Journal of Archaeological Science (1995) **22**, 409–415

Magnetic and Geochemical Variations as Indicators of Palaeoclimate and Archaeological Site Evolution: Examples from 41TR68, Fort Worth, Texas

Brooks B. Ellwood

Center for Geoarchaeological Studies, UT Arlington Box 19049, Arlington, Texas 76019, U.S.A.

Duane E. Peter

Geo-Marine, Inc., 550 East 15th Street, Plano, Texas 75074, U.S.A.

William Balsam and Jürgen Schieber

Geology, UT Arlington Box 19049, Arlington, Texas 76019, U.S.A.

(*Received 1 February 1994, revised manuscript accepted 15 April 1994*)

The River Bend site, 41TR68, is located on the West Fork of the Trinity River near Fort Worth, Texas, in the Upper Trinity River floodplain. A magnetometer survey was performed at this site to identify hearths, and utilizing these data backhoe trenches were placed adjacent to significant magnetic anomalies. Test excavations were then conducted. Several physical properties measurements, including magnetic susceptibility, an indicator of magnetic mineral concentration, calcium carbonate percentages, and percent spectral reflectance in the red colour range were performed on samples from stratigraphic sections adjacent to two excavation units at the site.

The data are interpreted in terms of cultural and palaeoclimatic controls during sediment accumulation. Distinctive peaks in all parameters were exhibited by samples associated with hearths and shell concentrations. Broad magnetic susceptibility highs, indicative of high magnetic mineral concentrations, are closely associated with hearths and result from the production of new magnetic minerals by chemical redox reactions during heating. Variations in red spectral reflectance percentages, indicative of hematite mineral concentration, appear to be the result of pedogenesis at the site and therefore are controlled primarily by climate. Susceptibility highs are correlated with reduced hematite concentrations, apparently resulting from the chemical reduction of hematite during heating. Calcium carbonate percentage peaks are indicative of shell debris concentrations from mollusks which were an abundant food source at those times. Superimposed on these peaks are broad variations in calcium carbonate percentages which reflect palaeosol development at the Riverbend Site and suggest the presence of several indistinct palaeosols.

While overall variations appear to be the result of palaeoclimate, we interpret the local variations associated with hearths to result from several factors. First, the presence of abundant carbonate and sulphur at the site has resulted in the formation of authigenic iron carbonate and iron sulphide minerals from dissimulatory iron reduction by bacteria during pedogenesis. Second, at low temperatures these iron carbonates and sulphides oxidize to highly magnetic mineral phases, including magnetite and maghemite, thus increasing the observed magnetic susceptibility in samples acquired from the site. And third, at moderate temperatures, produced in sediments surrounding and beneath hearths, the abundant hematite at the site is reduced to maghemite, thus further increasing the magnetic susceptibility in the samples collected.

Keywords: GEOARCHAEOLOGY, MAGNETIC SUSCEPTIBILITY, SPECTRAL REFLECTANCE, PALEOCLIMATE, TEXAS.

Introduction

The River Bend site, 41TR68, is located on the West Fork of the Trinity River near Fort Worth, Texas (Figure 1 inset), within the Upper Trinity River floodplain forest zone. The floodplain forest supports a wide variety of food resources which were attractive to prehistoric hunters and gatherers. Although the Trinity River floodplain is an ideal location for archaeological sites, the discovery of archaeological settings has been hampered because of burial depth. It is apparent that both

0305-4403/95/030409+07 $08.00/0

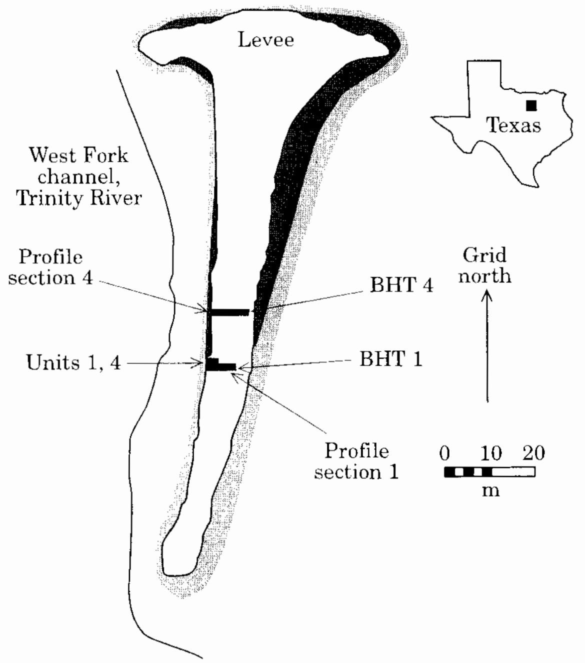

Figure 1. Plan view of the River Bend site, 41TR68, in northeast Texas, with backhoe trench (BHT) and excavation unit locations. Shaded contours represent decreasing elevations in areas which were being removed by construction crews. The solid line to the west of the levee represents the river's edge.

palaeoenvironmental and archaeological studies are generally only feasible in the upper sections of the floodplain.

