to no more than the occasional fragment of rock within a finer matrix. Measures have been devised to quantify and identify such rock fall according to angularity and shape (Butzer, 1973b; Laville et al., 1980).

As suggested by the dripstones and flowstones deep within some limestone caves, a potential range of calcite precipitates form in archaeological caves during the course of paleoclimatic cycles. These may form crusts on older deposits, horizons of soft tufa, or dense, laminated travertines that can merge with stalagmites (Butzer et al., 1978; Hennig et al., 1983; Butzer, 1986, 2004). The seasonal cycle of cave moisture is certainly implicated, but other variables include a) the carbonic acid acquired from decomposing organic material by percolating surface water, and b) the supersaturation with calcium bicarbonate of fissure and cave-floor waters. Interpretation is facilitated by stable isotope records but even then may remain inferential. Important is that limestone solution produces only limited ratios of insoluble residues, mainly clays and colloids. The bulk of non-carbonate sediment of limestone caves is introduced from the exterior or comes from breakdown of biogenic products.

4.4. Biogenic components

The organic fraction of cave sediments is derived from human, animal, or plant residues. In detail it includes the residues of dung/feces, urine, body parts and bone, plant foods, and wood ash. Such materials register on routine tests for organic matter, phosphates, potash (potassium), or amino acids (Goldberg and Macphail, 2006, pp. 344–50). But one-to-one links are difficult to establish, and some such compounds can be leached or illuviated down to lower levels (Butzer, 1981a). More biochemical research on the formation of biogenic products and the comparative role of human and other animal contributors is needed. Thin-section studies of morphology have been incisive (Courty and Vallverdú, 2001; Goldberg and Macphail, 2006, Ch. 10, pp. 354–58), but the resources or expertise to study representative suites of micromorphology samples from all levels are not generally accessible. Uncertainty persists about the abundance of amino acids in some cases, or the high percentages of mainly organic colloids released in acid. As a result, the biogenic components and their origin remain inadequately investigated or understood in most cave sites.

In short, study of cave sediments requires specific geoarchaeological strategies, methods, and collaborative links. Few of the 'standard' cave archaeostratigraphies meet all the criteria. The most successful projects are those where new investigative methods have continued to be applied and tested. These would include the australopithecine breccias of South Africa (see Butzer, 1984, pp. 3–18). Bone taphonomy has also been applied with great success, while giving the requisite attention to repeated, small-scale solution and refilling of cavities that develop in older calcified beds (Brain, 1981, 1983).

5. Urban geoarchaeology

In urban and other architectural sites (McIntosh, 1977; Butzer, 1981b, 1982, pp. 87–97; Butzer et al., 1983; Butzer et al., 1986; Rosen, 1986; Goldberg and Macphail, 2006, ch. 11; Beach and Luzzadder-Beach, in press), cultural sediments tend to be preeminent. Whether structures are built of adobe, mudbrick, rough or cut rock, or fired brick, they provide a three-dimensional framework of walls and foundations that define house interiors versus streets and alleys. Sediment accumulates within such spaces during occupation, after abandonment or again during demolition and subsequent rebuilding on similar or transformed ground plans. Sediments in such settings are primarily derived from disintegrating building materials that accumulate within structures, in dumps or refuse middens, and on streets. Unless scavenging of brick or rock is commonplace, or an imposed system of waste removal exists, building debris and rubbish will continue to accumulate within or around such modules, while the site grows upward.

5.1. Site formation and growth

Building materials are transported to a nucleated site as long as the settlement grows. Rock, mud, wood, and components for plaster are initially processed in a number of locations, and then incorporated into residential, civic or religious buildings. Structures that collapse are rebuilt, often on a new plan, while some houses are removed to make way for defensive walls or monumental architecture. Habitation floors and streets may or may not be kept clean, and substrates are excavated for wells, drainage ditches, irrigation conduits, and the like. These processes mimic 'natural' sedimentation and erosion. A special kind of accumulation are the Amazonian Dark Earths (*terra preta*), that formed on prehispanic habitation sites, often on a large scale, as a result of complex organic accretion (Glaser and Woods, 2004).

