Towards a Benign Reburial Environment: the Chemistry of the Burial Environment

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Introduction

The soil is a chemically, biologically and physically complex medium. There are an enormous number of variables that can influence the preserving/degrading nature of any soil and the burial environment it creates. Archaeological remains are recovered from all soil types. Most come from the moist aerobic soils that support plant life, however, particularly rich and informative assemblages come from dry arid soils and waterlogged deposits. The soil matrix is composed of; crushed rock and mineral particles, clay particles, organic material, water containing dissolved salts, gas and micro-organisms. It is a porous medium that rarely achieves equilibrium. Processes such as micro-organism activity, the weather, evaporation and ground water movements ensure that it is a state of constant change. In particular the cycles of wetting and drying, either through rising ground water or through surface water percolating down through the soil ensure that most soils containing archaeological remains have variable levels of water content, dissolved salts and oxygen.

The chemistry of soils is summarised in articles [1] and described in detail in frequently updated textbooks [2]. The principal parameters of soil chemistry of interest to archaeologists and conservators, such as pH, speciation and redox potential (Eh) have been clearly described by Pollard [3]. The interaction of soil and soil solutions with archaeological materials such as metals has been described by Edwards [4] and McNeil & Selwyn [5]. For the purposes of this article I will focus on the extent of variability of some of the key factors in the soil environment, their influence on buried archaeological materials and how this may lead to recommendations for reburial materials and environments.

For the purposes of exploring its chemistry, soil can be considered to be composed of 3 components:

Soil solution ↔ Labile soil ↔Non-labile soil

The soil solution contains ions and organic molecules in solution, readily available for chemical activity. Soil gasses are also readily available for interaction. The labile soil represents the clay and organic particles that exchange ions with the soil solution and form a reservoir buffering the chemical changes (Eh, pH, conductivity). The non-labile components are the minerals and organic material that are still being broken down. These component's chemical influence is slow and occurs over a long period of time. The short term effects of soil solution and the labile component can be relatively fast and they frequently interact with the biological components of the soil.

Water

The water content of soil depends on rainfall, drainage capacity of the soil, groundwater level and soil composition. The upper levels of soil in arid regions may have very low moisture levels, only saturating during very occasional periods of high rainfall. The lack of water, which is so essential for the corrosion of metals, the mobility of salts and the activity of biological life, can lead to minimal levels of decay in the upper reaches of arid soils. This is exemplified by the survival of textiles at Pacatnamu in Peru [6] and the wooden beams in the pueblos of Chaco Canyon. For dry sites periodic inundation may lead to physical damage of artefacts due to the stress of repeated swelling and contraction of organic matter and degraded glass. The outer layers of cellular structures such as wood can suffer evaporation and capillary stresses leading to weakening and cell collapse. These occasional episodes may be the primary decay periods in environments that otherwise have low levels of decay. In arid sites the moisture levels in the soil are the key parameter for determining the rate of decay.

'Our world is carved from wind and summer thunderstorms'

Vera Teller, Pueblo Indian, New Mexico

Many soils in temperate regions contain high levels of moisture throughout much of the year, and are frequently waterlogged (water filling all the pore spaces) at depth. Excess water can lead to the exclusion of oxygen and the anoxic conditions in which anaerobic microbes flourish. Permanently waterlogged sites preserve organic material such as the prehistoric wooden trackways recovered from the Somerset Levels in England and the ritual deposition site of Nydam in Denmark. For wet sites periods of drought lead to falling water levels and the ingress of oxygen giving rise to increased acidity and flash corrosion of metals. These occasional episodes may be the primary decay periods in environments that otherwise have low levels of decay.

Oxygen

The soil normally contains gasses similar to those in the atmosphere, though CO_2 levels are often raised and O_2 levels lowered due to respiration of soil aerobes. Oxygen levels are maintained in the soil through the ingress of oxygenated water and the diffusion of oxygen through air. The reduced level of diffusion of oxygen through water; $2 \times 10^{-9}\ m^2s^{-1}$ c.f. $2 \times 10^{-5}\ m^2s^{-1}$ through air, will lead to reduced oxygen conditions in any period where water saturates the soil, though days (or weeks) of saturation are required before anoxic conditions are created [7]. The relative depth of the soil as well as the volume and rate of water ingress, the volume and rate of drainage (soil porosity) and level of aerobic activity will affect such conditions. Whilst the rising levels of anoxia that occur in the base of many freshwater lakes in the summer is primarily due to rise in the growth and oxygen consumption of aquatic plant life (aerobic activity), it is often the periods of heavy rainfall in the winter which primarily give rise to anoxia below the soil surface (rate of water ingress & rate of drainage). 'Anaerobic processes can occur in most free draining soils' [8] usually through periods of inundation or high biological activity. In frequently saturated soils, the constantly changing conditions often favour the development of facultative anaerobes; organisms which can thrive in both aerobic and anaerobic conditions.

