Accepted Manuscript

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PII: S0305-4403(15)00216-2

DOI: [10.1016/j.jas.2015.06.010](https://doi.org/10.1016/j.jas.2015.06.010)

Reference: YJASC 4448

To appear in: *Journal of Archaeological Science*

Received Date: 28 November 2014

Revised Date: 3 June 2015

Accepted Date: 7 June 2015

Please cite this article as: Bleicher, N., Schubert, C., Why are they still there? A model of accumulation and decay of organic prehistoric cultural deposits, *Journal of Archaeological Science* (2015), doi: 10.1016/j.jas.2015.06.010.

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Abstract

The circumalpine lake side settlements are a unique source of detailed information on the past. Nevertheless, little has been published by now on why the organic matter (fumier lacustre) in these settlements has been preserved and how exactly this happened. It is, therefore, necessary to closely explore the decomposition of organic matter under different conditions. We present data from the literature and a decomposition model simulating the outcome of different archaeological hypotheses and comparing the result with the actual archaeological record. We conclude that different scenarios of deposition should result in clearly discernible and measurable features in the archaeological record, whose presence or absence allows deducing the mode of deposition. The best conditions of organic preservation are to be expected under such conditions where a large organic input happens in shallow still water. Seasonal flooding and a later rise in lake level can also result in good preservation but imply a greater loss through mechanical erosion and in many cases clear preservation gradients within the deposits. The theoretical outcomes presented here find clear analogs in the archaeological record.

Keywords: Organic preservation, wetland archaeology, degradation, decay model, lake side settlements, organische Kulturschichten, fumier lacustre

1 Introduction

1.1 Context and aims

Due to organic preservation prehistoric wetland settlements provide detailed data on the past environment and the cultural of their population. For archaeological interpretation it is important to know how complete the actual record is and how the milieu of deposition can be characterized. This is particularly obvious, where social and economic reconstructions are heavily based on organically preserved material (e.g. Doppler et al. 2010, Schibler, 1997, Schibler and Jacomet 2010) but where there is still an unresolved debate over the setting of the houses on the shore (see for a summary Dieckmann et al., 2006, 207-219). Little has been written on how the organic matter has been preserved. In archaeological literature it is commonly thought that the term *waterlogged* sufficiently explains the presence of organically preserved finds. If this was true then all organic matter that was ever naturally deposited in lakes should be preserved as well.

For English sites Caple (1994) has drawn attention to the lack of knowledge and research in the chemical conditions of waterlogged archaeological deposits that give rise to preservation of organic material. His main concern was to maintain or re-establish such conditions in order to preserve archaeological remains in situ. Since then quite a number of studies have been conducted focusing on soil chemistry and the relation between organic preservation and water tables (e.g. Kenward & Hall 2000, van de Noort et al 2001, Holden et al. 2006, Martens 2012, Hollesen & Matthiesen 2014). The aim of virtually all these studies, however, is to elucidate how such conditions can be maintained and how deposits can be preserved for the future. In the past, the question, why and how such conditions evolved in the first place was mostly only of marginal concern and was only dealt with to the extent it seemed necessary. Caple (1994) sketched the general process and although it became clear that apart from the water table other (chemical) factors were important for organic preservation (van de Noort et al. 2001, Holden et al. 2006), the influence of the water table remained the major focus.

In the circumalpine lake shore sites water tables are of much less importance, since most sites are situated well under the lake's water table. In lake Zurich for example the highest organically

preserved archaeological deposits lie at around 404.5 m above sea level and thus 1.5 m below current lake level. Concerning the protection of these sites mechanical erosion has proven to be far more detrimental and thus research was more focused on sediment movement and wave action (Hofmann et al. 2013, Weber 2013, Weber et al. 2013). Virtually no research was done on the chemical characterization of archaeological lake deposits. Again there are no studies on why conditions for organic preservation have developed at all. Since the beginnings of lake side settlement research some scholars thought that only a lowering of the lake level made it possible to settle on the shore with organic accumulation analogous to fens (Speck, 1990) and this idea has remained popular (e.g. Corboud, 2001). Magny (2004, 72) used archaeological layers as a proxy for a declining lake level by treating them just like peat that formed during phases of low lake levels. It should, however, be noted that on lake shores the organically preserved cultural layers have never been shown to be linked to fen peats outside the settlement. It appears, therefore, questionable whether the conditions under which the organic layers formed, were the same as for peat. This is what sets the lake side settlements apart from the bog settlements. To understand the formation of the organic cultural deposits we need to consider the processes of organic preservation that have been studied in soil- and peat-sciences. While the studies cited above focus on the maintenance of preserving conditions, the scope of this paper is rather to elucidate how and why these conditions developed in the first place and what this means for the interpretation of prehistoric sites.