The River Bend site is situated on a narrow peninsula between the recently active channel of the West Fork of the Trinity River and the channelization efforts of a local developer. Burned rock associated with hearths and mussel shells was visible for 130 m along both sides of the peninsula, which is only 10–15 m wide (Figure 1). This cultural material was eroding from the upper 1·5 m of the West Fork palaeosol, the top of which is located 0·3–0·8 m below the present floodplain surface. Other than the cutting action of the river channel and the borrow pit activities, there had been little disturbance of the site context. Brush and timber placed on the site had effectively prevented any further disturbance of the site area. Initial examination of the site indicated that occupation surfaces were located within the buried West Fork palaeosol and excavation revealed that several occupation episodes are represented. The locality apparently served as a specialized foraging camp between AD 850 and AD 1300 (Peter *et al.*, 1987).

It was the purpose of this work to characterize the effect of fires associated with hearths, the spectral colour variations and the carbonate horizons on the magnetic properties of sediments at the River Bend site. Using magnetic anomaly data obtained from the proton magnetometer, probable subsurface hearth sites were identified, and these were exposed. Closely spaced samples were collected from a profile close to a zone containing two hearths and several discrete, thin carbonate horizons, and from a profile that appeared to be hearth-free but also contained discreet, thin carbonate horizons. The magnetic properties of these samples were analysed. Samples from the profiles were used to study the magnetic properties of palaeosols at the site and to characterize the modifying effect of hearths on these magnetic properties. Following this work, most of the site was removed by the developer; a small segment of the site has been preserved for future study. A video, entitled "*Applied Geoarcheology*", documenting much of the work performed at the site, was televised on PBS in the Dallas–Fort Worth metro area (Pratt & Ellwood, 1988).

Methods

A magnetic survey was performed at 41TR68 using a two-bottle proton magnetometer (Williams & Williams, 1984). Based on the magnetic patterns, several backhoe trenches (BHTs) were excavated near but not immediately over areas with distinct magnetic anomalies. A series of small sediment samples were taken for geochemical and magnetic susceptibility studies from the wall of BHT 1, close to where two stacked hearths were exposed. BHT 1 actually intersected the edge of these hearths. A second set of samples were recovered from BHT 4, approximately 15 m to the north of BHT 1 (Figure 1), where no magnetic anomalies were observed and from where very little cultural material was recovered.

Geochemical and magnetic susceptibility measurements

Two profiles of 8 cc sediment samples were collected, one from BHT 1 and one from BHT 4 (Figure 1) by pushing small plastic sample boxes into the exposed sides of each trench and returning the boxes filled with sediment to the laboratory for analysis. A continuous vertical sequence of unoriented samples was recovered from BHT 1, covering the stratigraphic interval of 99·3–97·21 m (relative to main datum at the site; $N=82$). A suite of unoriented samples was also recovered from BHT 4 covering the stratigraphic interval of 99·78–97·81 m ($N=74$). High resolution calcium carbonate percentages, magnetic susceptibility measurements and spectral reflectance values over the range of 250–850 nm were determined for each of these samples.

Magnetic susceptibility measurements

Magnetic susceptibility (χ), is a fundamental property of all materials. When used in an archaeological or geological context, it is generally considered an indicator of iron mineral concentration (Nagata, 1961), that can be quickly and easily measured on small samples using a susceptibility bridge. Iron-containing mineral grains within samples are "susceptible" to becoming magnetized in the presence of a magnetizing field. The measurement is made by placing samples in a small magnetic field and measuring the resulting magnetization. A common expression for magnetic susceptibility is

$$M = \chi H \qquad (1)$$

where χ is a proportionality constant relating an inducing magnetic field, H to an induced magnetization, M. Susceptibility for samples reported here was measured using a susceptibility bridge calibrated with standard salts. The bridge was built for high sensitivity and has a square access coil slightly larger than the cubic boxes used to collect samples. Therefore, the cross-sectional measurement space is at a minimum for these measurements ensuring maximum sensitivity. The practical sensitivity limit for the bridge is $1 \pm 0{\cdot}2 \times 10^{-9}$ m^3 per kg.