The amount of oxygen present in soils normally determines the nature and activity of the microbes present. In moist, well oxygenated, soils bascidiomycetes fungi such as brown and white rots are present. The low levels of oxygen encountered in partially or occasionally waterlogged soils support ascomycetes fungi such as soft rots, whilst in fully waterlogged conditions anaerobic bacteria are the primary active microbes. Brown and white rots rapidly consume wood and other organic materials very quickly; anaerobic bacteria consume wood and other organic material slowly [9].

Oxygen levels are usually high in arid soils but the lack of moisture keeps the population of aerobic microbes and their activity low. During the occasional periods of rainfall the microbes become highly active and the decay rates of organic materials and the corrosion rates of metals will be high.

The amount of oxygen present within the moist soils fundamentally affects the nature and rate of metal corrosion. Work by Galliano [10] has shown high levels of iron corrosion are correlated with well drained soils, whilst poorly drained soils, e.g. at the site of Pommern, showed oxidation (redox) levels reducing as the ground saturated following rain leading to reduced levels of metal corrosion.

Specific events such as burning can draw oxygen from the soil and enrich it with charcoal deposits that adsorb the dissolved salts required to support microbial life. This leads to unusual conditions that preserve organic and metallic artefacts e.g. a quill pen preserved below 15th century burning deposits at Dryslwyn Castle, Wales.

Cations & Anions

Dissolved in the soil solution are numerous different anions (CO_3^{2-}, NO_3^-, SO_4^{2-}, S^{2-}, OH^-) and cations (Na^+, K^+, H^+, Fe^{2+}, Ca^{2+}, Al^{3+}, Cu^{2+}). The original sources for these ions are minerals that dissolve at different rates in the surrounding water. The dissolution of minerals depends on the solubility product of the mineral i.e. the extent to which it will split into ions and enter solution e.g. $CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$. This will be affected by the concentrations of ions already in solution; pure water with few dissolved ions such as rainwater will dissolve minerals more readily than soil solutions already laden with dissolved salts. Other crucial factors in affecting the solubility of minerals include pH, redox potential (Eh), the presence of organic molecules which can act as chelating or sequestering agents and even the temperature of the solution. This ability to dissolve is crucial for some archaeological materials such as glass, plaster and mortar. High levels of water flow and/or water with a pH, in which the mineral is highly soluble, can lead to high levels of loss of the mineral e.g. loss of calcium carbonate and thus loss of strength from mortar, plaster, chalk and limestone.

The chemical balance for soils are primarily related to their ion exchange capacity, in particular their cation exchange capacity (CEC). At low concentrations the movement of soluble salts and pH (H^+), depends on the capacity of the soil to hold and exchange cations. This is invariably determined by the organic materials and clay particles present within the soil. Large amounts of organic matter and clay can act as a buffer to protect the soil from extreme level of pH or high levels of mineral salts such as iron oxides, gypsum or soluble sodium salts.

The movement of cations through the soil, via the soil solution, can sometimes be considered slow in modern agricultural terms. Evidence of liming the surface of soil suggest that Ca^{2+}, despite being one of the more mobile ions, hadn't moved further than 100mm in 5 years [8]. However, over archaeological time, periods of hundreds or thousands of years, cations can readily travel many metres. The fact that they don't, as shown by the lack of dissolution of corroded metal on many sites, demonstrates the limited solubility of many of the common metal corrosion minerals and that the rate of cation exchange in many soils can be relatively slow.