1.2 Decomposition of organic matter

Organic matter usually consists of biopolymers, notably cellulose, proteins, chitin, lipids, and lignin. These compounds are degraded to their monomers i.e. carbohydrates, fatty acids, amino sugars, and amino acids. However, these substances and their precursors are not equally degraded. Most sugars and amino acids can be quickly broken down, while complex carbohydrates such as cellulose are more recalcitrant. The slowest material to decay in most organic litter is lignin. In the literature on organic decay a distinction is therefore made between so-called solubles, non-lignified carbohydrates, lignified carbohydrates and lignin (Berg and McClaugherty 2008). Under aerobic conditions organic material is generally decomposed by the cooperation of several agents. Animals feeding on litter- and organic detritus use energy-rich compounds such as sugars, starch and proteins and achieve a mechanical breakdown of the refractory material, aiding the further decomposition by bacteria and fungi. Microorganisms use oxygen to break down organic matter into increasingly smaller and less complex chemical substances. Carbohydrates are broken down into water and CO₂. The decomposition of lipids, proteins and amino acids also releases nitrogen. During the process enrichment of more refractory material such as lignin is achieved. Lignin then can be decomposed under oxic conditions by specialized fungi and bacteria (Killips and Killips, 1993; Berg and McClaugherty, 2008), while it is practically not decomposable if oxygen is absent (Madigan et al. 1997, 516). Normally not all organic carbon is reduced but a lower limit is reached with the organic material partially entering a stable state. This organic fraction (humus) can persevere for millennia and consists mainly of humic acids, humic substances, and fulvic acids. Humus can accumulate and form considerable layers in the topsoil (Berg and McClaugherty, 2008, 228).

For different substrates there are factors that favor or hinder decay. While higher levels of nitrogen, phosphorous and sulphur cause higher rates of decay in solubles, nitrogen will slow down the degradation of lignin (Berg and McClaugherty, 2008; Jacob et al., 2010; Enríquez et al. 1993). In some situations nitrogen was also added separately, e.g. as faeces, with the same effect (Carpenter and Adams, 1979). Abundant availability of water is favorable for decomposition as long as no anoxia develops. Finally, higher temperatures favor higher rates of decay, but interdependencies are complex (Berg and McClaugherty, 2008). For twigs of different species very different rates of decay have been reported, with sometimes even lower rates for small diameters than for larger ones (Erickson et al., 1985). Probably smaller twigs dried quicker which prevented further decay. In a scenario in which water was not as limiting twigs of beech had completely decayed after four years

(Müller-Using, 2005). A recent study has also shown that today's climate change will probably speed up decomposition of woody debris in temperate forests (Berbeco et al., 2012). Anaerobic conditions can arise especially in water, since the diffusion rate of oxygen is much slower in water than in air. For an anoxic environment to develop a period of time is necessary where oxygen demand outstrips oxygen supply. This happens when the sum of both the production of oxygen by plants, algae and phytoplankton on the one hand and the uptake at the interface between water and air on the other is less than the sum of oxygen needed by all organisms for respiration and decomposition. Furthermore, rising water temperatures and increased salinity lead to decreased oxygen solubility and the size and surface area of the water body and the water - gas exchange through water flow are also important. Since respiration and decomposition are the most prominent factors, the probability of anoxic conditions rises and falls according to the amount of decomposing activity. Organic preservation through eutrophication is a well-known phenomenon (Killops and Killops 1993, 224 f.) and it has been noted very early on that sewage sludge can build banks and reduce the amount of oxygen even in flowing water (Baity 1938). Anoxia also quickly develops within sediments because oxygen enters the pore water only through water flow or diffusion. Both processes are slow, so that oxygen is quickly depleted in the sediment's uppermost millimetres due to microbial decay (Killops/Killops 1993). The depth to which the milieu in sediment is still oxygen-rich is determined by the characteristics of the sediment, which influence the rate of water flow. The most prominent factor is the size of the interstitial spaces, which is controlled by grain size (Caple 1994, 67). This is probably the reason why on archaeological excavations it has frequently been noted that wood under clay-rich loam was better preserved than the same wood embedded in organic detritus or sand. Pore size is equally relevant to lateral water flow. Therefore, once that organic material is buried anoxia depends on the relation of infiltration speed and oxygen uptake speeds. If infiltration is low, oxygen will not reach the interior of a sediment (Banwart 1996). Under anaerobic conditions detritivores and fungi as well as all obligate aerobic bacteria cannot decompose organic matter. During decomposition of organic detritus first a group of bacteria uses hydrolysis to break down macromolecules into simpler components. These smaller molecules form the substrate of other bacteria. These can be obligate or facultative anaerobes and have to use other electron-acceptors than oxygen such as nitrate or sulphate. Consequently they become dependent on the availability of these electron-acceptors (Killops / Killops 1993, Caple 1994). Furthermore anaerobic decay will lead to a build-up of reducing species to a degree where they suppress microbial activity (Caple 1994). The breakdown of organic matter using oxygen is much more energy-efficient and therefore much quicker than anaerobic decay. Decomposition of organic matter can be modelled numerically (Berg and McClaugherty, 2008) and numerous studies for very different ecological settings exist. Frequently a simple exponential model is applied:

$$M_t = M_0 e^{-kt} \quad (1)$$

where M_0 = mass of litter at time 0,
 M_t = mass of litter at time t ,
 t = time of incubation (usually in years)
 k = decomposition rate constant (dimensionless).

The decay coefficient k is estimated from the mass loss of a given substrate in a given time and accordingly this model only describes the decay of the given substrate and setting despite the fact that numerous substrates could be present.

In its basic form this model has been introduced by Olson (1963). Given the difficulties outlined above the decomposition of organic matter is most adequately described by more complex models such as triple exponential models that take into account the quality of different substrate fractions (Berg and McClaugherty, 2008) and such refined models have been applied in aerobic and anaerobic systems such as peat lands (Bauer, 2004).