Susceptibility can be affected by a number of natural and man-made processes. New, highly magnetic mineral phases, primarily the iron oxide minerals magnetite and maghemite which increase the susceptibility in sediments, are readily produced during weathering (Ellwood *et al.*, 1986), by bacterial organisms (Frankel *et al.*, 1979) due to chemical reduction during organic matter decay, and by chemical oxidation in association with natural or man-made fires. Increases in magnetic mineral concentrations result in corresponding increases in magnetic susceptibility.

Climate is also clearly important in the development of magnetic susceptibility signatures in sediments, due primarily to variations in magnetic mineral production during pedogenesis. For example, magnetic susceptibility curves from Chinese loess sequences have shown close correlations with oxygen isotope curves (Heller & Liu, 1982; Kukla *et al.*, 1988), known to reflect climatic cycles (e.g. Imbrie *et al.*, 1984). This work has shown that during glacial periods, when pedogenesis is at a minimum, χ is low, but during interglacials when pedogenesis is high, χ is also high (e.g. Kukla *et al.*, 1988).

Percentage carbonate measurements

Calcium carbonate is often measured by geoarchaeologists working with archaeologists in caves and rock shelters (Laville *et al.*, 1980), but is not routinely measured during archaeological investigations. Weight percent carbonate was determined for each sample from BHT 1 and BHT 4 using the Vacuum Gasometric Technique described by Jones & Kaiteris (1983). Precision is $\pm 0{\cdot}25\%$, a little better than for the gasometric method used by most geoarchaeologists, which is $\pm 0{\cdot}3\%$ for very careful measurements (Dreimanis, 1962). We used the method of Jones & Kaiteris (1983) because it is inexpensive, offers excellent precision and is fast. Samples were ground to a size of less than 38 μm and dried for at least 10 h at 50°C. Approximately 0·2 g of sediment were immersed, under vacuum, in 5 ml of concentrated (85%) phosphoric acid for 1 h. Pressure generated by the reaction was measured on a pressure measurement manifold. Weight percent carbonate was calculated by comparing the pressure generated by the sample to pure calcium carbonate after correcting for temperature and atmospheric pressure.

Spectral reflectance measurements

Visible light spectra (VIS) in the red colour range give an indication of hematite concentration in sediments. VIS of samples from BHT 1 and BHT 4 were determined on a Perkin-Elmer Lambda 6 reflectance spectrometer with a diffuse reflectance attachment. This machine consists of a light source, a moving grating used to separate light into different wavelengths, and a photomultiplier tube to measure the intensity of light reflected from the sample surface. Reflectance intensity, which is recorded as a function of wavelength, is the ratio of the amount of light reflected from a sample divided by the amount of light incident on it. The intensity of light reflected from a surface is measured by comparison to pure white standard.

The data were analysed at 10 nm intervals throughout the visible light spectrum. Analysis included determination of the percentage of reflectance in standard colour bands in addition to determination of sample brightness calculated by summing reflectance values at 10 nm intervals in the VIS. In addition, the first derivative of each curve was calculated to estimate the percentage of hematite present in the sample (Deaton & Balsam, 1991). Sample preparation for spectral analysis (Balsam & Deaton, 1991) was performed as follows: (1) the sample was ground to less than 38 μm and dried at ~50°C for at least 10 h; (2) ~0·15 gm of sample were placed on a clean glass microslide (2·5 × 3·5 cm) and suspended in five drops of distilled water; (3) the slurry was mixed and smoothed with a spatula and dried at low temperature (<40°C).

Results and Discussion

Correlation of the sequences within different units at any site is often severely hindered by the depositional or site construction context. It appears that aggradation of the West Fork palaeosol at 41TR68 was very slow and most likely variable. Consequently, the same surface may have been occupied repeatedly or flood sediments may have been deposited between occupations. Correlation of the spatially separated units at the site is therefore quite tenuous, but using geoarchaeological methods such as those discussed below, such correlations are possible. The primary results of the excavation at 41TR68 are reported elsewhere (Peter *et al.*, 1987).

Stratigraphy

Approximately 7·5 m of sediment was exposed in the cut-bank of the West Fork of the Trinity River at the River Bend site. The upper portion of this unit (between 0·75–2·5 m; corresponding to a depth of approximately 99·25–97·5 m below main datum) consisted of a tough, plastic-like palaeosol containing dark brown clay with minor amounts of silt, exhibiting a vertical prismatic structure. At 0·75 m an undulating erosion surface occurs. The prismatic structure extends to the present day surface and is typical of the B-horizons found in clay-rich soils that undergo seasonal dehydration. Because the prisms extend to the present day erosional surface, it is inferred that the A-horizon has been partially eroded.