5.2. Site stagnation or destruction

When neighborhoods begin to stagnate or an urban site suffers economic decline, structures will no longer be maintained or are left abandoned. When houses or public buildings are not rebuilt, chaotic masses of collapsed rubble may pile up. On a larger, catastrophic scale, settlements may also be destroyed by fire after hostile conquest, or demolished in natural disasters such as earthquakes or floods, to create destruction levels (Butzer, Miralles and Mateu, 1983; Butzer, 2005). Cycles of demolition and reconstruction may be repeated several times. Older materials are commonly reused, and mudbrick may contain pollen, micro-artifacts (Sherwood, 2001), or distinctive clay/sand mixes that offer a genealogical record of provenance. In a disused stone building, sheetwash may intrude even before the superstructure crumbles; eventually wash and construction rubble accumulate in an adjacent stream channel (Butzer, 1981b). When a site is permanently abandoned, the debris is partly sorted and rearranged by a host of natural processes, directly or indirectly facilitated by human action.

5.3. Site degradation

Additional processes come into play after abandonment (Butzer, 1982, pp. 117–22). Rainsplash and sheetwash continue to erode the surface, aided by gravity and other forms of running water. Redeposition in hollows and voids favors compaction, and site topography is leveled. Even as high points continue to erode, and peripheral footslopes are extended, the surface is altered by vegetation, soil formation, and biogenic activity, while the subsurface is diminished by removal of solubles. Deflation and eolian sedimentation may also remodel the surface. Over time, the stump of the site typically acquires a smooth, concavo-convex profile (Kirkby and Kirkby, 1976).

5.4. Discussion

The cyclic growth and decline of ancient urban sites has left hundreds of informative settlement mounds in drier environments of the Near East and Mesoamerica (Kirkby and Kirkby, 1976). Many were never reoccupied. Similar architectural sites flourished in other topographic situations and environments, where mud was less abundant and more parsimonious building methods have left only compressed urban sediments at the roots of contemporary towns in Europe or the northeastern USA.

Urban geoarchaeology requires a range of expertise, dictated by multiple facies and a unique sedimentary architecture. Except for studies of mudbrick and material provenance, this is a branch of the field that has engaged few specialists, primarily because urban excavators may not recognize the utility of geoarchaeological inputs. It has considerable promise for practitioners to participate in the unraveling of settlement histories and demographic cycles. But above all, provenance studies and the interfingering of slope screes, colluvial, and flood deposits with cultural facies offer processual links between a site and its wider environment (Beach and Luzzadder-Beach, in press). This lays out an underexploited avenue for addressing human land-use change and transformation of surrounding landscapes.

6. A role in archaeological discovery

Archaeological sites are discovered by accident, exploration, or testing. Archaeologists also conduct larger surveys to record surface artifact scatters, incidental sites, and non-sites. Despite preoccupation with a key site, once excavation has begun, archaeologists are cognizant of the spatial dimensions to mobility and subsistence pursuits, and have explored the utility of site catchment analyses, central place theory, road networking, optimal foraging theory, and the like. Such models have proved useful, but other, more empirically-based possibilities have not found access to the general literature. There is a wide range of possibilities for a spatially-oriented geoarchaeology to go beyond archaeological applications, to the intersection of space, time and environment with problems of prehistory or human evolution. The following examples outline some of these opportunities that should receive far more attention.

6.1. Spatial components to settlement history

Some major, multiseason surveys have incorporated geoarchaeologists and with good effect in southern Greece. Such attention primarily focuses on surficial sediments and forms. The confluence of a spatially differentiated settlement history with observations on soils, soil erosion, debris flows, and valley alluviation brings together hypotheses and data-supported insights on changing patterns of land use and landscape impacts (Jameson et al., 1994).

At a much finer scale such principles can be incorporated to examine clusters of rock art sites that, outside of caves and overhangs, commonly lack sedimentary contexts. In the Northern Cape of South Africa, petroglyphs are found at Kinderdam on the smooth, patinated surfaces of diabase boulders, that form an exhumed volcanic hill. Gerhard Fock mapped the distribution and numbers of human figures, different animals, or symbolic themes represented on each rock. These were found to be spatially clustered, although many similar surfaces were not engraved, to suggest that late prehistoric use of this site complex included several symbolic focal points for possible ritual use (Butzer et al., 1979). Across the Northern Cape the large inventory of animal taxa represented in multiple rock art clusters further shows a biotic zonation, from more closed to more open land cover, consonant with the modern precipitation gradient but implying a moister climate overall.