Anoxic conditions in lakes develop when a thermally induced stratification of the water takes place or when an anoxic layer evolves chemically from the lake floor towards shallower depths. During a thermal stratification, the two water bodies (warm surface layer and cold bottom layer) will not mix due to their difference in density. The lower part of the lake, called hypolimnion, will soon be depleted of oxygen because of the decay of organic material sinking down while the supply of oxygen from the upper part is held back by the stratification. Depletion thus benefits from an increased organic input. Since the latter can be altered by anthropogenic input sediments can be used as a record of cultural impact on lakes (e.g. Routh et al. 2004). The upper part of a lake, called epilimnion, is oxygen-rich due to the gas exchange with the air and the metabolism of macrophytes and algae. However, it can be depleted in nutrients if these have been used up by the phytoplankton or macrophytes. In temperate regions, the stratification of lakes is mostly seasonal and breaks down in autumn, causing the two water bodies to mix, thereby activating an aerobic breakdown of organic matter in the hypolimnion and transporting nutrients upward that will be used the following spring. It is for these reasons that water in the epilimnion is normally permanently very rich in oxygen and even in the hypolimnion conditions can seasonally favor aerobic decomposition. Still, the organic compounds of lake sediments normally produced by a progressive breakdown of organic matter do rarely exceed the molecular scale or at best the microscopic scale.. Among the larger particles are mostly buried seeds such as oögonia of Characeae, which are designed to survive being buried in sediment.

All the organically preserved settlement layers of prehistoric lake side dwellings lie in shallow water where oxygen levels must have been high and it has frequently been shown that in the lake marl below and above the cultural layers no visible remains of organic material except some buried seeds and oögonia occur.

Analogous to the situation in the hypolimnion, anoxic conditions can develop in shallow water when the decomposing activity itself uses up all available oxygen. In freshwater lakes this can take place when either eutrophication occurs, causing very large amounts of algal growth and hence deposition of dead algae and fecal pellets of zooplankton or when the amount of deposited allochthonous organic material is extraordinarily high. It has been shown that organic deposits will decay, when lateral flow of fresh water through the sediment introduces aerated water and / or nutrients for microbes (Caple 1994, Banwart 1996). Accordingly mere deposition of larger amounts of organic material and ephemeral establishment of anoxia is not enough to cause organic preservation. Lateral water flow can be brought forward by higher water speeds and higher hydraulic conductivity. Compaction and consolidation of the organic deposit reduces pore size, thereby raising water retaining capacity and reducing water through flow. Therefore, both compaction and a cover of fine-grained silt or clay deposits are further factors for long term preservation. As a matter of fact a high water retaining capacity can even lead to anoxic and preserving conditions above the water table (Holden et al. 2006, 7).

2. Material and methods

To study the mechanisms of accumulation, decay and preservation in a lake side settlement, a decay model was applied. Different archaeological hypotheses on the milieu of formation lead to dissimilar trajectories of the model. The different outcomes can be compared to the actual archaeological record in order to test which hypothesis leads to the best match.

The actual decay rate (k) is difficult to estimate without empirical data. While the general mechanisms are well known, some measured data are needed to predict the further development. In the case of cultural layers from lake side settlements we lack such empirical data since the substrate has no viable analogies in current studies. Compost and sewage share common characteristics with the nutrient-rich anthropogenic organic detritus from the sites but their degradation is studied in settings such as continuously stirred tanks or compost heaps that can heat up to 65°C (Wagner and Illmer, 2004).

Consequently, we need to identify the range of possible decay parameters for different settings from literature and calculate ranges of possible outcomes. In a second step the robustness of any

interpretation is tested by calculating the model's sensitivity to the parameterization. It is difficult to attribute probabilities to actual decay rates within this range, but we can state, that the general level of nutrients must have been high due to the continuous input of human and animal faeces as well as ash and butchering-remains. As different authors have pointed out (e.g. Moore and Basiliko, 2006, Jacob et al., 2010) the decay of solubles and cellulose is favored by such conditions. Consequently, we should attribute a higher probability to the higher decay rates within the possible ranges.

In wetland settlements, conditions of decay can be expected to have changed drastically between deposition, burial and excavation. It is therefore appropriate to apply a model which modulates the decay parameters according to changing conditions. Although one could have calculated decay models for the different substrate fractions and treat lignin-rich debris different from cellulose, we concentrated on the decay of cellulose. Cellulose-rich remains such as leaves are regularly encountered in cultural layers. Since these are much more prone to decay than lignin, we can test archaeological hypotheses for their minimal conditions of preservation by estimating the consequences on the preservation of cellulose.

The decay rates from the literature are given in the electronic supplementary material. The ranges are given in table 1.

In analogy to the peat accumulation model (Clymo, 1984) we can thus define a model for presence and growth of waterlogged cultural deposits (what we might call a "Pfahlbau-formula" because it is these deposits that made the circumalpine lake side settlements, the so-called "Pfahlbauten", so famous).

$$M_t = M_{t-1} + \text{Acc}_t - \text{Decay}_t - \text{Erosion}_t \quad (2)$$

with M_t = Mass of cultural deposit in year t

Acc_t = Accumulation of organic material in year t

$\text{Decay}_t = \text{Acc}_t * e^{k_1} + M_{t-1} * e^{k_2}$

Erosion_t = mechanical mass loss

For scenarios that assume underwater deposition or seasonal flooding the mechanical mass loss could be modeled (e.g. following Whitehouse, 2000) if we could find a viable estimate for the cultural deposit's resistance to shear stress, which is as yet not the case. We therefore define Erosion to be zero (in order to restrict the model's sensitivity exclusively to decay).