The paleosol contains archaeological remains from 0·20 to 1·40 m below its surface. Dates from charcoal recovered from occupation surfaces at the site reveal that the site was still occupied at least as late as AD 1300. Ages at 41TR68 range from AD 860 ± 70 (corrected ^{14}C Beta-22028 age) to AD 1330 ± 100 (corrected ^{14}C Beta-22488 age). Artefacts found above the erosional surface at 0·75 m are considered to be reworked and out of context.

Sediments at the site exhibit characteristics typical for deposits associated with meandering streams (Reineck & Singh, 1980), and contain high proportions of mud with mean sediment size fining upwards. Thickness and maturity of the near-surface paleosol horizon (up to 2·5 m thick) indicates a long period of only minor vertical accretion (Birkeland, 1974). Dominance of mud and silt as well as rootlet traces and partial destruction of primary sedimentary structures within the central portion of the section (~5 to 2·5 m) represent flood plain deposits. The basal portion of the exposed section (~7·5 to 5 m) probably represents a fining upward point bar sequence deposited during lateral migration of the Trinity River channel.

The sedimentary sequence can be interpreted with regard to sedimentation rates, which are an important control on the archaeological variability that is to be expected (Ferring, 1986*a*,*b*). For example, the point bar portion of the exposed sequence shows well-preserved primary sedimentary structures and was deposited relatively quickly, indicating high sedimentation rates. The floodplain sediments were deposited at intermediate sedimentation rates, while the well-developed palaeosol horizon resulted from very low sedimentation rates. Thus, the palaeosol horizon was expected to contain the highest artefact density at the site. This prediction was realized during excavation at 41TR68.

Physical properties measurements

A unique aspect of this work is our ability to correlate units at the River Bend site using geochemical, magnetic and spectral data. Magnetic susceptibility data

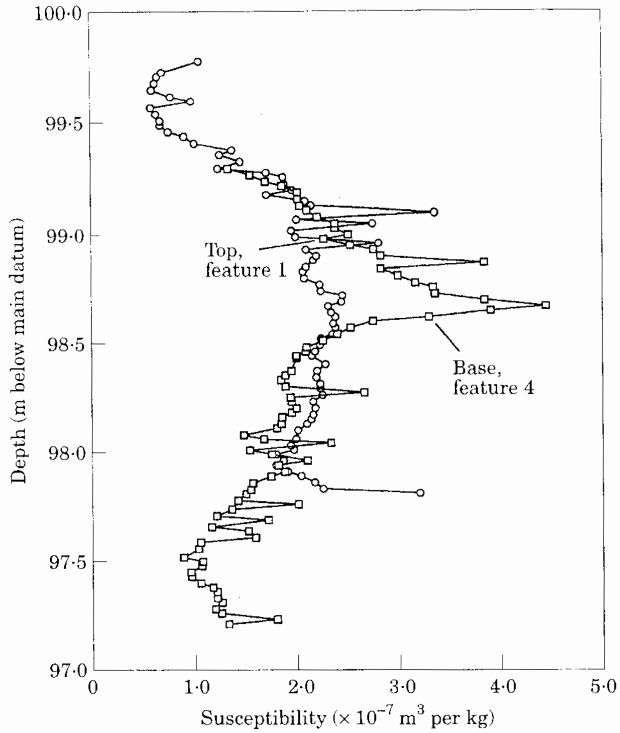

Figure 2. Microstratigraphy for 41TR68 for two sampled sections: □—□, BHT 1 (section 1); ○—○, BHT 4 (section 4). Susceptibility (χ) values range from 0·45–4·42 × 10^{-7} m^3 per kg. Depth represents stratigraphic level below the main datum at the site. Samples do not extend to the modern-day surface.

for samples from BHT 1 and BHT 4, separated by ~15 m (Figure 1), are reported in Figure 2. A set of distinctive susceptibility peaks were found in section 1 from BHT 1, associated with two well defined hearths excavated in units 1 and 4 (Figure 1). The superimposition and close proximity of these features to section 1 (labelled features 1 and 4 in Figure 2) has resulted in a broad susceptibility peak, extending over ~0·3 m of the section. Other pronounced peaks in section 1 probably represent hearths located at different stratigraphic levels than features 1 and 4, but at some distance from section 1.

Section 4 shows the overall trends in susceptibility, magnitudes and shapes exhibited by section 1, except for the large susceptibility bulge produced by features 1 and 4 in section 1, and a departure toward higher susceptibility's in four samples at the base of section 4. This departure is probably due to an unrecognized and unexcavated hearth near to section 4. A few one- or two-point deviations are seen in the χ values from these profiles, but these do not represent trends and are typical for χ data sets (Ellwood *et al.*, 1994).