6.2. Site discontinuity or absence

Surveys, including a geoarchaeological component, can also examine whether site absence or gradients of site density have better cultural than physical explanations. In Egypt, for example, where most late prehistoric sites tend to be buried under alluvium or younger settlements, some sites and most cemeteries of the period are situated on the desert edge (Butzer, 1960, 1982, pp. 261–263, Fig. 14.1). Yet in Middle Egypt only a few stretches have sites. Was this area thinly settled at the time? If so, why? Survey of typical locations clarified that preservation was optimal where non-functional alluvial fills abutted directly on the floodplain. If, however, the low desert alluvia dipped smoothly down to the floodplain margin, recent floodplain extension by farmers probably destroyed many such sites, if they had not already been covered with Nile mud. In other sectors of Middle Egypt, eolian sands and dunes veneer or bury the former desert edge. This project suggested that site physical properties and geomorphic changes were most likely to be responsible for site absence.

A quite different example can be drawn from southern Africa, where settlement gaps were widespread during the time span of MIS 5 to 2 (Butzer, 2004). The archaeological information for seven key sites, site clusters, or site surveys was assembled along an environmental transect with a modern precipitation gradient from 1250 mm in the ESE to 300 mm in the WNW (Butzer, 1988). The resulting patterns imply that settlement in the east during the later Pleistocene was semicontinuous, but in the western sector with less than 500 mm rainfall today settlement is undocumented over a vast area for periods of 30 to 80 ka. In this semiarid region the archaeological record (the Middle Stone Age) is concentrated around dry lake beds, springs now defunct, or floodplains currently entrenched. In effect, the period of late Pleistocene settlement here was tied to dependable sources of water, although not all periods of moister climate were accompanied by settlement expansion, and some perennial streams or springs persisted in the wider area. The best explanation for this paradox is that unspecialized hunter-gatherers did not venture far into dry macro-environments, preferring to avoid the risk of severe drought stress and limited information exchange among widely scattered groups as to animal migrations and available plant foods.

Such a risk-minimization model – for marginal, drought-prone and low predictability environments – may explain long intervals of settlement retraction, leading to population isolates in wetter habitats and favoring punctuated equilibria (Butzer, 1977b). Recent research, based on mitochondrial DNA, has renewed interest on mosaic evolution in southern and eastern Africa (Mellars, 2006; Cohen et al., 2007; Shea et al., 2007), and lends fresh relevance to geoarchaeological research on environmental cycles and human response during the last 200 ka. This complements evidence and insights to the effect that evolving Middle and Later Stone Age technologies also incorporated new organizational strategies and abilities to exploit complex spatial resources and subsistence opportunities (Helgren, 1997). Implications for the evolution and dispersal of anatomically modern humans out of Africa may well be enormous.

6.3. Survey as more than location

Such cases show how, at a basic level, geoarchaeological potential or results can be mapped, to identify settings where sites might be found, or to single out their absence. In conjunction with traditional recognition of appropriate strata, advanced techniques, such as laser scanning or ground-penetrating radar, can transcend matters of prospection to test advanced applications of GIScience (Brown, 2008-this volume). But the qualifiers for application to foreign fieldwork are availability, cost, and the requisite permits.

Ultimately, however, the discovery of critical sites will depend on heuristic models that combine mobility patterns with resource configurations (e.g., Butzer, 1986, Fig. 4.6), to stimulate out of the box strategies that are followed up by patient field exploration. It is here that the larger issues become more clearly defined. The almost improbable discovery of human coprolites, verified by mtDNA, in several studied caves of southern Oregon (Gilbert et al., 2008), suggests that an open mind is a good thing.

The ultimate challenge for archaeology and geoarchaeology does not yet have a practicable solution, despite some modeling and underwater exploration. The late Pleistocene to early Holocene glacioeustatic rise of world sea level submerged countless sites on low-lying coastal plains, making them effectively inaccessible, so as to severely limit discussion of Pleistocene hominin dispersals or agricultural origins.

7. Environmental degradation in historical perspective

7.1. Complexity and contestation

Geoarchaeology also intersects with contemporary concerns about environmental degradation. Human impact on landscapes is not a recent phenomenon, and in some parts of the Old World has long been responsible for forest removal, and destruction of ground cover, to stimulate accelerated runoff, soil erosion, flooding, and rapid alluviation. Geoarchaeology provides basic methods to monitor long-term impacts of improvident land use, information that is crucial today (a) for an objective assessment of damage of the land surface, (b) to formulate remedial strategies, and (c) to project the long-term effects of contemporary processes already set in train by modernization and globalization.