At higher concentrations the soluble salt concentration within groundwater is normally described through conductivity, defined in mS. For normal soil/agricultural use; 0-2mS is considered salt free, 2-8 slightly saline, 8-15 moderately saline, and >15mS strongly saline. High levels are only normally seen due to evaporation activity in hot climates, excessive fertiliser use or pollution. Values from Caple & Dungworth [11] suggested that conductivity values around 0.8mS (800µS) were normal for water run off from soil. Raised values of 1 – 1.7mS were derived from fertiliser enhanced agriculture in Cambridgeshire and Yorkshire. However, higher values can be encountered in the urban environments e.g. values of 2.4-17.8 mS for the groundwater of the Parliament St site in York [12] where dissolved salts, principally gypsum, had been formed from previously waterlogged deposits which had oxidised and probably reacted with flooring mortar.

In arid regions higher levels of soluble salts lead to specific problems with physical degradation of porous archaeological materials from stone and plaster to bone, and ceramics, through the crystallisation and growth of soluble salts [13]. Exposed evaporative surfaces are particularly vulnerable, though depending on the moisture level within the soil and the relative humidity in the soil pores, this can result in salt deposition within voids and soil pores. This problem of salt efflorescence and cryptoflorescence from soil solutions is difficult to model since the presence of one salt influences the crystallisation of the other [14]. In complex solutions such as soil waters which may contain several salts it appears likely that crystallisation can occur over a wide range of relative humidities.

The relative pore sizes of the soil or reburial media surrounding a porous archaeological material will determine which media retains water. Crystallisation of soluble salts and salts with limited solubility such as calcium carbonate or iron oxides often occurs at surfaces where pore sizes change e.g. at the interface between soil or burial media such as bone, mosaics, masonry, plastered walls etc.

Lower level of dissolved salts, raise the conductivity levels of the solution and lead to an increase in the corrosion of metals and the activity of micro-organisms. The lowest levels of dissolved salts/ions are seen in rain water falling on upland and raised bogs. The waterlogged and mineral poor conditions, especially in sphagnum peat bogs lead to a lack of biological activity and the remarkable survival of bog bodies [15].

pH

The pH of soil, the concentration of hydrogen ions (H^+) in the soil solution, normally occurs in the region pH 2-10, most usually in the range 6-8.5, and is controlled by cation exchange and a series of chemical equilibria such as:

$$Ca^{2+} + CO_2 + H_2O \rightarrow CaCO_3 + 2H^+$$

[this equilibria operates below pH 8 where Ca^{2+} is available through ion exchange]

Other chemical equilibria NH_4^+/NH_3, $FeOOH/Fe^{2+}$, sulphide/sulphate, and ion exchange media such as clay particles, organic material, etc all determine the pH of the soil, and the ability which any soil has to buffer its pH.

The degree of spatial variation within soil chemistry is rarely appreciated with single pH measurements often used to describe large areas of soil. However, work on the relatively homogeneous agricultural top-soils, has shown pH values ranging from 4.5 to 7 in a single field (0.45ha), leading Cresser, Killham & Edwards [8] to state that 'soil pH can vary by 2 units over very small distances'. pH also changes with soil depth, usually becoming acidic as depth increases. The stratified deposits of an archaeological site will almost certainly have greater compositional variation than agricultural top-soil.

The measurement of pH of soils, especially aerobic soils which normally have samples removed for analysis, presents problems of accuracy. Such soils are frequently not saturated; so they cannot be reproducibly analysed in situ with pH probes [16] consequently soil samples are normally taken and saturated in the laboratory. The amount of water added, whether distilled water or calcium chloride solution (to avoid the dilution of dissolved salts) can affect the pH reading by half a unit or more. The depth from which the soil sample was taken, the season, time since last rainfall, level of fertiliser present, also all influence pH readings. The charged surface of clay particles and their associated cation and anion sheaths leads to variations in pH associated with the presence of clay particles around any monitoring probe. Whilst standardised laboratory procedures allow comparative pH results to be established, these are not necessarily the conditions experienced in the soil by the artefacts. For archaeological work a number of accurate, in situ, pH readings are ideally required.

Changes in the pH of the soil result in the stability (solubility) of different minerals and concentrations of different cations being present. Thus acid soils are usually rich in iron and manganese, potentially leading to iron and manganese minerals forming in or on archaeological materials leading to staining. Alkaline soils, which are frequently encountered in hot climates with high evaporation levels, can be rich in base metal ions such as sodium potentially giving rise to soluble salt formation within porous archaeological materials.