Other parameters, high resolution calcium carbonate percentages and spectral reflectance in the red visible light range also show good correlations between sections 1 and 4. For example, calcium carbonate exhibits close similarity between cores to a depth of 98 m,

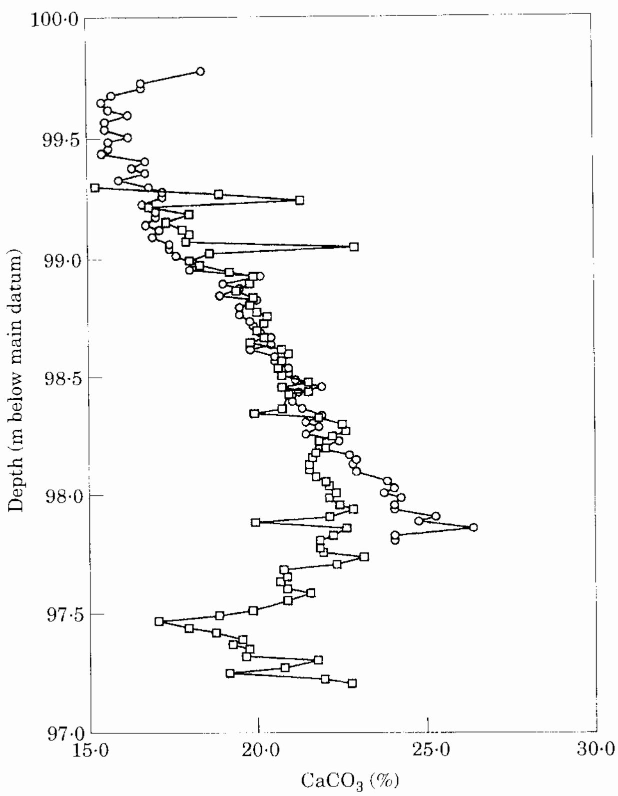

Figure 3. Calcium carbonate ±0·25 (values range from 15·2 to 26·4%) for sections 41TR68-1 and 41TR68-4. Depth and key as in Figure 2. No distinct effect from features 1 or 4 (identified in Figure 2) is observed in this data set.

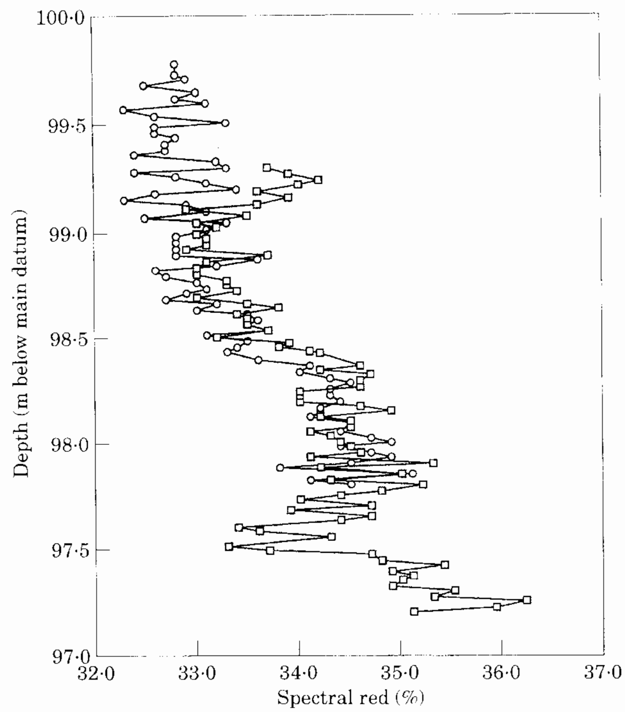

Figure 4. Spectral red colour (32·3–36·2%) as a percentage of total reflectance of red (630–700 nm) relative to the visible light range, 400–700 nm. Data for sections 41TR68-1 and 41TR68-4 are reported. The 400–700 nm reflectance data result primarily from hematite (Deaton & Balsam, 1991). Depth and key as in Figure 2.

where a distinct difference emerges between sections 1 and 4 (Figure 3). This difference is the result of locally high shell densities within section 4. These local $CaCO_3$ highs appear to result from man's concentrating the calcium carbonate shells. Spectral reflectance in the red visible light range, indicative of the presence of hematite in samples, shows larger scatter than either magnetic susceptibility or $CaCO_3$ (Figure 4). There is a good correlation between BHT 1 and BHT 4 samples with the exception of the upper portions of the sampled sections (above 99·1 m).