Consequently, assuming that no later changes such as erosion or interruption of anoxia has occurred, we can express the Mass of the complete cultural deposit (M_d) as

$$M_d = \sum M_t * e^{k_3 dt} \quad (3)$$

with k_3 = anoxic decay coefficient after burial until excavation

dt = deposition time from burial until excavation.

For simplicity our model assumes a constant input rate for the whole time of a settlement's occupation.

For every year a constant input is calculated along with its decay taking into account different k -values according to changing conditions. After burial, k remains constant until excavation, resulting in a negative exponential development of the remaining cellulose (fig. 1).

Assuming a **first scenario** (in accordance with the interpretations following Stöckli, 1979; Suter, 1987, Corboud 2001) in which the houses were built at ground level on the shore and were flooded by a rising lake level after 15 years of occupation, a decay rate between 0.2 and 0.45 was applied to the cellulose of the first year's deposition for fifteen years. For the material, that was deposited during the second year these rates were applied for only fourteen years and so on. The material of the last year decomposed only for one year before being flooded. From the year after flooding onwards decay rates of buried material (table 1) were applied to the material of all years. It should be stressed, that it appears highly dubious both that in the described scenario anoxia should instantly

develop and that loss through erosion should be zero. Furthermore, the outwash caused by precipitation during the time of occupation would lead to a great loss of nutrients in the deposit. This would cause a considerable loss of reducing species and hence lower the potential to maintain anoxia, since it is the large amount of these species, that use up oxygen and other oxidizing species (Caple 1994, 68). This model, which we will call the "instant-flood ground-level scenario" was nevertheless calculated to cast light on the importance of decay.

In a **second scenario** the same situation was assumed but the flooding takes place ten years after the settlement is abandoned. Accordingly decay rates between 0.2 and 0.45 were applied for further 10 years before abrupt anoxia developed. To this model we will refer to as the "delayed ground level scenario".

In certain cases the settlements seem to have been built in the seasonally flooded zone of the shore (see above). This raises the difficult question whether one should assume high underwater decay rates during summer and lower decay rates during winter on the dry shore or rather the opposite which would mean to assume the development of underwater anoxia during summer. Due to the uncertainties mentioned above both possibilities were tested, i.e., in the **third scenario** ("seasonal flood - winter reduced") high decay rates during summer and low rates during winter were applied for 15 years. In order to model decay after an increase in the lake level, burial decay rates (see above) were used from the 16th year onwards. This was parameterized by applying decay rates of $k=-2$ to -5 for 9 months (273 days) and $k=-0.1$ to -0.2 for four months (92 days).

In contrast, in the **fourth** scenario ("seasonal flood - summer anoxia") it was assumed that during summer a quick anoxia develops, leaving only the current year's material exposed to moderate decay (-0.2 to -0.5) which carries on during winter when low temperatures hinder quick decay. From the second to the fifteenth year a low decay rate ($k=-0.01$ to -0.05) was applied and from the abandonment of the settlement onward a decay rate of deep sediment burial ($k=-0.0001$) was used. Again in both the third and fourth scenarios the zero-erosion appears unrealistic.

In the **fifth scenario** houses and accumulation are located in shallow water and strong underwater decay depletes oxygen within the deposit, causing reduced decomposition (Killops and Killops, 1993). In this scenario, which we will call the "Pfahlbau-scenario" the deposition would take place under water all year long. This is parameterized as three years of quick decay according to the underwater decay rates given above. After that, it was assumed that anoxia has developed within the organic deposition so that from the fourth year onward only the material of the current year is exposed to restricted decay, while the material of the precursor years is thought to be buried. It is understood that the assumption of a period of three years for the development of anoxia is completely arbitrary and any other number of years could be used. Given the occasional presence of green leaves in the deposits one should even discuss mere hours between deposition of fresh material and complete anoxic burial, once that anoxia has established on the site.

3. Results

The results of the different scenarios are visualized in figures 2 and 3. Figure 2 shows the modelled course of build-up and decay of cellulose in the deposits. The years between -3214 and -3200 relate to the time of occupation. The full 100% relate to the total amount of deposited cellulose. This is why organic matter is building up during occupation and decreases after -3200. Because of continuous decay during settlement the full 100% is never reached.

The ground level scenario with instant flooding (scenario 1) resulted in between 8 and 20 % of original cellulose entering the anoxic burial. Between 7 and 17% are preserved after 5000 years. Scenario 2 (ground level with delayed flooding) led to only 0.1 to 3.9% of original cellulose mass entering the anoxic burial, of which a maximum of 2.3% are still preserved after 5000 years. The scenario of seasonal flooding with winter-reduced decay (scenario 3) resulted in a preservation of 0.3 to 8.3 % of the original cellulose. In contrast, scenario 4 ("seasonal flood - summer anoxia") resulted in almost 30 to nearly 50% of preserved cellulose. With comparably low decay rates assumed here little difference between the representation of single years was observed. Higher rates led to the last years being preserved nearly twice as good as the first. So depending on the decay

rate one might find a preservation gradient here as well. The "Pfahlbau-scenario" (5) led to a preservation of 17 to 40% of the cellulose. The first years until anoxia develops show nearly no cellulose preservation, but all the following years were more or less equally well represented.