The stability of various archaeological materials with regard to pH was tabulated by Darvill [17]. Perhaps the most serious problem is the loss of bone, shell, ivory, tooth etc. where acidic soilwater demineralises the bone and leads to increased rates of collagen hydrolysis [18]. The loss of bone fundamentally affects the interpretation of archaeological sites and their associated cultures.

The pH of the soil will affect the lime constituent of any mortar; acid soil waters partially dissolving the lime and weakening any plaster, wallpainting, mortared masonry or mosaic. The loss of calcining elements may also occur through ion exchange with the soil water low in dissolved calcium minerals.

The nature of the soil, can make a considerable difference to the effect of pH, calcareous and loam soils in Sweden showed considerable buffering capacity to the effects of acid rain and prevented enhanced levels of corrosion. Thin acid soils, which had little buffering capacity, reflected a more corrosive environment [19-21].

Organic Matter

The organic matter of the soil is primarily present as the polyphenolic humus largely derived from the breakdown of lignin, but with a substantial polysaccharide component derived from the breakdown of cellulosic material as well as living plant and animal tissue. The role of organic matter in soils is crucial to provide the adhesion of the soil particles and maintain its structure. Adhesion occurs both as a physical (filamentous) form and chemical binder (degraded polysaccharide and humic acids ‘sticking’ particles together). It also acts as a cation exchange reservoir, maintaining pH and cationic equilibria. Soils need a minimum of 4-5% organic matter to be structurally stable. As organic matter is constantly lost through biological activity so structural integrity degrades with time unless renewed through addition; by the decay of surface vegetation and their attendant root systems. In temperate Europe grasslands approximately 3 tonnes per hectare of organic matter are naturally added to the soil every year, so maintaining its structure integrity [2, 7, 8]. This would indicate that without vegetational cover any soil is doomed to dry and form dust as experienced by agriculturally exhausted soils and deserts. Consequently vegetational cover, though with minimal deep root activity to disturb sub soil archaeological remains is important. The rich turf lawns, or sheep clipped pasture, which overly large areas of Britain’s ancient monuments, effectively maintain a cohesive soil structure, a buffered in situ burial environment and a high degree of protection against denudation, exposure and damage.

The survival of archaeological organic objects and structures in the soil depends of the nature and level of microbes present within the soil. This is a function of the water and oxygen contents of the soil, as described in the Oxygen section. It is also dependent on the physical form and chemical nature of the archaeological organic material. Thus organic materials composed of relatively pure forms of cellulose in thin sheet form e.g. cotton and paper are consumed by microbes very quickly. When combined with lignin and in massive form, such as large pieces of wood, the organic material will survive for much longer. A similar differential survival is seen between pure collagen materials such as skin and mixed materials of collagen and hydroxyapatite in bone.

Clay

Clays are particles of alumino-silicate complex, <0.002mm in diameter, they retain water and have a significant role in cation and anion exchange. The nature of clays as well as amount of clay in soil determines texture, water retention capacity and ion exchange capacity. Clays form from the breakdown of feldspar minerals, thus the geological history of the rocks which have been broken down to form the soil determine the nature and volume of clays present. Clays (2:1 clays) such as micas, vermiculites and smectites have the greatest capacity for water retention and cation exchange capacity. Kaolin (1:1 clays) have lower water retention and cation exchange capacities, whilst the most degraded are iron and aluminium oxides that have even lower water retention and cation exchange capacities, though increasing anion exchange capacity [2, 7, 8].

Clay particles in arid soils can hold water tightly minimising its availability for use by plants. Dry clay rich soils contract and crack increasing dehydration rates deep into the soil. They expand upon hydration, adsorbing water from occasional rains, sealing cracks and retaining the water in the soil surface layers. Waterlogged clay soils are fully hydrated, extremely dense and compressed and undisturbed they are virtually impervious to water or gasses. Thus they maintain their water and associated chemistry.