The combined carbonate data from sections 1 and 4 are interpreted to show a complete palaeosol, including both the A and B horizons, from ~97·5 m to 99·5 m, the base of a second B horizon from 99·5 m to the top of the section, and the top of a third paleosol, from the base of the sections to 97·5 m (Figure 3). The upper portion of the uppermost palaeosol is eroded and the lower portion of the lowermost palaeosol was not sampled, but the middle palaeosol, containing most of the artefacts recovered from the site, appears to be essentially complete. The complete palaeosol is characterized by low $CaCO_3$ percentages at the top and bottom with a generally increasing $CaCO_3$ content with depth in the B horizon until just above the base of the unit. The A horizons at ~99·5 m and ~97·5 m show the lowest $CaCO_3$ values due to leaching and reprecipitation in the underlying B horizons. Magnetic susceptibility variations also show low values in these A horizons and highs in the B horizon (Figure 2). These variations are interpreted to result from chemical reduction and mobilization of the iron in the A horizon, followed by concentration and oxidation in the B horizon during pedogenesis.

Iron carbonates and sulphides in soils

It has long been known that weathering and pedogenesis commonly releases Fe^{2+} (e.g. Krauskopf, 1967) and that the formation of secondary iron-bearing minerals depends on the E_h–pH conditions in the soils (e.g. Garrels & MacKenzie, 1971). Recently, several bacteria have been observed in laboratory experiments and in natural sediments to precipitate iron oxides, carbonates and sulphides by dissimulatory iron reduction (Bell *et al.*, 1987; Lovley *et al.*, 1987). For example, Bell *et al.* (1987) predicted the formation of a variety of iron minerals, including siderite, from E_h–pH geochemical equilibrium models. The outcome depends upon the form of the substrate (carbohydrate or organic acid), E_h–pH conditions, and the levels of mineral reactants in the cultures (Bell *et al.*, 1987). In the presence of sulphide ions, Fe^{2+} produced during dissimulatory iron reduction should favour production

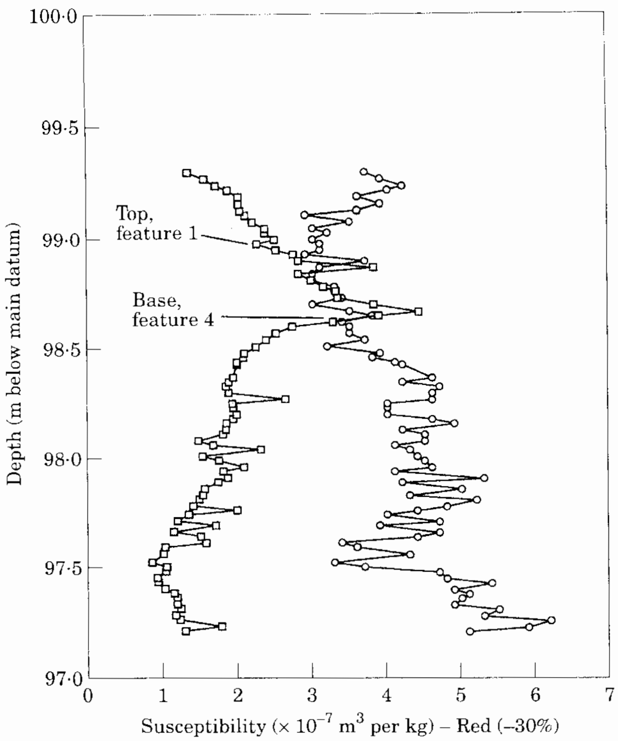

Figure 5. Comparison of susceptibility (□—□) and spectral red (○—○) for samples from 41TR68-1. Depth as in Figure 2. Note the clear inverse relationship between these two parameters at depths in the section corresponding with two hearths identified as features 1 and 4.

of iron sulphides, but this outcome is strongly influenced by microenvironmental conditions. Depending upon E_h–pH relationships, reduction to Fe^{2+} leads to the production of siderite or pyrite (Bell *et al.*, 1987). The appearance of both pyrite and siderite suggests that processes controlling the formation of these minerals are not mutually exclusive but probably occur simultaneously in adjacent microenvironments (Ellwood *et al.*, 1988).

Iron variations at 41TR68

There is a striking inverse correlation between χ and spectral red at depths in section 1 where features 1 and 4 (the two hearths) are located (Figure 5). Initially, this inverse correlation between two iron content indicators was a surprise. Susceptibility is dominated by relatively magnetic mineral phases like magnetite and maghemite, and these appear to increase in the sediments associated with the hearths at features 1 and 4. Hematite, responsible for the red spectral changes, is controlled primarily by climate but decreases in the zone of heating around the hearths. We had expected increasing spectral red, due to fire oxidation, and decreasing χ. Instead, decreasing red but increasing χ suggests that the iron in hematite was chemically reduced to allow the formation of maghemite or magnetite. This is probably due to chemical reduction by the abundant carbon found in hearths and the early removal of oxygen during heating. In the sediments surrounding such fires, chemical reduction appears to have been active, thus destroying the hematite. In samples taken at some distance away from features 1 and 4, the inverse correlation between red and χ disappears and these parameters show better correlations. Such a correlation was expected because maghemite as well as hematite is also produced in soils during pedogenesis.