The problems become murky when alternative explanations of historical or prehistoric impacts are considered (Butzer, 2005; Butzer and Harris, 2007). A high recurrence of exceptionally strong rains can lead to similar geomorphic outcomes as may degradation brought on by infelicitous land-use practices. But equally so, one of these options can precondition the environment for significant change by the other. Climate and land-use change do not demonstrably co-vary, but they may well be reinforcing processes in a sequence of preconditioning, triggering, and intensifying change.

Five case studies illustrate the point. Although undertaken by the author, each comes to a somewhat different conclusion, despite comparable premises and procedures. The point is that there is no universal truth, as we continue to search for understanding. Yet in each academic or public discourse strongly contested issues may arise, even 'accepted truths' in regard to the environment. Some people believe they 'know' the history of environmental degradation in their region, based on limited information and sometimes faulty assumptions. The neutral investigator may also be perceived as someone who believes he/she knows better, and in the worst case scenario, is accused of having a political ax to grind, from whatever particular bias. Geoarchaeologists can and should stand for empirical pragmatism among such controversies. Good research always combines inductive and deductive procedures and creative but rigorous testing.

7.2. The tablelands of SE Australia

European settlers entered Australia after 1788, and it is commonly believed that their descendants destroyed much of the woodland and upset the hydrology, leading to soil erosion by gullying. But the earliest scientific travel accounts from SE Australia clearly record significant gullying at many sites before 1830, i.e., prior to settlement expansion. Further, a suite of alluvial fills and paleosols that date back a millennium and more documents cycles of gullying and alluviation that extend back indefinitely into the past, reflecting a non-equilibrium climate (Butzer and Helgren, 2005). Comparing the vegetation of the travel itineraries with the modern land cover indicates limited net change, except in terms of frequency of select arboreal taxa as a consequence of selective cutting. Charcoal frequencies in pollen cores further suggest that strong wildfires were as prominent before as they were after European–Australian Contact. Without disputing the growing impact of industrial-era damage, or the current vulnerability of the environment, it appears that some contemporary assessments of long-term damage are more alarmist than objective.

7.3. Interior, semiarid Mexico

North-Central Mexico has vast tracts of what appear to be degraded landscapes. It is tempting to read this as a consequence of Spanish intrusion and land use after the 1570s, but detailed research shows that aridification destroyed soil resources around AD 1400 and eolian sands were readvancing in some areas well before Spanish sheep appeared. Since this region had no systematic indigenous agriculture, strong cyclic alternations of wet phases and channel instability were responsible (Butzer et al., 2008-this volume). Attributing shifting systemic response and soil erosion to climate, in this case, raises legitimate questions about areas further south, in the indigenous agricultural heartland, where repeated episodes of accelerated lake sedimentation have been attributed to land-use histories.

7.4. The lower Illinois Valley, USA

The Australian case contrasts with evidence from the Illinois Valley, where the first century of Euro-American rural land-use favored accelerated runoff, gully entrenchment, slope soil stripping, and footslope colluviation (Butzer, 1977a). Heavy prehistoric use of a site perimeter on a loessic slope also seems to have contributed to soil erosion, a strong increase of colluvial accretion, and clogged a low-order stream channel with silt. This is dated to the pre-agricultural, Middle Archaic, Helton phase (horizon 6) of about 6000 BP. Climatic co-agency is quite well possible, but the point is that even such low-technology land use can have impact in a vulnerable setting.

7.5. The Sierra de Espadán, north of Valencia, Spain

In this mountainous environment, light prehistoric settlement (Chalcolithic, ~3350 BC) in a few locations coincided with abrupt replacement of pine forest by oak steppe, while stream flow shifted from permanent to episodic and flashy (Butzer, 2005). Following partial ecological reconstitution, the vegetation was degraded further, to a cultural steppe, with a termination of soil formation on slopes, accelerated soil erosion, and strong flooding. This ecological change was too abrupt to be attributed to climatic change, and is directly tied to heavy Late Bronze Age settlement ~1650 BC. These mountains were essentially abandoned around AD 500 and allowed renewed soil formation and forest recovery. In late Medieval times (~AD 1400), deforestation, accelerated soil erosion, and strong stream peak discharge resumed, a trend only reversed by terrace construction and slope stabilization towards 1700. But a different story emerges from urban archaeology in Valencia and Alcira, where strong floods, draining much larger basins, truncated channel Vertisols and buried them under high-energy deposits as early as ~AD 1000. The Espadán case study, which incorporates significant archival components, interjects a different pattern of alternating degradation and reconstitution that was directly tied to local land-use practices. But these cycles are poorly correlated with population pressure, considering that maximum rural population density – during the 19th century – was not accompanied by degradation. Further, the episodes of vegetation and hydrological change were not synchronous between basins, and were too abrupt to primarily attribute to climatic changes.