Redox Potential

This defines the type of chemistry seen in the burial environment and is measured in terms of the ease with which chemical reactions involving the transfer of electrons in an aqueous environment takes place e.g. $Cu \rightarrow Cu^{2+} + 2e^-$. In oxidising conditions such as those seen in contact with the atmosphere this corrosion reaction proceeds generating 0.34V in standard conditions. However, in reducing conditions, such as those seen in waterlogged deposits where there is no oxygen, there is a surfeit of electrons and this reaction may not proceed at all. Redox potentials are normally measured in aqueous conditions and are useful for describing the chemical condition of wet and waterlogged soils. Redox potential is rarely measured for aerobic soils since it is difficult to determine it in anything but saturated conditions. As with other parameters, Eh is highly variable depending on the location sampled, season, rainfall etc. Measuring the redox potential of soil or groundwater samples is fraught with the same problems as accurate determination of pH. Redox reactions (Eh) invariably involve both proton (H^+) as well as electron transfer, consequently redox reactions affect and are effected by pH and are consequently usually defined on Eh, pH diagrams.

$$FeOOH + 3H^+ + e^- \rightarrow Fe^{2+} + 2H_2O$$

$$SO_4^{2-} + 10H^+ + 8e^- \rightarrow H_2S + 4H_2O$$

For any specific pH, the Eh values of specific reactions, important to the chemistry of soil activity, can be derived. Those for pH around 7.0 are listed Table 1.1. Work by Bass Becking, Kaplan and Moore [22] in defining the Eh and pH of all soil environments led them to propose a definition of waterlogged, wet i.e. partially or occasionally waterlogged and normal i.e. 'aerobic' soil environments. The Eh values for a number of archaeological sites mentioned in the PARIS 2 Conference in 2001 and values derived by Caple, Dungworth and Clogg [23], Peacock [24], Soerensen and Gregory [25] and Davies et al [12] are listed in Table 1.2.

The redox levels reported by Hogan at Kilsmeldon Meadow showed that above 500mm, well drained sites enjoy Eh >300mV for > 90% of the time. However, at depths of below 500mm, Eh levels are primarily in the –200 to 200mV zone [26]. Consequently a substantial number of sites in the UK and Western Europe have archaeological deposits which would fall in the wet and waterlogged defined zone of Bass Becking, Kaplan & Moore [22].

The onset of anoxia leads to a rise in the pH, whilst the oxidation of anoxic deposits results in the acidification of the soil. This can lead to the increased decay of bone, something that has been noted in the, now oxidised, organic rich soils of the Netherlands [27]. Cycling through periods of aerobic and anoxic conditions as may occur through annual flooding. Seasonal inundation of any soil such as monsoon flooding in tropical climates or the base of a graves, pits or moats in temperate Europe can lead to periods of acidity and high levels of decay for materials such as bone, mortar, plaster or limestone. Acidified soil water derived from previously waterlogged deposits reacting with lime rich soils or fertilisers can create soluble salts, and partially waterlogged sites such as Haddenham in Cambridgeshire produced charcoal beams from a Neolithic barrow impregnated with calcium sulphate as well as iron salts [28].

A problem specifically associated with anoxic (low Eh) solutions is the solubility and mobility of Fe^{2+}. This is frequently precipitated as iron sulphides in porous waterlogged materials such as leather or wood, leading to long term problems of acidity following the oxidation consequent upon excavation [29]. Similarly deposition on and in porous materials such as glass, ceramic and stone can lead, upon oxidation, to unsightly orange iron oxide staining.

Monitoring

The problems of accurately characterising highly variable aerobic soil deposits have long been appreciated. To interpret single sample measurements, models of the aerobic soil need to be used. The most accurate picture of the oscillating conditions of aerobic soils are provided by long term monitors such as the tissues of long lived plants such as trees. Chemists have used the chemical composition of leaves and the width of tree rings to describe the chemistry of groundwater and the level of soil moisture. Similarly archaeologists have used the condition of objects buried in the soil to derive a picture of the extent of decay on the site. In Sweden, Germany and Denmark attempts have been made to survey corroded copper alloy artefacts excavated by earlier generations and compare the levels of corrosion to those of artefacts excavated in recent years [19-21, 30, 31]. The occurrence of increased numbers of more heavily corroded artefacts from more recent excavations, which was observed in all 3 countries, was interpreted as the effects of increased acidity in the soil due to acid rain pollution. Other significant factors associated with decay included:

- The type of soil. Thin acid soils above bedrock providing little buffering and thus giving higher corrosion levels than loam or calcareous soil [21].

- Additions of soluble salts such as the salting of roads [21] or the application of fertiliser [10, 30].

- The high level of soil disturbance resulting from agricultural activity and thus high levels of drainage may also be a factor [31, 10, 30].