The sediments at 41TR68, forming right at the edge of the Trinity River where periodic flooding creates swamp-like conditions, have abundant carbonate (Figure 3). As discussed above, in such environments pyrite (FeS_2) and siderite ($FeCO_3$) are expected to form as authigenic minerals, tying up the iron (i.e., Postma, 1982). Heating such sediments has two effects on the iron. Initially, oxidation of siderite produces maghemite (Ellwood *et al.*, 1986), and later, at higher temperatures after the oxygen diminishes, chemically reduces the iron in hematite to maghemite. Both processes have the effect of increasing χ in the fired zone. Thus man-made fires modify the natural pedogenetically formed iron minerals in sediments.

Methodological implications for other geoarchaeological studies

We utilize here three different but complimentary methods in our study of 41TR68: magnetic susceptibility, calcium carbonate percentage and spectral reflectance percentage in the red range. Because all materials exhibit magnetic susceptibility, such measurements provide a parameter which can be very useful in solving a broad range of problems at any archaeological site where sedimentary materials are available for measurement. Calcium carbonate variations provide a useful, complimentary sedimentological tool for interpreting palaeosol development, and can be useful in areas where sediment samples exhibit low to moderate carbonate percentages. However, in caves or rock shelters, where carbonate percentages are high, the utility of carbonate measurements may diminish. The utility of susceptibility measurements also appears to diminish when carbonate percentages are extremely high. Spectral reflectance data are useful when combined with magnetic susceptibility measurements to characterize the type of magnetic material present in samples. The two parameters together allow one to determine those mechanisms that produced the minerals responsible for the observed magnetic variations; including climate, chemical alteration effects, biological effects, or man's influence on the environment.

Of these parameters, susceptibility is easiest to measure and instrumentation is simple and commercially available at a reasonably low cost. However, care must be taken to evaluate each suite of samples to ensure that the instrument used has enough sensitivity to measure with sufficient precision the range of samples being studied. Calcium carbonate percentages are also relatively easy to measure, and high precision instruments can be built for low cost. Many laboratories performing geoarchaeological measurements already have carbonate instrumentation available. Instruments to measure spectral reflectance are expensive and are not available to most geoarchaeology investigators.

Conclusions

Test excavations were performed at 41TR68, the River Bend site, located along the West Fork of the Trinity River near Fort Worth, Texas. These were preceded by a magnetometer survey which was conducted to aid in identifying hearth locations and other cultural activity areas. Physical properties measurements, including magnetic susceptibility (χ), calcium carbonate percentages and spectral reflectance percentages in the red colour range, were performed on samples from two stratigraphic sections from the site. Characteristic curves for these parameters provide an effective method for intra-site correlations. Distinctive peaks in χ were exhibited by samples associated with hearths, and can be explained by several factors. Magnetic susceptibility highs in sediments associated with the hearths at the site result from the production of new magnetic minerals due to two effects during heating. First, at lower temperatures, chemical oxidation of siderite (and possibly other effects such as oxidation of pyrite) produced the magnetic mineral maghemite with corresponding increases in χ. Second, at higher temperatures, chemical reduction after oxygen availability diminishes causes the reduction of some of the hematite to maghemite. The effect of this process is to increase χ and decrease spectral red in the vicinity of hearths.

Calcium carbonate peaks reflect the use of mollusks, abundant in the area, as food and provide calcium for the formation of siderite. The calcium carbonate variations also delineate a set of three palaeosols, one relatively complete, in the sections sampled. With the exception of reworking and near-surface scatter, the relatively complete palaeosol contains the artifacts found at the site.

Spectral red variations reflect hematite variations developed primarily during pedogenesis at the site. While these variations are locally effected by heating in hearths, overall variability appears to be controlled by climatic variations during pedogenesis.

Acknowledgements

Funding for this project was provided by Newell and Newell Development Corporation. We would like to thank Paul and Jan Lorrain, and Sue, Amber, Robin and J. Richard Ellwood for their help in excavation of the site.

References

Balsam, W. & Deaton, B. C. (1991). Sediment dispersal in the Atlantic Ocean: evaluation by visible light spectra. *Reviews in Aquatic Sciences* **4**, 411–447.