Figure 3 shows the representation of single occupation years within the preserved deposits in the different modelled scenarios. It visualizes the effect of different decay rates before burial in a permanent anoxic environment on the relative proportion of cellulose from any given year within the total amount of preserved cellulose (note that here 100% is equal to the total preserved cellulose while in fig. 2 100% represent the total accumulated amount prior to decay). This serves the purpose to test the rather intuitive assumption that the lower X% of the stratigraphy should relate to the first X% of the occupation time as would be correct if all years were equally well represented. In the two ground-level scenarios (1&2) the single years are differently well represented because the amount of preserved cellulose is inversely proportional to the number of years between deposition and burial. The cultural deposit would therefore be characterized by a strong gradient of preservation with the lower parts of a soil profile being much heavier decayed than upper parts from later years. In the third scenario (seasonal flooding with reduced winter decay) nearly all remaining material is from the last two years. The fourth scenario (seasonal flooding and summer anoxia) shows interesting variability as consequence of different decay rates applied. With comparably low decay rates little difference between the representation of single years was observed. Higher rates led to the last years being preserved nearly twice as good as the first. Therefore, depending on the decay rate one might find a preservation gradient here as well. In the Pfahlbau-scenario the first years until anoxia develops show nearly no cellulose preservation, but all the following years were more or less equally well represented.

4. Discussion

The models predict not only the amount of preserved material (fig.2) but also the internal structure of the resulting stratigraphy (fig.3). Therefore they are a useful tool to compare model outcomes with excavation results. Scenario 1 (ground level-instant flooding) gives a cellulose percentage that is plausible for many well preserved sites. Other sites, which exhibit a far worse organic preservation might, however, be better explained by the preservation rates of scenarios 2 (ground level-delayed flooding) or 3 (seasonal flooding with winter-reduced decay). However, all these scenarios have the same important implication: Logically inherently they lead to a strong preservation gradient from low preservation at the bottom to progressively better preservation higher in the deposit (fig. 3). However, this feature has so far not been recognized and published for any site. It is questionable whether it was visible for excavators without chemical analyses, but also on-site pollen data have to our knowledge never pointed in this direction. Far more critical therefore is that these scenarios have important implications on the vertical distribution of finds within cultural deposits. It appears to be the most reasonable assumption that people produced similar quantities of refuse every year. Consequently, one would expect the same density of finds per volume of originally accumulated organic sediment – especially in the scenarios on dry ground, where erosion plays no role. If the organic material of the first years had been decayed, all inorganic material would be concentrated, forming a horizon of inorganic finds at the bottom of a cultural deposit. This is also true for mineral anthropogenic deposits within a stratigraphy such as loam layers. Similarly, in case of later erosion at the deposit's surface we would have to expect a concentration of non erodible finds like stone axes or millstones at the top of a deposit. So the scenarios 1, 2 (ground level) and 3 (seasonal flood with winter reduced decay) all predict a gradient of preservation from bottom to top (fig. 3) and a higher density of loam layers and finds in the lower parts of the stratigraphy. Both are features that could be checked and measured at excavation sites. Lastly, in the two ground level scenarios, we should expect underneath the deposits traces of soil

development due to bioturbation and leaching of degraded organic compounds. This is a feature that can be easily verified as well.

In scenario 4 (seasonal flood with summer anoxia) we find that presence or absence of a preservation gradient is dependent on comparably little differences in decay rates (fig. 3). Keeping in mind that the decay rate itself might fluctuate around its mean, we conclude that scenario 4 can result in a great variety of individual results, including special cases like horizons of heavily decayed material from individual years within an otherwise well preserved deposit. It should also be noted that in this scenario it was assumed that anoxia developed quickly even in the first year, whereas in the Pfahlbau scenario it takes several years. For this reason the results in figure 2 cannot be taken as an indication that more matter is preserved in the fourth scenario than in the fifth.

It has already been stressed that in the scenarios 1 – 4 the role of mechanical erosion is unclear. If we compare the results of the two ground level scenarios (1&2) we find that in all cases of well preserved deposits we cannot assume a slowly rising lake level to have preserved them. Even a short time such as ten years led to nearly complete degradation. Furthermore, a slow rise would imply that the deposits had been subject to seasonal erosion for many years. Given the strong erosive effect of seasonal water tables (Schlichtherle & Mainberger 2006) that can easily be studied in the open air-museum of Unteruhldingen, where all organic matter under the houses on the shore is eroded during summer, it is hardly possible to expect any preserved layers. It has been stated above that organic material can be preserved above the water table by its own water retaining capacity as in peat (Holden et al. 2006). But this process works effectively only when the deposit has small interstitial spaces and has been compacted. The comparison with peat is in itself of little value since decomposition in bogs is reduced by acids and low nutrient contents. Both features are not given in cultural deposits. Nutrient rich, well aerated and uncompacted deposits above the water table are therefore prone to heavy decay. Similar observations have been made in reed belts on the shore of Lake Constance, where summer flooding leads to considerable loss of organic matter (Ostendorp, 1992, 22). Most interestingly is that in this study a strong correlation was found between elevation, organic matter concentration and degree of degradation. The higher in relation to the mean water table the litter was deposited, the more organic matter was preserved but also the more it was degraded. Here the material landward from the beach ridge was protected from erosion but subject to more frequent aeration. Yet it was possible that peat formed due to generally wet conditions and lack of nitrogen. In deeper water on the other hand more material was eroded but the material that was left was never aerated (Ostendorp, 1992). For our purpose we can use this study to demonstrate that the accumulation of organic matter in a seasonally inundated environment is the result of a complicated balance of nutrient availability, water depth, water flow velocity and duration of inundation. In a cultural layer of a lake side settlement organic degradation would not be limited by lack of nitrogen or phosphorous. Locally, anoxia can have developed underneath loam from building activities, where the organic detritus was also better protected from erosion.