7.6. The southern Peloponnese, Greece

A range of studies documents events in four basins of the southern Peloponnese (critically reviewed in Butzer, 2005). Substantial change, with debris flows, sheet erosion, and very strong floods, coincided with Early Bronze settlement (~2400–1800 BC) in three of them, following a long period of soil stability (Jameson et al., 1994). Changes between 1200 BC and the 19th century instead played out as spans of soil attrition that began and ended at different times, intensifying and then leveling off repeatedly. With soil formation in one basin contemporary with colluviation in another, these later events were not synchronous but specific to particular landscapes with their own land-use histories. Early Bronze alluviation at Olympia was limited to the axial river, with gravel bedload transported from a distant upstream watershed, whereas Classical age alluvium was locally derived and only formed tributary fans. This argues that Early Bronze erosion did not significantly affect local hillsides, but that sustained high-energy floods carried gravel over long distances in response to climatic anomalies.

These Greek basins are particularly complex, because both climate change and land-use impacts were involved to some degree. Climate appears to have been the dominant factor during the Early Bronze, but land-use impacts became increasingly effective during the last 3000 years. With sufficient temporal resolution it is quite possible that both variables played interactive roles. For example, on Cyprus it appears that the cumulative impact of land use on ground cover prepared the environment for serious damage from a limited number of extreme precipitation events during late Roman times (Butzer and Harris, 2007). That need not posit climatic change per se, but a climatic anomaly with a high recurrence of extreme precipitation events, across a few decades and at most a century or two. Such an anomaly in conjunction with longer-term land-use pressures would trigger and reinforce waves of soil destruction and alluvial response.

8. Changing interests, fresh opportunities

Geoarchaeologists have come a long way from the time when they had to be satisfied with travel and living expenses, while the analytical costs for sediment samples were left to be resolved by the researcher. Today, consulting companies set their own fees and consign laboratory work to subcontractors, which of course is not ideal, but at least more realistic. Yet I would see the most critical part of our collaborative links to be less about material issues, and more about opportunities for sustained engagement with archaeologists — through active participation in strategic implementation of excavations and in publication of the results.

These disciplinary barriers have indeed been breaking down, faster than the reluctance of some major research foundations to support interdisciplinary grant applications without shunting them over to a disinterested cognate program. Smaller foundations more dedicated to interdisciplinary efforts, or university funding, are no more than short-term solutions. Nonetheless many established archaeologists and paleoanthropologists today recognize the significance of a strong geoarchaeological role and are able to assure that adequate funding is available. In good part this reflects a fundamental sea change, in response to the cumulative practice and input of geoarchaeology, especially in highly visible projects.

The self-representation of geoarchaeologists also is critical to achieving more productive, multidisciplinary working relationships. How well do our textbooks reflect the conceptual diversity and intellectual dimensions of our field? We need to articulate our engagement better and be properly attuned to the problems and issues of projects, and engaged in their intellectual goals. We must discuss more explicitly why we do what we do, and how we interpret and project what we do. As archaeology itself continues to shift its major focus to younger time ranges, new opportunities are opened for geoarchaeological skills.

Today, with an era of increasingly variable and extreme 'weather,' environmental degradation represents one of the most challenging issues. Our empirical and systemic expertise in monitoring change offers a direct line to examine current environmental problems. Greater attention to the 'historical' record of human landscape impact will open a broader spectrum of interdisciplinary linkages. In the meantime we must more successfully interest students in the links between the environment and how our ancestors lived with it in the past, and of the windows that our science opens to better understand how we are doing today and the uncertain prospects that this implies for the future. Geoarchaeology deals with the real world in a very practical way.

Indeed, if we step beyond the battery of techniques that we employ, much of what we do is highly relevant to the academy and the public — in its own right. Environmental history and geomorphology, or environmental degradation and planetary change, offer especially *challenging issues* to incorporate into our lecture curricula and seminars.

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