- Proximity to the coast, with higher corrosion levels noted in coastal soils [31].

- The level of human activity in the soil. Relatively undisturbed soils around votive offerings providing a less corrosive environment than those of burials which were in turn less corrosive than those associated with human settlement [21, 31].

Recently some larger pan European projects have been funded to look at decay of artefacts on a larger scale. Work on the use of bone as an indicator of decay using samples from 50 sites across Europe and correlating the level of bone decay with factors derived from standard soil classification e.g. pH, has revealed increased decay rates associated with road salting and in recently drained wetlands. A similar study on wood is reported to be underway [27]. These surveys are hampered by not knowing the original extent and nature of the materials or the detailed history of the burial conditions.

Large surveys have focussed primarily on features such as soil type and climate. Smaller scale studies such as those at Nydam Mose [24] or Firestone Creek [32] are staring to provide more detailed examples of the relationship between water flow, biological organisms, soil depth, soil chemistry and the decay of archaeological artefacts or monitoring materials such as cotton strips.

Modelling/Experiments

Almost all the published information related to aerobic soils pertains to their ability to support vegetation [2]. As a result of this work there are models of how specific variables within a soil affect plant growth, which take into account the range of variable conditions. The seasonal nature of vegetation means that models can be quickly established over 1 or 2 growing seasons. At present few if any studies have correlated individual factors within the soil environment to the decay of archaeological materials. The time taken for decay pattern to clearly emerge is considerable. The only burial/decay experiment to have been running for some time, since the late 1950's, are the experimental earthworks at Overton Down and Morden Bog, Wareham [33]. The lack of chemical and biological definition of the conditions prior to the start of the experiment has limited the use of the experiments for answering present day questions.

The decay of organic material in the soil which describes a first order kinetic reaction [8] with 2/3 of the organic matter breaking down in one year, but some small fraction remaining for many years. Similarly the rate of decay of archaeological artefacts in the ground is initially fast but slows as equilibrium with the surrounding environment is established. The rate of reaction is increasingly determined by the rate of the diffusion of reactants through the developing decay layer. Consequently the initial years for any burial/reburial project are the crucial ones where decay rates will be at their highest. If we wish to wish to develop more accurate information about conditions experienced by objects in burial environments and consequently develop more detailed models about how materials decay under a range of specific conditions, it is appropriate to create, bury and retrieve long-term decay monitors in monitored/defined burial environments. Such decay monitors would be composed of materials that were designed to corrode quickly, using known decay pathways. Monitors might include:

- chemically unstable glass
- porous wood with low lignin and high cellulose content, or cotton strips
- porous lime rich stone susceptible to salt damage
- readily corrodible mono-metallic and bimetallic tokens

These would be buried and retrieved after specific periods in environments which were typical of archaeological burial conditions, and whose cyclic variables (pH, Eh, CEC, oxygen level etc) were monitored. Similar monitors composed of unstable glass have been developed by researchers for monitoring gaseous pollution in museum environments [34]. Samples of wood were also buried for a number of a number of years at the Rose Theatre site and subsequently retrieved and checked to see if aerobic fungi were active (Corfield pers. comm.).

Despite the large number of archaeological excavation in which there is subsequent reburial of extant remains with the soil from which they were excavated. Few are recorded or reported and virtually none are scientifically monitored. In the case of waterlogged sites e.g. Glastonbury Lake Village and The Sweet Track were, when re-excavated from re-established waterlogged conditions, reported as being in 'good condition' (B. Coles pers comm., R. Brunning pers comm.). Other waterlogged sites e.g. Sutton Common and Eaton where waterlogged conditions were not re-established were shown to be highly degraded (Corfield pers comm., M.Taylor pers comm.).

The pressure from farming, redevelopment and from chance archaeological finds such as the Rose Theatre [35], the Kollerup Cog [36], the San Diego Royal Presidio [37] has led to a small number of sites and objects having to be reburied with new/additional material. These sites in particular should be regarded as experiments and they need to be accurately recorded, monitored and re-examined at regular intervals to assess the effectiveness of the added burial materials in establishing/retaining a preserving environment.

Additional Material

Where we seek to preserve existing archaeological sites, whether arid e.g. Chaco Canyon pueblos or waterlogged such Vindolanda it is clearly essential to maintain the conditions which have preserved the remains thus far. Any material added to give further physical protection should not change the existing chemistry of the preserving environment. Without monitoring and data on the original burial condition, this is an empirical estimation process.