So a sudden and strong rise in lake level where the surf zone quickly passes across the anthropogenic deposit is the only possible explanation for well preserved organic deposits in scenarios 1 - 4. However, even then it is still unclear, how the anoxia has developed and why the quick underwater decay has not destroyed the deposits after flooding, since the deposits must have lost much of their reducing species through lateral water flow before burial. This process would hinder development and long term maintenance of anoxic burial conditions (Banwart 1996).

The Pfahlbau-scenario (5) has been chosen to offer solutions for both the last problems: Being deposited under water the deposits are exposed to lower bottom current speeds than in the surf zone. Furthermore, empiric analogies exist to explain anoxia. One can however only speculate on the time it takes until anoxia develops. If it developed slowly, scenario 5 also predicts a concentration of finds at the bottom of the deposit. If on the other hand the anoxia developed quickly, scenario five can work out to show no horizons of heavy decay and elevated find density within the stratigraphy. The model also predicts organic deposits without traces of soil development underneath, because in the constantly water saturated lake sediment no leaching takes place. In the first time detritivores can be expected to have played a role until the oxygen level fell below 0.03%, which puts an end to

their activity (Killops and Killops, 1993).

The degree of preservation in prehistoric finds is probably also dependent on the mode of deposition, because it affects the balance of oxygen supply and demand. In a continuous steady and moderate accumulation of organic material constant decomposition at the sediment surface is likely to take place, with decreasing intensity with burial depth. In a quick accumulation (episodically or continuous) anoxia is more likely to quickly build up and restore after events of water mixing. So the degree of preservation is heavily influenced by the rate of accumulation as can be seen also in aquatic systems (Stein, 1991). In lake sediments one could normally not measure any oxygen below a few millimeter in the sediments, since oxygen can only very slowly diffuse into a sediment layer from the water column. In Lake Zug for instance oxygen penetrates only between 0.8 and 1.5 mm into the sediment although oxygen is measurable in the overlying water (Märki et al. 2009). Hence the faster a site is covered by sediments or debris, the faster anoxia will build up, leading to weaker degradation.

If we consider scenarios in which the organic input was not sufficient to trigger local anoxia, scenario 5 would predict more or less complete degradation. The last remaining organic material would take the shape of a lake sediment with slightly or clearly elevated humic compounds. So we find that scenario 5 performs well in explaining the whole range from well preserved deposits without traces of soil development to poorly preserved humic horizons in lake sediments.

In order to test whether the scenarios outlined above are only speculations or actually relate to historic reality, we can study soil profiles of prehistoric lake side settlements.

Fig. 4 represents an example of a well preserved cultural layer showing nearly no traces of soil development except for a 5 mm thick layer of lake marl, in which structures are discernible that resemble burrows of bioturbation. It could, however, as well be root traces of plants that grew much later and that preferred the cultural layers to the nutrient-poor lake marl. Numerous examples of non-lignified carbohydrates in the botanical record were found (pers. comm. Prof. St. Jacomet, University of Basel). This might have been caused by the depletion of oxygen, at the same time preserving the organic matter and killing burrowing animals.

Fig. 5 shows examples with traces of soil development from the excavation of Zurich-AKAD-Pressehaus, including leaching and transport of organic substances into the lake marl. The limit of organic preservation is mirrored by the height of the pile with decayed tip. Soil development is indicative of aeration and clearly accompanied by a much higher degree of decomposition.

Fig. 6 shows an example of a cultural layer of very poor preservation. Traces of bioturbation but no leaching are present. The profile is located far from the shore in the direction to the lake's centre. We can therefore deduce that it was not above the water level. So we speculate that here it was not air that ventilated the organic matter but rather that the rate of accumulation was insufficient to deplete the oxygen in the water column.

There is a general difficulty to produce viable analogies for the taphonomic processes in cultural layers. We hence think that the discussion of processes as carried out above is as yet the best approximation to the real historic mechanisms in prehistoric lake side dwellings. Nevertheless, for a better understanding of layer genesis there remain numerous hypotheses to be tested.