Bell, P. E., Mills, A. L. & Herman, J. S. (1987) Biogeochemical conditions favouring magnetite formation during anaerobic iron reduction. *Applied Environmental Microbiology* **53**, 2610–2616.

Birkeland, P. W. (1974). *Pedology, Weathering and Geomorphological Research.* New York: Oxford University Press.

Deaton, B. C. & Balsam, W. (1991). Visible spectroscopy—a rapid method for determining hematite and geothite concentration in geologic materials. *Journal of Sedimentary Petrology* **61**, 628–632.

Dreimanis, A. (1962). Quantitative gasometric determination of calcite and dolomite by using Chittick apparatus. *Journal of Sedimentary Petrology* **32**, 520–529.

Ellwood, B. B., Balsam, W., Burkart, B., Long, G. J. & Buhl, M. L. (1986). Anomalous magnetic properties in rocks containing the mineral siderite: paleomagnetic implications. *Journal of Geophysical Research* **91**, 12,779–12,790.

Ellwood, B. B., Chrzanowski, T. H., Hrouda, F., Long, G. L. & Buhl, M. L. (1988). Siderite formation in anoxic deep-sea sediments: a synergetic bacterially controlled process with important implications in paleomagnetism. *Geology* **16**, 980–982.

Ellwood, B. B., Harrold, F. B. & Marks, A. E. (1994). Site identification and correlation using geoarchaeological methods at the Cabeço do Porto Marinho (CPM) locality, Rio Maior, Portugal. *Journal of Archaeological Science* **21**, 779–784.

Ferring, C. R., (1986*a*). Late Quaternary geology and environments of the Upper Trinity Basin. In (B. Yates & C. R. Ferring, Eds) *An Assessment of the Cultural Resources in the Trinity River Basin, Dallas, Tarrant, and Denton Counties, Texas.* Institute of Applied Sciences, North Texas State University, pp. 32–109.

Ferring, C. R. (1986*b*). Rates of fluvial sedimentation: implications for archaeological variability. *Geoarchaeology* **1**, 259–274.

Frankel, R. B., Blakemore, R. P. & Wolfe, R. S. (1979). Magnetite in freshwater magnetotactic bacteria. *Science* **203**, 1355–1356.

Garrels, R. M. & MacKenzie, F. T. (1971). *Evolution of Sedimentary Rocks.* New York: W. W. Norton.

Heller, F. & Liu, T. S. (1982). Magnetostratigraphical dating of loess deposits in China. *Nature* **300**, 431–433.

Imbrie, J., Hays, J. D., Martinson, D. G. *et al.* (1984). The orbital theory of Pleistocene climate: support from a revised chronology of the marine delta ^{18}O record. In (A. L. Berger *et al.*, Eds) *Milankovitch and Climate, Part I.* Boston, MA: Reidel, pp. 169–305.

Jones, G. A. & Kaiteris, P. (1983). A vacuum-gasometric technique for rapid and precise analysis of calcium carbonate in sediment and soils. *Journal of Sedimentary Petrology* **53**, 655–660.

Krauskopf, K. B. (1967) *Introduction to Geochemistry.* New York: McGraw-Hill.

Kukla, G., Heller, F., Liu, X. M., Xu, T. C., Liu, T. S., & An, Z. S. (1988). Pleistocene climates in China dated by magnetic susceptibility. *Geology* **16**, 811–814.

Laville, H., Rigaud, J.-P. & Sackett, J. (1980). *Rock Shelters of the Perigord.* New York: Academic Press.

Lovley, D. R., Stolz, J. F., Nord, G. L., Jr. & Phillips, E. J. P. (1987). Anaerobic production of magnetite by a dissimilatory iron reducing microorganism. *Nature* **330**, 252–254.

Nagata, T. (1961). *Rock Magnetism.* Tokyo: Maruzen Company.

Peter, D. E., Ellwood, B. B., Schieber, J. & Yates, B. (1987). *Test excavations of the River Bend Site (41TR68).* Report submitted to the U.S. Army Corps of Engineers.

Postma, D. (1982). Pyrite and siderite formation in brackish and freshwater swamp sediments. *American Journal of Science* **282**, 1151–1183.

Pratt, C. & Ellwood, B. B. (1988). *Applied Geoarcheology.* UT Arlington Television, 20 minutes.

Reineck, H. E. & Singh, I. B. (1980). *Depositional Sedimentary Environments*, 2nd edition. New York: Springer.

Williams, J. M. & Williams, M. (1984). A new differential proton magnetometer, *On File.* The Lamar Institute, Watkinsville, GA.