From the information in the preceding sections on soil variables a number of guidelines may be suggested:

- The reburial medium, in addition to providing physical protection, will potentially raise the water table. This should be planned so that it reproduces the previously seen conditions, to which buried materials had equilibrated and establish a relatively permanent oxic or anoxic condition. Uncontrolled variation of oxic/anoxic conditions can lead to changes in pH and Eh which could lead to dissolution of materials and the deposition of minerals, both of which could be highly damaging.

- The additional material should have a physically robust form to withstand weathering, the outer layer should normally have a reasonable organic component to the soil and support surface vegetation to ensure a well structured soil which will resist weathering. Surface vegetation should be minimal maintenance and without substantial invasive tap root growth. Protection against erosion from severe weather events such as flash flooding in arid regions is important.

- The reburial material should have a similar pH, Eh and CEC to the original burial material.

- No soluble salts, or potentially soluble salts such as concentrations of iron oxides or calcareous material should be introduced since it could lead to the deposition of minerals within the archaeological remains.
  [Tests to monitor the pH and conductivity of samples of soil water introduced from the site to the proposed reburial medium should indicate precipitation or dissolution and thus the stability of the medium]

- Avoid extremes of pH, since rates of decay and mineral deposition are greatly enhanced. If the added reburial material has an organic and clay component it can act as a buffer establishing, preserving and protecting the pH, Eh and cation level of the substrate.

- The porosity of the reburial medium and the archaeological material should be similar in order to reduce the risk of mineral precipitation at interfaces where pore size changes and maintain the level of drainage.

- It may be appropriate to have a specified level of clay in the soil. On arid sites a low percentage of clay in the added soil could maintain drainage, alternatively higher percentages of clay could improve soil cohesion and thus physical protection and it could trap water in the upper levels from where it could evaporate. On wet sites clay rich added soils could impede drainage and preserve waterlogged conditions without the need for constant re-wetting.

The deliberate selection of sands with similar composition to the substrate material at Laetoli [38, 39] and the widespread practice of reusing the most recently excavated material to rebury features would appear sound and correspond with the guidelines described above. They have similar chemical and physical properties to the substrate. Seeking to actively control vegetation and yet avoid soil erosion e.g. through re-turfing excavated and reburied sites, would appear to be a sensible measure. Though washed sands, which have been used for some re-burial work are fairly inert and introduce little direct contamination, they do not provide a chemical buffering effect.

Consequently though they provide physical cushioning, they may have limited protective benefit in chemical terms to archaeological materials within the soil. In such cases, e.g. the Rose theatre [35], active control measures are required to control water level since the surrounding sand will not retain water next to the wooden foundations. Similarly the sand will not develop reduced form minerals such as iron sulphides to maintain the anoxic environment.

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Table 1.1 Eh values for soil oxidation reduction reactions at pH 7 (from Russel 1970 & Cresser, Kilham & Edwards 1993)

(mV)	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
½O_2 → O^- (H_2O)													**820**	
NO_3^- → NO_2^-/N_2O/N_2									**420**					
Mn^{4+} → Mn^{2+}									**410**					
Organic matter → acids									**400**					
Fe^{3+} → Fe^{2+}			**-180**											
NO_3^- → NH_4^+			**-200**											
SO_4^{2-} → S^{2-} (H_2S)			**-220**											
CO_2 → CH_4			**-240**											
$2H^+$ → H_2 ↑	**-413**													
Bass Becking et al 1960	**-380**		Waterlogged			**120**	Wet	**300**	Normal		**640**			

Table 1.2 The Eh recorded at archaeological sites (from Caple 1998, & various authors at the PARIS II conference London 2001)

(mV)	-400	-300	-200	-100	0	100	200	300	400	500	600	700	800	900
Over (Cambs)							**190**							
Sweet Track 1										**540**				
Vale of Pickering 1							**260**							
Nydam					**0….150**									
Tondheim		**-250……………..100**												
York (Parliament St)			**-150……………200**											
Picts Knowe				**-90**										
Tonsberg			**-200………-6**											
Tower of London				**-100**										
Woodhall 1		**-270**												
Woodhall 2			**-200**											
Vale of Pickering 2														
Sweet Track 2					**-8**									