5. Brief outlook and comparison to layergenesis in bog settlements

Waterlogged preservation of prehistoric settlements also took place in bogs. Here, the anthropogenic material accumulated in an already peat-producing environment. Such ecosystems produce annually litter on the surface that is decomposed since it is not cut off from oxygen. A very large amount (there are different numbers according to different ecosystems and authors) of the original plant mass is lost before the remainder is incorporated into the peat body. Afterwards, due to high water levels, oxygen can only enter the decomposition process by diffusing through the water. The deeper in the peat, the more the organic matter is cut off from oxygen. Different kinds of peat forming ecosystems and processes exist, two of which will be outlined here:

In nutrient-poor peat bogs, where mostly sphagnum-mosses grow, the peat itself acts as a water

reservoir and these bogs are independent of local water supply, relying on rain as main water source. They can grow to thicknesses of several meters. Inside the peat, sphagnum tends to lower the pH-value, creating a heavily acidic environment (Keddy, 2010). Activity of many bacteria ceases when the pH-value is lower than 5 (Killops and Killops 1993, 81). Acidification is typical for bogs but not for fens (Naucke 1974, 135), which probably explains the lack of bog bodies in fens and lake side settlements, while they can be found in bogs – although it must be stated that these processes of diagenesis are also still not completely understood (Turner-Walker and Peacock 2008). Fens are dependent on local water supply, more nutrient rich than bogs and dominated by vascular plants. On many lakes, where seasonal changes of the water tables occur, peat is regularly exposed to oxygen and does not form thicker deposits without an accompanying rise in the lake level providing anoxia (Killops and Killops, 1993, Keddy, 2010).

The conditions in a waterlogged cultural deposit are close to those in nutrient rich fens. In the Neolithic site of Torwiesen 2 in Upper Swabia (Southern Germany) the botanical record demonstrated that eutrophication occurred during the settlement (Herbig, 2006, 129). Due to the high amount of nutrients released in settlements ombrotrophic bogs are no viable analogy. A village built in a bog will locally transform it into something similar to a fen, for which we have no natural analogy. So preservation conditions are different in various kinds of bogs and cultural deposits in a peat-forming environment are an extreme kind of nutrient rich fen. This also means that degradation is not any more nutrient limited and can be expected to be much higher than in a peat bog. How much of a cultural deposit can be preserved is dependent on its ability to act as a water reservoir itself and the speed of the surrounding peat growth. If the peat grows slowly and the water table is fluctuating close to the surface, most of the anthropogenic organic material will have been decomposed prior to burial and mostly wood remains due to its high content of lignin. A sudden burial is in such a situation hardly possible, since peat can only overgrow the ruins as plants reoccupy the former settlement and their litter starts to accumulate. This gives plenty of time to degrade everything that has not entered the peat body under the water table e.g. by trampling. If at a later time the water table falls, the degradation will be even more pronounced, as could be shown in Torwiesen 2 (Herbig, 2006). In contrast to model 5 a bog settlement needs no minimum organic accumulation to induce anoxia, because peat forming conditions are already given. At any rate the preservation of such a deposit is heavily dependent on the stability of the moor hydrology, both during and after settlement. The organic remains of a lake side settlement in a reed belt can only be preserved, if the lake's water table has never fallen below the level during or immediately after the occupation of the settlement (left aside effects due to consolidation).

So as a résumé we might state, that in a bog settlement we can find very good preservation of some remains, while we have to expect the overwhelming majority to be degraded. We cannot expect indications of soil development, because the organic deposits formed on organic peat.

6. Conclusions

It is consensus that models only mirror the knowledge of the modellers. Model results should therefore be handled with caution. However, results on organic decay have never been applied systematically on lake side settlements in order to understand the modes of their preservation. Current knowledge on decomposition of organic material suggests that archaeological traces of different deposition and preservation scenarios should differ clearly in their appearance: The best conditions for non lignified carbohydrates to be preserved is under water as part of a very high nutrient rich organic accumulation in shallow water with negligible or at least rare wave action. It is the sheer mass of organic input and degradation that causes oxygen depletion and leads to preservation of organic material. Every deviation from this scenario such as only seasonal flooding would cause stronger degradation but also mass loss due to erosion. Nevertheless, seasonal flooding is a possible scenario for many sites. If the organic matter input (or the remaining input after reduction through erosion) in underwater deposits was too low to induce oxygen depletion, subsequent degradation could also lead to complete decomposition. Therefore there is no need to postulate mechanical erosion or even lake level changes if a cultural deposit is less well preserved.

Deposition in only rarely or even non-inundated mineral-soil environments would necessarily cause a strong degradation gradient within the deposits, certain vertical find distributions and soil development into the underlying sediment. If flooding did not follow soon after occupation, degradation would be very high or complete. This scenario excludes a lower lake level in the millennia after the site's occupation. The consequences of the different scenarios are clear enough defined and even measurable, enabling us to better define what happened at the sites which still exist today and certainly exclude a number of unrealistic scenarios.

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Setting	decay rates
leaves under water	from -3.7 to -9
leaves on bog surface	from -0.16 to -0.45
Evergreen leaves on bog surfaces	from -0.15 to -0.16
leaves on forest soil surfaces	from -0.17 to -0.37
strict anoxia deeply buried	from -0.0001 to -0.0025

Table 1: Ranges of decay rates for different ecological settings as reported in scientific literature. A detailed table is given in the ESM.

Fig. 1: Development of remaining cellulose after burial over 5000 years until excavation. The two lines refer to two different extreme values of possible decay constants during settlement in scenario 1 (see below).

Fig 2: Accumulation and decay of cellulose of the five different scenarios. Note that in scenario 3 the y-axis is 1/10 of the other scenarios. Hundred percent on the abscissa relates to the total amount of deposited organic matter during 15 years of occupation. The shading marks the time until anoxic burial.

Fig. 3: Proportion of the cellulose of single years within the total remaining cellulose in the modeled cultural deposits.

Fig. 4: Detail of the base of a cultural layer at the site of Zurich-Parkhaus Opéra, dating to -3175. The label is 7 cm wide. Under the organic detritus a thin layer of Bioturbation is visible in the lake marl. (Copyright: Underwater Archaeology, Office for Urbanism, Zurich).

Fig. 5: Examples of cultural deposits with traces of soil development from the site of Zurich-AKAD-Presssehaus (Copyright: Underwater Archaeology, Office for Urbanism, Zurich).

Fig. 6: Layer 657 from the site of Zurich-Opéra-Parking with bad organic preservation and traces of coarse bioturbation but no leaching. (Copyright: Underwater Archaeology, Office for Urbanism, Zurich).

→ Using results from research on organic decay such as peat studies, a model of organic preservation in waterlogged sites is presented.

→ The focus is to understand taphonomy in order to interpret excavation data.

→ We demonstrate that some of the common interpretations of archaeologists concerning lake side settlements are highly improbable, especially those that postulate houses on level ground with waterlogged conditions as a consequence of subsequent lake level changes.

→ On lake side settlements our model predicts the best agreement with actual archaeological records in a scenario with deposition in shallow water.

→ One of the most important factors leading to organic preservation is the quick deposition of large amounts of organic material so that the oxygen demand outstrips oxygen supply.

→ Too little organic input will not lead to organic deposits because shallow waters are oxygen rich and decay is quick.

→ Quick consolidation of the deposit is important to reduce oxygen diffusion in interstitial spaces

→ The mechanisms of organic preservation in bog settlements are different from those in lake side settlements.

buried in sediment	under water	changing conditions at water	soil at air	Material	Region	Source	Kommentar	g/kg/dy	remaining	k
-0.04				Typha-leaves	temperate bog	Moore & Basiliko 2006				
-0.0025				Fen-peat	Canadian Fen	Frolking et al. 2001	deeply buried			
-0.0001				bog-peat	Canadian Bog	Frolking et al. 2001	estimate in bog peat deep under water table			
-4.233607				Phragmites-Leaves	Lake Constance	Ostendorp 1992	Protected from erosion in shallow water	2.7	#REF!	#REF!
-5.84				Phragmites-Leaves	Danube delta	Sangiorgio et al. 08	mean of several lakes			
-8				Phragmites-Leaves	Tschech. Fish ponds	Ulehlova 1978	cited after Ostendorp: decayed within 1 year	5.8	#REF!	#REF!
-8.5775				Typha-leaves green		Nelson et al. 1990, cited after Enriquez 1993				
-3.7024				Typha-leaves senesc.		Nelson et al. 1990, cited after Enriquez 1993				
-1.6425				Phragmites-Leaves		Tanaka 1991, cited after Enriquez 1993				
-9.125				Alnus glutinosa		Gessner et al. 1991, cited after Enriquez 1993				
-8.979				Salix		Gessner et al. 1991, cited after Enriquez 1993				
-2.087474				Phragmites-Leaves	Lake Constance	Ostendorp 1992	Protected from erosion in shallow water	2.4	#REF!	#REF!
		-0.05		Fen-peat	Canadian Fen	Frolking et al. 2001	estimate at the water table in fen			
		-0.088		spruce needles	Canadian Bog	Moore & Basiliko 2006				
		-0.32		sedges	poor fen Canada	Moore & Basiliko 2006				
		-0.158		evergreen leaves	Canadian Bog	Moore & Basiliko 2006				
		-0.448		birch leaves	Canadian Bog	Moore & Basiliko 2006				
		-0.22		leaves	Canadian Bog	means of ranges from Moore et al. 2005 cited after Moore & Basiliko 2006				
		-0.15		evergreen leaves	Canadian Bog	means of ranges from Moore et al. 2005 cited after Moore & Basiliko 2006				
		-0.21		Typha-leaves	temperate bog	Moore & Basiliko 2006				
		-0.2555		Fagus leaves		Gosz et al. 1973, cited after Enriquez 1993				
		-0.511		Populus leaves		Aber et al. 1990, cited after Enriquez et al. 1993				
		-0.4015		Quercus leaves		Aber et al. 1990, cited after Enriquez et al. 1993				
		-0.3285		Betula leaves		Berg & Ekbohm 1991, cited after Enriquez 1993				
		-0.365		Fagus leaves		Gosz et al. 1973, cited after Enriquez 1993				
		-0.4745		Fagus leaves		Jørgensen 1991, cited after Enriquez 1993				
		-0.657		Populus leaves		Taylor et al. 1989, cited after Enriquez et al. 1993				
		-0.584		Populus leaves		McLaugherty et al. 1985				
		-0.17		Fagus leaves	Germany	Jacob et al. 2010				
		-0.3		Fagus leaves	Germany	Jacob et al. 2010				

Fazit:

Leaves under water	from -3.7 to -9
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strict anoxia deeply buried	from -0.0001 to -0.0025

Tanaka is outlier due to high levels of nutrients

Setting	decay rates
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